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Editorial

Special Issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO_2 Capture and Storage

CO_2 capture and storage (CCS) has established a prominent role in the climate change policy debate, especially since the publication of the Intergovernmental Panel on Climate Change (IPCC) Special Report on CCS: IPCC SRCCS (IPCC, 2005). The IPCC SRCCS was a turning point for CCS because it raised the profile of the technology within the expert community that was dealing with climate policy. As a result, CCS then became accepted as a major option for reducing global emissions of CO_2 and hence it was included in the long term scenarios where significant greenhouse gas emission reductions were required. In the most recent assessment, the 5th IPCC Assessment Report (IPCC, 2014) it was observed that many of the global mitigation models could not meet the 2 °C target[1] without CCS and also that mitigation costs would increase significantly if CCS and Bio-CCS were excluded from the mitigation scenarios. Despite the strong messages on the need for CCS from IPCC AR5, there are still some in the expert and policy communities that harbor doubts and misconceptions about the real capability and maturity of CCS to combat climate change. The co-Editors of this Special Issue, that updates the status of CCS from IPCC SRCCS, hope that some of those doubts and misconceptions can be dispelled by the review papers published in this volume.

With this Special Issue (SI), we present to the CCS community, and to society as a whole, a collection of 17 review papers covering many areas in which significant progress has been made in the 10 years since the publication of the IPCC SRCCS. Just over 100 authors participated in this major review exercise, who have used nearly 3000 references to support their work, including peer reviewed scientific and technical documents as well as gray literature. All of the review papers were peer reviewed according to the journal's usual processes. The variety of topics covered in this SI provides a glimpse into the diversity and multidisciplinary nature of CCS scientific and technical community. What follows is a brief summary of the main highlights from each set of review papers, grouped by theme. We also explain why some areas covered in the IPCC SRCCS have been left out of this SI.

[1] The Internationally agreed policy target is to limit CO-equivalent concentrations in 2100 to about 50 ppm or lower to maintain warming below 2 °C over the 21st century relative to pre-industrial levels.

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1. CO_2 capture

The separation of CO_2 with amine-based solvents was already mature technology in some industries when the IPCC SRCCS was published. However, great advancements have been made in terms of scaling up in the last 10 years. A commercial system is already operating in a coal power plant, namely the 110 MWe Boundary Dam in Canada, which captures 1 million tons CO_2 per year. Furthermore, a variety of solvents have been tested at laboratory and pilot scales, generating a larger set of solubility data, reaction kinetic parameters, and other key design data which has aided in the development of new solvent-based capture systems. Corrosion prevention strategies using specialized corrosion inhibitors, solvent degradation mechanisms, solvent reclamation methods, and analysis of solvent emissions are still active areas of R&D. Improved absorber design, as well as accurate modeling and simulation of control procedures will further enable deployment of large-scale post-combustion units in industrial environments.

CO_2 capture by oxy fuel combustion has also experienced a drastic advance in the last decade, underpinned by the vast experience and know-how in the field of combustion science and power technology. Different burner and boiler designs, process configuration involving different gas recycles, formation of SO_x, NO_x and Hg species, agglomeration, fouling and corrosion, management of air ingress, and other operational and flexibility studies, are all aspects that have been investigated at a wide range of experimental scales and using robust modeling tools. Oxyfuel combustion technologies could be particularly well suited for some large scale industrial applications (cement, steel or oil refining) and several oxyfuel combustion large-scale projects in coal power plants (pulverized fuel and circulating fluidized bed designs) have reached the level of confidence and detail needed to make investment decisions (such as the White Rose Project in the UK, for a supercritical power plant at 426 MWe), although the lack of economic incentives for CCS remains a detractor. Oxyfuel combustion is also emerging as an option for capturing CO_2 from natural gas combined cycles, expected to reach critical pilot testing scale in the near future. Second generation oxyfuel technologies may include higher integration, alternative O_2 supply and other options in order to increase overall efficiency and reduce costs.

As stated in the IPCC SRCCS pre-combustion CO_2 capture process routes can use commercially mature equipment for producing a syngas (by reforming and partial oxidation or solid fuel gasification) or for separating the H_2/CO_2 resulting from the water gas shift reaction. The first fully integrated coal-based pre-combustion large scale system is the Kemper County-Mississippi Power, in the US, rated at 582 MWe, which will be ready for operation in 2016. Pre-combustion CO_2 capture can be applied in the short term to high CO_2 emitting industries including the chemical (gas and coal based), iron and steel industries. R&D work on pre-combustion CO_2 capture systems seeks to improve the efficiency in both coal- and natural gas-fired systems. Alternative configurations of the water gas shift section such as a split flow configuration, development of new shift catalysts which can operate with less steam consumption, or combining the water gas shift reaction with CO_2 adsorption, are key R&D topics to further improve efficiencies.

The IPCC SRCCS recognized the potential for developing and scaling up a wide range of capture systems that promised to deliver breakthrough reductions in energy efficiency penalties and cost. These included new energy conversion technologies such as chemical looping and novel capture systems based on the use of solid sorbents or membrane-based separation systems. In the last 10 years, a very substantial body of scientific and technical literature has been published in an attempt to: demonstrate these concepts at increasing pilot scales, test and model the performance of key components at the bench, investigate and develop improved functional materials, optimize full process schemes for a range industrial applications, and undertake cost studies. A particular focus of research has been on certain specific process routes that have experienced a substantial increase in their technical readiness level: chemical looping combustion for solid fuels, post combustion calcium looping systems, CO_2 separation at low temperature by solids adsorbents and polymeric membranes for post-combustion. A much wider range of emerging systems and their variants are being investigated at conceptual level and at lower scales, offering additional opportunities for substantial reductions in cost and energy penalties in CO_2 capture in power generation and large scale industrial systems.

2. CO_2 storage

The subjects in whom most progress has been made regarding CO_2 storage in the last ten years are: storage efficiency, CO_2 plume and pressure evolution, capillary trapping of CO_2, convective mixing triggered by CO_2 dissolution in aquifer water at the plume/water interface, and subsurface geochemical effects of impurities present in the CO_2 stream. All these subjects relate to CO_2 storage in deep saline aquifers; little or no progress has been made in the field of CO_2 in coal beds, and storage in shales is a new emerging topic. Injection projects in depleted gas fields have mostly concerned themselves with monitoring activities and as such are presented under that section. The most notable CCS project in an oil field, the IEAGHG Weyburn–Midale CO_2 monitoring and storage project was the subject of its own Special Issue in 2013.[2]

Storage efficiency has both spatial and temporal dependencies, being first pressure limited and then space limited. It depends on the characteristics of the storage aquifer and confining caprock, operational characteristics of CO_2 storage, and regulatory constraints, with values varying widely, from <1% to >10%. This wide variation in storage efficiency correspondingly impacts storage capacity.

In 2005, research related to pressure build-up and brine displacement was almost non-existent. Modeling studies since then have demonstrated that injection-induced pressure changes can propagate in the injection aquifer much farther than the CO_2 plume itself and that they can limit storage capacity. Pressure-driven lateral and vertical brine migration should not be of concern except through local leakage pathways such as leaky wells and transmissive fractures and faults. Geomechanical effects of pressure build-up include microseismicity and ground deformation, but generally pressure management strategies exist for mitigating the effects of injection-induced pressure build-up.

A significant amount of theoretical, numerical and laboratory work has been published over the last ten years on the subject of capillary, or residual, trapping of CO_2, which is controlled by fluid and interfacial physics at the pore scale in the aquifer. Laboratory observations confirm that CO_2 at irreducible saturation will occupy at least 10% and more typically 30% of the pore volume, ultimately leading to plume immobilization and storage security. Dissolution of CO_2 at the interface between CO_2 and aquifer water leads to a slight increase in water density in the layer adjacent to the CO_2 plume, which, under certain conditions, may lead to gravitational instability and onset of free convection in the aquifer, with the effect of significantly accelerating the dissolution of free-phase CO_2. This has the combined effect of reducing the amount of free-phase mobile CO_2 and increasing storage security since dissolved CO_2 is no longer buoyant and prone to leakage.

The presence of inert or non-condensable gases in the injected CO_2 stream, such as Ar, N_2 and CH_4, will have no or negligible geochemical effects in the subsurface, notwithstanding the physical effect of reducing CO_2 storage capacity. The presence of acid gases such as SO_x and NO_x will likely have a negative effect, particularly in the near-well region, due to their tendency to accumulate in acidic forms around the injection well. Other impurities, such as O_2 and H_2S, may or may not have a negative effect, depending on aquifer mineral composition. In summary, the reviews in this SI indicate that CO_2 storage is by and large a safe operation if storage sites are properly selected, characterized and managed.

3. Environmental impacts of CCS

Studies of environmental impacts have made considerable progress, aided particularly by studies of natural analogs, as well as laboratory experiments and controlled release field experiments both on- and off-shore. These controlled releases are a new development since 2005. An important conclusion is that impacts of CO_2 leakage are generally quite limited in space and time, in part reflecting the fact that CO_2 is naturally occurring and organisms have some ability to adapt to unusual CO_2 levels. Another important finding is that the surface expression of leaks is usually in the form of isolated small areas. In the case of artificial leaks the surface expression may be at some distance from the source. This finding suggests that locating leaks at the surface may be quite difficult, although the corollary is that, again, impact is limited. The impact of CO_2 leakage on groundwater is a continuing concern. Here both laboratory work, and the study of natural analogs, have again suggested that impacts – whether of CO_2 itself, or mobilized brine – may well be limited, both in severity and in spatial extent. Again, while positive, this also means that monitoring groundwater systems is probably not a good method of leak detection. An important remaining research gap is the need to better define the most likely leakage scenarios and the range of fluxes and spatial footprints associated with them. This relates to a gap identified by the IPCC SRCCS in 2005 which still needs to be addressed: methods to conduct end-to-end quantitative assessment of risks to human health and the local environment.

[2] International Journal of Greenhouse Gas Control vol. 16, Supplement 1, Pages S1–S308 (June 2013). The IEAGHG Weyburn–Midale CO_2 Monitoring and Storage Project.

4. Monitoring of CCS impacts

Monitoring and verification has developed many shallow monitoring methods in parallel with the assessment of environmental impact, reflecting societal concerns about leakage to the near-surface. However very significant progress has been made in the deep-focused monitoring techniques, particular examples being marine seismic monitoring at Sleipner and the combination of pressure and seismic imaging at Snøhvit. In the case of Sleipner, both conformance and containment have been convincingly demonstrated by innovative analysis of a superb dataset. Snøhvit is a textbook case of pressure monitoring detecting non-conformance and a mitigation strategy being successfully adopted. Another success for monitoring of reservoir-level processes was at In Salah, where ground surface displacements were detected by the new (in terms of application to CCS) method of InSAR, the measurement of ground surface displacement from satellite platforms. The interpretation of those results in terms of geomechanical processes was subsequently shown to be consistent with micro-seismic observations and time-lapse seismic imaging, all suggesting initiation and reactivation of fractures. The common theme to these examples, which now emerges for many projects at all scales, is the ability of the available techniques for monitoring and interpretation to test containment and conformance. Shallow-focused monitoring methods have also been exploited extensively, and have played an important role in countering leakage allegations at Weyburn and providing assurance that environmental impacts of hypothetical leakages are undetectable above natural variability in key parameters. Related to the study of environmental impacts is the need for more predictive leakage modeling; without this it is difficult to interpret the numerous null results from shallow monitoring. An important new question – as yet unresolved, is to what extent normal operational CO_2-EOR practice provides necessary and sufficient monitoring for conformance and containment assurance both during EOR and for the CO_2 that remains stored in the reservoir after the EOR operations cease.

5. CCS risk assessment

Risk assessment has become a mature field over the decade, with a range of methodologies now available. These range from qualitative to quantitative and many include uncertainties within probability frameworks. Methods to study risks by large-scale stochastic simulations have been developed and linked to risk assessments of various proposed project sites. While the technical risks identified for geological storage have not greatly changed, public perception, financial considerations and regulation have become more prominent in risk assessments. Of the technical risks, wellbore integrity continues to be the most prominent. The nature and frequency of wellbore failure has been better quantified over the decade, and concerns about the chemical stability of properly completed wellbore cements in particular have reduced. However it is recognized that old wells pose risks that are difficult to assess and the long-term fate of wellbore systems over several hundred years remains uncertain. A new technical risk to emerge for CCS is induced seismicity, not as a result of geological storage but, largely because of increased public awareness associated with the shale oil and gas boom in the USA. The research community has been quick to respond to this, with quite detailed procedures now proposed for assessing and managing this particular risk – although there are no examples yet of felt seismicity associated with CCS. A gap that remains in risk management is mitigation. To some extent this gap reflects the lack of credible mechanisms for major loss of containment from current or foreseen storage projects. Quite simple mitigations – for example, simply ceasing injection – have been shown to be effective in various modeled scenarios, but this is an area where more research would be useful.

6. Economics of CCS

The costs of CCS will remain an emotive issue; CCS needs to be cost competitive with other low-carbon technology options to enable it to take a significant market share. One key development since the IPCC SRCCS is that costs for oxy fuel plants can now be evaluated, while at the time of the report, the technology was at too early a stage of development for costs to be accurately assessed. However, the costs of CO_2 avoidance (mitigation cost) for CCS, including pipeline transport and geologic storage, now calculated, turn out to be the same as those estimates made in the IPCC SRCCS, after taking into account the real escalations in plant and fuel costs reflected in the indices used for cost adjustments. This is a direct result of: (1) little change in the cost of electricity and (2) the fairly stable costs projected for CO_2 pipeline transport and geological storage costs after adjusting for recent cost escalations. The review has not compared the costs of CO_2 avoided with other low-carbon technology options which are very regionally dependent. However, based on current cost estimates for the four CCS pathways analysed (SCPC, NGCC, IGCC and oxyfuel plants), there are still no obvious winners or losers. The range of mitigation costs for all four options show considerable overlap. Overall, therefore, the results of this study support the general conclusion of the IPCC SRCCS report and other subsequent studies that there is still no single technological ”winner” in low-carbon power generation using CCS.

7. Bio-CCS

Bio-CCS has become a focus of interest since the IPCC SRCSS because of its potential for negative emissions. The recent IPCC 5th Assessment Report (IPCC, 2014) paid close attention to the potential for Bio-CCS, which is estimated to be on the order of at least 100 EJ/year, based on the majority of current publications. However, it is noted that there are limitations on the potential for Bio-CCS, such as competition for land with food production. The technological maturity and costs for Bio-CCS are comparable with conventional CCS technologies. Although there is no large-scale Bio-CCS demonstration project yet, several smaller projects are now operational, for example the Decatur project in Illinois, USA, which combines ethanol fermentation with CO_2 enhanced oil recovery (CO_2-EOR). The main problem with this technology is that many low-carbon policies and associated greenhouse gas accounting frameworks do not appropriately recognize, attribute and reward negative emissions from Bio-CCS. For example, the European Trading Scheme, which is by far the largest existing carbon market in the world, does not include these items, especially if they occur in the context of agriculture and forestry activities. The public perception of Bio-CCS remains unclear, as only a very limited number of studies have investigated this topic specifically. The few studies that have found diverging results that were highly dependent on the characteristics of the Bio-CSS facilities and the socio-cultural context of the participants. Further uncertainties exist around the competitive environment for Bio-CCS. There will likely be competition between different mitigation options for biomass, CO_2 storage and funding resources, but the extent remains unclear. Additionally, the complex links between food, water, energy and climate emphasize the necessity of a nexus approach. Discussion and resolution of the sustainability issues around Bio-CCS simply cannot take place outside this context.

8. CCS policy

When the IPCC SRCCS was written in 2003–2005, the principal area of focus at that time was marine treaties – namely the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) and the London Convention – as they had been the focus of prior legal analysis and the parties to the treaties had begun their own consideration of the topic of regulating CCS. Both marine treaties proceeded to remove their prohibitions on CO_2 geological storage under the seabed in 2006 and 2007. In the years following, there were numerous developments at the national and regional levels. For, example, the EU CCS Directive was developed in 2007 and 2008 (Directive 2009/31/EC), to create an "enabling framework" for CCS. CCS-specific laws and regulations have also been established at both the federal and state levels in the United States, and the commonwealth and state levels in Australia. The next significant development was inclusion of CCS into the Clean Development Mechanism (CDM) under the UNFCCC's Kyoto Protocol in 2011 (UNFCCC, 2011). These international developments potentially cover over 180 countries, so quite a lot has been achieved in 10 years

9. Public acceptance of CCS

When the IPCC SRCCS report was released there was very little information on public acceptance and no information on communication of CCS. Ten years on, there is an extensive database of published material in this area, as well as case reviews, toolkits, best practice guides, and more. Much progress has been made on how best to communicate the concept of CCS, and there has been a movement away from public surveys to communication revolving around demonstration and pilot projects. Broadly one could state that the public at large is no more aware of what CCS has to offer in the climate arena than it was then. At a local level, however, around specific CCS projects, the public and local stakeholders are much more aware of what CCS means and offers. As more projects develop, public communication will be built in, and the success of the last ten years in creating better tools and environments to communicate on CCS should begin to broaden awareness on CCS and help allay public concerns.

10. Other topics

Despite the comprehensive nature of the review project presented in this special issue, we would also like to acknowledge some gaps in this issue that were covered in the IPCC SRCCS.

10.1. System economic analysis and emission accounting

Macro-economic analysis of plausible scenarios for CCS deployment is of critical importance to assess CCS as a climate change mitigation option. However, the main scenarios reviewed in Chapter 6 of the recent IPCC Assessment Report (IPCC, 2014) already consider CCS within the portfolio of mitigation technologies, in the context of discussions about the limited fraction of burnable carbon reserves, or comparing the overall system cost of different low carbon emission energy technologies. The IPCC Guidelines for Emissions Accounting (IPCC, 2006) specify that CCS should be included in greenhouse gas inventories.

10.2. Ocean storage

Research in this area has largely been curtailed following the decision by the London Convention to ban ocean storage in 2007.

10.3. Mineral carbonation

"Ex-situ" mineral carbonation processes have evolved little except in some niche applications: the slow carbonation rates of a natural mineral, even when it is finely crushed and submitted to high partial pressures of CO_2, lead to very large reactors and/or complex process schemes. They are also linked to unacceptably high energy requirements and/or the need of aggressive additives to activate the mineral, with unassessed collateral environmental impacts.

10.4. CO_2 utilization

The concept of "CO_2 utilization", or "CO_2 uses", is often confused with the concept of "CO_2 recycling". It is well known that all major industrial uses of CO_2 (urea production, food industry etc.) have no mitigation potential because of the short life of the carbon product (IPCC, 2005). Enhanced Oil Recovery (EOR) can be a CO_2 storage option, especially if compared to oil extraction operations without EOR. These large scale industrial uses of CO_2 are responsible of the great maturity of some CO_2 capture, transport and storage technologies. However, these uses cannot be mistaken with process schemes aimed to transform CO_2 into a fuel or other product ("CO_2 recycle"). We note an increasing research interest on new chemical reaction paths to incorporate renewable (or nuclear) energy into such reactions of CO_2, as a large scale climate change mitigation technology. Although some niche applications may exist for these processes, we are not aware of a plausible scenario where a massive source of carbon-free energy is available at the same time and location as a massive source of CO_2. Solving this mismatch by capturing CO_2 from air would lead to processes with an even more daunting energetic and economic task. On a planet that is just struggling to abandon its addiction to transform fuels into CO_2, a popular quotation seems appropriate here: *extraordinary claims require extraordinary evidence*.

CO_2 Transport an essential enabling technology for any large scale CCS project. This was perceived as a mature technology 10 years ago and we have not identified sufficient critical mass of new material to complete a dedicated review.

We use this opportunity to emphasize that the subjects of these review papers have been selected by us, as co-Editors of the Journal, and in consultation with IJGGC's Editorial Board. Specialist readers of IJGGC may identify other topics they perceive to be insufficiently covered in this special issue, or that simply deserve a different review approach. The contents of some of the reviews published in this SI may have evolved from the original plan for a number of reasons. There are also some topics where the literature is now building such as capture at industrial facilities and the development of transport infrastructure that will themselves warrant reviews in due course. Therefore, where relevant, we are open to further regular submissions of Review papers to IJGGC, which will be subject to the normal high peer review standards of the journal.

11. Summary

The contents of this SI indicate that capture and geological storage of CO_2 is truly ready for large scale deployment to mitigate climate change. There are several demonstrations of this already at large scale and several others will join in the near future. The cost of avoided CO_2 from the full CCS chain, once corrected to account for inherent variations in the market of power equipment, will go down as leading technologies are deployed. Emerging technologies are also being demonstrated at increasing scales, offering opportunities for more substantial reductions in cost and energy penalties. In sort, the science and the technologies supporting CCS as a climate change mitigation tool have experienced a great advance in the last 10 years, consolidating and expanding the knowledge base to estimate more accurately the impacts, risks and cost associated with large CCS projects.

In closing, we would like to express once again our thanks to the authors and reviewers that have contributed to this Special Issue. We hope that these 17 review papers, celebrating the advances and successes in the rapidly evolving field of CCS, will be of interest to our readers and to society as a whole.

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Note: The planned review on O_2 separation and CO_2 compression and purification technologies was not completed in time for this special issue but may be published in a subsequent regular issue.

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