

Editorial

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Human activities have led to quite dramatic increases since 1950 in the ‘basket’ of ‘greenhouse gases’ (GHGs) incorporated in the Kyoto Protocol; concentrations rising from 330 ppm to about 430 ppm presently (IPCC, 2007). Prior to the first industrial revolution, the atmospheric concentration of ‘Kyoto gases’ was only some 270 ppm. The cause of the observed rise in global average near-surface temperatures over the second half of the twentieth century has been a matter of dispute and controversy. But the most recent scientific assessment by the Intergovernmental Panel on Climate Change (IPCC) states with ‘very high confidence’ that humans are having a significant impact on the global warming (IPCC, 2007). They argue that GHG emissions from human activities trap long-wave thermal radiation from the Earth’s surface in the atmosphere (not strictly ‘greenhouse’ phenomena), and that these are the main cause of rises in climatic temperatures. In order to mitigate anthropogenic climate change, the Royal Commission on Environmental Pollution in the UK (RCEP, 2000) recommended at the turn of the millennium a 60% cut in UK carbon dioxide emissions by 2050. The British government subsequently set a tougher, legally binding target of reducing the nation’s carbon dioxide emissions overall by 80% by 2050 in comparison to a 1990 baseline (DTI, 2007).

Carbon dioxide, the main ‘greenhouse gas’, is thought to have a ‘residence time’ in the atmosphere of around one hundred years. Carbon dioxide accounts for some 80% of the total GHG emissions in the United Kingdom (UK), and the energy sector (including transport) is responsible for around 95% of these. The 2007 energy white paper (EWP) accepted that Great Britain should put itself on a path to achieve a goal by adopting various low-carbon dioxide options, principally energy efficiency measures, renewable energy sources and next-generation nuclear power plants (DTI, 2007). Technologies for carbon dioxide capture, or sequestration, were also identified as an important element in any energy RD&D programme. Similar emphasis has been given by the UK Energy Research Partnership (ERP, 2010) – a high-level, public–private forum bringing together key stakeholders and funders of energy RD&D. EWP targets for new renewable electricity supply were set at 10% by 2010 and 20% by 2020. It is going to be difficult for renewables (principally wind) to fill the perceived ‘electricity gap’ (Hammond *et al.*, 2011). The UK coalition government is supportive of building a new generation of nuclear reactors to replace those currently undergoing decommissioning. This, together with carbon dioxide capture and geological storage (commonly known as ‘carbon capture and storage’ (CCS) (DECC, 2012; IEA, 2009)) technologies and renewables (mainly onshore and

offshore wind power), are likely to be their preferred route to a ‘decarbonised’ power generation system (ERP, 2010; Hammond *et al.*, 2011). In any event, the UK electricity supply network is in need of major renewal and reconfiguration in terms of both power plants and grid infrastructure over the coming decades (Hammond and Waldron, 2008). CCS facilities coupled to fossil-fuelled power plants or industrial sites provide a climate change mitigation strategy that potentially permits the continued use of fossil fuel resources, while reducing the carbon dioxide emissions. The CCS process involves three basic stages: capture, drying and compression of carbon dioxide from power stations or industrial sites, transport of carbon dioxide, and storage away from the atmosphere for hundreds to thousands of years. Transport of the carbon dioxide can be via pipeline or by ship.

CCS is a technology that is seen as providing an important transitional energy option on a pathway towards a decarbonised electricity future. This themed issue is, therefore, particularly opportune coming, as it does, in the immediate aftermath of the publication by the UK government of its CCS ‘roadmap’ (DECC, 2012) and the announcement of its latest competition (known as the ‘CCS commercialisation programme’) for £1bn capital funding to build a commercial scale, coal or natural gas-fuelled power plant and capture facility in Great Britain to be operational by 2016–2020 with an appropriate storage site offshore. The paper by Agus and Foy (2012) in this issue sets out the UK legislative framework for carbon dioxide capture, derived, as it is, from the EU Directive 2009/31/EC. This requires that new fossil-fuelled power plants over a capacity of 300 MW should be ‘capture-ready’. They argue that this will necessitate the ‘provision of clear and concise guidance, with clear definitions that can be easily understood and applied’. The present state of the art is illustrated via a discussion of a case study around the development of the so-called Spalding Energy Expansion. This is the proposal to construct a new 900 MW combined cycle gas turbine (CCGT) power plant at Spalding in Lincolnshire. It was required to demonstrate a number of criteria for capture-readiness: (a) sufficient space for the carbon dioxide capture equipment; (b) the technical feasibility of retrofitting the capture technology; (c) a suitable location and site for offshore deep geological storage; (d) an appropriate means of transporting the carbon dioxide to the offshore storage site; and (e) the economic feasibility of the full CCS chain over the power station’s lifetime.

Pulverised coal and natural gas combined cycle plants are currently operational in the UK and globally. Post-combustion

capture separates carbon dioxide from the exhaust (flue) gas after combustion. This system typically exploits chemical solvents such as amines (Agus and Foy, 2012; Davidson and Thambimuthu, 2009; Hammond *et al.*, 2011; IPCC, 2005; Orr, 2009), like mono-ethanolamine, to absorb the carbon dioxide. This is the most common method of capture and, therefore, has the most operational experience. However, the low concentration of carbon dioxide in the flue gas inhibits the capture process. It therefore requires powerful chemical solvents and large-scale processing equipment to handle the emissions. This is both a costly and energy-intensive process. Nevertheless, it offers significant potential for the retrofitting of capture systems to current post-combustion systems and, for that reason, it was originally favoured by the UK government (see, for example, Gough *et al.* (2009)). In this issue Lucquiaud and Gibbins (2012) consider the post-combustion, capture-ready options available in connection with modern CCGT power plants. It is argued that such natural gas CCS options will be required if the UK is to decarbonise its electricity sector by 2050. The authors first lay down a set of general principles for capture-ready design: no upfront performance penalty, low additional capital cost (compared with state-of-the-art standard plant), good performance with capture and the ability to operate with the capture unit bypassed. But they believe that power plant developers may be subject to technological lock-in in an era of substantial innovation in capture facilities, including more advanced solvents. Thus, they analyse several practically useful approaches that are available to handle radically different solvents than current state-of-the-art amines. These include steam turbine options for steam extraction CCS retrofits and separate gas CHP power cycles for either power-matched or heat-matched CCS retrofits.

Pre-combustion capture (Agus and Foy, 2012; Davidson and Thambimuthu, 2009; Hammond *et al.*, 2011; IPCC, 2005; Orr, 2009) separates carbon dioxide from the gas stream before combustion, where the concentration of carbon dioxide in the gas stream is high. This aids the capture process and enables less selective capture techniques, such as physical absorption using 'Selexol'. The quantity of gas involved is lower, reducing the need for large equipment, and this can reduce the energy requirements. But the process involves more drastic changes to the power station. Oxy-fuel combustion capture (Agus and Foy, 2012; Davidson and Thambimuthu, 2009; Hammond *et al.*, 2011; IPCC, 2005; Orr, 2009) involves combustion of fuel in oxygen instead of air. This produces a gas rich in carbon dioxide that aids the capture process significantly. The process is, nonetheless, expensive and is presently only at the demonstration phase. Research is currently examining more effective chemical and physical absorbents, as well as the development of novel capture techniques. The latter include new adsorbents, membranes and cryogenics that may lower the costs and energy penalties associated with carbon capture (Davidson and Thambimuthu, 2009; Hammond *et al.*, 2011; Orr, 2009).

Methods for storing carbon dioxide away from the atmosphere could potentially involve storing carbon dioxide under the ground, under the ocean, in solid carbonates and in industrial products. Geological storage is currently the most viable option in the UK context (Gough *et al.*, 2009; Hammond *et al.*, 2011). Potential methods include storage in depleted oil and gas reservoirs, deep saline formations and depleted coal seams. Enhanced oil recovery (EOR) and enhanced coal-bed methane techniques can provide revenue to offset costs for oil reservoirs and coal seams, respectively. Currently, the most attractive geological option is EOR. It involves the injection and storage of carbon dioxide into oil fields that are coming to the end of their useful life (IPCC, 2005). This delays costly oil field decommissioning, and can utilise the existing infrastructure of the oil well. In addition, the extra oil captured due to the injection of carbon dioxide can be sold for financial gain, which depends on the oil price. Enhanced gas recovery is another option, but it could only increase the recovery rate by around 5% compared to levels of 15% for EOR (Hammond *et al.*, 2011). There has been one major storage project undertaken in a saline formation in the Norwegian sector of the North Sea – the Sleipner field (Hammond *et al.*, 2011; IPCC, 2005). Monitoring suggests that no carbon dioxide has escaped. However, the monitoring of saline formations is a lot less well developed than in the case of oil and gas wells. The confidence in the permanence of storage is consequently lower, especially because the majority of the potential storage is in 'open saline formations' that provide an eventual escape path for carbon dioxide. More development is required in these cases (Hammond *et al.*, 2011) to simulate options and determine whether the carbon dioxide will be held over hundreds to thousands of years in order to mitigate climate change.

This themed issue contains two papers that deal with the monitoring of geological reservoirs. Hannis (2012) provides specific examples of fit-for-purpose monitoring techniques that 'can be used to validate pre-injection predictive methods, image plume development and detect surface anomalies'. A range of monitoring techniques previously designed to address leakage risks associated with the In Salah carbon dioxide storage site in the Algerian Sahara desert are examined. The author then draws on experience from various geological storage sites: the Sleipner field in the Norwegian North Sea; Laacher in Germany; Lateral in Italy; Frio, Texas in the USA; Nagaoka in Japan; and Otway, Victoria in Australia. This suggests that monitoring data can provide an 'early warning' system of surface carbon dioxide leakage, better understanding of leakage pathways and the nature of leaks in order that appropriate mitigation measures may be put in place. Verdon *et al.* (2012) employ synthetically modelled data to examine one specific leakage risk – injection-induced pressure increases that may lead to fractures in the caprock and, therefore, the leakage of buoyant carbon dioxide. Passive seismic monitoring (PSM), using 'geophones' placed in boreholes around a reservoir or in

larger arrays at ground level, is then shown to yield a relatively inexpensive means of permanently surveying this type of phenomenon. The technical basis of PSM is described, along with its previous usage in the hydrocarbon sector, before its potential use for CCS site monitoring is outlined. The authors discuss several circumstances where PSM has been adopted to evaluate subsurface carbon dioxide injection. These include the CCS site at Weyburn in Saskatchewan, Canada, where carbon dioxide has been injected since 2000 for the purpose of EOR and storage. They also noted that the approach has again being utilised at the In Salah site.

The final two papers in this issue deal with aspects of risk analysis associated with CCS projects. Carpenter and Braute (2012) employ a hypothetical CCS demonstration project schedule to test the risk management implications of front-loading of project costs as a means of meeting an imposed 2015 deadline for the start of operations. Increased commercial or financial risk exposure is also caused by the inability to find adequate carbon dioxide reservoirs. These are evaluated in the context of the CO₂qualstore joint industry guidelines. The authors argue that finding a balance between 'deadline risk' and 'site qualification risk' for a real project would 'require careful modelling of project activities and costs at a greater level of detail' than in their simplified example. Kimmance and Rogers (2012) address a variety of risks – strategic, technological, geological, safety, environmental, commercial – across a full CCS chain (or 'lifecycle'). The complex 'whole systems' approach consists of several phases: site characterisation and selection, design, construction, operation and closure (or decommissioning). Both quantitative and qualitative risk determination was involved in the process. But only operational GHG emissions via the stack are considered and not 'upstream' emissions ahead of the power plant. Upstream environmental burdens arise from the need to expend energy resources in order to deliver, for example, fuel to a power station (Hammond and Jones, 2011). They include the energy requirements for extraction, processing/refining, transport and fabrication, as well as methane leakage that occurs in coal mining activities – a major contribution – and from natural gas pipelines. Kimmance and Rogers (2012) employ a risk management framework based around the ISO 31000:2009 standard. They argue that it has the merit of being able to manage multiple risks associated with many stakeholders, and can provide the basis for a Monte Carlo-type simulation of costs and revenues. The authors suggest that the most critical element of the CCS chain is the storage component. Failure at initial injection or during longer-term containment would make the project commercially non-viable. Delays at the start of a full scale CCS project can also make the project financially unattractive. Likewise, if public perception turns against CCS, then regulatory authorities may tighten requirements.

In a mini-energy report (state-of-science review) for the UK Government Office of Science, Gibbins and Chalmers (2008)

noted that commercial deployment would require secure funding mechanisms to reward firms for carbon abatement via CCS, along with legal and regulatory frameworks for carbon dioxide transport and geological storage (Gibbins and Chalmers, 2008; Gough *et al.*, 2010). Indeed, it has been observed that several of the industry representatives to the UK CCS stakeholder workshop organised (in May 2007) by Gough *et al.* (2010) expressed concern over the perceived failure of the UK government to provide sufficient enabling technology 'push' across the entire CCS chain. The workshop participants identified a potential to reduce CCS costs of 50–75% by 2040. Greater financial incentives for carbon abatement need to be secured through a higher carbon price from the European Union Emissions Trading Scheme (Hammond *et al.*, 2011), which the UK coalition government have recently supported via the introduction of the so-called 'carbon floor price' (DECC, 2012). These were viewed as critical factors for deployment, as well as reducing the energy penalty, achieving a niche for CCS in a more decentralised energy market, and technology transfer to rapidly-growing developing country markets, such as China and India (Gough *et al.*, 2010). Beyond the consensus, a 'vision' was felt by stakeholders to be needed for what might constitute an onshore UK carbon dioxide transport network, and for the State (or the Crown) to take on the ownership and liability for long-term geologically stored carbon dioxide (Gough *et al.*, 2010). Chalmers *et al.* (2009) adopted an innovative way to draw out lessons for the development of CCS in the context of the original UK government-sponsored competition. They examined previous major UK 'energy transitions': the post-World War II development of nuclear electricity, the increase in size of pulverised coal power stations in the decade around 1960, the opening up of North Sea oil and natural gas fields in the 1960s and 1970s, and flue gas desulphurisation in the late 1980s and 1990s. In addition to the requirement for the sort of financial incentives for CCS deployment outlined above (Gibbins and Chalmers, 2008; Gough *et al.*, 2010), these historical transition studies provided a number of insights into critically important underpinning actions – the importance of active public engagement, together with the desirability of reviewing skills and capacity requirements (Chalmers *et al.*, 2009).

CCS forms part of a wider low carbon strategy for the future (DECC, 2012). It is clearly important to reduce energy demand in the UK and elsewhere. This could be achieved, in part, by the array of methods available to improve the efficiency with which energy is produced and consumed (Hammond *et al.*, 2011). That would militate against climate change and enhance energy security. But on the supply side the situation is arguably more complex. In the period leading up to 2050, the choice of UK power technology will not just be determined by economic factors, and the way in which they dynamically interact with a smart grid and consumer demand will also be important issues. The UK coalition government has recently stated in its CCS roadmap (DECC, 2012) that it intends to support the commercial

deployment of CCS in the UK by the 2020s. This includes the EU-stimulated requirement on any new fossil-fuelled power stations to demonstrate this technology – that is, to be ‘capture-ready’ (Agus and Foy, 2012). The papers in this issue make an important contribution to the discourse on carbon dioxide capture and geological storage. They address the critical issues of the legislative framework (Agus and Foy, 2012), capture-readiness of CCGT plants (Lucquiaud and Gibbins, 2012), the monitoring of geological storage sites (Hannis, 2012; Verdon *et al.*, 2012) and full CCS chain risk assessment (Carpenter and Braute, 2012; Kimmance and Rogers, 2012). The limitations of the CCS strategy as adopted by various UK governments have been discussed by Scrase and Watson (2009). It involves an element of ‘picking winners’ – for example, the British government’s original (failed) CCS demonstrator competition, based only on post-combustion capture technologies. The latest CCS commercialisation programme announced by the coalition government in April 2012 is much less restrictive in terms of the technologies that it will entertain. However, Scrase and Watson (2009) also noted that the uncertainties over full-scale power plant CCS technical performance and costs may only become clearer when the first demonstrators are operational in perhaps five years’ time.

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