IChemE Energy Centre

The Future of CCS

An IChemE Energy Centre Green Paper

The world's population is expected to exceed nine billion by 2050, a figure that will undoubtedly increase demand for energy. Currently fossil fuels provide more than 85% of the world's energy. Despite significant global efforts to shift to renewable energy generation, renewable sources only accounted for 2% of the global energy supply in 2014. It is therefore logical to assume that fossil fuels will remain an indispensable part of the world's energy landscape until at least the end of this century.

In signing the Paris Agreement the world reached a decision to limit global warming to 2°C, with the ambition of capping this at 1.5°C. To do this atmospheric CO_2 concentrations must be stabilised. This means that we must act now to decarbonise our electricity production; and carbon capture and storage (CCS) is a readily deployable technology solution to achieve this.

To meet the world's global warming limit, it is expected that we need to store 120-160 Gigatonnes of carbon dioxide ($GtCO_2$) from now until 2050. Globally there is a theoretical storage capacity of approximately 11,000 Gt of CO_2 with 1,000 $GtCO_2$ provided by oil and gas reservoirs, 9,000-10,000 GtCO2 provided by deep saline aquifers and a significant potential capacity in unminable coal seams. If we choose to sequester 120-160 $GtCO_2$ by 2050 there is more than enough storage capacity to do so, and enough for our CCS needs to be met well beyond the next century.

Translating major research findings to the market often takes many years, and developing a systematic procedure for the acceleration of the transition of academic research to pilot- and demonstration-scales is essential for CCS.

Key areas for discussion

Power sector and flexible CCS	Negative emissions technologies
Industrial CCS	CO_2 transport
The role of new sorbent materials	CO_2 storage, utilisation and conversion

It is vital that the near-term (2030) targets do not prohibit medium (2050) or long-term plans. Roadmaps must employ a whole-systems approach incorporating existing power sources, green energy sources, industrial plants, and carbon capture, transport and de-risked storage infrastructure. The balance of the components will evolve as the process of decarbonisation takes place across many decades.

Climate change is estimated to cause enormous direct costs due to changing weather patterns and crop yields. These global financial losses will vastly exceed the costs of implementing CCS. The deployment of CO_2 capture, transport and storage infrastructure will support the creation of new, high skills STEM jobs, directly contributing to the health of the global economy.

To limit global warming to the 1.5°C degree limit CCS deployment must be progressed as an urgent priority, this will require proactive support from governments around the world. We have the ability to deploy CCS technology today, and in so doing, take a major step forwards to the least-cost mitigation of dangerous climate change.

Priorities for CCS

1. **Creation of a computational framework to understand the dynamic interplay between scientific and technological advancements**, their impacts on the power markets, and the broader socio-economic consequences of deploying CCS.
2. **Development of a methodology to rapidly screen new solvents and sorbents** for CO_2 capture based on molecular level information, and provide process level cost and performance information.
3. **Appropriate benchmarks must be identified and universally adopted** for the successful development of new processes for CCS. We recommend the use of the Cansolv technology as a new standard against which progress with sorbent development should be compared.
4. **CO_2 storage infrastructure must be de-risked around the world** via exploration and characterisation of suitable geological structures. This is more urgent than the development of new capture technologies.
5. **CO_2 utilisation via Enhanced Oil Recovery (EOR) is mature**, and has the potential to provide a near-term, market-driven pull for the deployment of CO_2 transport infrastructure. However, EOR is not a panacea and can lead to the net emission of CO_2.
6. **The environmental impact of products derived from CO_2 will be very small** compared to the level of CO_2 that is needed to be stored as part of climate change mitigation. However, using CO_2 can reduce the environmental footprint of existing chemical processes.
7. **The impact of CCS must focus on the £/MWh, rather than efficiency** improvements at the cost of increased CAPEX. Materials with accelerated rates of heat and mass transfer are essential.
8. **The cost of power generation or industrial processes must be decoupled from CO_2 capture and the CO_2 transport infrastructure**. Initial project costs are significantly inflated relative to the potential for the subsequent cost reduction once infrastructure costs are shared.
9. **The role of electricity markets in the development of CCS technologies needs to be carefully evaluated**, with particular attention paid to the way in which CCS power plants will interact with the electricity markets.
10. **It is vital that meeting near-term targets does not come at the expense of long-term targets.** Meeting the Paris Agreement depends on using bioenergy with CCS (BECCS), this cannot be implemented without a mature and established CCS industry.

To meet targets outlined in the Paris Agreement funds must be made available to support the research needs of CCS. It is imperative that funding for CCS is progressed towards deployment.

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CCS Forum Report

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#poweringCCS

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The CCS Forum, February 2016

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Executive Summary

The three-day CCS Forum, held in London, hosted delegates from academia, industry, and government to discuss the future of CCS and, in particular, to identify the key research challenges to be addressed in the near-to-medium term. In all sectors pertaining to CCS, it was agreed that translating major research findings to the market often takes many years and that developing a systematic procedure for the acceleration of the transition of academic research to pilot- and demonstration-scales is essential.

Over the course of the three days, the applications of CO_2 capture technologies to the power and industrial sectors were discussed in detail, as was the subsequent geological storage of the CO_2. In addition to the utilisation of the CO_2 in enhanced hydrocarbon recovery, the mineral carbonation of industrial wastes and also the potential for the further conversion of CO_2 into chemicals was discussed. Furthermore, the role of policy measures to enable the deployment of CO_2 to the power and industry sectors was discussed. The critical needs identified have been summarized in the Executive Summary and the detailed insights are included in each section throughout the remainder of the document.

Conclusions and key priorities for CCS

1. Creation of a computational framework to understand the dynamic interplay between scientific and technological advancements, their impacts on the power markets, and the broader socio-economic consequences of deploying CCS.

A the key outcome of this workshop was the recognition of the need for a framework to understand the dynamic interplay between scientific and technological advancements, their impacts on the power markets, and the broader socio-economic consequences of deploying CCS.

2. Development of a computational framework to rapidly screen new solvents and sorbents for CO2 capture based on molecular level information, and provide process level cost and performance information.

On the scientific front, there is a clear need to develop modelling tools that can rapidly screen new sorbents for CO_2 capture based on molecular level information. The development of a suite of tools or approaches to evaluate the potential role of novel technologies in the energy system will be essential for developing new technologies. Ultimately, these decision-support tools will be related to the overall process cost and how the addition of CCS affects the cost of the final product, be it electricity or another industrial product.

3. Appropriate benchmarks must be identified and universally adopted for the successful development of new processes for CCS. We recommend the use of the Cansolv technology as a new standard against which progress with sorbent development should be compared.

It was agreed that in order to assess progress in cost reduction, the identification of an up-to-date benchmark is vital. It was observed that the use of aqueous solutions of alkanolamines, specifically 30 wt% monoethanolamine (MEA), as a benchmark technology is near ubiquitous throughout the CCS research community. While this provides a useful method of comparison, it does not demonstrate how the research on trial actually competes against contemporary technologies in 2016. While not grave in and of itself, this can offer a false sense of improvement where none is actually warranted. Research into alkanolamine solutions for carbon capture applications has in fact progressed significantly. At the time of writing, the industrial standard is Shell's Cansolv technology, which is currently deployed at the Boundary Dam facility in Canada. For example, the regeneration of a conventional 30wt% solution of MEA requires 3.5 to 4 GJ/t_{CO2} of heat supplied at 150°C whereas Shell's Cansolv technology requires only 2.3 GJ/t_{CO2} at similar temperatures. Moreover, Fluor's Economaine and MHI's KS-1 solvents exhibit similar performance. Therefore, the use of 30 wt% MEA as a benchmark should be replaced. In this context, it would be exceedingly useful if one or more of the leading technology developers were to make sufficient information available to enable thorough comparisons to be made so as to appropriately rank novel technologies. Review of this comparative benchmark can and should be done down the track as new technologies progress and improve.

The importance of identifying appropriate benchmarking approaches was identified as being essential for successful development of new processes for CCS, be these processes based upon solid sorbents, membranes, hybrid processes, or other new methods. Efforts must be made for innovations to compete with solvent-based processes that are presently deployed, noting that their performance, in terms of physical properties and cost, will likely further improve in the time that it takes newer technologies to be commercially deployed. For this reason, only materials and processes that have the potential to lead to significant improvements in process performance in terms of both capital cost and efficiency should be pursued. For these reasons, the development of approaches to provide an early indication of process performance against a range of industry-relevant indicators should be pursued as a priority.

4. CO_2 storage infrastructure must be de-risked around the world via exploration and characterisation of suitable geological structures. This is more urgent than the development of new capture technologies.

The ultimate aim of CCS efforts is the permanent storage of CO_2, as part of a transition away from the extensive utilisation of unabated fossil fuels for power generation and industrial processes. In this context, perhaps more urgent than the further development of capture technologies is the de-risking of CO_2 storage infrastructure around the world via exploration and characterisation of suitable geological structures. Whilst this effort is proceeding well in Europe, the UK and the USA, the Asia-Pacific region (China and India in particular) were identified as being in need of further detailed studies with a view towards qualifying and quantifying their potential CO_2 storage infrastructure. It was noted that this initiative should heavily involve the oil and gas industries. Towards this end, the Oil and Gas Climate Initiative was identified as a multi-corporate grouping that could play a leading role in this effort, perhaps acting under the Mission Innovation initiative.

5. CO_2 utilisation via Enhanced Oil Recovery (EOR) is mature, and has the potential to provide a near-term, market-driven pull for the deployment of CO_2 transport infrastructure. However, EOR is not a panacea and can lead to the net emission of CO_2.

The role of CO_2 utilisation and conversion as part of the effort to mitigate climate change was extensively discussed. The most mature utilisation of CO_2 is to couple CCS with enhanced oil recovery (EOR). Work on EOR remains somewhat controversial because of the perception that it perpetuates the oil and gas industries, and thus leads to further CO_2 emissions. However, the role of CO_2-EOR in providing a near-term, market-driven pull for the deployment of CO_2 transport infrastructure must not be underestimated. Moreover, whilst it is true that CO_2-EOR would likely lead to the net emission of CO_2, there is evidence that oil derived by this process could displace both conventional and unconventional crudes, leading to substantial quantities of CO_2 avoided.

6. The environmental impact of products derived from CO_2 will be very small compared to the level of CO_2 that is needed to be stored as part of climate change mitigation. However, using CO_2 can reduce the environmental footprint of existing chemical processes.

The conversion of CO_2 to other compounds was also discussed in detail. Here, the conclusion was that the total market for any CO_2-derived commodity will be very small relative to the scale of what needs to be stored to avoid climate change. Importantly, the duration of storage associated with CO_2 conversion was discussed at length, with the conclusion that, from a human perspective, anthropogenic CO_2 needs to be permanently stored in order to contribute to the mitigation of climate change; temporary storage of ~ 50 years will have limited to no climate benefit. However, the use of CO_2 as a material to displace less environmentally benign materials can have the effect of materially reducing the environmental footprint of existing chemical processes.

7. The impact of CCS must focus on the £/MWh, rather than efficiency improvements at the cost of increased CAPEX. Materials with accelerated rates of heat and mass transfer are essential.

The commercial deployment of CCS does not only rest on scientific and technical advances but also the cost and performance impact of deploying CCS on the power and industrial sectors. To date, research efforts aimed at improving CCS processes were observed to have almost exclusively focused on efficiency improvement and fuel-OPEX reduction. Going forward however, an increased focus on CAPEX reduction is recommended. One promising route to achieving this is by developing materials for CO_2 capture, including solid or liquid sorbents and membranes, that exhibit substantial improvements in the rates of heat and mass transfer and the CO_2 carrying capacity, whilst continuing to reduce (or at least not increasing) the energy of regeneration. Another important requirement, especially in the context of post-combustion capture, is for improved models for predicting mass-transfer efficiency as the current lack of reliable models necessitates wide design margins and increased CAPEX.

8. The cost of power generation or industrial processes must be decoupled from CO2 capture and the CO_2 transport infrastructure. Initial project costs are significantly inflated relative to the potential for the subsequent cost reduction once infrastructure costs are shared.

Decoupling the cost of power generation or industrial processes with CO_2 capture and the requisite CO_2 transport infrastructure is a serious consideration. Initial efforts to deploy CCS have included both the cost of the power generation and the associated infrastructure in project costs. This leads to initial project costs being significantly inflated relative to the potential for the subsequent reduction of project costs once infrastructure costs can be shared. Thus, perceptions of CCS first-of-a-kind (FOAK) costs are likely inflated owing to the bundling of CO_2 generation (power plant), capture, transport and storage together. Therefore, a consistent, decoupled costing methodology that accurately reflects the costs of the major constituents of CCS is needed.

9. The role of electricity markets in the development of CCS technologies needs to be carefully evaluated, with particular attention paid to the way in which CCS power plants will interact with the electricity markets.

The role of electricity markets in the development of CCS technologies needs to be carefully evaluated, with particular attention to the way in which CCS power plants will interact with the electricity markets. As intermittent renewable energy generation sources more significantly penetrate power grids, thermal power *generation* (as distinct to thermal power capacity) could be increasingly displaced from the electricity market. It is therefore highly unlikely that CCS plants will provide baseload generation, although this will inevitably vary between national energy systems. This needs to be made clear in any case set out for the deployment of CCS strategies. The ability of CCS plants to provide ancillary services to the electricity grid will need to be explicitly valued, along with the role of CCS in providing co-benefits such as low carbon heat, hydrogen and negative emissions. Therefore, a multi-scale view of CCS that ranges from the molecular scale to the whole energy system is needed to reduce the risk of technology assessment with the associated supply chains.

Despite the fact that several key CCS projects, such as Sleipner, Snøhvit, Insalah, Quest and Gorgon are all industry-led projects, academic research efforts into explicitly-industrial CCS are nascent relative to those into the power sector. A key difference between power and industrial CCS is the highly heterogeneous nature of the industrial sector, with a paucity of public domain data, relative to the power sector. The fact that most industrial emitters exist within an internationally competitive market as distinct to the power sector which primarily serves a domestic market serves to compound this issue. For this reason, a “one-size-fits-all” solution for any one industrial sector is unlikely. Initially, highly-concentrated point source emissions of CO_2 from certain industrial sources should be pursued as “low hanging fruit”, with the gas purification and fertiliser sectors being obvious examples here. However, it is acknowledged that key enablers are required to deliver this, including an incentive to capture the CO_2 and access to adequate transport and storage infrastructure. The costs associated with industrial CCS remain unclear as this area increasingly becomes a priority and more systematic studies will be required.

10. It is vital that meeting near-term targets does not come at the expense of long-term targets. Meeting the Paris Agreement depends on using bioenergy with CCS (BECCS), this cannot be implemented without a mature and established CCS industry.

In the context of developing roadmaps to low carbon economies, it is vital that the near-term (2030) targets do not prohibit medium (2050) or long-term plans. For example, it is well recognised that very significant amounts of negative emissions technologies, likely bioenergy with CCS (BECCS), will be required in order to meet the targets agreed as part of the COP21 agreement post 2030. In this context we recognise that a mature, de-risked CCS industry and associated infrastructure will be required to facilitate the implementation of BECCS technology. Furthermore, these roadmaps must employ a whole-systems approach incorporating existing power sources, green energy sources, industrial plants, and carbon capture, transport and de-risked storage infrastructure. The balance of the components will evolve as the process of decarbonisation takes place across many decades. Favourable legislation is essential to incentivise these advancements. Further, policy must help to highlight the demonstrable benefits arising from the deployment of CCS technology, in addition to the provision of dispatchable, reliable, low carbon power. Climate change itself is estimated to likely cause enormous direct costs due to changing weather patterns and crop yields. These global financial losses will vastly exceed the costs of implementing CCS. Further, the deployment of CO_2 capture, transport and storage infrastructure will support the creation of new, high skills STEM jobs, again directly contributing to the health of the global economy. These positive impacts are difficult to quantify but will have undeniable fiscal benefits while tackling climate change. Therefore, CCS needs stronger representation as a technology that ensures a sustainable energy, environmental, and economic future.

Based on the research needs identified in this workshop, the Foreign and Commonwealth Office is requested to make funds available for projects via the Mission Innovation initiative. Therefore, the Mission Innovation initiative needs to explicitly include CCS as a technology of interest. In addition, there is interest in identifying whether the Oil and Gas Climate Initiative (OGCI)[1] can take the lead on the study of identifying the low hanging fruit for EOR. An effort to investigate opportunities for collaborative activities with Canada's Oil Sands Innovation Alliance (COSIA)[2] and the OGCI as part of the Mission Innovation initiative would also be of broad interest and is something that should be pursued in this context.

[1] OGCI: http://www.oilandgasclimateinitiative.com/
[2] COSIA: http://www.cosia.ca/

Introduction

In February, 2016, a three day CCS Forum was held at the Royal Academy of Engineering in London. The purpose of this forum was to discuss research progress in the broad field of CO_2 capture and storage and to identify key challenges to be addressed in the near to medium term.

The discussions were held under the Chatham House rule[3] and importantly, this document does not purport to represent the views of any individual, institution or organisation. Rather, it intends to provide a summary of the discussions that took place over the course of the Forum and to reflect the consensus that was formed.

Summary of discussions of the capture, utilisation and storage of CO_2

The following sections are presented in the same order as the discussions took place, dealing first with the capture of CO_2 arising from the power and then industrial sources, the development of advanced sorbent materials for CO_2 capture, negative emissions technologies and finally the storage and utilisation of CO_2.

Each section first provides a short summary of the discussion that took place and then concludes with an articulation of key research needs in this area for the near to medium term.

Power Sector and Flexible CCS

The integration of CCS with power generation is recognised to both significantly increase the capital and operating costs (CAPEX and OPEX, respectively) associated with power generation. The power sector always has had a natural focus on efficiency as their primary concern because implementing CCS will wipe away results of decades of work on improving power plant efficiency. Moreover, in a market environment the marginal cost of electricity will determine the ranking of power stations being able to deliver electricity. However, over the past decade, significant improvements in OPEX and process efficiency have been achieved, primarily via advances in the design of sorbents. In this context, it was agreed by Forum participants that the focus of research should now be shifted to prioritise reductions in capital costs for these improved CO_2 Capture systems. Doing so was agreed to be a key route to achieving significant reductions in the cost per MWh of low carbon power.

While continued improvements in the thermodynamic performance of both the underlying power plant and the sorbent for CO_2 capture are helpful, as this can have the double effect of reducing the emissions associated with the base power plant and implementing more efficient CO_2 capture technology will make the decarbonised power plant more efficient. However, care should be taken to evaluate whether the cost to implement efficiency gains outweighs the benefit. Indeed implementing marginal improvements in efficiency has the potential to increase total electricity costs at a rate greater than contribution of efficiency gains alone could reduce them. Unsurprisingly, approaches to reduce capital costs are multi-faceted and are subject to significant uncertainty, particularly around financing and contingency costs. Key opportunities may lie in reducing construction costs, noting that materials of construction (stainless steel, cement, etc.), labour rates and productivity and construction times play an important role here. One popular example is to move from expensive stainless steels to cheaper alternatives that have similar performance. Another approach to reducing costs is reducing the size of the equipment required. To achieve this, improvements in sorbent design for heat and mass transfer and reaction kinetics will be key, in addition to the conventional focus on CO_2 solubility/carrying capacity and the energy of regeneration. Methods and strategies for more efficient equipment production and construction also were proposed as a mechanism for total cost reduction. Advanced manufacturing techniques currently being developed have the potential to reduce the unit cost of equipment and to produce complex equipment designs that are highly-specific to the intended application; advanced manufacturing should enable similar or better performance in less expensive equipment. A final point was the potential value in modularity – if

[3] https://www.chathamhouse.org/about/chatham-house-rule

processes could be constructed on a mass-modular basis off-site and then assembled and erected on-site, this has the potential to reduce on-site construction times. This has the potential to unlock the cost reduction potential offered by mass production and would enable the application of CCS technology to smaller fixed point sources, the reduction in the effect of location factors on process costs[4] and, potentially, reducing bottlenecks in equipment supply chains.

While capital cost remains the primary concern, the value in further reducing operating costs and thermodynamic penalty should not be ignored. Regarding the latter, the net power requirement to run CCS systems must be clearly distinguished from any thermal investment required to operate the system; how thermal requirements translate to a power penalty in a heat engine cycle (eg the Rankine cycle of a conventional pulverised coal power plant) is highly dependent on the quality of heat (ie temperature) required, as well as quantity. This distinction is often lacking in the literature.

It was agreed that continued CCS cost and performance improvements must be measured against currently deployed technology to properly assess improvements. The typical benchmark 30 wt% monoethanolamine-based solvent system for CO_2 capture was agreed to be outdated, and its continued use as a yardstick could give rise to a false sense of improvement. Owing to its deployment in Canada, the current industrial standard would appear to be the Shell Cansolv technology[5], with Fluor's Econamine and MHI's KS-1 solvent offering similar performance. Therefore, potential new processes, eg new solvents, membranes, solid sorbents or hybrid process should be compared with the technologies that are currently deployed, noting that these already deployed technologies may well improve with subsequent deployment. Therefore, processes which offer only marginal improvements over existing approaches should likely not be pursued further.

Predicted future high penetration of renewables will mean that thermal power plants with CCS are unlikely to operate at base load in many electricity markets. As such, developing inflexible CCS operations is unrealistic for future applications. It is essential to address the adaptable nature of CCS operations while carefully considering the capital designs and operating procedures. This is predicated on the recognition that the energy system of the 21st century will be distinct to that of the 20th century. Where the system of the 20th century was characterised by a margin of installed capacity over peak demand of 10-20%, this margin will significantly increase in the 21st century, perhaps going well beyond 100% in scenarios with a high penetration of intermittent renewable generators. An integrated whole systems assessment is important to determine the value of CCS technologies in different national energy systems. Static metrics, such as the Levelised Cost of Electricity (LCOE), are insufficient as they do not capture the interactive nature of power generating technologies in the dynamic energy system of the 21st century. Consequently, flexible and dispatchable assets, such as CCS power plants, are undervalued by the LCOE approach. A whole-systems approach to energy system costs would be more likely to recognise the value of dispatchable low-carbon technologies such as CCS and would also highlight the cost of balancing the system in its absence. This would enable policy makers and system operators to explicitly value services that ensure grid stability, as opposed to having them implicitly provided as part of the contract. In turn, this would enable new providers feel a market pull to offer these services.

The deployment of CCS requires a level playing field from a policy perspective. This policy paradigm needs to adequately recognise the broader value provided by all forms of low carbon power generation and also explicitly recognise where the inclusion of some forms of low carbon power generation imposes costs upon the energy system. This is essential to protect the initial financial investment made without increasing the cost of electricity. It was agreed that aiming to decarbonise the electricity system, ie obtain an average grid carbon intensity of less than 50 kg_{CO2}/MWh using solely renewable energy would be essentially impossible, and even the deployment of very significant overcapacity combined with a

[4] Noting that, for example, the costs of similar projects in the US Gulf Coast and Northern Canada can differ by a factor of 2 -3 owing to so-called location factors
[5] See for example: http://www.shell.com/business-customers/global-solutions/shell-cansolv-gas-absorption-solutions/cansolv-co2-capture-system.html

substantial amount of electricity storage capacity would not solve this problem[6], further qualifying the role and value of CCS-based generation.

Given that CCS power plants will likely be required to act in sympathy with intermittent renewable generating sources, costs must be reduced with improved designs of CCS processes with an increased focus on the off-design point operation. This requires enhancing the ability for CCS systems to adjust to turndown requirements more efficiently and properly estimating the true equipment sizes. In this context, it was observed that both oxy- and post-combustion capture processes can interact with the electricity grid and have the potential to provide medium-sized and duration energy storage at low marginal cost. There will be implications for how the dynamically operating electricity system will interact with the CO_2 transport and storage infrastructure, and this must be accounted for explicitly in early phases of system design and operation.

Research Needs

The deployment of power CCS at commercial scale has been achieved with the successful deployment and operation of the Boundary Dam facility. However, power CCS still requires significant reduction in capital and operating costs to move forward. Indeed, whilst Boundary Dam does represent a milestone in the deployment of CCS in the power sector, this is only the first instance, and it is possible that the next iteration will include some process and/or plant-level modifications that could add to the cost of next offering and offset some of the expected cost reductions from learning. Until there are several years of operating experience, costs will still be uncertain. From an academic research perspective, priorities include the development of solid and liquid sorbents with improved heat and mass transfer characteristics, without compromising on reaction kinetics, selectivity and solubility/carrying capacity. Similarly the development of advanced membrane materials with high selectivity and suitability for low pressure operation should be prioritised. The development of improved approaches for the incorporation of lower cost materials of construction was also identified as a key near term priority, with a focus on low carbon steel alloy being highlighted. An improved understanding of the likely load-following role that CCS will be required to play in the dynamic energy system of the future will serve to more accurately inform the CCS design problem and will allow process “right-sizing” as distinct to the “oversizing” that is currently the norm. This includes not only addressing the dynamic energy systems that will influence CCS operations, but also how turndown requirements can be understood to keep costs down. Importantly, these newly flexible designs will work to focus on the valuable services CCS generated electricity can offer (particularly: firm capacity at peak, frequency response, reserve, and inertia) while being mindful of the impact on both capital and operating costs, as well as the resulting electricity cost.

From a more practical perspective, the impact of geography on CCS costs must also be included where local rates for labour, fuel, and construction must be included. Local and regional impacts on cost savings from deployed CCS must be assessed with cooperation from grid operators and policy makers. Finally, it is recognised that the key to cost reduction is deployment at scale, the decoupling of CO_2 capture costs from the significant costs associated with the deployment of transport and storage infrastructure (as will be the case for the early facilities), and proving the efficacy of the technology at a commercial scale, which will thereafter lead to a reduction in project finance costs.

[6] It was shown that solely relying on intermittent energy sources would require an installed capacity base of approximately 400% of peak demand in addition to energy storage capacity equal to 50% of conventional firm peak demand, ie 110% of peak demand, to reach a grid carbon intensity of less than 50 kg_{CO2}/MWh for 48 h, and that this system would still require some gas-fired power generation.

Industrial CCS

Despite the fact that several key CCS projects, such as Sleipner, Snøhvit, Insalah, Quest and Gorgon are all industry-led projects, academic research efforts into explicitly-industrial CCS are nascent relative to those into the power sector. A potential reason for this is that, relative to power sector CCS, the policies required to incentivise industrial CCS (iCCS) are more complex owing to the fact that while the power sector broadly operates and competes in a local, internal market, the industrial sector competes within a global market place; it is eminently possible for steel from Asia to displace steel produced in the EU. Thus, given the historical lack of regulations to support low carbon products, the industrial sector has been slow to move towards decarbonisation, despite substantial gains being made in energy efficiency.

As such, it was noted that border carbon adjustments (BCAs) are potentially a key policy option for incentivising iCCS within the EU. In 2010 – 2011 such policies were considered to be unworkable within the EU, yet this situation has now changed with some EU companies advocating a border tax on imported products with a high level of embodied carbon. Thus such taxes are possible within existing global trade agreements. A key challenge, however, is developing a measure for carbon intensity of different products from different jurisdictions. The certification process used for biofuels offers a precedent and methodology. To further incentivise iCCS, specifications for new construction projects and building could require specific percentages of low carbon steel and cement. Such an approach would increase the necessary demand from low carbon sources thereby maintaining homeostasis.

A further complicating factor is the heterogeneous nature of the industrial sector relative to the power sector. Indeed, there exists the potential for significant variability within key industrial sectors – for example, no two oil refineries are alike. This again is in contrast to the power sector where power plants of a given class have broadly similar layouts and operating conditions, thus allowing general conclusions to be readily drawn with regard to their decarbonisation. For these reasons, there exists significant variability in the literature around the cost of CO_2 capture from industrial sources, as illustrated in Figure 1 below.

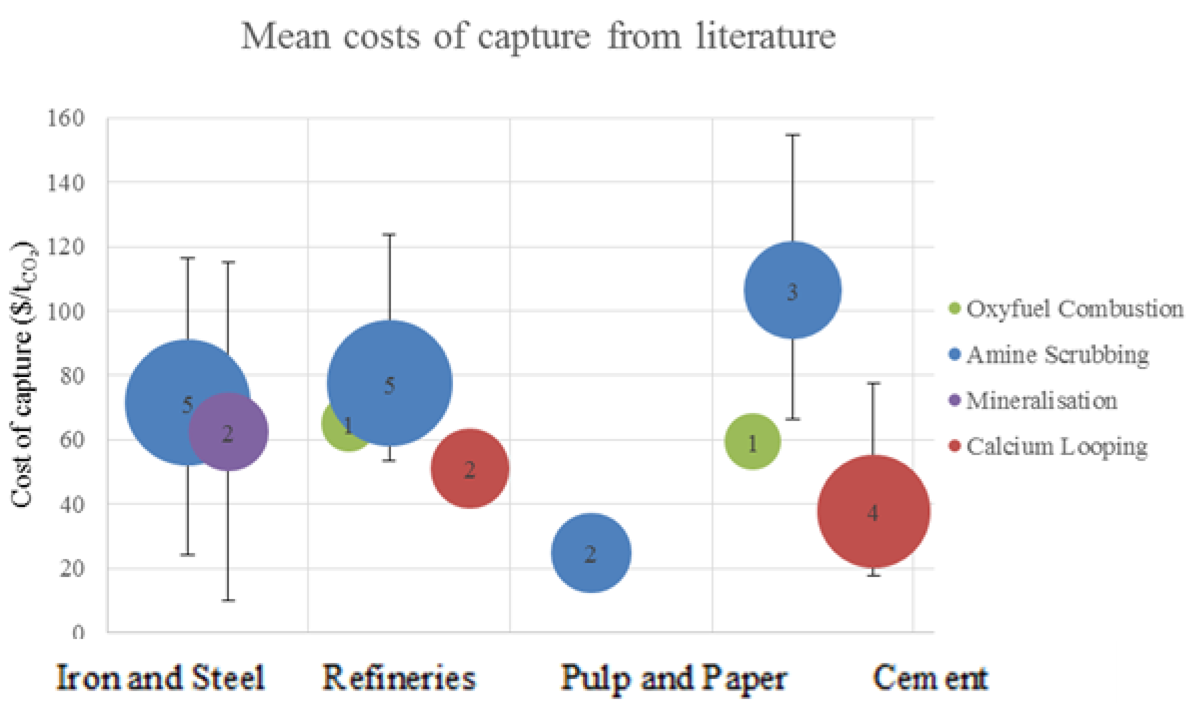

Figure 1. Mean costs of CO_2 capture from literature, adapted from Leeson et al.[7]

[7] Leeson, et al., Int J GHG Con, 2016 (Accepted)

For these reasons, a blanket 90% capture rate across all industry sectors may be an inefficient means to achieve a deep decarbonisation of the entire industrial sector. Deep carbonisation of the industrial sectors is likely to be achieved through a variety of actions, one them being CCS, but use of biomass, production technology innovation have the potential to be equally important. Techno-economic assessments will point towards those options which are most effective to implement and a ranking of these options is needed to result in pathways towards deep carbonisation. Partial CO_2 capture of the emission of a facility as determined by the quantity and quality of available waste heat is a good example. There is a secondary optimisation evaluating the most effective capture rate for a particular process application. Sector-specific targets (at a range of timescales) should be determined so as towards an overall achievable goal (ie deep decarbonisation), which must also consider the role of cost. To this end, partial capture solutions might represent more cost effective solution in some specific industrial cases. For example, a given facility might aim to capture only the fraction of CO_2 emissions that can powered using waste heat available on site. This approach could accelerate the deployment of industrial CCS by reducing the operational cost associated with operating a CCS plant.

It was further agreed that CCS, regardless of the sector, ie power or industry, needs a level playing field in which to compete, ie the provision of low carbon power or commodities such as steel or cement should be explicitly valued. It was also recognised that it takes time to build infrastructure and retain skills. Therefore, the cancellation of major projects such as the Peterhead and White Rose CCS projects means that useful infrastructure may be abandoned – the reinstallation of which will be costly and associated skills base will potentially be lost.

Investment in CCS will be at the same magnitude and will have a similar potential for job creation as the oil and gas industry – this is something that needs to be recognised by both industry bodies and labour unions. Thus CCS is not a “job killer” in the way that industrial changes are sometimes perceived as being. Rather it preserves and creates high-skills Science, Technology, Engineering, and Math (STEM) jobs.

Moreover, it was note that the marginal cost of CCS deployment is within the bounds of volatility of fossil fuel prices. Thus, the governments are facing a dilemma between the short term advantage in an increasingly carbon constrained world and the longer term costs associated with carbon mitigation. In this context, we need to think more clearly about the cost of not mitigating and then compare with the cost of mitigation,

As has been noted, industries are individual and require attention as such. The three largest industrial emitters of CO_2 are discussed in turn.

Cement

The cement manufacturing industry accounts for 5% of all global CO_2 emissions, with Ordinary Portland Cement (OPC) currently regarded as the industry standard. For this reason, any alternative cement production process should result in a product which yields cement having properties identical to OPC. In the production of OPC, limestone ($CaCO_3$) is first calcined, a process where heat is used to drive off CO_2 and leave CaO behind. This step accounts for 66% of the CO_2 emissions from a cement plant, and will some process reconfiguration[8], this CO_2 could be recovered directly for transport and storage[9]. The remaining CO_2 emissions from cement production arise from the combustion necessary for the generation of process heat. To reduce the cost of this heat generation, lowest cost, and therefore dirty, fuels are used resulting in impurities in the flue gas (eg SO_2 and dust). For such cases, oxy-fuel combustion technology is superior to amine scrubbing. Moreover, kiln capacity has the potential to increase by 20-25% relative to an air-combustion baseline through O_2 atmosphere enrichment to 30-35%. Calcium looping technologies also have the potential for synergies owing to the option to reuse purged CaO material in the cement production process and the availability of the option to recover and reuse heat

[8] As in, for example, the Leilac process: http://www.leilac.org.uk/

[9] IEA “Technology Roadmap: Carbon Capture and Storage in Industrial Applications”, 2011

rejected at approximately 650°C to run a sub-critical power cycle. It was suggested that the application of ore-processing reconfiguration to a range of industrial calcination processes, in combination with concentrated solar thermal power, could provide sufficiently high temperatures to run cement manufacturing reactions and produce a pure stream of CO_2 for transport and storage without necessitating the use of further fossil fuels.

An area of recent interest is the incorporation of carbonated materials into cement. While promising, compressive strength, and other industrial requirements of the materials must be maintained. Other innovations in this industry include the use of Mg-based cements. However, the role of these materials as fillers in addition to building and construction materials needs to be evaluated further.

Oil and Gas

Responsible for approximately 3% of total global emissions, the oil and gas industry leads industrial sectors in experience, interest, and research and development for implementation of CCS. This is paired with strong balance sheets and, potentially, access to low cost finance. Thus, this sector has all of the key elements required to make CCS deployment a reality.

The relevant experience of this sector is broad with a comprehensive understanding of relevant issues to CCS: geology, licensing, site operation, safety, high pressure operation/transport, and offshore engineering. Particularly, the oil and gas industry has considerable experience in upstream processing, which involves gas sweetening and produced CO_2, as well as CO_2-enhanced oil recovery (CO_2-EOR) with the associated CO_2 transport and injection infrastructure. An important element in our discussions of this sector was the observation that the marginal cost of CCS is low relative to long term volatility in oil prices, meaning that CCS could be deployed within existing financial frameworks.

One important factor to consider is whether the emissions would grow with an increase in hydrocarbon production (considering both conventional and unconventional oil and gas), and how these emissions can be mitigated at source. For example, it was suggested that decarbonisation by on-site hydrocarbon reforming to produce hydrogen with simultaneous storage of the associated CO_2 has the potential to be a more cost-effective option than the production of hydrocarbon and the subsequent capture and storage of CO_2.

It was noted that the downstream sector of the oil and gas industry was particularly challenging to decarbonise. Oil refineries offer a particular challenge here owing to their large, integrated nature, the heterogeneity of these facilities in general and finally the potentially large number of point sources in any given installation, which themselves have the potential to be diverse in terms of flow rate and composition. That said, there are some point sources of CO_2 at a refinery that are relatively easy to mitigate, such as catalytic crackers: decarbonisation of these units should be a high priority. It was further noted that decarbonising a complex refinery might require the use of more than one capture technology.

A final observation was that the oil and gas industry may have a role to play in enabling the transition away from the utilisation of fossil fuels in a range of sectors. It was proposed that while it is relatively commonplace for countries to produce and distribute CH_4, in the future gas exporting countries might reform the CH_4 as a matter of course, exporting the resulting H_2 and using the CO_2 for enhanced gas recovery. This would have the effect of removing concern about CO_2 – enhanced hydrocarbon recovery; if the carbon is being immediately returned to the subsurface, then there can be no subsequent CO_2 emission when the hydrogen is being used for heat, power or transport.

Iron and Steel

The majority of emissions from the iron and steel industry come from the worlds 180 large integrated steel mills, with the sector producing 7 – 8% of anthropogenic CO_2. A large integrated steel mill will produce over 10 Mt_{CO2} per year, with, for example, Tata's Ijmuiden facility producing 6 Mt of crude steel per year and emitting approximately 12.6 Mt_{CO2}/y[10]. China is the world's largest single producer, with 695 Mt

[10] http://www.tatasteel.com/global-network/steel-manufacturing/european-operations.asp

attributed to the Chinese iron and steel sector in 2011. Global steel production rates have increased since 2008, with an average rate of growth of approximately 4%/y. This has equated to a doubling of steel output over the last 12 years. However, within Europe there have been a significant number of facility closures. Firstly, due to stabilizing demand and increased productivity, from 1990 to 2004 inefficient small operations were closed. This was followed in the last decade by more closures due to a decrease in demand and raw materials crises.

Reducing the CO_2 emissions from the iron and steel sector requires an integrated systems understanding. Steel production uses two alternative technologies, a Blast Furnace (BOF) or an Electric Arc Furnace (EAF). The CO_2 impact of BOF in average, 1.8 t_{CO2}/t_{steel}, is more than double that of EAF, 0.7 t_{CO2}/t_{steel} if only scrap is used. Only limited possibilities exist to reduce CO_2 emissions while continuing BOF operations. The steel industry has acknowledged that a breakthrough development is essential to reducing CO_2 emissions. A €70 million program was run from 2004-2010 under the name of Ultra Low CO_2 Steelmaking (ULCOS)[11]; partners included ArcelorMittal, Tata Steel, ThyssenKruppStahl, Ilva, voestalpine, LKAB, Dillingen/Saarstahl, SSAB, Ruukki in conjunction with over 40 institutes, universities, and engineering companies to understand the impacts of CO_2 emissions reduction. The objective was to halve CO_2 emissions per ton of steel from iron ore based steel production by 2050. Conclusions drawn from this program and other academic studies suggest that in the steel industry significant carbon mitigation can only be achieved by (1) installing new, improved and very costly processes for efficient carbon use, (2) replacing fossil carbon with low carbon alternatives (biomass, electricity, hydrogen), and (3) putting in place CCS technologies. The main conclusion for an integrated steel mill with on-site power generation is that CCS is key to achieving substantial reductions in CO_2 emissions.

Research needs

There will not be a single solution for industrial CCS as the applications are too diverse. However, a clear methodology must be developed to assess the optimal approach for reducing carbon emissions in industry-specific cases. Efforts should be particularly focused on rapid implementation of more straightforward applications with high point sources of CO_2 (eg ethanol production, cement reconfiguration). In addition, the need for process intensification and "process decluttering" to remove CO_2 must be accomplished as early as possible. In some cases, as has been demonstrated with the cement industry, changes to industrial chemistry syntheses should be explored to produce less CO_2. In industrial CCS, the modifications to reduce the carbon footprint cannot affect the product specifications whilst retaining cost competitiveness. The development of industrial clusters in lowering the cost of iCCS through process/product integration and industrial ecology are important considerations. For the steel industry more R&D is necessary on capturing CO_2 from a $H_2/CO/CO_2$ stream and the reheating of the remaining H_2/CO gasses for reuse. An EU wide programme is needed for the development of large scale new CCS technologies. There are good examples in Japan which could be used as a template, such as Course50[12]. These factors all suggest that further academic research on a broad spectrum of carbon capture methods is also warranted.

[11] ULCOS: http://www.ulcos.org/en/index.php

[12] http://www.jisf.or.jp/course50/outline/index_en.html

The contrasting challenges of industrial and power CCS

The 2009 IEA CCS roadmap highlighted the importance of CCS in industrial sectors and called for dedicated actions in specific industrial sectors. Despite significant activity in some areas, notably gas processing, CCS action in a number of key industrial sectors is almost totally absent (IEA/UNIDO, 2011).

In the EU, it is notable that the European Technology Platform for Zero Emission Fossil Fuel Power Plants, now simply known as the Zero Emissions Platform or ZEP[13] initially focused entirely on power sector although recently it has considered industrial CCS given the lack of progress of power-sector CCS in the EU. Lack of bankable support (no CO_2 demand for EOR or other revenue streams, no binding Carbon Price Floor) has stymied progress in Europe. The EU has put forward both power and industrial CCS projects but poor policy design and no mechanism to deliver in a liberalised market have led to no current projects going forward. There has been limited government support for CCS (apart from Norway) and there is some local opposition in other countries, as in Germany for example.

Many CCS projects have relied on EOR CO_2 demand to get some projects off the ground. These have also benefited from regional partnerships and minimal opposition, but there is been little policy design other than significant financial support. Large sums are available but relatively little has been allocated to competitive projects and two largest power CCS projects have either failed (eg both incarnations of FutureGen 2.0) or have been repeatedly delayed and are significantly over budget (eg Kemper County).

There has, however, been some excellent progress on several industrial demonstration projects, notably in North America that have been funded largely with the 2009 stimulus spending, but without dedicated industrial or climate policy there is very limited chance of wider rollout. Unlike nuclear power or onshore wind, there are no strong opponents to CCS. Although few are actively opposed, many NGOs remain sceptical, and some viewed CCS as diversionary, or a white elephant, while others believe the approach harkens back to an earlier conceptions of pollution control or should be funded entirely by industry with no government subsidy. Equally, there are few if any advocates in industry willing to lobby strongly on behalf of the technology since their preferred alternative is unabated fossil generation, which is why Lord Oxburgh has coined the term of CCS as an ‘orphan technology’. Although Industrial CCS is more attractive than power CCS in terms of cost-effectiveness given the lack of viable alternative decarbonisations it is even more challenging to implement because these sectors (eg steel, cement, chemicals) are more exposed to trade and these industries are extremely sensitive to any rise in energy prices, particularly one that would have an impact on national competitiveness.

Research needs:

A forward-looking approach to CCS for the power and industrial sectors will be critical to reaching the 2050 climate objectives via a least-cost trajectory. This will require an enabling policy framework, including a reform of the Emissions Trading System and the Mission Innovation Fund, to increase business and investor clarity, which is needed to further develop this technology. For this reason, it is judged vital that the Mission Innovation fund adopts CCS technology as a near term priority. The UK is a good example where there has been significant investment in investigating the potential for rolling out CCS nationally through the work of the Committee on Climate Change and the Energy Technologies Institute, but a comprehensive assessment of the potential for industrial and power sector CCS is relatively absent in many other countries. More effort is needed to investigate more seriously the intersection between CCS policy and industrial policy and to consider potential consumer interest in low-carbon options and the challenges and opportunities within the value chain for implementing decarbonised industrial clusters. There have also been few serious efforts to analyse, let alone independently develop, the facilitating infrastructure needed to support larger-scale rollout.

[13] ZEP: http://www.zeroemissionsplatform.eu/

Moving beyond existing systems for post-combustion CO_2 capture

Alkanolamines have been used in natural gas sweetening operations for decades. These compounds, particularly 30 wt% aqueous solutions of monoethanolamine (MEA), are broadly regarded as the benchmark against which other technologies should be compared. However, this is no longer the case – at the time of writing the industrial standard is arguably the Shell Cansolv technology deployed at the Boundary Dam facility in Canada.

However, the use of aqueous solutions of 30% MEA solvents as a benchmark for CCS technology evaluation is common in the academic literature. The regeneration of MEA-based solvents requires 3.5 – 4 GJ/t_{CO2}[14], Other commercially available solvents offer a significant improvement on basic MEA, such as Fluor's EFG+ which requires approximately 2.8 – 3.0 GJ/t_{CO2} or MHI's KS1 solvent which requires approximately 2.5 – 2.8 GJ/t_{CO2}. At the time of writing, it would appear that Shell's Cansolv technology is 2.3 GJ/t_{CO2} at equivalent temperatures[15]. In all of the aforementioned cases, the solvent regeneration processes require heat supplied at 150°C[16]. Thus, the use of MEA-type performance as a benchmark against which to assess new technologies should be abandoned as it sets the bar unnecessarily low. It will be important that the community transition to a new standard as soon as possible. Further, it is vital that, when comparing the performance of sorbent materials, they must be compared on a consistent basis, ie comparing Cansolv, KS1, EFG+, MEA and others under the same conditions, specifically in- or excluding absorber intercooling, lean vapour compression etc.

However, at the time of writing, it is challenging if not impossible for the academic research community to adopt these commercial materials as a new standard, and this report would call upon the technology vendors to make available sufficient data pertaining to the thermophysical and kinetic properties of their solvents to make this possible.

Amine-based technologies have remained popular due to the relatively high CO_2 solubility and fast reaction kinetics; however, drawbacks include the degradation of the solvent (resulting in reduced efficacy in carbon capture) and corrosive attacks on most steels (necessitating expensive stainless steel infrastructure and/or corrosion inhibitors). Continued research into amine solvents may prove fruitful in addressing these issues. Further academic and pilot-scale research on alternative adsorbent and membrane processes are warranted. In the context of developing new solvents, a research focus on precipitating, thermo- or chemomorphic solvents was also identified as being a promising avenue for future efforts.

Consideration of amine-based solvents for CO_2 absorption has focused largely on CO_2 solubility and energy of regeneration. Whilst these properties are important, they are just a part of a large group of properties that should be considered. Firstly, it is essential to establish those thermophysical, transport and kinetic properties that most strongly impact system design and performance (Figure 2). Secondly, with efforts focused on capital cost reduction, transport and kinetic properties are essential for process size reduction. Thirdly and critically, the ageing and degradation of sorbent materials should no longer be viewed in isolation. Rather, the dramatic changes to the chemical composition and physical properties of the solution must be assessed as a function of operation time, where the results employed in all other aspects of system optimization. In particular, the process control operations must adapt to accommodate the changing solvent. This flexible infrastructure is essential to maintain high efficacy of the process, and to minimising losses.

Whilst the foregoing discussion focused primarily on liquid sorbents, it is important to recognise that there is a significant activity focused on the development of solid sorbents. A number of solid sorbents have been proposed and tested at lab-scale for CO_2 capture. These include porous materials such as: zeolites,

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[14] See, for example, Boot-Hanford et el., Energy and Environmental Science, 2014, 7 (1), 130-189

[15] See, for example, Singh, et al., Energy Procedia 63 (2014) 1678 – 1685 or Campbell, Energy Procedia 63 (2014) 801 – 807 for details

[16] The actual temperature of the solvent under regeneration will be closer to 120°C – a 20 – 30°C temperature difference is required for efficient heat transfer.

activated carbons, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and modified silica[17] and in the realm of high-temperature sorbents, hydrotalcites, calcium oxide and magnesium oxides[18]. Past and current research efforts have focused on measuring adsorption capacity and, in many cases, selectivity. The mechanisms of capture/adsorption have also been studied in details, especially in the case of CO_2 capture using MOFs or zeolites since novel phenomena, not observed with other solids, have been reported for these materials (eg breathing effect, gate opening/closing)[19]. A review of the current state of research points to a major gap between the large number of research studies focusing on testing solid sorbents for CO_2 capture and the comparatively small proportion of scale-up initiatives[20].

Astute selection and design of sorbents has the potential to substantially reduce both operating and capital costs via lower energy of regeneration and improved rates of heat and mass transfer leading to the requirement for smaller equipment. However, this does not address the necessity for relatively costly materials of construction. Of particular concern is the metal corrosion that occurs from exposure to CO_2 capture solvents and sorbents. While stainless steel is reasonably resilient, its extensive use substantially increases capital costs. Reticence to use alternative steels stems from the corrosion of cheaper steels when exposed to MEA and other aqueous amine solutions under CO_2-loading. A popular industrial approach employs anti-corrosion additives (even with stainless steels), based on metals (eg vanadium), with unsatisfactory results and high cost. As such, new approaches for steel protection methods to reduce corrosion have recently gained interest. Additionally, research has recently indicated that aqueous amine solvent selection can be tailored towards solvents which induce a less corrosive effect.

Research needs

For the large-scale implementation of carbon capture, research at the laboratory and pilot plant scale must consider more realistic conditions. This must be in combination with clear variables which require assessing and their competitiveness with current sorbent materials (eg Cansolv). To enhance efficiency of research into selection and design of improved sorbents for carbon capture, an integrated approach is essential. The aim of this would be: first, to link in a consistent manner sorbent properties and behaviour with molecular structure; second, to use these insights to establish relationships with unit-operation and process scale modelling, providing feedback on design and operability; and third, to co-ordinate such efforts with experimental pilot- and large-scale campaigns where realistic operating conditions are trialled.

For both solid and liquid sorbents, the importance of evaluating materials properties beyond capture capacity and selectivity was highlighted. In particular, it was recommended to complement equilibrium studies with studies focusing on the rates of mass transfer and chemical reactions. In addition, aspects such as material robustness, quantity and quality of energy required for regeneration, effect of flue gas components, manufacturing process and cost must be taken into account. It was recognised that, given the number of parameters to be evaluated, a purely experimental approach would be inefficient. Instead, a modelling approach providing a fast materials screening tool was perceived as a better option. This screening tool should provide a framework based on cost/energy that defines a range of acceptable values for each of the process parameters considered.

Such an approach is an enormous endeavour requiring materials synthesis and testing, physical property experimental work in conjunction with molecular modelling, and development of process systems modelling and optimisation tools. Several key factors such as solvent degradation and mass-transfer efficiency on industrial packing materials are recognised as especially important. A comprehensive approach of this nature has the potential to offer transformative progress.

The challenges to accomplishing this approach are significant. It is not obvious how to develop a standardized approach for solvent design with rigorous and realistic testing for which metrics are compiled. Further molecular-scale modelling research must be continued, ultimately becoming an

[17] Samanta, et al, Ind. Eng. Chem. Res., 2012, 51 (4), 1438–1463
[18] Fennell and Anthony 2015 - Woodhead Press, "Calcium and Chemical Looping Technology"
[19] Hyun, et al, Inorg. Chem., 2016, 55 (4), pp 1920–1925
[20] Global CCS Institute, The global Status of CCS report, 2014

established tool for engineering calculations through, with particular attention to establishing accurate intermolecular potentials for highly non-ideal systems and new materials by taking advantage of quantum chemistry, developing hierarchical methodologies for coarse grained molecular models, and creating parallel molecular simulation codes for multi-body force fields. These last points in particular will result in significant reduction of computing time for demanding calculations. Furthermore, this work will provide not only an industrially relevant outcome, but also a coherent methodology for rapid simultaneous screening and prototyping of new materials and processes[21,22].

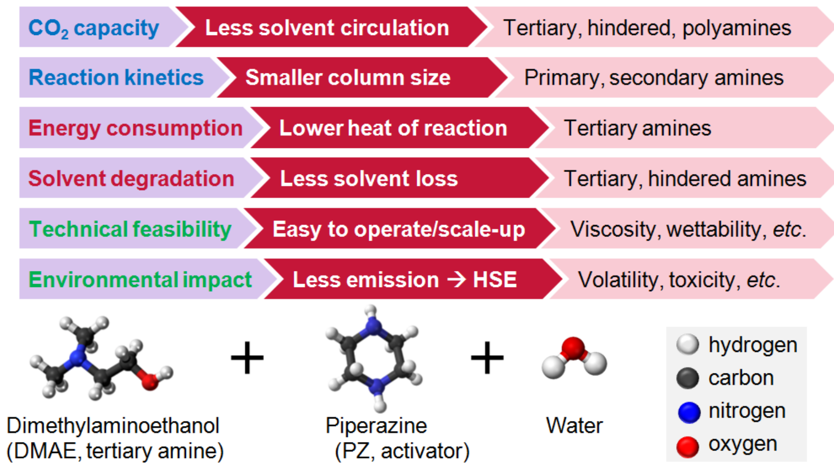

Figure 2: Solvent selection criteria, impact, and suitable amines

[21] Bardow, et al., Ind. Eng. Chem. Res., 2010, 49(6):2834–2840
[22] Qadir, et al., Int J GHG Con, 2014, 30:179–187

Negative Emissions Technologies

Negative Emissions Technologies (NETs) are processes where there is a net removal of CO_2 from the atmosphere. The implementation of these technologies will prove essential if CO_2 concentrations in the atmosphere continue to increase unabated in the next few decades. NETs include: direct air capture (DAC), ocean fertilisation or liming, afforestation, soil carbon management, biochar, enhanced weathering and bioenergy with CCS (BECCS or Bio-CCS). Creative NETs continue to be proposed, such as the incorporation of materials carbonated using CO_2 captured from the atmosphere into cement.

A decade ago the key concern for all NETs was the lack of large-scale demonstration, however at the time of writing, the Decatur project[23] in Illinois has stored over 1 Mt of CO_2 arising from a bioethanol process. Interest in DACs has recently increased, however, with concerns that sufficient CO_2 will not be captured using alternative methods to meet the global climate change goals. One NET is energy production or industrial processes from biomass with accompanying CO_2 capture and storage (BECCS). This technology is considered one of the most promising in the IPCC's 5th Assessment Report (AR5, Special Report on Renewable Energy SRREN), and the revised 1.5°C target from COP21. Of particular interest is the application of BECCS for the removal of historic CO_2 emissions from the atmosphere and the potential for net negative emissions. The IPCC AR5 finds that significant net negative emissions (>20GtCO_2/yr) plays 'an important role in many low-stabilization scenarios'.

Direct Air Capture

Direct Air Capture (DAC) is a highly touted NET for future use. This approach offers the potential to target sectors difficult to decarbonise, notably transportation. However, the grander vision is the use of DAC technologies to remove CO_2 from air and contribute to the net reduction of atmospheric CO_2 concentration. Similarly to conventional CCS, DAC also requires a downstream infrastructure for utilization or storage of CO_2, eg the DAC systems be integrated with a post-combustion dehydration, compression, transport and storage network. The minimum thermodynamic work for DAC is ~ 20 kJ/mol_{CO2}, significantly more than that for natural gas combustion (6-9 kJ/mol_{CO2}), coal combustion (5-7 kJ/mol_{CO2}), and coal gasification (1-4 kJ/mol_{CO2})[24]. It was also noted, with reference to mankind's accumulated experience with separating highly dilute mixtures, that this difference in cost of separation is likely to be exacerbated with practical application. On this basis, it was estimated that the cost of DAC would be on the order of \$1,000/t_{CO2} in current prices[25]. It is, however, important to note that these calculation assume the production of a stream of high purity CO_2. There exist opportunities for the catalytic conversion of CO_2 to products where the initial concentration of CO_2 can be relatively low. As a result, both start-up companies and academics are engaged in research and pilot-scale demonstration of DAC, with Carbon Engineering's facility in British Columbia, Canada a conspicuous example[26].

Bioenergy with CCS (BECCS)

Academic literature concludes that BECCS, including its CCS components, is technically feasible and with a Technology Readiness Level (TRL) of 3-7, except microalgae biomass applications which are on the order of TRL 1-3[27]. This primarily refers to biomass for power applications, as the forgoing discussion would imply that the Decatur project would bring the BECCS concept to a TRL of 9. There is a range of ongoing research (eg EBTP/ZEP Joint Task Force, SUPERGEN Bioenergy Hub, ETI, IEAGHG, IEA Bioenergy, several universities and government research organisations) with five currently operating BECCS projects at a scale of 0.1-1.0 Mt_{CO2}/y that use an ethanol plant as the source of CO_2. Most of these projects use the captured CO_2 for enhanced oil recovery. The first feasibility study to demonstrate negative emissions from a corn ethanol plant was the small-scale Russel project. This project was completed in 2005 with 7.7 ktCO_2 stored, a quantity insufficient for commercialisation. A milestone

[23] Decatur project: https://sequestration.mit.edu/tools/projects/decatur.html
[24] Minimum work calculation, as presented in Wilcox, "Carbon Capture", 2012
[25] It is noted that this is on the high side of costs that are reported in the academic literature, with the work of Goeppert et al., Energy Environ. Sci., 2012, 5, 7833-7853 providing a good discussion of this point,
[26] Carbon Engineering: http://carbonengineering.com/air-capture/
[27] Kemper, "Biomass and carbon dioxide capture and storage: A review" Int. J. GHG Con. 2015, 40, 401–430.

project, the Illinois Basin Decatur Project (and its successor Illinois Industrial CCS Project), stores the CO_2 captured in a sandstone formation (more than 1.1 Mt_{CO2} stored as of today). It was noted that there is an interchangeable nature between projects where the feedstock could be changed from fossil fuel to biomass sources, providing the potential to quickly increase the number of BECCS projects.

BECCS does not provide a panacea to reduction of atmospheric CO_2 and the IPCC AR5 makes clear that their conclusions on BECCS is based on only 'limited evidence, medium agreement'. The global bioenergy potential is estimated within AR5 to be 100 - 300 EJ/y, with a global BECCS potential of 10 Gt_{CO2}/y. A rough estimate of 60-250 $/$t_{CO2}$ has been suggested with variability due to the range of BECCS technology possible (at the smaller end for ethanol and black liquor, and at the higher end for power generation). Biomass prices and associated elasticity remains a key area of uncertainty as is the overall impact of land use, though biomass feedstocks with low life cycle emissions have been identified (eg miscanthus, short rotation coppice (SRC), short rotation forestry (SRF), sugarcane, waste/residues). To realize BECCS studies have identified CO_2 and natural gas prices, availability of infrastructure and cluster opportunities, access to low-cost sustainable biomass feedstocks and positive public perception as probable problem areas. The problem of public perception remains unclear for BECCS, with few studies specifically dedicated to it as opposed to other areas of CCS or the topic as a whole. Moreover, policy remains a significant concern with the failure of accounting frameworks that do not adequately recognise, attribute and reward negative emissions from BECCS, nor cover life cycle emissions and land use change impacts. Changes to include BECCS, eg in the Californian and EU Emissions Trading Systems (ETS), are ongoing but will likely be a time-consuming political process.

Research needs

To decarbonise the atmosphere NETs must become part of government policy and industrial accounting frameworks. The treatment of BECCS is complex vis-à-vis other NETs or fossil fuel based CCS. Suggested claims of 'double benefits' due to delivery of zero-carbon energy and negative emissions permits cause controversy.

The ability to develop and operate DAC process is not in question. It is agreed, however, that DAC will inevitably be a high cost option relative to other NETs such as afforestation, biochar etc. It was viewed that DAC would inevitably benefit from research that is aimed at developing advanced materials intended for conventional CCS. Yet the time horizon for the deployment of DAC technology is perceived as being significantly further away than that for CCS or BECCS. Insights from CCS developments can therefore be used to advance DAC technologies.

By contrast, BECCS is a relatively mature technology that needs unique treatment to improve its viability, focusing on implementation more than technological development. It should be noted that gasification-based BECCS pathways are less developed and would benefit from further research efforts as they provide a potentially efficient route to combine bioenergy and natural gas-fired power plants. Similarly, the pre-treatment of biomass for combustion and new approaches to reduce the energy penalty associated with biomass size-reduction were identified as key areas for future research efforts. Otherwise, some concerns continue to linger with scale-up requirements, including the high amounts (ie >30%) of co-firing for biomass pre-treatment and boiler modifications. Whilst it is recognised that there is significant industrial experience in the conversion of coal-fired boilers to 100% biomass[28], there is still substantial scope for fundamental academic research into the combustion behaviour and impact on process dynamics and efficiency at part load with extensive co-firing.

Another important task will be to overcome the uncertainty and lack of standard methodology for estimating BECCS potential and cost. The inclusion of NETs and BECCS in more policy and accounting frameworks needs to happen in a timely manner, including (a) the clarification of "double benefit" claims due to delivery of zero-carbon energy and negative emissions permits, (b) the development of approaches to prevent carbon leakage, and (d) the exploration of financial instruments for BECCS other than the Clean Development Mechanism (CDM).

[28] As in the case of Drax power in the UK: http://www.drax.com/biomass/our-biomass-plans/

Research in the past decade has underlined that for BECCS it will be essential to develop integrated approaches taking into account the whole food-water-energy-climate nexus. This will include evaluation and optimisation of both water and carbon footprints of BECCS systems and to address land use change (LUC) issues (eg monitoring and quantification, carbon debts, availability/freeing of land, improvement of land management and agricultural practices). It was noted that both BECCS and DAC need to evaluate their long-term impacts on land use and management.

Besides, the extent and implications of a competitive environment for BECCS are still unclear. For example, there might be competition for land, low-cost sustainable biomass feedstocks, CO_2 storage resources and funding. Apart from forest biomass, most other biomass supply chains are less mature and would benefit from development and/or optimisation. One of the large uncertainties that remains is the forecast of crop yield developments, especially under a changing climate. In order to avoid competition with food production, BECCS might experience a limitation to additional biomass, ie wastes and residues.

Furthermore, the extent and implications of a competitive environment for BECCS are still unclear, where competition for land, low-cost sustainable biomass feedstocks, CO_2 storage resources and funding could all become highly relevant. Finally, more research will be necessary to clarify the public perception of BECCS and to identify the “sweet spots” for BECCS deployment.

CO_2 Transport

Under the 2^{o}C Scenario by the year 2050 an estimated six billion tonnes of captured CO_2 must be transported to storage locations. This transport will be accomplished by high pressure pipelines and shipping. While considerable experience exists for the former from EOR, the transport of CO_2 derived from CCS could be different due to the potential for a wider range of impurities in the stream. These impurities can significantly alter the thermo-physical properties of the pumped fluid. This is important because the numerous studies in the literature investigating the design of pipeline networks almost exclusively consider the flow of only pure CO_2. Moreover, previous designs have focused on steady state pumping conditions, ignoring the potentially transient feed of CO_2 into the network from individual point CCS sources.

A further complexity in the design of these pipelines is the possibility of the necessity to construct required pipeline networks in densely populated areas, leading to concern over the potential impact of accidental failure of structural integrity under dynamic conditions such as start-up, shut-in or depressurisation. Corrosion caused by the presence of specific impurities also continues to be an active area of study.

Far less work is available in the literature regarding ship transport of CO_2; however, studies have shown that the long transport distance favours the use of shipping over pipeline transport. Interestingly, contrary to case with pipelines where capital investment is the main cost, the costs associated with shipping are dominated by operating costs such as the liquefaction of the CO_2.

Research needs

The key considerations of CO_2 transport include the effective design of a "flexible" network to deliver CO_2 for use in injection sites, the need to react to/ accommodate system interruptions (no flow situations), whole system grid management, the development of cost effective pipeline system balancing cost (associated w/over design) and risk (fracture/rupture). It is also important to consider the trade-offs around CO_2 purification location and intermediate pressure boosting. The practicality of long distance CO_2 transportation by ship including dealing with logistical issues needs to be evaluated.

CO_2 Storage, Utilisation, and Conversion

Geological storage

At the time of writing, there are 6 large scale projects sequestering CO_2 in geological storage. This is illustrated in Figure 3 below. Similarly, from 2004 to 2014 the number of CO_2-EOR projects has also increased from 80 to over 120[29]. The most significant storage risk factor for these projects is the leakage of old or abandoned wells. In several projects minor well leakage has been detected, notably because of improvements in monitoring. Since 2004, monitoring operations using a range of techniques, including seismic imaging, U-tube and geochemical analysis have been demonstrated at over 25 sites. Improvement in storage safety has gone well beyond monitoring, including appropriate clarity of terminology, new capacity assessment methods, and the development and identification of pressure and geo-mechanical constraints on storage capacity. Further, extensive modelling and predictive capability, active pressure management, accelerated secondary trapping, and contingency planning and intervention measures are all now in place. These successes result from the significant shared knowledge arising from projects such as Statoil's Sleipner project and the Shell Quest Key Knowledge Deliverables (KKDs)).

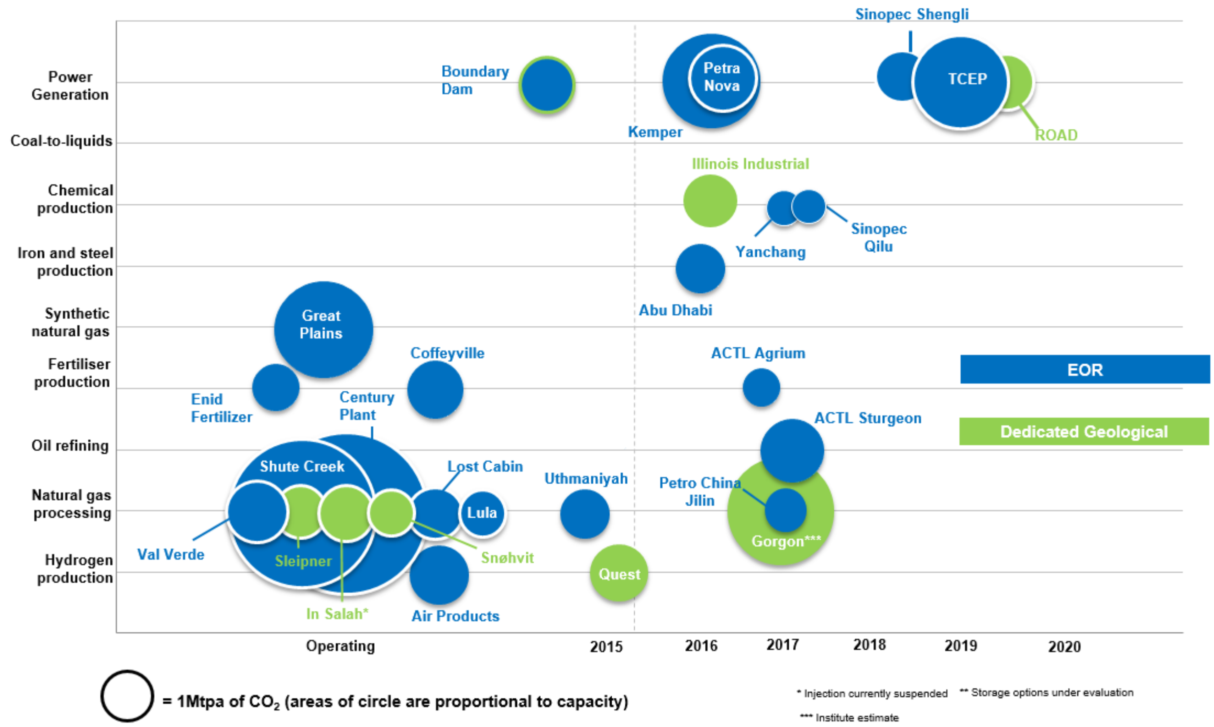

Figure 3. Global demonstration projects (Source: Global CCS Institute)

CO_2 Utilization: EOR

CO_2 EOR is one of the few ways to add value to captured CO_2 at scale, with a typical incremental oil production of 5-15% original oil in place (OOIP)[30]. Very approximately, one tonne of CO_2 will enable the additional recovery of three barrels of oil[31], leading to the production of 1.5 t_{CO2} once this oil is consumed[32]. Therefore, conventional CO_2-EOR does lead to the emission of more CO_2 than was sequestered by approximately 0.5 t_{CO2}. However, had that CO_2 not been injected, assuming a fixed

[29] Data from Global CCS Institute database
[30] Lipponen, J. et al., "Storing CO_2 through Enhanced Oil Recovery", International Energy Agency, 2015
[31] Godec, "Global technology roadmap for CCS in industry. Sectoral assessment: CO_2 enhanced oil recovery", United Nations Industrial Development Organization, 2011
[32] Calculation on the basis of data retrieved from: https://www.epa.gov/energy

demand for oil, the consumption of the oil would have led to the emission of 1.5 t_{CO2}. Therefore, conventional CO_2-EOR has led to the avoidance of approximately 1 t_{CO2} when compared to a conventional crude under a constant demand scenario. Moreover, it has been shown that oil derived from CO_2-EOR can displace unconventional oils that have very significantly higher CO_2 footprints, and consequently the avoided carbon could be significantly greater[33]. Finally, CO_2-EOR was traditionally optimised to maximise the recovery of oil per unit CO_2 injected. It is possible, however, to re-optimise this process to the opposite extreme, ie, the minimisation of the recovery of oil per unit CO_2 injected, thus maximising the quantity of CO_2 stored; this process is referred to as CO_2-EOR+[30]. This would, of course, only make sense in a world with a substantial carbon price justifies the approach. More than 140 projects for CO_2-EOR are available globally, and they account for about 0.35% (300,000 barrels/day) of the global oil production. Conventional CO_2-EOR has been shown to be profitable at ~$65 bbl oil and ~$30/t_{CO2}, although this price sensitivity is a function of the specific geology involved. The drivers for CO_2-EOR+ would be regulatory requirements or fiscal incentives to store CO_2 (eg higher oil prices and/or lower CO_2 supply prices).

There are three scenarios for CO_2-EOR operations: (i) light, (ii) balanced, and (iii) heavy. The light scenario uses conventional CO_2-EOR with full CCS risk assessment, monitoring and verification to achieve a net utilisation of 0.3 tCO_2/bbl oil for an incremental oil recovery of 6.5% original oil in place (OOIP). The balanced version would increase CO_2 storage and allow incremental oil production to achieve a net utilisation of 0.6 tCO_2/bbl oil with an incremental oil recovery of 13% OOIP. This balanced approach is achievable by best current and next generation R&D practices. The heavy version is focused on CO_2 storage with a net utilization of 0.9 tCO_2/bbl oil is expected to produce an incremental oil recovery 13% OOIP; this is with no produced water re-injection or CO_2 recycle. On this basis, and given the magnitude of global CO_2-EOR potential, it is very possible that CO_2-EOR could play an important and material role in enabling the market-driven deployment of CCS transport and storage infrastructure.

CO_2-EOR is not a panacea, however. In order to limit climate change to no more than 2^{o}C of warming above pre-industrial levels, the IEA's 2DS anticipates that it may be necessary to sequester approximately 124 Gt_{CO2} in the period to 2050. In the context of linking this ambition to the CO_2-EOR industry, it is important to recognise that there is an important discrepancy between regional CO_2 capture targets and regional EOR capacity. Figure 4 represents the global CO_2-EOR capacities with CCS targets.

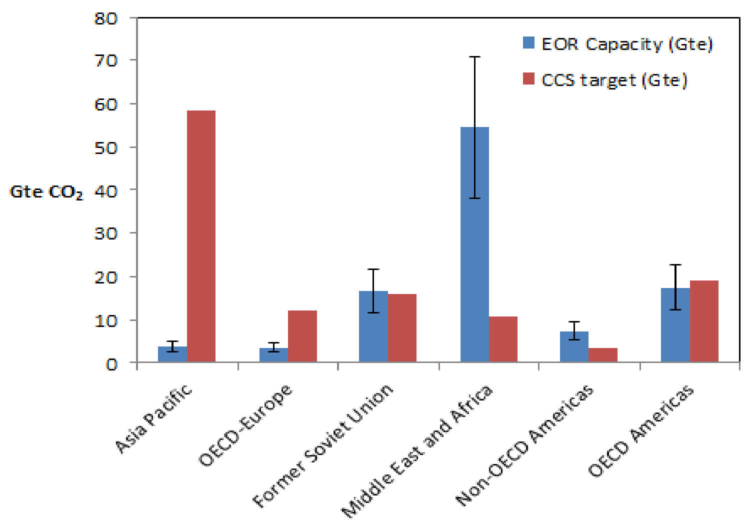

Figure 4. Global CO_2-EOR capacity with regional CCS targets

On this basis, one may conclude that CO_2-EOR has the potential to play an important role in the Middle East and Africa, the OECD Americas and the Former Soviet Union, but that OECD-Europe and Asia

33 Zakour and Cook, "Quantifying and monitoring emissions reductions from CO_2-EOR" IEA GHG R&D Programme, 2015

Pacific regions have limited CO_2-EOR capacity relative to their requirements to deploy CCS under the IEA 2DS.

CO_2 Conversion: Chemical

The concept of Carbon Dioxide Re-Use (CDR) has garnered significant attention recently from the research, policy and commercial communities. It is sobering to note, however, that the current global market for CO_2 use is approximately 200 Mt_{CO2}/y. Given that the current rate of growth of the global chemical industry is approximately 3% per year[34]. Extrapolating to 2050, this implies a utilisation rate of approximately 650 Mt_{CO2}/y in 2050, which is in broad agreement with the literature[35]. This quantity is negligible relative to the scale at which CO_2 emissions need to be permanently mitigated – on the order of 40 Gt_{CO2}/y in 2050, according to the IEA 2DS.

It is also important to note that current CO_2 utilisation focuses primarily on the production of urea and methanol, ie products which do not correspond to the permanent storage of CO_2, and only correspond to delaying the emission of the utilised CO_2 for a period of less than a decade. The largest market potential for CO_2 conversion to chemicals lies in the production of CO_2-based fuels, eg for transportation. However, also for fuels, the storage period will also be short. In fact, the majority of CDR options correspond to removing the CO_2 for less than a year, with some applications removing the CO_2 for perhaps 50 years. This means that from the perspective of climate change mitigation through storage, CO_2 conversion or utilisation will have little to no effect[36]. The conclusion of the discussion on the period for which CO_2 needs to be sequestered in order to accrue a climate benefit was, in human terms, permanently, and that even the benefit from storing CO_2 in polymers which degrade after approximately 50 years is still unclear[36]. The discussion on this point led to the conclusion that there is still significant uncertainty in this area and that further research is urgently needed to come to a conclusion on the benefit of short- and mid-term storage on climate change.

However, it is important to recognise that the substitution of CO_2 into an industrial process can have significant co-benefits resulting in a marked reduction of the environmental footprint of that process. As demonstrated, the conversion of 1 kg CO_2 into polyols can save up to 3 kg of CO_2 emissions compared to the current polyol production[37]. In this sense, CO_2 conversion to chemicals can be a means of increasing efficiency of production and should be thus regarded as efficiency measure and not as storage option. The ultimate target of CO_2 conversion to chemicals is closing the carbon loop leading to carbon-neutral production of chemicals and fuels. However, this target is not given for granted: a) Chemical activation of the inert CO_2 molecule may require additional effort leading to more GHG emissions for a CO2-based process compared to a fossil-based route; b) even if the novel production is more efficient, rebound effects through increased use of the chemical might reduce this effect. In fact, every tonne of CO_2 through addition use would correspond to the need of an additional tonne of CO_2 be sequestered above the original target. Thus, it is vital that efforts to develop CO_2-based chemicals and fuels include, as a minimum, an *in silico* evaluation of the potential climate benefits throughout the life cycle. . Such a life-cycle assessment needs to take into account actual displacement effects, potential rebound effects and a proper functional unit as basis for comparison (eg person kilometre and not litre for fuels to account for differences in energy density and engine performance)

One CO_2 utilisation option which does correspond to the permanent storage of the CO_2 is the mineral carbonation of industrial wastes containing Ca and Mg-oxides, silicates, and hydroxides. This option is

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[34] *World Chemical Outlook.* Chemical and Engineering News, 2013. **91**(2), 11.

[35] An upper bound of 650 – 700 Mt_{CO2}/ yr has been proposed by, for example, Song, C., *Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing.* Catalysis Today, 2006. **115,** 2-32 and Song, C., *CO_2 Conversion and Utilization: An Overview*, in *CO_2 Conversion and Utilization*, C. Song, Gaffney, A. F. and Fujimoto, K., Editor. 2002, American Chemical Society, 2-30.

[36] von der Assen, et al., Energy & Environmental Science, 6:2721-2734, 2013.

[37] von der Assen, et al., Green Chemistry, 16:3272-3280, 2014.

applicable to the waste streams associated with power generation, iron and steel production, cement, and aluminium production, ie fly ash, steel slag, cement kiln dust, and red mud, respectively. This conversion reduces the alkalinity of these materials and renders them safe for permanent disposal or reuse as filler, construction, or building materials. However, the potential offset of CO_2 emissions using industrial wastes alone is limited by availability of these materials relative to the CO_2 emissions associated with each sector. One of the challenges to be addressed is the variability in the alkaline contents of these waste materials and the associated impact on the design of industrial scale processes.

There is therefore a need for sophisticated and rigorous techno-economic, life-cycle assessments, and quantitative systems understanding to be developed in this area. When considering various technologies for CO_2 conversion, it is important to distinguish thermodynamically uphill routes (eg conversion to fuels) vs. downhill routes (eg mineral carbonation of industrial wastes) and comparing these with the status-quo and alternative potential routes to carbon-neutral chemicals and fuels (eg green chemicals). It has been shown that the substitution of CO_2-based chemistry into conventional industrial processes can have environmental benefits that are significant in their own right. The field of scientific enquiry into the area of CO_2 chemistry is highly interesting and has merit. However, it is important to accurately evaluate its potential for mitigation in the context of other options for CO_2 removal not be overstated; over-ambition may kill the whole field and one needs to be realistic in what can be delivered by this area.

Research needs

The criteria in defining a depleted oil or gas reservoir as suitable for a CO_2 storage site remains surprisingly poorly defined. Even more, methodologies to assess CO_2 storage capacities in deep saline aquifers at a regional or basin levels are often not properly applied. Such metrics are essential in going forward, particularly in seeking out a more thorough assessment of regional storage capacities in critical areas, with a particular focus on India and China. While industry has made substantial progress, and should be applauded for their extensive transfer of knowledge, large scale projects, such as the planned Peterhead or White Rose projects, with CO_2 storage on the order of 1 – 4 Mt/y, are essential. These projects should be backed with adequate modelling and laboratory research to fully extract understanding of these storage systems. Understanding the role of joint ventures between international oil companies to do these projects on an NPV-zero basis and dealing with the potential for no-flow situations are important considerations.

Some of the critical needs in CO_2-enhanced oil/hydrocarbon recovery include (i) defining and agreeing a clear methodology for assigning carbon footprint and credits, (ii) better quantification (and qualification) of the mitigation potential of EOR, (iii) allowing for better policies/regulations for enabling CO_2-EOR in the near term, (iv) pushing forward region by region with demonstrations, (iv) moving from traditional EOR to balanced EOR (PSE effort to provide insight and demonstrate this at a pilot scale), (v) identifying "low hanging fruit" (the combination of low cost CO_2 and favourable reservoirs – link with the multi-partner effort), and (vi) exploiting the residual oil zone (which is not traditional EOR). In order to use CO_2 for the recovery of shale gas, it is important to uncover the fundamental behaviour of the CO_2-shale interactions. Molecular modelling can provide a significant support in this direction and accurate prediction of the relevant physical properties (diffusivity, permeability, wetability etc).

In order to advance the use of CO_2 for treating industrial wastes, it is important to qualify and quantify the effect that the heterogeneous morphology and composition of these materials will have on the associated kinetics and conversion, and consequently the effects on the stability and strength of the carbonated-end products and resulting system design, operation and associated costs.

In order to properly quantify the value provided by the short-term storage associated with CO_2 conversion, there is a need for greater clarity in determining how long CO_2 has to be removed to accrue climate benefit. It is important to address the lack of an independent systems-wide understanding and benchmarking of various CO_2 utilisation options. The potential contributions and dependencies of these CO_2 utilisation options should account for the role of carbon credits, electricity prices, and renewable or low-carbon hydrogen. Such an analysis should identify potentially promising routes for CO_2 conversion to chemical and fuels which should be investigated for the identification of more efficient catalysis and production processes in order to mitigate climate change by more carbon-efficient production.

Outcomes and Conclusions

The three-day CCS Forum, held in London, hosted delegates from academe, industry, and government to discuss the future of CCS, and in particular to identify the key research challenges to be addressed in the near to medium-term. In all sectors pertaining to CCS, it was agreed that translating major research findings to the market often takes many years and that developing a systematic procedure for the acceleration of the transition of academic research to pilot- and demonstration-scales would be of significant value to advancing this area.

Over the course of the three days, the application of CO_2 capture technologies to the power and industrial sectors were discussed in detail as was the subsequent geological storage of the CO_2 in addition to the utilisation of the CO_2 in enhanced hydrocarbon recovery, the mineral carbonation of industrial wastes and also the potential for the further conversion of CO_2 into platform chemicals. In addition, the role of policy measures to enable the deployment of CO_2 to the power and industry sectors. The critical needs identified have been summarized in the Executive Summary and detailed insights included by section throughout the remainder of the document.

One of the key outcomes of this workshop was the need for a framework to understand the dynamic interplay between scientific and technological advancements, their impacts on the power markets, and the broader socio-economic consequences of deploying CCS. On the scientific front, there is a clear need to develop modelling tools that can rapidly screen new materials for CO_2 capture based on molecular level information. The development of a suite of tools or approaches to evaluate the potential role of novel technologies in the energy system will be essential for developing new technologies. Ultimately, these decision-support tools will be related to the overall process cost.

It was observed that the use of an aqueous solution of 30 wt% monoethanolamine as a benchmark technology is near ubiquitous throughout the CCS research community. While such a benchmark provides a useful method of comparison, it does not demonstrate how the research on trial actually competes against contemporary technologies in 2016. While not grave in and of itself, it does offer a false sense of improvement where efforts may not be truly fruitful towards implementation of CCS. This report recommends the adoption of the Cansolv technology as a new standard against which progress with sorbent (solid or liquid) development should be compared. In this context, it would be exceedingly useful if Shell were to make sufficient information available to enable thorough comparisons to be made so as to appropriately rank novel technologies.

The importance of identifying appropriate benchmarking approaches was identified as being essential for successful development of new processes for CCS, be these processes based upon solid sorbents, membranes, hybrid processes, etc. Efforts must be made for innovations to compete with the solvents which are already deployed industrially, noting that their performance will likely further improve in the time that it takes new technologies to be commercially deployed. For this reason, only materials and processes which have the potential to lead to step change improvements in process performance in terms of both capital cost and efficiency should be pursued and the development of approaches to provide early indication of process performance should be pursued as priority.

Bioenergy with CCS continues to be a key area where there remain extensive research requirements. In particular, the question of the sustainability of BECCS will likely be very case specific. BECCS is neither a silver bullet nor a complimentary ticket for business-as-usual but it deserves full attention as a mitigation technology because we are running out of time and options. It is possible that the water demand of BECCS systems for electricity generation will be greater than that for simply CCS. However, there is significant uncertainty here, with suggestions that the water intensity of BECCS for power generation could be between +20% to +200% when compared to CCS. Significant amounts of land area will likely be necessary to grow the required biomass feedstock. Predictions indicate that a provision of bioenergy of 100 EJ/y will require up to 500 Mha of land. To put this into perspective, in 2010 the total global land area for agricultural crops was around 1600 Mha. Unless crop yields increase substantially and/or diets change drastically, the possibility of direct competition with food production exists. This is one of the biggest concerns related to bioenergy deployment. Low-cost sustainable biomass seems to be a "jack-of-all-trades” for deployment of BECCS, similar as other technology routes hinge on cheap renewable H_2. Another concern is a perceived over-reliance on BECCS in many mitigation scenarios, especially towards the end of the century, with little concern having been shown for the fact that other industries, eg biofuels have already "earmarked" this biomass. BECCS deployment will be contingent on the roll out of Fossil-CCS and its infrastructure.

The ultimate aim of CCS efforts is the permanent storage of CO_2 from the atmosphere, as part of a transition away from the extensive utilisation of unabated fossil fuels for power generation and industrial processes. In this context, more important than further development of capture technologies, is the de-risking of CO_2 storage infrastructure around the world via exploration and characterisation of suitable geological structures. Whilst this effort is proceeding well in Europe, the UK and the USA, the Asia-Pacific region and China and India in particular, were identified as being in need of further detailed studies with a view to qualifying and quantifying the quantity and quality of potential CO_2 storage infrastructure in these regions. It was noted that this initiative should heavily involve the oil and gas industries, and the Oil and Gas Climate Initiative was identified as a multi-corporate grouping that could play a leading role in this effort, perhaps acting under the Mission Innovation initiative.

The role of CO_2 utilisation and conversion as part of the effort to mitigate climate change was extensively discussed. The most mature use of CO_2 is to couple storage with enhanced oil recovery (EOR). Work on EOR remains somewhat controversial because of the perception that it perpetuates the oil and gas industries, and the subsequent CO_2 emissions. However, the role of CO_2-EOR in providing a near-term, market-driven pull for the deployment of CO_2 transport infrastructure must not be under estimated. However, EOR is a facilitator – not an end in and of itself. Moreover, whilst it is true that CO_2-EOR would likely lead to the net emission of CO_2 as a result of producing more oil, there is evidence that oil derived by this process would displace both conventional and unconventional crudes, leading to substantial quantities of CO_2 avoided. CO_2 utilisation and conversion to chemicals and fuels is naturally limited in scale and aims at contributing to mitigation climate change by increasing carbon-efficiency of production and usually not by storage.

The commercial deployment of CCS does not only rest on scientific and technical advances but also the cost and performance impact of deploying CCS on the power and industrial sectors. To date, research efforts aimed at improving CCS processes were observed to have almost exclusively focused on efficiency improvement and OPEX reduction. Going forward however, an increased focus on CAPEX reduction is recommended. This can be achieved by developing materials for CO_2 capture that exhibit substantial improvements in the rates of heat and mass transfer and the CO_2 carrying capacity, whilst continuing to reduce (or at least not increasing) the energy of regeneration.

Decoupling the cost of CO_2 capture from that of transport and storage is important and accurate reporting of this in the context of early projects is another serious consideration. Initial efforts to deploy CCS have included both the cost of the power generation and the associated infrastructure in project costs. This, arguably, will lead to initial project costs being significantly inflated relative to the potential for the subsequent reduction of project costs once infrastructure costs can be shared. Thus, perceptions of CCS first-of-a-kind (FOAK) costs are likely inflated owing to the bundling of CO_2 generation (power plant), capture, transport and storage together. Therefore, a consistent, decoupled costing methodology that accurately reflects the costs of the major constituents of CCS is needed.

The role of electricity markets in the development of CCS technologies needs to be carefully evaluated. Greater understanding of the way in which CCS power plants will interact with the electricity markets is needed. As intermittent renewable energy generation sources more significantly penetrate the energy system, thermal power generation (as distinct to thermal power capacity) will be increasingly displaced from the electricity market. It is therefore highly unlikely that CCS plants will provide baseload generation, although this will inevitably vary between national energy systems. This needs to be made clear in any case set out for the deployment of CCS strategies. The ability of CCS plants to provide ancillary services to the electricity grid will need to be explicitly valued, along with the role of CCS in providing co-benefits such as low carbon heat and negative emissions. Therefore, a multi-scale view of CCS that ranges from the molecular scale to the whole energy system is needed to reduce the risk of technology assessment with the associated supply chains.

Research efforts into explicitly industrial CCS are nascent relative to those into the power sector. A key difference between power and industrial CCS is the highly heterogeneous nature of the industrial sector. For this reason, the likelihood of a "one-size-fits-all" solution for any one industrial sector is small. Initially, highly concentrated point source emissions of CO_2 from certain industrial sources should be pursued as "low hanging fruit". This can be followed by more complex cases, with large oil refineries being held up as key examples of "hard to reach" industrial emitters. The costs associated with industrial CCS remain unclear as this area increasingly becomes a priority and more systematic studies will be required.

In the context of developing roadmaps to low carbon economies, it is vital that the near-term (2030) targets do not prohibit medium (2050) or long-term plans. For example, it is well recognised that very significant amounts of negative emissions technologies, likely bioenergy with CCS (BECCS), will be required in order to meet the targets agreed as part of the COP21 agreement. In this context we recognise that a mature, de-risked CCS industry and associated infrastructure will be required to facilitate the implementation of BECCS technology. Furthermore, these roadmaps must employ a whole-systems approach incorporating existing power sources, green energy sources, industrial plants, and carbon capture. The balance of the components will evolve as the process of decarbonisation takes place across many decades. Favourable legislation is essential to incentivise these advancements. Further, policy must help to highlight the demonstrable benefits arising from the deployment of CCS technology, in addition to the provision of dispatchable, reliable, low carbon power. Climate change itself is estimated to likely cause enormous direct costs due to changing weather patterns and crop yields. These global financial losses will vastly exceed the costs of implementation of CCS. Further, the deployment of CO_2 capture, transport and storage infrastructure will support the creation of new, high skills STEM jobs, again directly contributing to the health of the global economy. These positive impacts are difficult to quantify but will have undeniable fiscal benefits while tackling climate change. Therefore, CCS needs stronger representation as a technology that ensures a sustainable energy, environmental, and economic future.

Based on the research needs identified in this workshop, the Foreign Research Office is requested to make funds available for projects via the Mission Innovation initiative. It is therefore imperative the Mission Innovation fund explicitly includes CCS as a technology to be progressed towards further deployment in the near term. In addition, there is interest in identifying whether OGCI can take the lead on the study of identifying the low hanging fruits for EOR. An effort to investigate opportunities for collaborative efforts with COSIA and OGCI as part of the Mission Innovation initiative would also be of broad interest and is something that should be pursued in this context.