# Appendix 2
## Research Area Summaries

UKCCSRC Research Area Champions, in conference with other stakeholders where possible, have also prepared summaries of research needed in different areas and possible pathways to delivery for missing impacts.

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CCS Systems
Nilay Shah

Systems modelling and engineering as relevant to CCS covers four main areas: (i) unit operation analysis and design; (ii) systems integration of different components/technologies; (iii) whole system analysis and assessment and (iv) engineering design and scale up.

The systems engineering theme has a number of distinct elements which can be viewed in a “bottom-up” fashion:

- Individual unit operation/component modelling, optimisation and design. This is particularly important for novel processes (e.g., looping cycles for capture, new CO₂ compressors, sub-sea pipeline and CO₂ injection monitoring and modelling). It is best undertaken in conjunction with experimental studies and should be used to support systems engineering and scale-up of individual technologies relevant to CCS. An example project could be “Systems Engineering of Chemical Looping Combustion Technologies”. Both steady state and dynamic performance are of interest.

- Systems integration: this explores the issues around the integration of individual technologies (e.g., options for integrating capture plans and power plants or for integrating biomass in CCGTs with CCS). It explores what the options are for such integration (e.g., gasify the biomass or combust it in the HRSG) and how system performance (economic, energetic, environmental, safety and operability etc.) depends on integration structures and specific parametric degrees of freedom.

- Whole systems design and operational analyses: this uses models to explore configurations of whole systems (power generation, capture, compression and transmission, injection and storage). Interesting topics include understanding how best to optimise cost and minimise environmental impact, based on a rigorous and transparent methodology based on comprehensive life cycle analyses, in evolving networks, understanding dynamic operability, the effects of impurities and flow/pressure transients etc.

- Model reduction techniques: this involves moving from rigorous descriptions to a more simplified description, e.g., moving from a MS diffusion model to a meta-model approach. This enhances the suitability of the models for control and optimisation studies in addition to multi-source – multi-sink network studies.

- Engineering scale-up, impacts on other system components and RAMO: this experiment-led activity takes the preferred integration options from the above and explores the practical issues associated with engineering efficient and reliable systems, while also providing data for model validation. These studies use the Centre’s pilot-scale ‘shared’ facilities to run trials at simulated (and controlled) design, off-design and upset conditions in order to:
  - confirm the practical operating envelopes (e.g., avoiding degradation of solvents, sorbents and catalysts),
  - identify the preferred control strategies and monitoring needs,
  - determine the partitioning of fuel and other process-related species/contaminants
  - address the impacts on other system components (e.g., fouling and erosion),
  - define materials and manufacturing limitations, and
  - determine component and overall system reliability.
Along with techno-economic analysis, this aims to reduce the technical and commercial risks of further industrial scale-up.

In terms of analyses, most research uses some form of multiscale modelling concept, whereby higher level models can be used as quick screens between different alternatives and more detailed models used to explore the details of component performance and to drive systems optimisation.

**Research challenges: core and peripheral**

**Core**

- Building a technology evaluation platform: the “virtual system” concept. The aim here is to develop a model-based platform within which new technologies (power generation, capture, compression, transmission, injection and storage etc) can be included to understand their potential for improvement in whole systems performance and opportunities for systems integration. This could build upon the existing NERC and ETI projects. The aim is to develop an open-source “plug-and-play” system modeller which includes library components (power plant components, capture components, compression and transmission and injection) at a moderate level of fidelity. These can be used by the user to explore different configurations and understand issues around multiple source CCS systems, system operability, new design and operation insights etc. By defining clear protocols, users can also develop models of new components and explore their ability to be effectively integrated. Members are encouraged to contribute their individual models to the library to get the programme up and running as quickly as possible.

- Development and validation of dynamic process models key to supporting likely scenarios of “flexible fossil fuel + CCS” – this requires a tight integration between modelling and pilot/demo scale equipment to ensure that the models are sufficiently detailed to capture the necessary physics whilst concurrently being suitable for long-term dynamic simulation.

- Multi-scale modelling approaches for developing capability in linking high-fidelity models (e.g. CFD) with less computationally demanding models for evaluation of different capture and power sources within a network.

- Model-based exploration and scale-up of key next generation capture technologies. A small number of next generation technologies should be selected; these will be modelled with a view to understanding the key performance-determining phenomena which can then support further experimental research. The models will be developed to be compatible with the platform (to which they will be added) and periodically updated with new experimental data. This should exploit the CFD and bioenergy capabilities within the membership.

**Peripheral (supported by external or flexible funding)**

- Work on thermodynamics (including new solvent design, e.g. IL) and impurities

- Integrating novel CO₂ utilisation technologies

- Integration of industrial sources of CO₂ into the CCS network (see industrial RAPID)

- Whole energy/system minimisation of CO₂ emissions from UK plc

- Negative emissions technologies (biomass integrated CCS) and whole systems
Adsorption and Membranes
Stefano Brandani

In the development of second generation carbon capture technologies Adsorption and Membrane processes will play a key role in reducing overall costs and energy penalties of carbon capture from power plants and industrial large scale emitters. In a recent report prepared by NETL for the US Department of Energy (March 2012), looking at post-combustion capture from coal fired power plants, both adsorption and membrane processes were identified as next generation capture technologies capable of achieving the DOE target of less than 35% energy penalty of the combined capture and CO2 compression facility (http://www.netl.doe.gov/energy-analyses/pubs/NETLDOE20121557.pdf). These conclusions are based on an analysis of a complete flowsheet for the integrated process and include details of both CAPEX and OPEX costs. Similar conclusions can be drawn for pre-combustion capture approaches and in both cases the advancement of the technology must rely on improvements in both materials and processes. This will require close collaboration between chemists and engineers and this is a key strength of the UK.

The RCUK Energy programme, through a series of research projects on both coal and gas generation either ongoing or soon to commence, is already providing significant support to this theme. The work being carried out is at the forefront internationally and is exploring a wide range of novel nanoporous materials (Zeolites and Metal Organic Frameworks from St Andrews; Polymers of Intrinsic Microporosity from Cardiff and Manchester; Carbons with functional groups including amines from Edinburgh, Manchester, Nottingham, Strathclyde, UCL). The strength from the materials’ development can also be used to explore combinations of adsorbents and polymers to develop mixed matrix membrane materials. From the process side, the challenge comes from the requirements for carbon capture units which have very high constraints on both purity and recovery. This means that conventional configurations are not feasible and advanced cycles and multi-stage or hybrid systems are being considered. For adsorption processes an additional requirement is to push the technological development towards fast cycles, which in turn leads to requirements on forming materials into structured packings and rapid kinetic response. For membranes there is the need to optimise multistage configurations and integrate them also in the initial compression stages.

Adsorption and membrane processes will play an important role also in additional fields relevant to CCS:

- Gas conditioning before the final compression stages.
- Enhanced Oil Recovery – once the CO2 breaks through there will be the need for new offshore gas separations solutions which require high efficiency and very small footprint.
- Improved pre-treatment of Air Separation Units, potentially coupled to direct air capture.
- Abatement of emissions of amine based degradation products on first generation carbon capture processes.

To aid the deployment of these technologies in a wide range of conditions (temperature, pressure and composition) there is also the need to develop further the laboratory testing capabilities in order to determine the equilibrium and kinetic properties needed for rigorous dynamic models.
Moreover, some of the most promising carbon capture nanomaterials, such as MOFs, PIMs, and functionalized carbons and silicas, are currently manufactured only at the lab scale using batch synthesis methods. Before any of these materials can be applied economically at an industrial scale, or even tested on a large scale, these synthesis processes will need to be scaled-up using continuous processing. Because most of these materials are synthesized in solution through nucleation and growth processes, this is a non-trivial problem and substantial scale-up research will be needed.

There is a clear opportunity here for the UK to become a leader in high value manufacturing of carbon capture materials, and some work is already in progress towards this at Strathclyde. There is already a significant research activity in the UK and this should be developed into a UK-wide facility open to both academic and industrial access.

**Priority challenges and research areas**

**Materials:**
- Novel nanoporous solids for both adsorption and membrane processes.
- Mixed matrix membranes (MMMs).
- Further research on PIMs – these materials have been invented in the UK and are now being investigated worldwide. We should be investing resources to maintain and improve our lead position.
- Development of structured monoliths and packings.
- Improved asymmetric membrane modules for MMMs.
- Slip-stream access and small scale movable testing units for rapid evaluation of material stability to impurities in flue gases (SO$_x$, NO$_x$, etc.)

**Processes:**
- Prototype multistage processes for lab scale testing requiring small sample quantities (less than 10 kg).
- Hybrid process configurations for both low and high pressure conditions.
- Slip-stream access to test processes and deployment of larger scale pilot tests.

**Material testing and manufacture:**
- Development of standard protocols and automated techniques for the determination of properties, including kinetic properties. This is needed to facilitate direct comparisons.
- Development of a UK facility for testing nanoporous solids for adsorption and membrane processes open to shared access from academic and industrial users. The facility should combine fundamental measurements and a range of process configurations to accelerate the deployment of novel or existing materials.
- Development of methods for scale-up and continuous manufacture of carbon capture nanomaterials. This is needed to translate lab-scale discoveries to large scale testing and application.
Pre-combustion Capture/Hydrogen
Colin Snape and Trevor Drage

This document provides supporting information for the pre-combustion capture RAPID table and focuses on knowledge application areas where UKCCS research can potentially have the greatest impact. This assessment is based on the proposed level of development of the different technologies indicated in the impact table and principal focus given to knowledge application areas that require fundamental to small pilot scale research.

Pre-combustion capture is a multistage process with a number of unit operations from the air separation unit, gasifier to the gas clean up and CO₂ separation technologies. The RAPID table and this document deals with these components in order to propose areas where UKCCS research can have significant impact. The potential for the use of existing pre-combustion capture technologies for carbon capture from underground coal gasification is also discussed.

Air separation
Oxygen blown gasifiers, preferable for carbon capture applications, require an air separation unit. Whilst cryogenic air separation is a commercially available technology, development is on-going of a number of air separation techniques, for example membranes, with potential to reduce the energy penalty of this process. Membrane systems have been developed based on ion transport membranes (ITMs)/oxygen transport membranes (OTMs), which use pressure difference and chemical potential respectively to separate oxygen from air. At present there is a requirement for material development to improve performance and reliability, especially their mechanical reliability during load changes is low, there is also a need to improve lifetime and reliability by improving resistance to creep, corrosion and contamination at the high temperatures of operation.

Gasifier technologies
Gasifiers are considered to be a mature technology, with a number of off shelf options available, with a number of number of near commercial gasifiers also under development. The development of solid feed systems is an area where research could have impact, especially for maximising fuel and operation flexibility by avoiding slurry feed. This technology could be especially beneficial for the feed of biomass.

Gas clean up
A key requirement of pre-combustion capture is the removal of ash, particulates as well as sulphur and nitrogen compounds to protect downstream components, for example turbine and HRSG. Current commercially available technologies, cyclones, venturi scrubbers and scrubbing systems require the gas to be cooled to approx 100°C, by quench or heat recovery, to operate. Hot gas clean up technologies have been proposed and tested to remove the cooling requirement.
**Water gas shift reaction**

A range of catalysts have been developed for WGS to operate at high (350 – 500°C), low (185 – 275°C) and under sour conditions. There is always potential for improvements and incremental development of these materials. Sorption or membrane enhanced water gas shift reaction has been proposed as a route to perform WGS and CO₂ capture simultaneously in a single reactor. This can be achieved using a solid sorbent or through the use of a membrane system in conjunction with a catalyst. Extensive research of this technology is currently being undertaken, for example by ECN. Overall development of this technology requires the development and optimisation of materials as well as process to develop beyond the small pilot scale testing currently underway.

**CO₂ capture**

A range of technologies are available for CO₂, H₂ separation. The current physical solvent technologies are at an advanced stage. A number of alternative capture processes have been proposed with potential to offer improvement over the current physical solvent technologies in terms of cost, efficiency and flexibility. Most of these technologies, for example membranes, solid sorbent, ionic liquids are the focus significant research a development. These 2nd and 3rd generation capture technologies are at varying stages of development. However, similar for all is the need for the development of functional materials [1], to achieve the required capture performance, and long term stability for scale up and application. There is also the need for the development of processes for application and integration.

**Hydrogen gas turbine development**

Development of gas turbines is required to optimise efficiency, reduce emissions and the lower cost for operation when hydrogen rich fuel are used. Advances in combustion technology are proposed as one to achieve this for example lean premix technology. Other improvements can be achieved through increased pressure ratio and a slightly higher mass throughput. [2]

**Plant integration and novel cycles**

A number of options exist for variations in plant design and given the large number of operation in IGCC for better integration across the whole plant. These include flue gas cycling on the turbine, air/N₂ integration of the ASU and more novel process designs such as oxy-fired IGCC systems [3]. There is significant scope for the assessment and bench marking of these technology options.

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Underground coal gasification with carbon capture

CCS has been proposed to be applicable to UCG via a number of routes. Pre-combustion capture technologies can potentially be applied to the syngas produced by UCG. A number of research challenges result from different gas compositions (for example CH4), different clean up requirements and overall integration of the process.

Proposed research areas where UKCCS research could have most impact

- Improved plant integration of ASU.
- Development of materials for oxygen separation membranes.
- Development of high pressure solid feed systems for gasifiers.
- Development of materials and processes for sorption/membrane enhanced water gas shift reactions.
- Development of 2nd and 3rd generation capture technologies (adsorbents, membranes).
- Simulation and benchmarking novel gasification processes against the current state of the art.
- Studies into component and plant performance for part load and flexible operation.
- Exploration of options for integration of CCS with UGC.

Oxyfuel Combustion
Mohamed Pourkashanian and Richard Porter

Technology maturity: Technical challenges induced by the change of oxidant environment in oxyfuel combustion are believed to be surmountable because the technology is derived from existing processes and its robustness has been confirmed through several years of oxyfuel pilot operation. CCS deployment with oxy-combustion will therefore play a significant role in parallel to post-combustion technologies. Oxy-combustion technology can be retrofitted to existing plants or be applied to capture ready plants with no significant modifications to the turbine island being required.

“Oxy-combustion is eligible to retrofit and to CCS-ready concepts”
(Thomas Stringer, Director of R&D Execution at Alstom, 2012)

Oxygen production for oxyfuel systems

- Advanced cryogenic distillation
  - Cost reduction and process integration
- Oxygen separating membranes and adsorbents
  - Further materials development (flux, selectivity improved performance at lower temperatures, manufacturing methods)
  - Materials resistance to poisoning and corrosion
  - Scale up, process intensification and process integration including dynamic simulation
  - Demonstration and pilot and commercial scale
Oxy-Solid fuel retrofits and new boilers

- Slagging, fouling and corrosion caused by oxyfuel conditions require further investigation at laboratory and pilot scale
- Sulphur species investigations
  - Capture in fly ash
  - SO₂/SO₃ conversion and its impact on Hg retention
  - Deposition
- Numerical modelling
  - Radiative heat transfer in oxy combustion is modified as non-gray radiative properties of the combustion gases cannot be neglected. The accurate prediction of radiative heat fluxes and temperature is essential for modelling combustion.
  - Char oxidation/gasification and burnout is influenced by the high concentrations of CO₂ and H₂O in oxy-coal combustion and the classic models are not capable of predicting the transition between combustion regimes in oxy-coal combustion.
  - Intermediate pathways for fuel-NOx formation should be re-considered in chemical kinetic mechanisms.
  - Techno-economic evaluations should incorporate state-of the art CFD generated data into system simulations because no full-scale data exists for validation.
- Design of Pulverised Fuel (PF) and Continuous Fluidised Bed (CFB) for size and cost reduction
  - Flue gas recycle reduction and increased O₂ concentration
  - Combustion behaviour at high O₂ concentrations
  - Pressurised oxyfuel combustion
- Operational experience with biomass and co-firing coal/biomass in PF and CFB

Oxy-fuel gas turbine combustors e.g. oxy-gas, high pressure, supercritical CO₂ cycle, oxy-gas with CO₂ for EOR

- Fundamental investigations of gaseous oxyfuel fuel combustion with O₂ in CO₂ and H₂O environment under high pressure
- Design of combustor for complete and stable combustion in modified heat transfer conditions
- Optimisation and cost reduction of Trigen rocket engine technology with EOR
- Supercritical CO₂ cycles

Material tests for higher operating temperatures and CO₂ / H₂O working medium mixture

- CFD studies of combustion and heat transfer in CO₂ / H₂O mixtures
- Process control for large scale flue gas recirculation systems
- Development of cooling systems
- Demonstration plants to improve understanding and provide data for model validation
Flue gas recycling and O₂ mixing

- Safety testing of technologies and material for mixing of recycled flue gas and O₂ in environments that may contain dust and unburnt carbon particles
- Experimental and CFD investigations into positioning of O₂ and recycled flue gas mixing points
- Investigations into O₂ mixing for oxyfuel gas turbines

Flue gas treatment

- DeNOₓ plants (Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR)) require investigation into deactivation and S-conversion due to high dust arrangements in oxyfuel flue gas conditions. Issues may relate to downstream fouling and corrosion by NH₃ and sulphur species additionally.
- Very little experimental data and few modelling studies on the behaviour of mercury and other trace metal in oxy-coal conditions. Predictive tools for the impact of SO₂/ SO₃ on heterogeneous processes of mercury with UBC in fly-ash are required.
- Effective removal technologies for corrosive SO₃ and Hg species.

CO₂ compression

- Further research into removal of SOₓ and NOₓ removal during compression stage
- Improved CO₂ compressor efficiencies at full and part loads and extension of load ranges.
- Compressor material tests under oxyfuel stream conditions

Process intensification

- Chemical looping combustion
  - Development and sourcing of oxygen carriers for different fuels
  - Fuel conversion efficiency and CO formation avoidance
  - Scale up of all process components to industrial scale
  - Reactor design, optimisation and materials selection
  - Integration into power production process

Overall process development and integration

- Optimisation and cost reduction
- Pathways to commercial scale through demonstration
- System simulations
  - Techno-economic evaluations incorporating state-of the art CFD generated data into system simulations
  - Development of dynamic models to study whole system load variations, identify system flexibility weak points and solutions
High Temperature Looping
Stuart Scott

High temperature looping cycles are designed to overcome the very large energy penalties that are imposed by other carbon capture techniques. The first generation capture plants will be based on temperature swing scrubbing units (working at low temperatures) or oxy-fuel plants. For post-combustion capture, high temperature looping cycles are able to approach the thermodynamic limit on energy penalty, because, unlike lower temperature systems such as amine scrubbers, the heat they reject is at a very high temperature and can be recovered back into the power cycle. Large scale trials are currently underway looking at both carbonate looping (http://www.caoling.eu/) and metal looping schemes. Both types of looping cycles require two interconnected reactors to operate continuously, typically fast or bubbling fluidised beds.

The carbonate looping cycle is already being trialled at the 2MW large scale (http://www.caoling.eu/) and shows promise in the near term as it can be applied as a post combustion capture technique. In this case, CO₂ is absorbed onto calcium oxide (in the carbonator), which is then transported to a second reactor (the calciner) where the temperature is raised by oxy-firing coal, and the CO₂ released. The energy content of this extra coal can be recovered from carbonator which operates at a temperature above that of a supercritical boiler. There is some energy penalty associated with having to oxy-fire the calciner, but much less than if all the fuel were oxy-fired. Such a scheme adds a second source of heat to the power cycle which can be used to generate power. Although clearly feasible, and thermodynamically favourable, several engineering issues need to be addressed with this approach:

▶ Although attractive as a post combustion capture technique, the power cycle would have to be considerably up-rated if this was applied as a retrofit (or implemented with a sub-optimal steam cycle), thus work is needed on how best integrate the high temperature looping cycle into the power cycle (for new and retrofit cases).

▶ Secondly, the sorbent may degrade over time, and there is a trade off-between the cost of using cheap natural materials (i.e. limestone), and more advanced manufactured sorbents; more understanding on how the chemical and physical structure of the sorbent particle affects performance is required. There is also a considerable amount of work on the regeneration of sorbents (or their reuse in other systems, such as cement manufacture, or as sorbents for sulphur capture), and whilst results are encouraging, the underlying mechanisms have still to be elucidated.

▶ Thirdly, understanding of the system as a whole is required, from the performance of the sorbent particles through to the dynamic response of the power station and the economics of operating the power-station within different energy markets. In terms of practical application, calcium looping is already being demonstrated and engineering issues such as the reactor conditions to maximise capture, control, role of minor fuel components, through to the final CO₂ purity and the need for further gas cleaning before compression and transport are still to be addressed.

Whilst the carbonate and similar cycles allow post combustion capture, metal-oxide (or similar) cycles allow the fuel to be oxy-fired without the energy penalty associated with producing pure oxygen. In-fact, metal oxide looping was first suggested as a way of improving combustion efficiency (by removing the thermodynamic irreversibility associated with traditional combustion) and avoiding NOx formation.
The oxygen contained in a solid metal oxide “oxygen carrier” is first used to combust the fuel in the absence of air in the “fuel reactor” (avoiding dilution with N₂ and allowing nearly pure CO₂ to be recovered by condensing the water), and the spent solid then regenerated in a separate step using air. As with the calcium cycle, the theoretical efficiency is high because all of the heat generated is at a high temperature, so can be recovered into the power cycle. This has already been demonstrated at pilot scale for gaseous fuels (http://www.chemical-looping.at/). Rather than circulating bed, there is also interested in using packed beds, with a 0.5 MW demonstration planned (http://www.sintef.no/Projectweb/DemoClock/); this system will also operate at elevated pressure. Work is ongoing in application to solid fuels, with recent EU grants focussing on the scale up to small demonstration scale. A 100 kW unit using solid fuel is now running at Chalmers University (http://www.entek.chalmers.se/~anly/co2/100kWunit.pdf)

However, without pressurized operation, chemical looping on natural gas is not competitive in efficiency terms with NGCC + CCS. In general, very little work has been done on pressurised CLC in fluidised systems. Solid fuels are more challenging as the fuel must first be gasified or pyrolysed, and there may be interactions between the ash and minor components which affect the longevity of the oxygen carrier and pollutant profile. The success of the approach relies on the ability of the oxygen carrier to undergo many cycles of oxidation and reduction; thus, further research is needed into mechanisms of degradation of the oxygen carriers. The fact that solid fuels must be gasified adds complexity to the process, in particular the mismatch between the rates of gasification and combustion of the generated syngas can lead to a build up of char in the fuel reactor. Whether or not this issue can be solved by schemes such as CLOU (Chemical looping with oxygen uncoupling, where gas phase oxygen is generated locally), or by separating the un-reactive char using a carbon stripper (at the expense of increased reactor complexity) is currently an active area of research. Details of the reactors have yet to be finalised, with problems of fuel slip identified as one problem that needs to be overcome with current fast-bed designs.

Thus, both post combustion looping cycles (e.g. carbonate) and oxy-fuel looping cycles face similar research challenges. Both require solids which can be cycled many times or be regenerated and research in this area is ongoing. This area would still benefit greatly from an understanding of the fundamental material chemistry and science, since most work is currently empirical. In addition to studying existing materials to either tune their performance or elucidate fundamental mechanism, there are also novel materials which require investigation (e.g. perovksites, mixed metal oxides, structured hydroxides, modified natural materials), which may provide a step change in performance. Applying looping cycles to a full scale power cycle will require a large amount of material, which is either very cheap, or will last indefinitely. Scaling up novel materials from the few grams in the laboratory, to kilogram, then tonne scale is challenging, and more work is needed in this area. Although these schemes are very dependent on the performance of the particles, more understanding is needed at the system level, both in terms of power-station performance, but also economics and environmental benefit, and interaction with other industry sectors. This latter point is important since not only are some industries large sources of CO₂, but they also may be able to provide materials which act as looping agents or add value to the waste looping materials (e.g. CaO in cement, or iron oxides in the steel industry). In addition to the obvious synergies between high temperature solid looping cycles and either iron and steel manufacture or cement production, there also opportunities for more efficient operation by properly integrating looping cycles in the industrial flow sheet.

Finally, these cycles have applications in pre-combustion capture, the upgrading of syngas and the production of hydrogen. Materials such as CaO which can absorb CO₂ can be used in the water-gas shift reaction to produce H₂, and many metal oxide looping cycles can be adapted to produce H₂ rather than heat, e.g. by oxidising with steam.
**Industrial Capture**
Paul Fennell, Tamaryn Napp and Thomas Hills

Carbon Capture and Storage (CCS) is frequently associated with coal-fired electricity generation, and to an increasing extent with gas-fired generation. However, there are many other sources of CO₂ which can also benefit from the technology; many of these are substantially easier to retrofit with CCS than are power stations. Due to rising energy costs, many energy intensive industrial processes have made significant advancements in energy efficiency over the past 40 years and are now operating close to their thermodynamic limits. The options for further reduction are highly limited. Furthermore, for process-related emissions (those inherent to the process itself, such as the emission of CO₂ during the calcination of limestone for lime or cement manufacture) there is little choice other than to apply CCS if the industry is to be substantially decarbonized. In light of this, it is surprising that the power industry, where technologies such as wind, tidal and hydropower offer serious alternatives to the application of CCS (through clearly there are issues with intermittent generation) has dominated the research and development agenda. A synthesis report for the United Nations Industrial Development Organisation (UNIDO) [1] states that “This area has so far not been the focus of discussions and therefore much attention needs to be paid to the application of CCS to industrial sources if the full potential of CCS is to be unlocked”. For context, the IEA Blue map scenario suggests that industrial CCS will be almost as important as CCS on power by 2050.

**Systems**

Industrial CCS is a broad area, and in a number of cases the basic model for post-combustion CCS is similar to that for power generation; however, in all cases the heat integration and optimisation is different, leading to requirements for systems analysis for even the most basic configurations. Much of the literature refers back to a small number of IEA studies [2, 3], there is much less independent validation of costs by different researchers. Figure 1 demonstrates the wide variety of partial pressures that CO₂ can be captured at, from different CCS processes. Optimisation of heat flows between industry and power generation, especially when CCS is added to the plant, is another key way to enhance the overall efficiency of the combined processes, including carbon capture. Of particular note here is the synergy between power, cement manufacture and the carbonate looping cycle for CO₂ capture.

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**Figure 1.** Partial pressures of CO₂ from a variety of industrial and power generation sectors. [4]
Basic research: Most industrial processes are amenable to a post-combustion CO₂ capture step. Basic research here is similar to that required for the application of CCS on power. However, it is important to note that the temperature, partial pressure and O₂ content (as well as many other trace element contaminants), together with the availability and temperature of low-grade heat, will be different to that for CCS on power, necessitating testing of novel sorbents under realistic conditions for each system desired.

Basic research: Many manufacturing processes have the potential to integrate well with high temperature solid looping cycles.

Iron and steel
Top-gas recycling is a new method to reduce the coke requirements in a blast furnace. The reducing gas from the top of the blast furnace is stripped of CO₂ and sent back to the furnace. Currently, this involves cooling the gas to allow stripping via an amine solution; however, a high temperature stripping stage, using CaO as the absorbent would allow the recycled gas to be returned to the blast furnace hot. Furthermore, there are other potential integration possibilities with chemical looping combustion, particularly when Fe₂O₃ / Fe is used as the looping material.

Cement manufacture
The unique synergy of cement manufacturing with carbonate looping is that CaO, the regenerable absorbent for CO₂, is also the primary feed to the cement works. This means that the process as a whole generates zero waste. Topics of interest are the re-use of looped material in cement manufacture (i.e. are there any cement quality issues?) and the basic integration and design of the plant, though both Edinburgh and Imperial have integrated models of Ca looping with cement manufacture. Another topic of great interest is the re-use of ashes from other novel combustors (for example, oxyfired PF boilers) in cement manufacture.

Oxyfuel (cement)
Oxyfiring of a cement kiln can lead to significantly higher efficiencies for the cement manufacture process, owing to the removal of the thermal ballast associated with the nitrogen in air. However, the recycling of CO₂ in the process would significantly change the calcination temperature for CaCO₃, and potentially the cement clinker reactions. The development of such a process would be a dual win – a more efficient process which also captured CO₂. Blast furnaces are already oxyfired – but work on integrating oxygen membranes and blast furnaces may be interesting.

Petrochemicals
The firing of significant quantities of fuels for the purposes of generation of heat, as opposed to electricity, is an opportunity for chemical looping combustion; in this context, if natural gas is fired, there is no conflict between the fact that the efficiency of generation using NGCC with post-combustion capture is higher than that of atmospheric pressure chemical looping. In particular, firing using sour gas is an area of significant promise.

2 IEA GHG RD&D Database [http://www.co2captureandstorage.info/project_specific.php?project_id=71]
Transport
Julia Race

The majority of the research that is being undertaken in the transportation area worldwide concentrates on pipeline transportation of dense phase CO₂. The Centre is extensively linked into the current RCUK and EU transport related projects through direct research activities and through research participation with key academic researchers and industrial research co-ordinators in the UK, Norway and Europe. The key themes of this research relate to materials selection, infrastructure and network development, risk assessment and standards development. The recognition in the aims of these projects is that little is known on the transportation requirements for CO₂ from power and industrial capture plant and the development of design protocols and standards is an immediate requirement in order to be able to safely design, construct and operate a CO₂ pipeline.

RAPID for Transportation
For the purposes of the RAPID exercise, the transportation theme has been organised into 5 application areas (dense phase pipeline transportation onshore; dense phase pipeline transportation offshore; gas phase pipeline transportation onshore; ship based transport inland waterways and ship based transport offshore). The technology areas and research areas for each of these application areas have been defined by asking the question; “what do we need to know in order to design a transportation system” and “what is the specific research required to address the technology area?”. The current level of understanding in the technology area is then ranked on a scale of 1–9. The RAPID table also indicates the area in which the impact of the research will be focussed; CAPEX, OPEX, Safety, Regulation and System Efficiency.

Setting priorities for research
The RAPID impact tables provide a snapshot of the level of understanding in the different technology areas and the research projects currently delivering this knowledge. The research from the current projects will be available within the next 2–3 years; however, the FEED studies for the transportation system are currently in progress. It is therefore considered that the early transport projects will need to focus on the use of existing technologies and that, in order to be able to set the priorities for research in transportation, the key questions should be;

- What research is required to enable safe transportation of CO₂ using existing technologies in the short term?
- What information do we need to be able to transport CO₂ more efficiently using existing technologies in the medium term?
- What new technologies and methodologies might enable us to transport higher volumes of CO₂ from more disparate sources more efficiently in the long term?
Pipeline transportation
For pipeline transportation, the key priority issues in the short term, are considered to be:

- The specification of the water content in the pipeline with impurities. The specification of the drying requirement will impact the capture plant (in terms of the dehydration required) and the pipeline (in terms of the materials and maintenance required) and needs to be specified with certainty.

- Improvement in the understanding of the effect of impurities and whether existing methodologies used for natural gas pipeline transportation can be transferred to CO₂. Immediate research projects should focus on the validation of the existing phase behaviour models for use in hydraulic models, fracture models and dispersion models to confirm their suitability for design of the first dense phase pipeline systems.

- Development of robust models and methodologies for conducting quantitative risk assessment of pipeline systems, onshore and offshore. These include appropriate failure frequency and dispersion models for dense phase and gaseous phase CO₂, particularly with impurities.

- Development of methodologies and equipment for metering the CO₂ into and out of the pipeline.

- Development of methodologies and equipment for leak detection in the pipeline both onshore and offshore.

- Validation of the use of polymeric materials in CO₂ service.

In the medium term, research should be focussed more on the development of technologies to allow the transportation of CO₂ more efficiently. For example:

- Development of more accurate equations of state for input into updated models for specification of phase behaviour. This will allow more accurate prediction of phase behaviour and allow unnecessary conservatism to be removed. In particular, there is a requirement for an equation of state which can model CO₂ in the solid phase with impurities.

- Development of materials for transportation of CO₂ streams containing increased levels of impurity, e.g. steel materials with increased toughness and resistance to potentially sour environments.

In the long term, research projects should be focussed on the development of technologies to transport higher volumes of CO₂ from potentially more disparate sources.
Ship based transportation

There has been much less research conducted on ship based transportation compared with pipeline transportation. In part, this is due to the priority which is given to pipeline transportation, which is considered as the optimum solution for the transportation of large quantities of CO₂. However, shipping could be considered for transportation over large distances, where it will become more economical than pipeline transportation, and could also be considered at the initial stages of CCS infrastructure development, particularly for stranded sources and sinks. In order to be able to analyse the shipping option effectively, it is considered that priority should be given to short term feasibility studies prior to the development of larger research projects like:

- Development of CO₂ ship transportation logistical models to evaluate the basis on which ship based transportation of CO₂ could be undertaken e.g. storage at port, port equipment requirements (liquefaction facilities), potential shipping routes, analysis of number of vessels required etc.
- Analysis of the technical requirements for unloading CO₂ from a ship at the injection site e.g. floating buoy arrangements.

Once the feasibility of these options has been determined then further research work should focus on research related to risk assessment and transfer technologies.

Integrated transportation systems

It is recognised that at either end of the transportation system, the link must be made to the capture or storage facility. Much of the transport related research is being conducted independently and there is a need to bring the strands together in an integrated manner which takes into account the capture plant and storage site requirements, as well as addressing systems, environmental, social, legislative and economic issues.

Monitoring R&D

Andy Chadwick

Monitoring is a key element of storage site performance verification and is integral to storage requirements under European regulations (principally the European Directive, OSPAR and the EU ETS). Primary objectives in the UK context are:

- To show that the site is performing safely and there will be no adverse environmental or safety impacts
- To show that the site is performing as expected by calibration and verification of predictive models and will continue to do so in the future
- To demonstrate that the site is not leaking
- To measure emissions (in the event of leakage to seabed)
- To provide suitable information for mitigation or remediation actions should these be necessary

Monitoring programmes will comprise a judicious combination of deep-focussed monitoring focussed on the reservoir and deep overburden (the ‘Storage Complex’) and shallow-focussed monitoring to characterise any overburden emissions (both natural and man-made).
Deep-focussed monitoring

The main deep-focussed tools have been used extensively in the oil industry and are technically mature. 4D seismics are of proven efficacy, providing 3D time-lapse imaging of the reservoir and overburden (e.g. Sleipner, Weyburn, Snohvit). Downhole (or less ideally wellhead) pressure monitoring is similarly effective, providing reservoir calibration at In Salah, Snohvit, Weyburn etc. More complex reservoir and overburden pressure monitoring systems are also being trialled e.g. at Cranborne (US), but results so far are not straightforward to interpret. Specialised deep-focussed tools have been deployed at pilot-scale injection sites e.g. VSP/MSP (Frio, Ketzin etc) crosshole seismics (Frio, Nagaoka), cross-hole electrical and various surface-downhole electrical configurations. Well-based methods however run into significant problems at the industrial-scale where widely-spaced (and expensive) wells preclude crosshole techniques and near wellbore measurements are limited in their ability to unravel spatial detail. A good example of this is at Ketzin where unexpected CO₂ breakthrough times were measured in one of the Ketzin monitoring wells but the explanation of this is uncertain. Geomechanical stability of the reservoir is a key issue and microseismicity monitoring will have a role to play. A key aim is to provide early warning of geomechanical instability, perhaps by identifying precursors to fault slip? Cost-reduction is always an issue and the benefits of continuous (rather than time-lapse) monitoring might be significant.

Issue

- Induced geomechanical instability is perceived to be a significant potential containment risk. Early warning (preferably prior to fault instability) would be very desirable.

Research action

- Design tools and methods for robust seismicity baselining. Develop real-time predictive passive monitoring methodology to measure seismic precursors and provide pre-warning of geomechanical instability. Improve geomechanical modelling and understanding of in situ stresses.

Outcome

- Reduced risk of serious induced seismicity and/or leakage. Improved public acceptance.

Issue

- No tools currently exist for continuous (well-based) monitoring of the reservoir with any degree of spatial resolution.

Research action

- Develop novel tools for imaging CO₂ in reservoir between widely-spaced wellbores.

Outcome

- Improved understanding of reservoir performance, complementary to time-lapse seismic.

Issue

- Currently available monitoring systems (e.g. time-lapse seismics and downhole methods) are generally expensive. A low-cost passive or passive/active monitoring system, capable of measuring changes in a key diagnostic trigger parameter could radically lower longer-term monitoring costs.
Research action

- Develop low-cost monitoring system designed to trigger conventional monitoring only if key diagnostic threshold exceeded.

Outcome

- Lower costs due to reduced time-lapse repeat frequency on conventional monitoring systems.

Issue

- Reliable characterisation of CO₂ in the reservoir via detailed wellbore measurements and/or time-lapse geophysical measurements is essential to demonstrate understanding of reservoir processes and to calibrate and verify predictive performance models. So far quantitative seismic analysis suffers significant ‘non-unique’ uncertainties.

Research action

- Design improved analytical methodologies, either by deploying complementary tools (e.g. seismic plus gravimetry) or improving seismic analysis (e.g. inversion tools, or integrated studies e.g. simultaneous seismic and flow-modelling) to reduce uncertainty.

Outcome

- Improved calibration and verification of predictive models – key regulatory requirement

Shallow-focused monitoring

In contrast to the deep-focused tools, shallow-focused tool development is relatively immature. There are two key requirements: to reliably identify leaks (emissions) at the seabed to a known sensitivity and to measure these emissions to a known precision. The types of tools that will be used for this (seabed acoustic imaging, bubble-stream imaging and characterisation, detection, seabed flux measurements, geochemical measurements in the water-column etc) are all available, but further development and the design of integrated monitoring systems, novel data storage and transmission systems is required. A further important element of shallow monitoring is to develop a proper understanding of natural baseline emissions (e.g. CO₂, methane) variations in a range of settings. This must capture all spatial and temporal variation both on the short-term and longer seasonal/annual timescales). The importance of a full understanding of baseline variation cannot be over emphasised, because, once injection has started, any wandering of observed measurements outside of the assumed baseline variation might be misconstrued as leakage. Public acceptance issues surrounding leakage are acute, particularly onshore (which impacts on transport issues).

Issue

- Regulatory requirement to demonstrate ‘no leakage’ to a specified accuracy.

Research action

- Design suitable shallow-focused tools and deployment methodologies to ensure all leaks above a certain threshold will be identified.

Outcome

- Improved compliance with regulatory requirements.
Issue
> Regulatory requirement to demonstrate measure emissions to a specified accuracy.

Research action
> Design suitable shallow-focussed tools and deployment methodologies to measure total site emissions.

Outcome
> Improved compliance with regulatory requirements and possible reduced emissions penalties.

Issue
> In the event of leakage a regulator will need to know which storage site, or CO₂ stream is leaking. This might be problematical in the event of stacked or adjacent storage sites.

Research action
> Design system for artificial or natural tracers to uniquely identify specific CO₂ streams.

Outcome
> Correct attribution of leakage to responsible party.

Issue
> Proper understanding of natural emissions variations to establish robust baselines.

Research action
> Measure emissions from a range of natural systems to cover spatial and temporal ranges at required scales.

Outcome
> Robust definition of natural variation at a range of storage site types to avoid ‘false positives’ for leakage.

Issue
> Leakage associated with transport infrastructure.

Research action
> Design low cost, low profile (i.e. non-invasive) leakage detection system for pipelines.

Outcome
> Reliable verification of pipeline integrity. Much improved public confidence.
Reservoir Engineering
Martin Blunt and Aaron Goater

Liabilities
Both industry and governments are potentially putting very large liabilities on their balance sheets due to a lack of understanding of the risk of leakage and the worst case cost. Due to the lack of understanding the insurers are also not providing insurance. One portion of this risk that needs better understanding is the risk of leakage up faults.

Resolution
- From the reservoir engineering angle: improved understanding of fault flow properties – especially vertical flow properties that could lead to leakage. Also, improved prediction of fault flow properties from geological data.

Impact
- More realistically sized liabilities are expected by operators/governments. This will improve the likelihood of commercialisation of CCS projects.
  Priority: high

Storage modelling
Ability of CO₂ storage modelling to provide the accuracy of prediction required under CO₂ storage regulation at close of injection. This is particularly relevant when migration is harder to predict in open aquifers.

Resolution
- Improved modelling parameterisation– including improved understanding of fundamentals such as relative permeabilities, convective mixing and others.

Impact
- This would reduce potential regulatory resistance to CO₂ storage towards close of projects. The alternative would be to change regulation.
  Priority: medium term

Cost
Cost of CO₂ storage needs to be reduced.

Resolution
- Using storage space more efficiently/ development of optimal injection scenarios
  Priority: medium term
- Development of potential for water production (more efficient use of space and reduced risk of reservoir damage due to high pressure) and WAG (higher residual trapping – lower risk of leakage) within regulations.
  Priority: important/medium term
- Reduce cost of modelling by developing a clear CO₂ modelling workflow. In particular this may highlight where different modelling techniques should be used.
  Priority: medium term
Impact

› Cheaper storage encouraging uptake - potential to develop IP.
› Cheaper storage as (more efficient use of space/lower risk of leakage)
› Reduced modelling expense

Time frame

Time-frame of post-injection monitoring is unclear.

Resolution

› Using storage design and modelling (related to previous issues) to make the storage safe shortly after injection phase. Use a brief, verifiable period of monitoring to confirm model predictions and allow closure of sites.

Priority: medium term

Impact

› Development of clear monitoring guidelines
› Cheaper monitoring over realistic time-frames

Engineering methodology

Engineering methodology for site selection and capacity estimation is needed for a coherent CCS storage strategy

Resolution

› Take best practice to develop a framework and guidelines for storage assessment and site selection that accounts for migration and pressure limitations and with stages related to modelling assessments and data collection.

Priority: medium term

Impact

› Agreed methodology for storage site assessment and delineating storage capacity
› Framework for operators and regulators.
Site Leasing and Regulation
Sam Holloway and Michelle Bentham

Site leasing, licensing and regulation is relatively well developed in the UK. The EU Directive regulating storage has been transposed into UK law, the EU has published four related Guidance Documents and Guidance on how to apply for storage licences and permits in the UK has been published by DECC. The first UK storage licence was issued (to National Grid Carbon) in 2013. However, no storage permits have yet been issued. Also, there are still a few gaps that need to be filled by research.

Site leasing, licensing and regulation are impacted on by scientific, technical, legal and socio-economic factors. Consequently the research required in this area is multifaceted. Our perception of the research needs is evolving as more work is completed: a current view of research needs summarised below:

Propose improvements to some of the regulations in the EU Storage Directive

- Article 38 of the EU Storage Directive states that a report reviewing the implementation of the Directive has to be submitted to the European Parliament before 31 March 2015. The report has to include (an assessment of the need for): “Further development and updating of the criteria referred to in Annex I and Annex II” (criteria for the characterisation and assessment of the potential storage complex and surrounding area and the criteria for establishing and updating the monitoring plan). An example of Directive recommendation that could be considered for modification is the minimum time frame recommended for the post-closure pre-transfer phase of the CO2 storage project life cycle. Though not binding, this could be regarded as arbitrary and not based on performance indicators. The priority for contributing to the review is regarded as high because there is an opportunity to feed into the 2015 update of the Directive.

Improve the understanding and communication of storage risk to government, regulators, operators and the insurance industry

- Liability, insurance and a perceived imbalance of storage risk and reward are three of the main barriers to deployment of CCS at present. This is regarded as very high priority of its potential impact on the economics of CCS and the viability of commercial-scale storage.

Knowledge Transfer of learning relevant to storage site regulation, leasing and licensing from the UK government CCS Competition

- This may partly arise from publication of FEED and Storage Permit documents. Ideally further KT should be ensured by working with the Competition winners and DECC EDU. Priority will be very high immediately after award of contract(s).
Knowledge Transfer of potential environmental impacts of CO₂ storage to policy makers and regulators

- Significant evidence on the potential environmental impact of CO₂ storage particularly in marine environments, is becoming available. An effective mechanism to transfer the resulting knowledge into the realm of regulation is missing; knowledge transfer currently relies on dissemination actions by the individual projects. A coherent, international facilitation of knowledge transfer to policy makers and regulators would prove beneficial to leasing and licensing via Environmental Impact Assessments. This is of high priority and is described fully in the ecosystems and environmental impact summary and application impact tables below.

- Optimise the use of storage resources in sedimentary basins with multiple legitimate uses. Under current arrangements, licensing of CO₂ storage sites will follow a ‘market-driven’ approach in which the most economically advantageous individual projects are selected, though licensing and leasing will probably take into account other existing and potential uses of the subsurface and marine domain. Also, increased pressure in any reservoir from CO₂ injection may reduce storage capacity and increase costs in adjacent sites, potentially wasting good sites. Planning is needed to maximise the economic potential of sedimentary basins where CO₂ storage is planned/promote follow-on CCS projects after the UK Competition. The IEAGHG R&D Programme produced a report on many aspects of this issue in 2013. Two of the main remaining gaps are:
  - modelling of pressure/brine migration interference between storage projects in the same geological formation (using UK reservoir formations)
  - how would a reservoir formation in which multiple projects are planned be divided into licences?

The priority on the two bullet points above is high because they could impact on leasing and licensing of storage clusters.

Optimise storage efficiency and security through pressure management by water production

- Research into this is considered a high priority because of its potential offshore. It has licensing and regulatory impacts. This will improve reservoir sweep efficiency and is also a medium-term priority.

Provide evidence on the licensability of migration-assisted storage

- Some of the large, high-permeability Palaeogene fan sandstones in the North Sea, e.g. Forties Sandstone, appear to have excellent CO₂ storage prospects. However, in such reservoirs CO₂ is typically predicted to continue to migrate within a large storage complex for long periods (decades and longer) before becoming trapped in small closures and/or as a residual saturation or by dissolution. This means the regulator may be reluctant to licence them even if site characterisation and risk assessment indicate that they are secure and high quality stores. This is of medium priority because it probably won’t impact on the licensing or regulation of the first few projects. However, it would be informative for regulators and, depending on regulator’s views, impact strongly on policy makers because of the potential impact on the realistic storage potential of the UK.

Maximise the economically realistic potential for large-scale CO₂ utilisation, especially EOR

- Though many generic and case studies of offshore EOR in the North Sea have been undertaken, the economic case is continually changing due to advances in technology, changing perceptions of the value of maximising oil resources and the value attached to CO₂ emissions reduction. The potential impact of making a business case for CO₂-EOR on CCS in the UK is very high. There would be regulatory, leasing and licensing needs for combined EOR/CO₂ storage projects.
Storage
Stuart Haszeldine

Overview
Storage comprises the prospective identification of subsurface sites for injection of CO₂ and associated impurities. Storage differs from other parts of the CCS chain, in that sufficient storage for 30 years of CO₂ has to be proven before a project is built, so that learning opportunities are very condensed into the next 10 years.

Calculation and simulation of CO₂ injection tonnages are established protocols, although imperfect. Injection of CO₂ overlaps with reservoir engineering, and suffers from incomplete information on rock properties. Understanding the retention of CO₂ into the future requires qualitative and, as far as possible, quantitative understanding and computational simulation. The accuracy of predictions, and especially the precision, overlaps with requirements for both monitoring and licensing. Very little work has been undertaken on UK-specific CO₂ storage, except for high level storage assessments. Because geological, geophysical and petrophysical principles are generic, it may be possible to undertake work in other locations which is of direct use to the UK. In most assessments of CCS, the storage aspects are perceived as poorly quantified, and of high irreducible uncertainty, equating to a project risk.

Impact of research on storage will be to: i) increase confidence in storage volumes, ii) identify and quantify the processes which could result in adequately-performing or under-performing storage sites, iii) increase mutual knowledge and understanding of the sub-surface with professionals and publics, iv) increase understanding of pressure interactions between multiple CO₂ sites and hydrocarbon operations.

State of art
The great majority of UK work on storage is focused on fluid CO₂ to be physically and chemically retained in porous rock media. There are several additional possibilities to store CO₂ i) by reaction with natural minerals on an industrial scale at the surface, including engineered injection into basalt or accelerated weathering ii) by designed industrial process chemical reactions to form solids, plastics or fuels iii) by engineered injection to the deep ocean.

Research
- Pilot studies of these capture types has been undertaken since the 1990’s, and has recently been funded by ETI and NERC. Whilst technically feasible, all these options have far failed to impress as a real-world option for the immense tonnages of CO₂ generated in the UK. Consequently, the focus is on fluid injection to support commercial projects.

Impact
- Scientifically interesting, chemistry of CO₂ rock has little practical effect. Priority 2/10.

Overburden
To predict the ability of the overburden to provide secondary and tertiary seals, and to predict rapid and slow pathways of CO₂ leakage from a storage site, requires more fundamental information about the 1 – 2km of rock above and around the primary seal. There are geographically and temporarily widespread gaps in such data, especially representing the past 10Ma, and this is site specific to the different offshore regions of the UK.

Research
- Basic logging whilst drilling of rock sequences is needed, combined with samples on which to make laboratory measurements of sediment properties.

Impact
- Fundamental data to improve retention modelling. Priority 9/10
Seal in overburden

Although primary seals are conceptually understood, the multiple secondary seals to promote retention and dispersion of any leaked CO\textsubscript{2} are poorly established. This has large gaps of basic data on subsurface temperature, rock physics, critical stress, chemical reactivity, 3D regional geometry, effective permeability, coupling to reservoir.

Research

› Additional logging data. Valuable special core samples from 0.1 – 2km for laboratory measurements

Impact

› Improved rock properties for modelling of CO\textsubscript{2} retention  \textit{Priority 8/10}

Reservoir

The reservoir holds liquid CO\textsubscript{2} that will gradually dissolve into pore water. Many and varied geochemical, geophysical and fluid effects influence CO\textsubscript{2} in the reservoir. Present understanding and simulations are based on derivatives from hydrocarbon approaches, together with some softwares for prediction, which are specific to CO\textsubscript{2}. Inevitably there is scope for more research. Fundamental rock properties to CO\textsubscript{2} are poorly quantified or understood, e.g. relative permeability to CO\textsubscript{2}-water-brine-diverse hydrocarbons in different pore systems; mineral wettability; microbiological effects. Uncertain implications for fluid pathways at pore scale, swept area, residual saturation values; linked thermal and mechanical effects on reservoir; dissolution rates; geochemical reaction rates. Consequently, it is difficult to predict pressure pulse magnitudes, duration, geographic extent and rate of decay.

Migration modeling of CO\textsubscript{2} flow through reservoirs has focused on sandstones in the UK, with (presumably) carbonate work at IC. Dual porosity networks in CO\textsubscript{2} prediction are poorly investigated, in sandstones or carbonates. The effect of aquifer geometry on prediction is understood to be crucial, yet precise information and case studies are lacking on: top reservoir micro-trapping, Dietz tongues around injection sites, up-dip tongue fingering, or up-dip displacement of deep saline water. Simulation of regional aquifers is crude, due to lack of detailed data and lack of computer resource time, with deterministic software.

Research

› Laboratory studies of basic rock properties, validation by deliberative field or test injection large scale experiments. Improved modeling to understand and quantify processes, with modular improvements to open-source software. Are capillary or D’arcy flow assumptions significant? Linkage to regional models for pressure prediction, and increased resolution inputs of reservoir bounding geometry and internal inhomogeneity. New approaches to rapid simulation of regional aquifers to produce fit-for-regulation results.

Impact

› Improved modeling of CO\textsubscript{2} within reservoir and future-time migration physically, and in pressure, especially for regional aquifers.  \textit{Priority 10/10}

Storage assessment methods

› Different States and continents have made individual assessments of storage capacity. These all use different sets of assumptions or constraints. International collaborations could produce better convergence and agreement. This is particularly important across the North Sea national boundaries.

Research

› Compare protocols internationally; understanding of definitions of maximum storage capacity – theoretical or engineered; treatment of limitations by pressure, critical stress induced earthquakes; rock fracture pressure; engineered interventions – geo-steering or formation production for overpressure relief. North Sea and Irish Sea cross-border harmonisation.
Impact

- Harmonised, or inter-convertible storage resource estimates; protocols for downgrading by effects of geological structure, induced fracturing, pressure, sweep efficiency, water composition, engineered interventions. 
  Priority 6/10

Remediation of leakage risk (through faults or seal)
How will leaks be detected (multiple methods, site specific). If leakage occurs through a primary seal, or through induced fracturing or faulting, does that need to be remediated? How will leaks be remediated? What effect does that have on a risk assessment of P50 or P10 leakage probability?

Research

- Work with industrial partners to understand intersection of natural process rates (link to environment), with engineered interventions to remediate. Use of reservoir properties to predict maximum leakage (finance).

Impact

- Evidence based public, political, and financial assurance of retention tonnages. 
  Priority 9/10

Improved Oil Recovery
Injection of CO₂ can potentially improve oil recovery by 5 – 25% of the original oil in place. This is a substantial cost offset on the expense of the entire CCS project, but has never been achieved commercially offshore. Many of the reservoir principles are understood from USA experience onshore EOR.

Research

- Understanding of commercial propositions and CO₂ storage reliability

Impact

- Confidence in permitting CO₂-EOR under CCS Directive. 
  Priority 5/10

Trapping integrity
Pathways of rapid leakage can be induced by CO₂ flow up prior faults. Overpressure haloes around injection sites, even tiny increases 50km distant, can induce microseismic tremors, or may infrequently induce larger earthquakes. Greater reservoir pressures certainly hydrofracture the reservoir and seal. Sealing capacity of faults for fluid CO₂ and mixtures poorly known.

Research

- Principles are understood, but investigate the application to UK.

Impact

- Important, to defuse any adverse perceptions by publics. 
  Priority 5/10

Natural and subsurface analogues
Natural analogues exist worldwide for CO₂ retention through geological timescales. These can demonstrate and quantify many of the aspects discussed. Test injection sites exist on several continents, but none in the UK. Such controlled experiments are very useful to enable field measurement of many of the aspects discussed, develop and test drilling methods, and especially to test predictions against measurement in extremely well monitored sites. The UK has no domestic test site, but should, and could partner with overseas experiments.

Research

- Testing tools and principles.

Impact

- Vital for trading. 
  Priority 7/10
**Single user and multiuser sites**

Much conceptualization of storage has been with “AtoB” projects. These are expensive. Cost reduction could be achieved by MultiUser sites, where one trunk pipeline accesses several storage reservoirs at different levels, or several sites within one regional aquifer. Contrast this with multiple other AtoB projects.

**Research**

› Investigate pressure interference or trespass of CO₂ plume into another storage complex licence; investigate the application to UK, to identify which regions offshore have diverse and resilient high tonnage storage.

**Impact**

› Shared costs of appraisal, pipes or monitoring. *Priority 9/10*

**Damage or benefit to incumbent and future hydrocarbon production**

CO₂ storage proposals have been made to incumbent hydrocarbon operators, they have replied to with vigour and threats of consequences. There is certainly a perception that commercial damage or difficulty could result.

**Research**

› Investigate pressure interference or trespass of CO₂ plume into another offshore licenced areas; investigate the application to UK, to identify which regions offshore have diverse and resilient high tonnage storage. And which regions may have no hydrocarbons, but are geologically poorly tested.

**Impact**

› Important to demonstrate impartial desk study. *Priority 9/10*

**Outreach and education**

Deep geological storage is perennially not understood by UK publics. More education is needed. Ideally a few questions, with comments each time – led by an experienced researcher. Leakage, durability and catastrophe are themes.

**Research**

› Storage is a particular fear for CCS, and wrapped up with anything in the subsurface – radioactive waste, shale gas or mining, so needs technically understandable communication to the relevant publics. But only those directly affected, a national campaign is too much.

**Impact**

› Vital for local stakeholders and listening NGO. *Priority 8/10*

**Integrating actions**

Storage CCS has numerous sub-topics listed above. The interaction of these is important, so a sensible way to investigate may not be through segmented projects, but through case studies or site studies, which can reveal the links.

› Reservoir and basin modelling as an integrating action
› Engineered small test sites as integrating action
› Natural analogues as integrating action
› DECC competition site studies as integrating action
› Deterministic drilling of North Sea gaps as an integrating action
› Database of CCS storage as an integrating action
Ecosystems and Environmental Impact
Jerry Blackford and Tom Vance

This document aims to help maximise the future impacts from CCS research by identifying priority areas of environmental research directly relating to CCS. In preparation of this document, input was sought from academics active in environmental CCS research together with the following stake holders: MMO, Crown Estate, Greenpeace, Natural England, DECC, IEAGHG and SEPA. To date, responses from these parties have been minimal, however this living document will be updated as new information becomes available.

The following text describes environmental CCS research priorities focussing on necessary impacts and research outputs rather than methods. Currently these areas are not ranked in terms of importance, and research in some areas is on-going but not complete or fully funded. The outputs described here address the CCS critical areas of public perception and environmental safety, monitoring for verification and regulation.

Marine

Collation of baseline and time series biogeochemical data describing proposed CCS sites

Output: Some data describing chemical, biological and physical parameters in UK shelf seas relevant to CCS is available, but fragmented. Collating this data, addressing the substantial gaps and presenting it in an accessible format, with a focus on variables that are expected to be influenced by CCS activity, would provide a cost effective and useful tool to aid site selection and would assist in the detection of environmental change resulting from CCS activity.

Output: In order to recognise and quantify potential impacts on marine ecosystems, site specific baseline natural biological variability must first be established. This baseline allows ‘abnormal’ ecological change to be detected and put in context of natural variability and impacts from other drivers. Such variability can be significant and multiscale. Criteria and methods for site specific surveys need to be established to ensure that information gathered is sufficient whilst remaining tractable.

Comparison of carbonate system variation from natural processes and CCS leakage scenarios

Output: in order to effectively monitor for changes in carbonate system parameters (pH, pCO₂ and DIC) produced by leakage from proposed CCS sites, baseline natural carbonate parameter variability must first be established. This baseline allows further carbonate parameter change to be detected and compared with normal variability, which is often significant over a range of temporal and spatial scales.

Output: In order to detect changes from baseline variability that can be attributed to CCS leakage, the threshold of change that different leakage scenarios are likely to generate needs to be established. These threshold changes then act as indicators of environmental change resulting from CCS activity.
Understand the tolerance of marine ecosystems to acute pH variability

> Output: Models of seawater pH surrounding artificial CCS leakage scenarios describe very low pH water masses being driven around epicentre point sources by ocean tides. This situation would result in benthic organisms experiencing transient exposure to severe low pH conditions. Most biological research to date has focused on measuring responses of marine organisms to continuous non-variable low pH treatments rather than transient conditions. Understanding biological responses to transient low pH conditions is a requirement to fully quantify the environmental consequences of catastrophic CCS leakage events.

Development of efficient and robust tools to enable monitoring of marine environments

> Output: Given the challenges of complex natural variability and leakage plumes, operation tools that can effectively monitor large areas of sea with remote communication are required. Additionally ‘smart’ analytical processes that can detect a leakage signal from background noise would significantly decrease the risks of false positives.

Quantify the environmental implications of large scale hypersaline discharge from saline aquifers

> Output: CCS activity in saline aquifers could result in the large scale release of hypersaline water. Currently, very little research has focused on predicting the environmental impacts of relatively rapid hypersaline discharge into marine environments on the scale likely to occur as a result of CCS activity. The environmental implications of hypersaline discharge should be investigated before consideration of saline aquifers as storage reservoirs.

Geo-physical

Determine spatial, temporal and biogeochemical characteristics of different CCS leakage scenarios

> Outputs: In order to ensure that environmental CCS research objectives are scaled appropriately, it is a priority to understand the likely range of leakage events, from small scale chronic seepage to large scale catastrophic containment failure. International consistency would benefit from a recognised nomenclature for CCS leak scenarios. Equally important is an understanding of the full chemical composition of the leakage gas/liquid in order to predict the dispersal, bioavailability and persistence of toxic compounds.

Understand how microbial ecology in spent hydrocarbon reservoirs responds to the introduction of new carbon sources resulting from CCS activity

> Outputs: Microbial ecology in active oil and gas reservoirs can limit production rates and generate severe human health risks. To date, the consequences of re-introducing a carbon rich source into disused hydrocarbon reservoirs is not fully understood. Ensuing microbial action has the potential to compromise reservoir integrity and produce undesirable compounds from microbial metabolic activity. Understanding microbial ecology in disused hydrocarbon reservoirs is a requirement before the full long term environmental implications of CCS activity can be quantified.
Terrestrial

Gas dispersion following leakage events

- Outputs: Low lying pockets of carbon dioxide following terrestrial leakage events pose potential human health risks. In order to quantify and reduce this risk, carbon dioxide dispersal and accumulation in terrestrial (including built) environments should be assessed to provide best practice for selecting routes for gas transport infrastructure and monitoring systems. Monitoring could include sensor or vegetation impact recognition.

Quantify the implications for human health and environment from amines used in capture process

- Outputs: Amine-based capture processes have the potential to release toxic amines to the atmosphere with potential to pose a risk to human health and the terrestrial environment. There is a need to quantify release scenarios and determine the resulting persistence and toxicity leaked gases.

General

National facilities for impact and monitoring studies

- Outputs: Facilities that allow for realistic release of CO₂ into real world environments have demonstrated utility for the testing of monitoring systems and studying impacts. Recent CCS research activity has produced different CCS research infrastructure facilitates, such as the QICS release site in Oban, Scotland and the ASGARD site in Nottingham. These facilities have high set up costs and time limited funding and permission for specific projects, but could still be capable of further activity for a new generation of experiments to address high priority research areas if appropriate permissions were granted. Re-using existing CCS research infrastructure would provide a cost effective way of beginning to address some of the research priorities described in this document, in particular testing monitoring systems and impact studies.

Transfer of environmental assessment and knowledge into effective legislation

- Outputs: Currently there are several strands of environmental research on-going, relevant to CCS. However an effective mechanism by which to transfer the resulting knowledge into the realm of legislation is missing, currently relying on project specific knowledge transfer ambitions. A coherent, international facilitation of this process would prove beneficial. For example the trans-boundary movement of CO₂ streams (where the exporter retains legal responsibility) is a highly relevant concern.
Public Acceptability and Social Impact
Clair Gough and David Reiner

State of the art
As a first step to considering pathways to impact, it is important to get a sense of what the baseline of public perceptions research is in terms of research activity and existing impacts. Social science research on public perceptions of CCS in the UK has thus far focused on three key areas:

> Qualitative research, centered on interviews, focus groups and direct interaction. The aim of such research is generally to look at how publics talk about CCS and get a handle on the contexts that shape publics’ perceptions of CCS – in such approaches, the researcher can ask questions and probe more deeply to get information. The Tyndall Centre studies in various cities were cited in the IPCC Special Report on CCS (2005), and in House of Commons PostNote 238 (2005);

> Research based on questionnaires in order to assess how communication of relevant information shapes people’s opinions. In other words, how do people’s views change after they have received information about CCS? The annual surveys carried out by Reiner and team at Cambridge aim to address some of these issues. The results of these surveys have been used in evidence submitted to the House of Commons Science and Technology Committee CCS Inquiry in 2005/6 and the Energy and Climate change Committee inquiry in 2013/14. The GCCSI Large Group Process in Edinburgh also included a questionnaire element, and its report (Howell et al, 2012) was launched on the GCCSI website in April 2012;

> Analysis and meta-analysis of case studies. Such work analyses real-world CCS demonstration and deployments (as well as other analogous technologies) with the aim of evaluating the efficacy of public engagement strategies. The review carried out by Hammond and Shackley (2010) and the work of the NearCO2 project (Desbarats et al, 2010) are both widely cited in the academic CCS literature.

What are the priorities for CCS public perceptions research?
A key issue requiring further exploration surrounds rationales for CCS. The most common justification for CCS presented to publics thus far begins with the problem of climate change, proceeding to the need for deep cuts in anthropogenic CO2 emissions before moving onto CCS as a vital piece of technology in delivering these reductions. However, recent public perceptions work (e.g. GCCSI Large Group Process, SiteChar Moray case study, UKERC work by Cardiff) suggests that some people may never accept the anthropogenic climate change argument, or that even if they do, they may not accept that CCS is the most effective way to mitigate climate change – they may instead argue for renewable energy sources or behavioural change. There is thus a need to explore more fully how publics perceive different rationales for CCS. These could include, for example, enhanced oil recovery (EOR), energy security, job creation or ocean acidification.
Related to the above is the value in developing quantitative modelling approaches, for example structural equation modelling. Such methodologies could explore the extent to which publics’ perceptions of CCS are related to issues like knowledge of climate change, belief that carbon cuts are necessary and so on. The aim would be to go beyond descriptive statistics and start to tackle issues of causation, dependency etc. These methods using survey data could address some of the same questions as qualitative techniques, therefore potentially allowing triangulation – and thus reinforcement – of data.

A second open area is the heterogeneity of CCS projects. Much work to date has engaged to only a very limited extent with the differences that can arise at the capture (e.g. oxyfuel/pre-/post-coumbustion), transport (e.g. pipeline/ship) or storage (e.g. offshore/onshore) stages. Whilst the presentation of the CCS chain to the publics has perhaps been necessarily broad due to the lack of real-world projects and the technical complexity involved, it is still vital to remain open to the possibility that different forms of CCS may be perceived differently.

The controversy at Barendrecht versus the offshore storage of the ROAD project in the Netherlands clearly suggests the need for some systematic comparative work between offshore and onshore storage. Given empirical work that also hints at publics negatively perceiving CCS due to its fossil fuel connotations (Pidgeon et al, 2012), further enquiry into public perceptions of fossil-fuel CCS versus BECCS may be valuable. With the development of both demo and commercial-scale CCS projects in the UK and many other countries, there is much to be learned from investigating the challenges of CCS communications in different local and national contexts. An associated issue is public perceptions of the discourse of storage. There is a small but burgeoning body of empirical work to suggest publics do not always see CO₂ as a problem, instead viewing it as an opportunity. The destination or fate of captured CO₂ may thus be a key factor shaping public perceptions of carbon capture and transport. For instance, public perceptions could be changed if captured CO₂ is to be used for agriculture or material production. At a more philosophical level, publics have also expressed concern over the psychological effects of storing CO₂ – what would the psychological effects on society be if we were to view the need to ‘store’ CO₂ as the result of our failure to meet emissions cuts through behavioural change?

A third area warranting systematic enquiry pertains to the management of public expectations in the engagement and deployment process. Work carried out by researchers in the USA (Bradbury et al 2009) suggests that communities who perceive they have been treated unfairly in the past are more likely to be opposed to CCS developments. Outside of CCS, there are numerous examples of public perceptions of projects turning negative as costs rise and projected jobs fall. A key challenge for public perceptions research could thus be to consider how public expectations of all aspects of CCS – economic benefits, job creation, climate change mitigation potential, what can be achieved through participation in the engagement process etc – can be managed so as to avoid disappointment, frustration and potential hostility at later dates. A possible outcome of this might be a set of good practice guidelines for CCS public engagement work, which would seek to avoid some of this disappointment and its associated problems. Conversely, what might the role of the public be in the emergence of ‘clumsy’ solutions that allow a range of standpoints to work together?
The challenge of proper, long-term impact assessment

Given its focus on trying to understand the messy and sometimes seemingly contradictory ways in which society works, social science is in a very good place to acknowledge the difficulties in trying to accurately measure impacts. On one hand, impacts can be traced to a limited extent through formal techniques. These may include measuring citations in non-social science/non-energy journals, tracking citations in governmental/NGO publications, and the tracking of diagrams/graphs/schematics as a way of following the flow of ideas. The distribution of survey questionnaires to academics and stakeholders can help to give insight into what research areas are of most benefit to stakeholders, and providing space for respondents to write comments can give even more explanatory insight.

Nonetheless, this perhaps only goes some way to measuring and assessing impacts. What techniques such as those listed above cannot do is track the development of ideas planted through informal interaction and expanded over long periods of time, or pinpoint the role of individuals in consensus emerging among a particular community. Perhaps more pertinently, such approaches also cannot get at the confidential but very influential information given at key moments, nor can they necessarily track our impacts outside of the CCS community.

One potential way round this is to apply the tools and techniques of social science to the challenge of assessing impact itself – almost treating the impact assessment as a piece of social science research in its own right! This could involve interviews with stakeholders (under conditions of confidentiality/anonymity if required), discussion groups, or ethnographic observation. However, the time and resource commitments required to do this in a thorough and comprehensive manner would not be inconsiderable.
Financing, Policy and Deployment
David Reiner

In June 2012, the Cambridge Centre for Carbon Capture and Storage and the Electricity Policy Research Group (EPRG) conducted a stakeholder survey to identify research gaps in the areas of policy, economics and financing of CCS. The survey was distributed to the EPRG/C4S mailing list (300+ stakeholders drawn from policy, economics and financing experts in business, government and academia – the vast majority of these stakeholders have wider interests in energy and electricity economics and policy rather than CCS per se). Over the period 7 – 22 June we received 53 responses in total. Based on the results of this survey together with outcomes from other stakeholder consultations this brief will outline recommendations regarding priority areas of research that would improve knowledge of the economics, finance and policy of CCS.

In general, our stakeholder community believe that CCS deployment in the UK will increase gradually over the coming decades. The majority of respondents indicated that by 2030 CCS will have at least one plant, but less than 5% of the UK’s electricity generation (i.e. roughly 3–4 GW), while by 2050, the majority of respondents (62%) believe that CCS will have between a 5% and 20% share of UK electricity generation.

Almost all respondents (91%) feel that financing of CCS is a barrier to a large-scale deployment of CCS; likewise, the policy framework (88% of respondents) and legal and regulatory issues (83%) are considered to be at least moderate barriers to full scale CCS roll-out. Our stakeholders feel that the following areas of CCS research are the most poorly understood: (i) impact on ecosystems and environment, (ii) public acceptability, (iii) CCS systems integration, (iv) CO2 storage, and (v) policy, economics and finance. Given their backgrounds, our stakeholders felt less qualified to answer questions about the technical state of knowledge, particularly, with regard to capture technologies. Several expressed the view that CO2 for EOR and transportation of captured CO2 are quite well understood areas of CCS research.

More specifically, we asked stakeholders to indicate what are the priority areas for CCS research to focus on over the next 5 years in order to improve the knowledge about CCS policy, economics and finance. We listed 16 economics and finance topics and below are the top 8 priority areas according to our stakeholders:

1. Economics of the whole CCS value chain (34%)
2. Insurance and risk management of end of CCS life cycle (33%)
3. Policy uncertainties associated with regulation, taxation and energy (32%)
4. Policy support mechanisms (28%)
5. Economics and financing of CCS for industrial applications (27%)
6. Industrial policy and macroeconomic issues related to CCS (25%)
7. Allocation of public funding for CCS research (25%)
8. Economics of CCS hubs or clusters (25%)
We also asked the stakeholders to indicate the most effective pathways to disseminate CCS research and knowledge. According to our survey, the most effective pathways to disseminate CCS research and knowledge are:

- Discussions with individual academic researchers
- Small workshops
- Policy (non-technical) papers
- Individual company briefings
- Research reports

Drawing on the results of the survey, we recommend the following three areas within the policy, economics and finance of CCS research stream that would have an impact on both the practice of CCS investment and our understanding of CCS economics and finance.

- Economic modelling of the whole CCS infrastructure system (from the plant with capture through transport and storage) and its interactions with the UK electricity market. This topic could address how CCS, as a system, will interact with the UK electricity market and the effects of these interactions on: (i) the developments of different capture technologies, and (ii) investment in and operation of networks of CO₂ pipelines across the UK. If addressed properly, this area of research will have significant impact on the economics and financing of CCS in two ways:
  - It will improve our understanding in the following areas: (i) how electricity system in the UK will operate if CCS is assumed to be rolled out at a large scale, (ii) interactions of the CCS system with electricity demand uncertainties and with energy policy uncertainties (such as support mechanism and wider energy policy objectives), and (iii) optimal allocation of public funding for different carbon capture technologies, given uncertain future development of the UK's energy mix and policy objectives.
  - Second, research in this area would broaden our understanding of the economics of CCS system integration and together with other UKCCSRC priority research areas (notably the systems, transport and storage themes) could create synergies within UKCCSRC’s overall research portfolio.

- Options and flexibility analysis. Developing an economic framework to compare different carbon capture technologies could help improve our understanding of project financing from the investor and lender points of view. The framework should be able to incorporate and properly value strategic optionality embedded in each capture technology and thereby move beyond a technology-by-technology assessment, allowing for different models of uncertainties. It will be important to include the value of flexibility of these technologies in response to demand and different dispatch requirements of the electricity system.

- Impacts on national competitiveness. An economic model together with a valuation framework is required to understand the impact of public funding of CCS research and the potential impact of the growth in the UK’s CCS industry on the competitiveness of its national economy. The CCS industry in the UK could have positive externalities for the whole economy and we need to properly understand and value these externalities. Doing so will broaden our knowledge about the benefits of funding CCS research beyond Government’s efforts to decarbonise the electricity system (including the CCS industry’s contribution to overall economic growth and competitiveness and the potential benefits of CCS knowledge transfer to other economies).
CCS Construction Materials
John Oakey

This cross-cutting theme focuses on the components and structures involved and their engineering requirements to put CCS technologies into practice. The issues addressed range between the engineering of new components to produce reliable and efficient systems to the impacts that CCS components have when integrated into existing plants. As such, the focus of this theme extends beyond the components directly involved in the capture, transport and storage of CO₂, to those that need to provide improved performance or are adversely affected by new CCS components, whether introduced into newly engineered power systems or retrofitted with existing hardware, e.g. gas turbines or pipelines.

Challenges relevant to this theme arise across all the CO₂ capture options and in the transport of CO₂ up to the point of the injection wells, but less so in sub-seabed storage. A key example would be, for new coal or gas fired power plants, the need to ensure that maximum efficiencies and reliabilities are maintained when post-combustion capture is added, while at the same time not restricting the use of co-firing in coal plants or the use of bio- and waste- derived gases in gas turbine plants. This approach has been underpinning the strategies employed in the UK and across Europe in recent years. For example, by ensuring that any new PF coal plants will operate at advanced steam conditions (e.g. >650°C steam), the impact of adding post-combustion capture on overall efficiency and minimising the impact on the cost of electricity, as well as retaining flexibility to continue to co-fire biomass, meeting all safety and regulatory requirements and delivering at least equivalent RAMO (reliability, availability, maintainability and operability) performance to current plants.

A further example would be the impact of introducing pre-combustion capture into an IGCC (integrated combined cycle gasification) plant, where the choice of pre-combustion technology will have a substantial impact on the performance of the gas turbine used. Current IGCC schemes use significantly de-rated gas turbines to accommodate the combustion characteristics of syngas and the downstream effects of this on hot gas path components (e.g. through increased heat flux). Achieving the levels of performance found with natural gas-fired gas turbines in IGCC schemes, while using H₂-rich syngas will minimise the overall efficiency impacts and will limit increases in the cost of electricity. This challenge is further complicated by the sensitivity of gas turbine operability and reliability to gas contaminants. Physical solvent methods of capture will leave a different blend on contaminants in the H₂-rich syngas to approaches using compression or membrane approaches.

As a result, it is necessary to review each potential CCS scheme and its component parts in order to determine the priority challenges and impacts. In generic terms, this theme considers the manufacture, materials and monitoring needs of components in order for them to perform as required, to be reliable in service and repairable, while at the same time being compliant with engineering design standards and meeting all necessary safety requirements. The following listing of priority challenges illustrates the breadth of this theme and its links with disciplines outside the immediate CCS area.
Priority Challenges

Post-combustion – coal PF plants:

- Advanced materials, manufacturing methods, life prediction methods and in-service process/component monitoring and for USC boilers, pipework and steam turbines to achieve efficiencies required to offset the penalties when using post combustion amine and other capture technologies.
- Corrosion resistant superheater and water wall materials/coatings to resist enhanced corrosivity when co-firing with biomass, including improved process and component monitoring.
- RAMO of amine and other post-combustion capture plants, corrosion potential assessment, effects of flue gas and other impurities and monitoring.

Post-combustion – natural gas CCGT:

- RAMO effects of changed environments on combustion and turbine hot gas path components due to exhaust gas recycle, steam additions, etc. used to increase exhaust gas CO₂ concentrations to reduce capture costs.
- RAMO of amine and other post-combustion capture plants, corrosion potential assessment, effects of flue gas and other impurities and monitoring.

Pre-combustion – coal IGCC:

- Condition and process monitoring of the gasification/gas clean-up hot gas path for reliable operation, including the impacts of the introduction of various pre-combustion CO₂ capture approaches.
- Effects of combustion of H₂-rich syngas on gas turbine materials and RAMO with different pre-combustion capture processes.
- New corrosion resistant bond-coats and thermal barrier coatings.
- H₂-rich syngas monitoring – H₂ content, impurities, etc.

Oxy-firing in coal PF plants:

- Improved understanding and monitoring of the effects of varying levels and methods of oxy-combustion on boiler environments and ash behaviour to minimise fouling and corrosion effects.
- Corrosion resistant superheater and water wall materials/coatings to resist enhanced corrosivity when oxy-firing and allow continued co-firing with biomass, including improved process and component monitoring.

Oxy-firing in coal/biomass/waste CFB plants:

- Improved understanding of the potential for erosion-corrosion and fouling due to the novel process environments and high solids loadings.

Solid looping cycles:

- Improved understanding of the potential for erosion-corrosion and fouling due to the novel process environments and high solids loadings CO₂ transport pipelines and CO₂ injection sea-bed engineering and wells.
- Understanding the effects dense phase CO₂ transport, operating cycles and impurity levels on pipeline materials, inhibitors, and compressor materials, seals, etc.
- Impacts of dense phase CO₂ transport and variable/intermittent operation on sea-bed pipeline, christmas tree, control/monitoring umbilicals and tie-backs, etc. materials and designs, and including condition and process monitoring to ensure reliable and safe operation. Consideration of likely failure modes, fail-safe strategies and leakage monitoring.
CO₂ Properties
Martin Trusler

The processes of carbon capture, transportation and geological storage involve handling CO₂, almost always as a component of a mixture, in a very wide range of conditions under which it has numerous and complex interactions with other substances. In order to design effective, efficient and secure processes for CCS, it is essential to have adequate knowledge of the physical and chemical properties of the various mixtures in which CO₂ is a component. This is an underpinning theme cutting across all aspects of CCS technology including capture, purification, compression, transportation (by pipeline or tanker), injection and long-term storage. The range of thermodynamic conditions is vast: in temperature, from below 50°C to more than 1000°C and in pressures from below atmospheric to as much as 1000 bar. The range of mixtures is equally extensive in terms of both the concentration of CO₂ and the number of other chemical components with which the CO₂ is mixed. Tackling this problem calls for a scientifically valid approach in which a substantial body of experimental data and one or more well-founded theoretical approaches combine to provide systematic and validated modelling tools, suitable for engineering applications.

The thermophysical properties of CO₂ as a pure substance are well understood and reliable modelling tools are available for engineering purposes. Of course, much is known about the properties of CO₂-containing mixtures but, because of diversity of composition, temperature and pressure, it is not presently possible to predict all relevant properties under all relevant conditions with the necessary confidence. Thus, further research into CO₂ mixture properties is required. The RAPID table identifies research areas having potential impact in matrix form by application area and property type. The areas of application are broken down into the three major categories of capture, transportation and geological storage, with appropriate sub-categories. Properties are classified as bulk thermodynamic properties (including phase equilibria and the thermodynamic properties of homogeneous phases), bulk transport properties (viscosity, thermal conductivity etc), interfacial properties (surface/interfacial tension, contact angle, wettability) and chemical properties (pH, reactivity etc).

Capture
Solvent-based post-combustion
In solvent-based post-combustion CO₂ capture, the areas of highest potential impact are probably in characterising the vapour-liquid equilibria (VLE) of CO₂ with aqueous amine systems other than those most commonly used today. Other areas of potential impact include assembling the data and models required to fully characterise mass transfer in absorbers and strippers on a microscopic scale, including transport properties (viscosity and diffusion coefficients) and interfacial properties (interfacial tension and wettability). These properties are required for real systems including impurities such as those present in the CO₂ streams and those that arise from degradation of the solvents. Finally, enthalpic effects have been neglected and high-quality calorimetric studies of CO₂ absorption/desorption in relevant solvents would have significant impact.

Pre-combustion capture
In the area of pre-combustion capture, the thermodynamics of synthesis gas (syngas) are key including topics such as low-temperature VLE of hydrogen-rich syngas and the removal of acid-gas impurities by solvents and other processes. Although these are classical areas, incremental improvements in understanding the basic thermodynamics can have significant impact.
Oxy-fired combustion

In relation to oxy-fired combustion, the key issue from a properties point of view is the process of CO₂ cleanup. Significant impact could follow from a better understanding of the low-temperature VLE of typical oxy-fuel flue gases and thermodynamic aspects of the processes for removal of oxygen, inerts and acid-gas impurities prior to and/or in the compression train.

Transport

Post-combustion – coal PF plants:

Advanced materials, manufacturing methods, life prediction methods and in-service process/component monitoring and for USC boilers, pipework and steam turbines to achieve efficiencies required. Impacts of dense phase CO₂ transport and variable/intermittent operation on sea-bed pipeline, christmas tree, control/monitoring umbilicals and tie-backs, etc. materials and designs, and including condition and process monitoring to ensure reliable and safe operation. Consideration of likely failure modes, fail-safe strategies and leakage monitoring.

Storage

Geological storage will bring CO₂ into a high-temperature high-pressure environment in which it will contact brines and possibly hydrocarbons within the pore space of possibly reactive reservoir rocks. Here, the greatest impact may come from tackling difficult measurement problems, such as interfacial properties, pH and chemical interactions between brines and reservoir minerals in the presence of dissolved CO₂. Better understanding of CO₂ solubility in reservoir fluids and of the onset of flow-assurance issues such as asphaltene deposition would also have great impact. Some of the simplest properties, such as density and viscosity changes that occur when CO₂ dissolves in reservoir fluids, need to be better understood and addressing these issues will have impact in terms of increasing confidence in predicting the long-term fate of CO₂ underground.

Integration of Properties Research

The impact of UKCCS research in the area of CO₂ properties will be maximised by integrating the effort in both the organisational and scientific senses. In respect of the latter, it is essential to combine excellent experimental work with advanced property modelling with the ultimate aim of developing an comprehensive and consistent approach that can be applied with confidence.
Appendix 3

Overall Research Needs for CCS

Research area champions and their colleagues have also assessed overall research needs more widely in single page summaries.

Research Area Champions (RACs) were asked to review the priorities set out by all RACs for the 18 UKCCSRC theme areas and comment on overall priorities for CCS. RACs, informed by the wider CCS community, consider CCS as a whole and highlight links between themes, thus identifying overarching and shared priorities. Comments may also reinforce the views on priorities in certain theme areas or point out the need for inclusion (or greater emphasis) of certain priorities.

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CO2 Properties 56
CCS Systems
Nilay Shah

Key:
› priorities that particularly resonate with me
› priorities that I feel might have been emphasised more

Materials
› Flexible temperature ranges and flexible H₂ content
› Corrosion/erosion effects in high temperature looping cycles
› Effects of trace elements (especially metals) from gasification on downstream materials, what is the right level of abatement?
› More needed on optimal materials for seals etc

Systems
› Model-based technology evaluation platform
› Model-based scale-up from lab and pilot plant
› Operability and safety analysis; flexibility analysis

Adsorption and membranes
› Flexible facility to test different materials
› Cost engineering and new manufacturing techniques

High temperature cycles
› Pilot testing platform
› Effective heat transfer

CO₂ properties
› Mixture properties over a wide range of temperature, pressure and species
› CO₂-solvent interactions prediction especially association/dissociation energy

Capture
› Characterising the performance of a wide range of solvents
› Hybrid systems
› Cryogenic/antisublimation processes with coolth integration?

Transport
› Transport performance dependence on purity
› Pipeline integrity and purity relationship
› Materials vs CO₂ composition
› Scoping study on ship-based transport (technical, economic, etc.)
Storage
› Understanding injectivity and capacity and implications for the upstream part of the chain
› Effect of impurities
› Model-based scale-up from lab and pilot plant
› Pressure behaviour – short and long term

H₂/pre combustion capture
› Systems integration and intensification (e.g. sorption enhanced reactions, UCG)
› Model-based scale-up from lab and pilot plant
› Operability and safety analysis; flexibility analysis

Financing and deployment
› Economics across the value chain: how do all participants benefit?

Eco-systems and environmental impact
› Quantifying impacts of solvent degradation products and other non CO₂ emissions
› Quantifying long-term impacts of CO₂ storage (cf. nuclear waste)

Reservoir engineering
› Storage and injection modelling and optimisation
› Well/platform operability and safety analysis; flexibility analysis

Monitoring
› Design of effective, multilayered monitoring strategy
› Systems integration
› Piloting and testing in key industries
› CO₂ utilisation
Capture technology selection
It is highly likely that the leading capture technologies will all play an important role for the foreseeable future. However, technology choices may be case specific that depend on a number of factors, including fuels specifications, scale and the level of required flexibility. These issues may be addressed by high-level whole-chain techno-economic assessments based on dynamic simulations. To enable these models, many other areas of modelling will require further development such as the use of CFD for radiative heat transfer in oxyfuel calculations or the improvement of thermodynamic models to cope with CO₂ phase change in the presence of impurities.

Pathways from demonstration to commercial deployment
Policy considerations are required to encourage the deployment of CCS on a large scale and avoid “demo to death”. This will involve more cost-effective cluster based approaches with associated issues relating to initial scale, the co-ordination of different entities, business models, the impact of impurities on shared transport networks, management of fluctuations and interruptions etc. A driver for commercial deployment of CCS is EOR which requires site specific feasibility and geological studies.

Public perception
Negative public perception of CCS has led to major disruption of projects in a number of countries. Countering negative perceptions requires both social science (policy, education effective communication and public liaison strategies etc.) and technical research approaches. Public concern of technology hazards and reliability may be addressed by whole chain environmental assessments (a prime example is assessing the formation of nitrosamines from post-combustion capture amines), storage monitoring strategies that include conclusive demonstration of storage integrity and alleviate concerns of induced seismicity, and safety testing of materials used to handle CO₂ in the presence of anthropogenic impurities.

High priority research themes on oxyfuel capture technology
Virtual System simulation: The development and validation of the Virtual Dynamic Simulation of the power plant with CCS capabilities have the potential to significantly reduce the time, capital, and operational costs required for the development and deployment of novel carbon capture technologies. The developed software could provide information on the molecular-level dynamics of carbon capturing materials, and on scale up to explore how this material functions at the device-level then see how the device functions in a production power plant on a time frame of weeks and months. The data generated from all recent large scale projects will provide a significant scope for the validation, assessment and benchmarking of the developed software. The validated tool will provide:

- Quick identification of “proof of concept” via process screening and modelling followed by design time reduction, intelligent optimization and troubleshooting of new devices and processes
- Assess and manage the technical risk in taking new/modified equipment/process from laboratory-scale to commercial scale
- Provide operations dynamic simulation and control with real-time applications
- Provide a platform for supply chain management plant-side optimisation
- Provide cost effective approaches for deployment by reducing the number of physical operational tests required by utilising the virtual system simulation software
Innovative cycles for GT-CCS technology: The impact of innovative cycles such as Humid Air Turbine (HAT) and Oxy-HAT on reducing the cost of GT-CCS and research into associated challenges. Another innovative cycle which requires significant RD&D is oxyfuel, high pressure, supercritical carbon dioxide cycle (e.g. Allam Cycle). These types of novel cycles produces pipeline-ready CO₂ for sequestration or use in enhanced oil recovery, without reducing plant efficiency or increasing costs.

Oxy-EOR Capture technology: Investigation into the innovative power system firing NG-CO₂-O₂ and separating and collecting pressurized CO₂ without adding on a carbon capture system followed by CO₂ subsequently used for enhanced oil recovery.

Conversion to Biomass (Biomass-CCS): Biomass usage in combustion based power generation is an enormous research field in its own right to which CCS adds an additional layer of complexity. Some specific issues include the impact on ash deposition, slagging and fouling, and the development of fuel feed systems for pre-combustion capture. A number of recent policy & technology roadmaps highlight the Biomass-CCS as alternative option (e.g. Biomass-CCS: The Way Forward for Europe, ZEP, 2012 & Committee on Climate Change 2011).

High Temperature Looping
Stuart Scott

In the review of the research priorities document, several links have been identified between the high temperature looping theme and priorities in other themes. These links are highlighted below:

Second generation CCS processes (links to adsorption and membranes theme)
High temperature looping represents a broad class of processes which includes chemical looping (which links with oxyfuel combustion) and carbonate looping. These technologies (along with other novel technologies, involving membranes, and novel low temperature sorbent systems), aim to resolve the fundamental issue of the energy penalty associated with the first generation technologies. Some of these novel capture processes share aspects of fundamental science and detailed understanding of materials is a common theme, whether the material is a part of an oxygen transport membrane, an oxide in an oxygen carrier for chemical looping, or a CO₂ sorbent. The importance of testing of materials in realistic process conditions, e.g. using slip streams (as highlighted in the adsorption theme) applies equally to high temperature looping. Scale up to produce material for carbon capture which is both effective, robust and cheap is also required.
Links to systems, transport and storage
High temperature looping and other more novel technologies for capture are still at an early stage of development, either at lab, pilot, or first demonstration stage. Some work has been carried out to understand the benefits of these processes by taking a systems level view, i.e. looking beyond the plant scale, to interactions with wider economy and other industries. How a full scale system will operate in practice as part of real energy system, where issues such as flexibility, control etc. will be important is less well known than for the first generation technologies. Thus, the true benefit of e.g. a second generation looping system compared to a first generation technology, which takes into account how the plants will actually be run over the next 20–50 years is required. The fate of pollutants in the process, and whether the final CO₂ stream is of sufficient purity is of relevance to the materials, transport and storage themes.

Links to industrial CCS
For high temperature looping cycles, the “system” is larger than just the electricity supply network or CO₂ supply/capture chain, since looping cycles have important links with industrial capture. The high temperature of heat rejection from these systems makes heat integration of critical importance, and also provides opportunities for large cost reductions in capture. Furthermore, the materials used as sorbents or oxygen donors may themselves be of value, e.g. spent calcium sorbent from a carbonate looping plant can be used in cement manufacture and iron and other metal oxides are used as oxygen donors in chemical looping.

Links to pre-combustion capture
High temperature looping cycles have been proposed as subunits of pre-combustion systems, with both carbonate looping (via the sorbent-enhanced shift process) and chemical looping (e.g. the steam iron process and its variants) able to produce hydrogen.

Process optimisation and reactor modelling/design
High temperature looping cycles are likely to use circulating fluidised systems, or packed beds. The modelling and design of these systems to allow scale up is common across many themes (e.g. circulating fluidised bed oxyfuel combustion, packed beds for absorbents).

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Industrial Capture
Paul Fennell and Tamaryn Napp

Carbon Capture and Storage has a crucial role to play in mitigating CO₂ emissions and avoiding dangerous climate change. However, a full-scale integrated CCS plant (not to mention a CCS network) is highly complex and many different factors need to come together for it to be a successful venture. Three issues which are pivotal to the wide-scale deployment of CCS and which impact every stage of the CCS chain are: (i) scale-up design, (ii) flexible operation and (iii) a viable business case.
CCS plants will have to operate successfully and economically within the future electricity network. It is likely that there will be limited scope for base load CCS-power generation and CCS will have to demonstrate flexible operation in order to be viable. All options for flexible operation of different CO₂ capture plants should be explored. The impact of intermittent operation on CO₂ capture performance, pipeline transport, CO₂ injection and overall economics needs to be assessed.

CCS is a high-risk venture. It requires large initial capital outlay and there are many uncertainties surrounding future prices, policies and regulations. The following areas are key:

- **Limitation of business risks:** Reduce costs at every point in the process by taking a systems view, i.e. a techno-economic analysis of a full integrated CCS process in order to identify areas for optimisation. Understand how CCS would operate within the electricity network and the implications of flexible operation, electricity prices, fuel costs and policies on economic feasibility.

- **Limitation of legal risks:** Development of accurate monitoring and measurement in order to detect early any indication of geomechanical instability, limit the risk of leakage and obtain legal insurance. This should be based on a detailed assessment of the impacts on marine, geological and terrestrial ecosystems and environments as well as an understanding of fault flow properties and modeling of CO₂ migration post injection.

**Industrial CCS links to other research areas**

**Links to CO₂ capture**

- Understand how gas components, properties and impurities in industrial CO₂ sources impact on the operation of different CO₂ capture processes.

- Modification of high temperature solid looping cycles for use with industrial CO₂ sources.

**Links to CCS systems**

- Heat integration and optimization modeling of industrial processes with CCS.

- Synergies between industry and power generation both through the integration of energy and material flows.

- Possibilities for demand side management at industrial sites with CCS.

**Links to transport**

- Assessment of potential industrial CCS sources and their proximity to both storage sites and other CO₂ sources in order to develop a CO₂ transport network. Effects of co-location on CO₂ purity - can pipeline specifications be met at lower cost by appropriate mixing of industrial and power sources of CCS?

**Links to materials**

- The importance of developing materials enabling high temperature and high H₂ content operation.

- Investigation of corrosion/erosion effects in high temperature looping cycles.

**Links to high temperature looping cycles**

- Co-production of cement, applications of novel looping cycles (developed for power generation) in other industries. Use of spent materials from CLC and carbonate looping cycles applied to power generation in industrial processes.
In the review of the research priorities document, several links have been identified between the transport theme and the work being highlighted as priorities in other themes. These links should strengthen the development of integrated, high priority research areas between themes. These links are highlighted below:

**Links to CO₂ properties**

It has been recognised in the RAPID assessment for pipeline and ship based transport that there is an urgent requirement to be able to model phase and transport behaviour across a range of temperatures, pressures (and therefore phase) and impurity combinations. This is critical for the accurate modelling of hydraulics, fracture propagation and outflow and dispersion in particular. In this respect, the ability to model phase behaviour in the solid phase and around the triple point is particularly important and it is considered that this should also be included in the work proposed in the CO₂ properties theme. In addition, it is also critical to understand the water solubility behaviour over a range of temperatures and pressures for CO₂-H₂O systems containing impurities. Removal of water is vital in controlling the risk of corrosion, cracking and hydrate formation in a pipeline. It is recognised that work is being proposed in the CO₂ properties theme in brines but the extension of this work to the CO₂-H₂O impurity system is also extremely important.

**Links to systems**

Much of the transport specific research has often been conducted in isolation without due reference to the whole system and an integrated approach needs to be adopted in future. However, one of the key gaps that has been highlighted in the transport area is the requirement for a robust techno-economic model which will allow decisions to be made, particularly on transport design and specification of the CO₂ entering the system. This will enable projects to identify where the cost reductions can be made across the CCS chain – for example, and with respect to the specification of CO₂ purity, more impure streams of CO₂ require higher input pressures to the pipeline and therefore have implications for the design of the pipeline i.e. thicker walled pipe or higher material strengths – all of which have a cost implication for the pipeline constructor – however, the reduction of impurity levels has cost implications for the emitter. A model is required to enable these type of decisions to be made independently on a project basis. This model should include the results of the technical “transport specific” research already conducted as part of other research projects.

It is noted that the requirement for an economic model across the whole CCS chain is also included in the Financing, Policy and Deployment theme.

**Links to public acceptability and social**

One of the areas in which the public will come into contact very visibly with CCS projects is during the construction phase of pipelines. The engagement of the public along the pipeline right of way is therefore key in terms of enabling pipeline routes, which have been determined on a design and risk assessment basis. Methodologies for engaging the public will be key during public consultation exercises for pipeline routes.

**Links to ecosystems and environmental impact**

The dispersion of CO₂ from leaks and ruptures of pipeline onshore and offshore has been identified as a priority in the transportation theme. This is required principally for the risk assessment process for routing a pipeline. However, an understanding of the potential longer term effects on flora and fauna (onshore and offshore) will also be required. It is considered that understanding is limited in these areas.
Monitoring R&D
Andy Chadwick

Key:

› Priorities that particularly resonate with me.

Systems

› Virtual systems models to optimise full-chain performance for a wide-range of scenarios.

CO₂ properties

› Mixture properties over a wide range of temperatures, pressures and species (cross-cuts with reservoir engineering).
› CO₂ solubility in reservoirs (cross-cuts with reservoir engineering and storage).

Transport

› See monitoring cross-cut.

Storage

› Pressure control and geomechanical stability.
› Verifying performance – what are the acceptance criteria for conformance?
› Fault properties – both in the reservoir (flow barriers) and in the overburden (flow pathways).
› Dissolution.

Ecosystems and environmental impact

› See monitoring cross-cut.

Reservoir engineering

› Upscaling and simplified models to optimise resolution on key model parameters.
› CO₂ dissolution/convection (key medium-term stabilization process).

Monitoring

› Monitoring for geomechanical instability.
› Quantitative imaging improvements from reservoir to shallow overburden.
› Low-cost monitoring for onshore pipelines – particularly onshore for public acceptance. (cross-cuts with transport, public acceptability and environmental).

Industrial capture

› Generically very important – only CCS can deal with industrial emissions.

Site leasing and regulation/public engagement

› Leasing issues with respect to conflicts of interest (e.g. stacked reservoirs, other users).
Site Leasing and Regulation
Sam Holloway and Michelle Bentham

Overall, the main issues for CCS seem to be:

- Is it possible to find a favourable balance of risk and reward for the storer, storage regulator and other stakeholders?
- What are the real costs of CCS compared to other means of low carbon electricity generation?
- What are the environmental implications of a persistent leak and how do these compare to not proceeding with CCS?

Other topics that are priorities are:

**Systems**
- Effects of load following on the downstream CCS chain.

**CO₂ properties**
- Impacts of the main classes of impure CO₂ streams on rocks and borehole construction materials (cements, steels, alternatives).

**Transport**
- Optimising transport in terms of the efficiency of the CCS system as a whole, e.g. smoothing out short term changes in mass of CO₂ transported, optimising transport pressures in terms of the other components of the chain.
- Safety and public acceptance issues.

**Storage**
- Reservoir pressure management.
- Geomechanical stability of storage sites.
- Fault properties - both in the reservoir (flow barriers) and in the overburden (flow pathways/planes of geomechanical weakness).
- Are fractures in cap rocks an issue for containment (many cap rocks can be shown to have good sealing properties provided they contain no fractures).
- The stress field in potential storage areas on the UKCS (knowledge needed for geomechanical modelling).

**Ecosystems and environmental impact**
- Improved modelling of environmental impact of doing nothing about CO₂ emissions.

**Reservoir engineering**
- Application of reservoir engineering techniques to global and regional storage capacity estimates.
- Coupled flow and geomechanical modelling.
- (Offshore) wells as potential leak paths and their remediation.

**Monitoring**
- Monitoring for geomechanical instability.
- Improve quantification of mass of CO₂ in the reservoir and shallow overburden using seismic data.

**Site leasing and regulation/public engagement**
- Leasing issues with respect to present and future conflicts of interest (e.g. stacked reservoirs, other users).
- What are the trans-generational issues and how should these play into the licensing and regulation of storage?
Ecosystems and Environmental Impact
Jerry Blackford

Overall priorities for an environmental perspective
CCS poses a range of interlinked engineering and technical challenges ranging from capture to storage. This sits within overarching requirements of economic viability, health and safety and environmental protection. Together these three areas contribute to public perception and acceptability.

From an environment perspective, the overall rational for CCS is the prevention or mitigation of the potentially severe environmental (and economic) impacts of climate change. However, experience with onshore sequestration plans and for example the siting of wind farms demonstrates that more local environmental concerns can have a significant impact on progress.

In order to reach a wider audience than the core environmental interest groups, linking environmental to economics is required. The key challenge is to identify pathways by which arising environmental knowledge can be transferred into appropriate regulation.

Finally, for CCS related environmental research, it is important to maintain a neutral standpoint, neither advocating nor criticising CCS (or any other carbon mitigation method). This approach has enabled current research to address a wide range of interested stakeholders, from industry to environmental campaigners.

The following links other research areas have been identified. These links should strengthen the development of integrated, high priority research areas between themes.

Links to capture
Quantifying impacts of solvent degradation products (especially amines) and other non-CO₂ emissions. Here there is a need to review existing knowledge and identify required research.

Transportation
The dispersion of CO₂ from leaks and ruptures of pipeline onshore and offshore has been identified as a priority both in environment and transportation themes. This is required principally for the risk assessment process for routing a pipeline. However, an understanding of the potential longer term effects on flora and fauna (onshore and offshore) as well as potential human health issues will also be required. Some research in both terrestrial and marine environments is ongoing. Aspects relating to human health could benefit from a review of existing knowledge.

Storage, site regulation, monitoring
In particular the choice of sites would benefit from environmental risk assessments, to ensure that valuable natural resources are not unduly put at risk. There are key linkages between storage characterisation/geological monitoring and environmental monitoring. Improved characterisation of the former would inform approaches to the latter. The issue of saline aquifers as potential storage sites will require novel environmental impact assessment, not yet considered.

Public acceptability and social
Improved certainty in environmental impacts is a key input to public opinion. A strategy for non-biased dissemination of understanding to a wide audience is necessary.
Public Acceptability and Social Impact
Simon Shackley, Leslie Mabon and Clair Gough

Economics, jobs and costs
Particularly important here is developing more accurate and realistic figures for the job creation potential of CCS. Doing so is not only important in terms of garnering national/regional government support, but also for the management of public expectations so as to avoid disappointment, frustration and potential hostility at later dates. Input from those with experience of project management of large infrastructural projects and who are knowledgeable about the personnel hiring practices of the oil and gas and related sectors could help to develop realistic figures for the number and type of jobs likely to be created in the UK by CCS.

Management and governance of large technical systems
This is an area key to the successful implementation of CCS projects, one that could be researched most effectively via collaboration between engineers, social scientists and others. The field of science and technology studies (STS) has some useful insights on the management of large technical systems, for instance relating to the measurement of the flexibility of technologies. The concept of neo-incrementalism as a technical decision-making strategy (making small steps in development and planning for learning from experience) also warrants further exploration. Critical input from engineers, especially those in industry and management consulting, could help to develop both of these ideas and further their applicability to CCS.

Liability
The issue of future liability for stored CO₂ and for the definition of permanent storage/acceptable leakage rates is crucial. This is a task that involves furthering physical science understanding of the migration and fate of CO₂, and greater legislative clarity. It can also benefit from understanding of liability issues as a regulatory- or mandated-science type of question. STS has made important advances in understanding how such types of science for policy differ from ‘normal’ science. There is also a role for public perceptions work here, in that public acceptance of CCS may to some extent hinge on the perception of ‘the taxpayer’ being liable for any future events, or for the potential for leakage.

More refined understanding of uncertainty
Perhaps feeding into the point above about the interface between physical science, governance and society is a deeper understanding of the different uncertainties surrounding CCS. For instance, following Wynne (1992), uncertainty could be characterised as risk, uncertainty, indeterminacy, ignorance etc. The nature of the uncertainty in question could have profound effects for insurers, governments and indeed publics, all of whom may react very differently to a calculated risk than to, say, an indeterminacy. A multi-disciplinary dialogue with the aim of building clarity on what we all mean by ‘uncertainty’ could help to avoid issues further down the line and help us decide what can be meaningfully quantified and what cannot.

Measuring impact in a meaningful way
There seems to be a broad consensus that the ‘impacts’ of CCS research cannot easily be measured or quantified. Nonetheless, we believe that applying the tools and techniques of social science research to the process of impact itself can help to give us a greater understanding of how impacts are achieved. In other words, looking at how stakeholders (especially developers) draw on the work of universities could in itself become a social science research project. Confidential interviews or discussion groups with developers, for example, could refine our understanding of how impacts are generated.
Financing, Policy and Deployment
David Reiner

From the perspective of the policy, economics and finance theme, there is an increasing need, especially from the finance community, to understand the risk/return profiles of different generation technologies and CCS configurations given the UK’s wider climate and energy policy. In this respect, the existence of a handful of capture technologies with different level of maturity and uncertain understanding of integration of capture, transport and storage just adds another layer of uncertainties for investors, thereby weakening any assessment of CCS relative to other technologies (both conventional and “green” ones). Another concern from an economic point of view is that because UK government support (e.g. the £1bn CCS competition) will choose from amongst different generation and capture technologies, there is a risk of being locked in to an inferior technology, given: (i) different capture technologies produce CO₂ with different properties which affect the design and operation of the CO₂ pipeline network (and hence costs), and (ii) CCS development based around clusters would reinforce the lock-in effect further.

Given these two concerns, we see numerous synergies between the priority areas proposed by the policy, economics and finance theme and the priority areas of the systems and transportation themes. In particular, we think that developing the “technology evaluation platform”/“virtual system” concept and “multi-scale modelling approaches” that allow high-fidelity models to link with lower-fidelity, less computationally demanding models can have great synergies across many of the UKCCSRC’s proposed research themes if this can be integrated with economic models.

Links to CO₂ properties theme
Further, the CO₂ properties and transport themes could focus on the potential impact of captured CO₂ with different properties from different capture technologies on the design of the CO₂ pipeline network, which minimises the unit cost of transport. An interesting question related to the CO₂ properties and pipeline theme is to define the potential trade-off between transport costs and the flexibility of the pipeline system in accommodating CO₂ with different properties.

Links to full CCS chain (capture, transport and storage) and systems theme
More research on economic mechanisms to de-risk (or minimise) investment in the CCS chain (capture, transport and storage) would be a priority for the policy, economics and finance theme. The risk profiles across the CCS chain (capture, transport and storage) differ substantially and involve many questions in need of answers: Should storage activities follow a ‘market-driven’ approach or be tightly regulated? Should the government bear the risks related to CO₂ transport and storage in order to unlock investment in CCS? What is the most economically efficient way to manage different risks along the CCS chain? Together with the three priority areas proposed by the policy, economics and finance theme, these questions could potentially have a large impact on CCS research.

In order to address these different elements, an integrated economic model (modelling markets for electricity and other energy commodities) could be linked with the Systems theme’s proposed technology evaluation platform, which would include all three major CCS infrastructure components (i.e. capture, transport and storage). This research strategy and approach could better integrate the two themes and address many interesting economic-engineering questions related to CCS, thereby widening our understanding of the technology and feeding back in to the other themes.
**CO₂ Properties**

**Martin Trusler**

In this section, I comment on some of the research priorities and key linkages between the CO₂-properties theme and other themes.

**CCS systems**

It’s probably worth emphasising the obvious fact that reliable property models are fundamental to understanding the operation of whole systems. Thus, there is a need for experimental research on CO₂ properties to be coupled with the development of integrated property-modelling packages.

**Adsorption and membranes**

Here a better understanding of the thermophysical properties influencing mass and heat transfer in absorbers and strippers is needed. This will involve properties such as the viscosity, thermal conductivity and interfacial tension, as well as enthalpy changes associated with CO₂ absorption/desorption.

**Capture**

Establishing improved processes for solvent-based capture will require further research on the vapour-liquid equilibria (VLE) of CO₂ with potential solvents, including blends. In addition to VLE, calorimetric properties are required (heat capacity and phase-change enthalpies). The kinetics of CO₂ absorption/desorption are also important and should be measured along with the VLE. There is a strong link with CO₂ properties in this area.

**Transport**

The main linkage here is the need to understand very well the phase behaviour of CO₂-rich streams under pipeline conditions, including the effects of a host of potential trace impurities.

**Storage**

This is another area of strong linkage with CO₂ properties, with the main requirement being to understand better all relevant physical properties of the multi-phase fluids present in the storage sink. Properties such as CO₂ solubility, interfacial tension and contact angle are key, with other interesting properties being the density and viscosity of CO₂-saturated brines and oils. Chemical interactions between CO₂-acidified brines and reservoir minerals are another area for consideration as, depending on the type of formation, reactive transport may be important.

**Pre-combustion capture/hydrogen**

This calls for a better understanding of low-temperature VLE in mixtures of CO₂ and H₂ with various minor components.