



UNIVERSITY OF  
CAMBRIDGE

Electricity Policy  
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# The current state of CCS: Ongoing research at the University of Cambridge with application to the UK policy framework

EPRG Working Paper 1228

Cambridge Working Paper in Economics 1257

**K.A. Daniels, H.E. Huppert, J.A. Neufeld, D. Reiner**

**Abstract** The Earth's climate is changing and the release of carbon dioxide (CO<sub>2</sub>) is recognised as the principal cause. To meet legally binding targets, UK GHG emissions need to be cut by at least 80% of the 1990 levels by 2050. With an increase in future fossil fuel use, Carbon Capture and Storage (CCS) is the only method of meeting these targets. Some key challenges face the deployment of CCS including cost, uncertainty of CCS deployment, the risks of long-term CO<sub>2</sub> storage, public communication and scale. Research at the University of Cambridge is resolving these issues and assisting the deployment of CCS technology. The right regulatory framework also needs to be set so that the technology is commercially deployed. The current UK policy framework for CCS is outlined in this document and the immediate barriers to deployment are highlighted. The ongoing CCS research taking place primarily at the University of Cambridge is described. There are many steps that need to be taken if CCS deployment is to ultimately succeed; this document attempts to highlight these steps and address them.

**Keywords** Climate change, atmospheric greenhouse gas emissions, Carbon Capture and Storage (CCS), the CCS Roadmap, Electricity Market Reform, carbon capture technologies, carbon sequestration, storage reservoir processes.

**JEL Classification** O13 Q40 Q41 Q42 Q48 Q51 Q54 Q55 Q58

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Publication December, 2012  
Financial Support EPSRC(UK) Bridging the Gaps Grant

[www.eprg.group.cam.ac.uk](http://www.eprg.group.cam.ac.uk)

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## Executive Summary in Brief

Climate change and the increasing carbon content of the atmosphere are causing great concern. The UK has legislation in place to decrease greenhouse gas emissions and still maintain a secure energy supply into the future, primarily through Carbon Capture and Storage (CCS) technologies. The University of Cambridge has many diverse groups conducting ground-breaking and innovative research on decreasing the costs and uncertainties surrounding different aspects of CCS and making its long-term storage as safe and as inexpensive as possible.

## Executive Summary

The Earth's climate is changing and the release of carbon dioxide (CO<sub>2</sub>) and other greenhouse gases (GHGs) into the atmosphere is recognised as the principal cause. To meet legally binding targets, UK GHG emissions need to be cut by at least 80% of the 1990 levels by 2050. It is acknowledged that the future energy supplies will likely depend on fossil fuels into the foreseeable future, and therefore Carbon Capture and Storage (CCS) is required to control atmospheric greenhouse gas (GHG) emissions.

Some key challenges face the deployment of CCS and are concerned with a breadth of different issues. Research at the University of Cambridge is resolving some of these issues and assisting the deployment of CCS technology. One significant challenge is cost, with the capture of CO<sub>2</sub> representing the largest share of this. Research at the Engineering and Chemical Engineering Departments has been conducted into alternative capture technologies with improved efficiencies to reduce costs, and innovative solutions have arisen. These include pre-combustion technologies such as chemical looping, using solid fuels that produce pure CO<sub>2</sub> as a by product, with energy penalties as low as 5-8%.

Uncertainty of CCS deployment is also a major challenge and is widely perceived as being mainly due to costs and liabilities should a storage reservoir leak. Research at the Departments of Applied Mathematics and Theoretical Physics, Earth Sciences and the BP Institute has addressed some of the concerns surrounding CO<sub>2</sub> storage and potential leakage from the storage site. Analytical and numerical models have been developed to assist understanding of the propagation of fluid CO<sub>2</sub> in a reservoir, the different methods of trapping that might occur and the likelihood of leakage through a fissure or fracture in the reservoir. Experimental studies have been conducted to help validate the models, and an understanding of the migration of CO<sub>2</sub> through a reservoir has also been gained through seismic studies of the Sleipner Field in the North Sea. Dissolution of carbonate or silicate minerals can provide the CO<sub>2</sub> with a leakage pathway or help with pathway sealing. Rates of reactions occurring in reservoirs that might act to dissolve carbonate or silicate minerals have been investigated using geochemical studies of analogue natural sites.

An important aspect of the CCS process is sending a clear and scientifically grounded assessment of the risks associated with long-term CO<sub>2</sub> burial. Thus public communication of CCS is also vital for commercial deployment. Research has been conducted at the Judge Business School into the communication of CCS, with the findings that CCS technologies are currently not sufficiently well known or understood by the public and that there are gaps in the types of information (predominantly technological) that are available and in the types of institutions (predominantly corporations and Government) actively providing information on CCS. Research is also conducted into the economics of CCS because cost is a major issue.

Another challenge is that the technology has not yet been tested at the commercial scale and therefore the associated risks may not have been fully characterised. However, unless the technology is commercially deployed, the full technological capability will not be understood. The key is to generate the right market conditions to allow the technology to be deployed and remain viable when competing with other low-carbon energies. The right regulatory framework needs to be set so the financial burden placed on operators of storage sites is not prohibitive, but negative environmental and health impacts due to leakages are minimised.

The current UK policy framework for CCS is outlined in this document and the immediate barriers to deployment are highlighted. The ongoing CCS research taking place primarily at the University of Cambridge is described. There are many steps that need to be taken if CCS deployment is to ultimately succeed; this document attempts to highlight these steps and address them.

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## 1 Introduction

The release of carbon dioxide (CO<sub>2</sub>) into the atmosphere has been recognised as the principal cause of changes to the Earth's climate [2]. The Intergovernmental Panel on Climate Change (IPCC) has carried out assessments of the state of the climate, producing reports<sup>1</sup> and providing information on climate change [2, 50]. In the 2001 report, the IPCC stated that climate change and its effects needed to be mitigated; this is still the case.

Using Carbon Capture and Storage (CCS) (described more fully below) is the only way of preventing greenhouse gas (GHG) emissions reaching the atmosphere whilst still continuing to use fossil fuels. It is acknowledged that in the foreseeable future, demand for energy will increase and future energy use at least to the mid-century (Figure 1) will likely contain fossil fuels, thus CCS, along with other renewable energy technologies and nuclear power, will be needed in order to balance the supply and demand for energy, whilst maintaining energy security [19, 12]. However, some CO<sub>2</sub> emissions are intrinsic to particular industrial processes and as such, can only be reduced by abatement processes such as CCS [19]. Thus CCS is regarded as a key mechanism for mitigating the effects of climate change [2] and is a component of long-term strategies for cutting back UK CO<sub>2</sub> emissions [3, 19, 37].

Carbon capture and storage schemes capture CO<sub>2</sub> from power plants or industrial sites before that CO<sub>2</sub> is emitted to the atmosphere. The CO<sub>2</sub> is then compressed and sequestered, either underground, in a deep submarine environment, or by reacting it with silicate minerals to form carbonate minerals. Carbon capture can be accomplished using different technologies and applying them to different industrial processes. In essence, CO<sub>2</sub> capture occurs via the chemical reactions of reduction and oxidation, allowing the CO<sub>2</sub> to be separated from the waste product of the industrial process. In the first instance, CO<sub>2</sub> will be captured from emissions of power stations as these provide the largest individual source of CO<sub>2</sub>.

Carbon storage involves pumping CO<sub>2</sub> into large porous reservoirs (for example saline aquifers, coal seams or oil and gas reservoirs) beneath the Earth's surface at depths greater than about 1 km. At these depths, the CO<sub>2</sub> is compressed such that it is in a liquid-like form (supercritical fluid) and free of any gas phase. The aim is then for the supercritical CO<sub>2</sub> to be retained underground for long enough to be both safe and to solve the problem of human release of CO<sub>2</sub> to the atmosphere.

## 2 The Policy Framework for CCS

### 2.1 The UK Policy context

To meet a legally binding target set by the government in the Climate Change Act (2008), UK GHG emissions should be cut by at least 34% of the 1990 levels by 2020 and 80% by 2050 [19, 24]. This legislation provides a framework for emissions reductions and combatting the effects of climate change, transitioning to a low-carbon economy and demonstrating international leadership in cutting carbon emissions [22]. Carbon budgets have been introduced to cap emissions [24] (Figure 1).

The power sector is the single largest emitter. In 2010, 27% of the UK emissions (157 MtCO<sub>2</sub>e<sup>2</sup>) were caused by power generation [19, 17]. The UK is currently a net importer of

<sup>1</sup>IPCC assessment reports have been produced in 1990, 1995, 2001 and 2007. The fifth assessment report is due in 2014.

<sup>2</sup>All GHG emissions are quantified according to their mass in terms of their equivalence with respect to CO<sub>2</sub> (termed tonnes of CO<sub>2</sub>e). This allows the different global warming potentials for each GHG to be accounted for [18]. CO<sub>2</sub> comprised 76% and 84% of GHG emissions in 1990 and 2010 respectively.

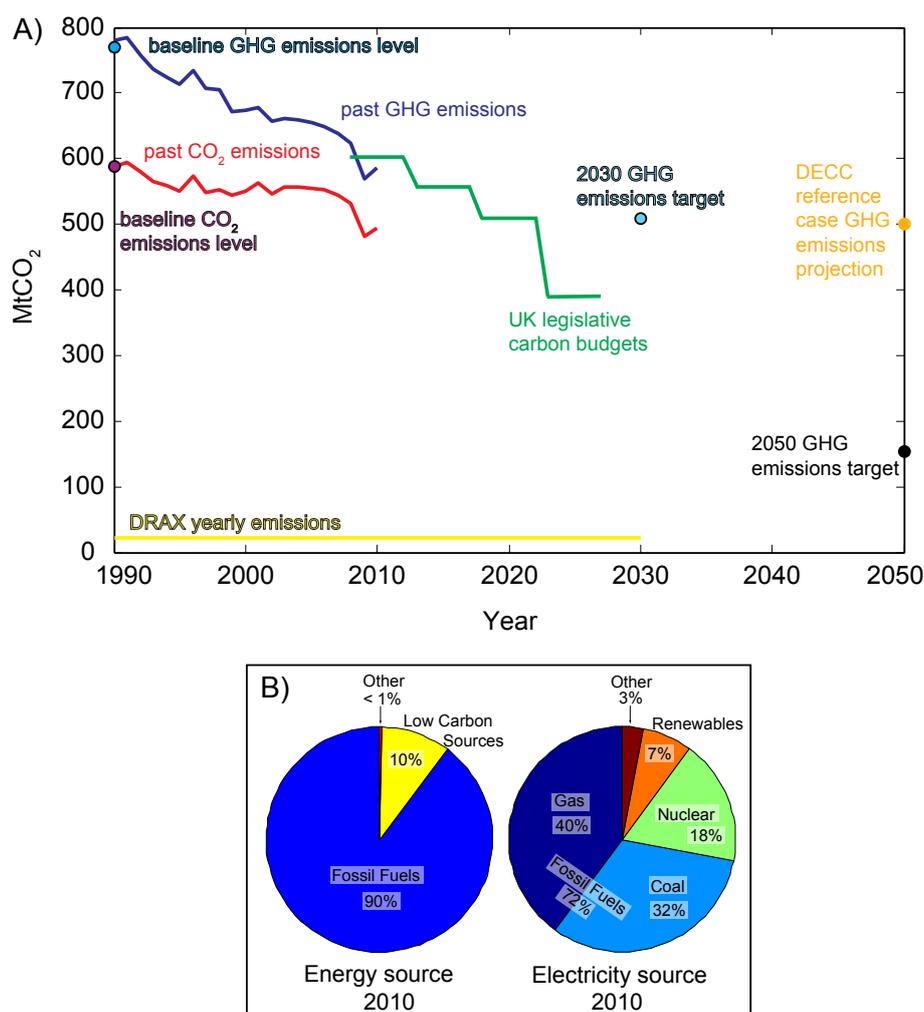


Figure 1: A) The current trend in GHG (solid blue line) and CO<sub>2</sub> (solid red line) emissions from the UK. The baseline levels, the 2030 and 2050 targets are shown. Drax, the UK's largest and newest power station with a 4000 MW production capacity, generates 22.4 MtCO<sub>2</sub> per year [68] (or 14% of the UK's power generation emissions) (yellow line). Carbon budgets are set for a budgetary period of 5 years: 3,018 MtCO<sub>2</sub>e (2008-2012), 2,782 MtCO<sub>2</sub>e (2013-2017), 2,544 MtCO<sub>2</sub>e (2018-2022) and 1,950 MtCO<sub>2</sub>e (2023-2027) and are designed to cap emissions [24] (green line). The orange point is the DECC estimate of UK emissions following an aggressive increase in energy generation from renewables and no increase in nuclear showing that fuel switching alone is not enough to reach the 2050 target [23]. B) In 2010, 89.8% of UK energy was sourced from fossil fuels, 9.9% was from low carbon sources (including nuclear and renewables for example: wind, solar photovoltaics, hydroelectric and biofuels) and 0.3% was from net imports of electricity and non-biodegradable wastes. Just over 99% of the electricity supply was generated in the UK with 72% generation from fossil fuels (40% gas, 32% coal, 18% nuclear, 7% renewables and 3% other (including oil)) [19].

energy, and in 2010 the net import dependency<sup>3</sup> was 28.5%, up from 26.7% the year before [14].

<sup>3</sup>Net import dependency is the imports minus exports, divided by the adjusted primary demand [14].

In 2010, the UK's total net greenhouse gas<sup>4</sup> emissions were 586.3 MtCO<sub>2</sub>e, an increase from 568.0 MtCO<sub>2</sub>e the year before [18, 17] (Figure 1). The baseline level<sup>5</sup> for net greenhouse gas emissions is 770.7 MtCO<sub>2</sub>e with baseline net CO<sub>2</sub> emissions of 588.9 MtCO<sub>2</sub>e. Whilst the 2010 levels were an increase on the previous year, the long-term trend for the UK's CO<sub>2</sub> emissions show them gradually falling. However, global atmospheric CO<sub>2</sub> levels are continually increasing at an average rate of 1.4 ppm yr<sup>-1</sup><sup>6</sup> [49] and achieving an 80% reduction on the baseline levels will require substantial changes to our energy usage and generation methods [16]. It is estimated that about 90% of the CO<sub>2</sub> emitted from a power station could be captured [19] and either utilised<sup>7</sup> or stored.

The industrial sector also emits CO<sub>2</sub> through processes such as cement and hydrogen production. However, CO<sub>2</sub> is emitted in lower overall volumes and from more dispersed industrial sites, so it is less likely that the industrial sector will experience the deployment of CCS schemes before the power sector does so, and then only after the development of the transport infrastructure from clustered sources of CO<sub>2</sub> capture [19].

According to scenarios modelled in the Carbon Plan, by 2030 between 40 and 70 GW of new low-carbon electricity generating capacity will be required [16, 19], and CCS schemes could contribute up to 10 GW of this [9, 19]. This equates to 50 MtCO<sub>2</sub> yr<sup>-1</sup> storage, increasing to 150 MtCO<sub>2</sub> yr<sup>-1</sup> by 2050 (for 30 GW electricity). In order to meet the 80% target by 2050, the UK would need to store in total between 2 and 5 billion tonnes of CO<sub>2</sub> (between 500 thousand and 1.3 million times the volume of the millennium dome); this may need to increase to 15 billion tonnes by 2100 [20]. For comparison, the StatoilHydro CO<sub>2</sub> sequestration project at the Sleipner Field in the North Sea stores 1 MtCO<sub>2</sub> yr<sup>-1</sup>.

The potential CO<sub>2</sub> storage capacity of the UK is up to 70 billion tonnes, which is sufficient to store the energy sector's emissions at current levels for the next 100 years [19, 20]. However, not all of the storage capacity is well-enough understood that storage permits can be granted<sup>8</sup> and whilst hydrocarbon fields are better known and understood, most of the storage capacity (over 85%) is in saline aquifers [20].

### 2.1.1 The CCS Roadmap

The Government has published a CCS strategy outlining the steps that need to be taken by the Government, industry and wider CCS community, in order to allow full scale deployment of CCS by the 2020s [19]. Three key issues that this CCS Roadmap is aiming to address are: 1) reducing the cost of CCS deployment and the associated risks; 2) creating good market frameworks that will allow CCS to be deployed; and 3) removing any barriers to the deployment of CCS [19].

One of the largest challenges for CCS is that the technology has not yet been deployed at the commercial scale. Whilst much of the technology associated with storage processes has been used for decades in the oil industry, capture technologies have not been tested on an equivalent scale to that required for use on existing power plants. The technologies have also not been used in an integrated system. This means that the technology has not been fully tested and the associated risks may not have been fully characterised. However, unless the technology is deployed commercially, the full capability of the technology may not be

<sup>4</sup>Greenhouse gases are CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, and SF<sub>6</sub>.

<sup>5</sup>1990 level for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, 1995 level for HFCs, PFCs and SF<sub>6</sub>

<sup>6</sup>Average rate of increase in CO<sub>2</sub> was determined by direct measurements for the period 1960 to 2005.

<sup>7</sup>Utilisation uses by-product CO<sub>2</sub> to manufacture chemicals, fuels or other materials [76].

<sup>8</sup>Storage permits are granted by the competent authority of each EU member state under the criteria outlined in Annex I of Directive 2009/31/EC, including data collection of the construction of a 3D-earth model of the storage site, dynamic modelling of CO<sub>2</sub> injection at the storage site, sensitivity analysis and risk assessment [33].

understood. Rapid technological progress may be made with large-scale fully-monitored field trials. The challenge is to generate the market conditions to allow the technology to be deployed and remain viable when competing with other low-carbon energies.

The government's programme to encourage CCS deployment includes the following measures.

1. A four-year programme of R&D with £125 million funding commencing 2012.
2. A commercialisation programme for deployment of commercial-scale CCS projects which has £1 billion capital funding. This funding includes £20 million funding for an innovation competition and £13 million funding for a new UK Carbon Capture and Storage Research Centre (UKCCSRC).
3. Electricity Market Reform, the introduction of a Carbon Price Floor (CPF) and Feed-in Tariffs with Contracts for Difference (FiT CfD) to create a market for low-carbon energy and allow CCS to compete with other energy sources.
4. Addressing the key deployment barriers such as transport infrastructure, storage site development and a regulatory framework for long-term CO<sub>2</sub> storage.
5. Promoting knowledge-sharing to accelerate CCS technology deployment.
6. Forming a CCS Cost Reduction Task Force to help industry reduce costs.

### 2.1.2 Electricity Market Reform

As CCS has not yet been deployed at the commercial scale, there is a large degree of uncertainty as to what its deployment will cost. There are capital costs associated with the building of the capture facility and transport infrastructure, energy penalties due to the operation of a capture-enabled plant, opportunity costs associated with the loss of energy and higher operating costs. These all contribute to making the deployment of CCS appear unattractive, if simply viewed in isolation from other sources of low-carbon electricity. The Government is incentivising the deployment of CCS through the CCS Roadmap as well as Electricity Market Reform.

The White Paper 'Planning our Electric Future' (2011) sets out the government's plans for secure and affordable electricity generated from low-carbon sources, and reforms to be made to the electricity market to provide an electricity system that is flexible but generated from a diverse range of sources [15]. While both the demand and the price of electricity are likely to rise in the future, electricity generation in the UK still needs to be decarbonised. Until the global cost of carbon-release is formally recognised, the electricity-generation system will continue to favour fossil fuels over renewable power. Fossil fuels drive the market price for carbon and the carbon price does not reflect the cost of potential damage due to climate change. A strategy is outlined for long-term contracts for new low-carbon electricity generation to be offered in the form of Feed-in Tariffs with Contracts for Difference (FiT CfD), giving a stable and predictable return for low-carbon energy generation and greater certainty with regard to revenues produced, increasing the likelihood of investment [15].

As well as the long-term contracts, a Carbon Price Floor (CPF) is introduced to price carbon fairly [15] and given the length of time between investment and energy production, the CPF reduces uncertainty in the carbon price. The CPF will start at approximately £16 tCO<sub>2</sub><sup>-1</sup> and will cost £30 tCO<sub>2</sub><sup>-1</sup> in 2020 having followed a linear path of price increase [43]. It is expected to rise to £70 tCO<sub>2</sub><sup>-1</sup> by 2030. The CPF is designed as an incentive to encourage investment in low-carbon generation (Figure 4).

## 2.2 The CCS Policy Framework within the EU

Within the EU a target of a 20% reduction of GHGs from 1990 levels by 2020 has been set [19]. Very few EU countries have their own specific legislation or a regulatory framework regarding the capture of CO<sub>2</sub> for geological storage [48, 46], although there are many existing pieces of legislation that will affect CO<sub>2</sub> sequestration. There are also a number of UK regulations that pertain to the geological storage of carbon dioxide, for example mining, hydrocarbon extraction, the control of pollution and waste disposal, clean water and subsurface property rights. The leakage of CO<sub>2</sub> is another aspect which is currently not well resolved [48], along with the ownership of long-term liability. The EU is the only body to have introduced a CCS incentive (the EU Emissions Trading System) [76]. The carbon price is variable. At the end of 2008, CO<sub>2</sub> was worth approximately £12.11<sup>9</sup> per tonne; throughout 2012, the price has only once exceeded the £4.84-7.26<sup>9</sup> per tonne of CO<sub>2</sub> range [31].

### 2.2.1 The EU Emissions Trading Scheme

The EU Emissions Trading Scheme (ETS) (under Directive 2003/87/EC) is the first international scheme to reduce GHG emissions and tackle climate change [35]. The scheme limits the total emissions of certain gases allowed by industries or energy producers. At the end of each year, allowances are surrendered to cover the emissions of each company and spare allowances can be retained or sold. The number of allowances provided has been and will continue to be reduced over the duration of the scheme [35].

In 2013, a number of changes will be made to the ETS. The gases covered by the scheme will be extended to include additional greenhouse gases, as well as the CO<sub>2</sub> and nitrous oxide already covered. Member states will no longer be able to set their own carbon cap or issue allowances; this will instead be controlled centrally. The majority of allowances are currently provided freely; it is intended that in the future, the allowances be auctioned. Some of the allowances will be retained for "new entrants" into the carbon market and 300 million of these will be retained until 2015 for up to 12 demonstration projects of CCS or innovative renewable energy technologies [68].

### 2.2.2 The CCS Directive (2009/31/EC)

The CCS Directive (2009/31/EC) provides a legal framework for the safe geological storage of CO<sub>2</sub>. Requirements for safe operating procedures and environmental protection over the lifetime of a CO<sub>2</sub> storage site are outlined and all EU geological formations used for CO<sub>2</sub> storage are covered [34].

For geological storage of CO<sub>2</sub> to be allowed at a site, a storage permit must be obtained and it must meet the requirements of the CCS Directive [34]. The risk of CO<sub>2</sub> leakage causing damage to the environment or human health should be minimal [34] and a site should only be chosen if there is "no significant risk of leakage" [33], environmental or health impacts. If CO<sub>2</sub> injection is combined with enhanced oil recovery, leakage of CO<sub>2</sub> is not to exceed that which is necessary for the extraction of the hydrocarbons (Directive 2003/87/EC), and the environment and storage ability are not to be adversely affected [33]. The CCS Directive also states that CO<sub>2</sub> injection must be monitored to ensure that migration and leakage are not occurring. Monitoring should also be adapted so that offshore CO<sub>2</sub> injection can also be properly managed [33].

Monitoring should be able to detect the behaviour of fluids in the reservoir, CO<sub>2</sub> migration and leakage, irregularities in behaviour, environmental impacts and the short and

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<sup>9</sup>Conversion factor €1=£0.807.

long-term integrity of the storage site [33]. Monitoring requirements are specific to individual storage sites, but should be carried out for the length of operation of the storage site and be continued after site closure on the basis of an individual post-closure plan. After the transfer of responsibility, the competent authority is required to continue monitoring the reservoir, but the operator should financially contribute a sufficient amount to cover 30 years of anticipated monitoring costs [33].

If a storage site were to leak, liability for damages caused to the climate is covered by Directive 2003/87/EC with surrender of emissions trading allowances [33] and the responsibility of the operator to stop any leakage that occurs. Liability for damages to the environment is regulated by Directive 2004/35/EC. Liability for damage to human health and property is to be addressed at the Member State level [34].

The CCS Directive (2009/31/EC) does not specifically determine the length of time that the operator is liable for a storage site after the site has been closed. Instead it suggests that the operator is responsible for the length of time of the post-closure plan, until the responsibility is transferred to the authority [33].

### 3 Current Research Output at the University of Cambridge

The University of Cambridge has ongoing research in a number of key areas related to CCS. This includes (1) the financing, economics and policy of CCS, (2) combustion processes, pre-combustion capture technologies such as Oxyfuel and Chemical Looping Combustion (CLC), and (3) in understanding both the monitoring (through seismic imaging), storage potential (through understanding geochemical reactions within the reservoir or trapping due to dissolution, capillary forces or reservoir structures) and long-term safety and viability of reservoirs. The Sleipner Field in the North Sea has been used as a field area for the study of CO<sub>2</sub> propagation [4, 5, 6], and used as a comparison for analytical and numerical models of CO<sub>2</sub> propagation in porous media [56, 65, 66, 64, 67, 79, 80]. Analogue experimental studies have also been carried out to understand the dynamics of fluid-CO<sub>2</sub> propagation [38, 39, 41, 56, 62, 69], as well as studies of natural analogue sites where CO<sub>2</sub> is leaking from underground reservoirs [30, 54, 55, 81].

Both Dr. David Reiner (for Financing, policy and deployment) and Dr. Stuart Scott (for High Temperature Looping) are Research Area Champions within the new UKCCS Research Centre. In addition, the EPSRC has funded two capture projects directly related to CCS at the university totalling over £780 K, as well as numerous other grants for research with CCS applications.

#### 3.1 The Policy and Economics of CCS

It is improbable that the large-scale deployment of CCS will occur before the policy framework strictly limits the emissions of greenhouse gases, or before the price of carbon is sufficiently high to incentivise this approach [48]. Economic modelling of CCS deployment suggests that the carbon price would need to be about US\$25-40 tCO<sub>2</sub><sup>-1</sup> [8, 44, 48, 52, 63, 82]. Whilst the UK is relatively far advanced, compared to other European countries, in implementing the CCS Directive and incentivising the deployment of CCS technologies, much more needs to be done before the large scale deployment of CCS can occur. Active areas of research within the University of Cambridge include the public and stakeholder perception of CCS [57, 71], attitudes towards CCS [53] and communication of CCS [13], analysis of CCS incentives [68] and the benefits of demonstration projects [70], amongst other topics.

If, in the near future, CCS is to be commercially deployed, it first needs to progress

through the demonstration phase [70]. This can only be achieved if there is the financial incentive to do so, which in Europe is taken to be government support. The European Union has generated two mechanisms to stimulate the deployment of up to 12 CCS demonstration projects. These are a share of up to 45 million EU ETS allowances from a total of 300 million, and a share of up to EU€180 million from a total of approximately EU€1 billion made available from the European Economic Recovery Plan [68]. Newbery et al. [68] argue that decisions need to be made as to what is being demonstrated, in terms of time-frames, scales and costs, before demonstration projects can be finalised. They suggest that for the limited number of intended demonstration projects in Europe, learning from replication will not be as useful as diversity in project selection. They also suggest that it is more likely that there will be too few demonstration projects put forward within the EU than too many, and that domestic support for CCS demonstration projects should be encouraged.

Issues have been raised about funding for the operational costs of running CCS demonstration plants [68]. Approximately 25% of the energy produced for sale is consumed by the capture process, thus depending on the profit margins, profit may be lost due to running the plant in capture mode. Because the price of the EU allowances varies with the price of electricity, the risk for the project-developer is enhanced [68]. If the price of the EU allowances is low, the plant may not cover its operating costs and may not choose to run in capture mode. In the UK, as well as the capital support provided by the Government, the Electricity Market Reform is designed to assist with the additional operating costs of plants with carbon capture capability [19]. DECC has also commissioned a report into the potential for reductions that can be made to the cost of CCS [19].

One of the key aspects contributing to the ultimate success or failure of a CCS project is the attitude of communities and society in general towards the project. Social or political acceptance of CCS is vitally important as demonstrated in Germany, where last year a proposal for a CCS Act (Act on the Demonstration and Implementation of Technologies for Carbon Capture, Transport and Permanent Storage of CO<sub>2</sub>) was rejected by the Bundesrat (Federal Council). In many areas of Germany, especially the north where more CCS sites are intended, there is strong opposition from local communities.

In their research into the communication of CCS, Corry and Reiner [13] find that it is a problem that CCS technologies are currently not well known or understood by the public and some policymakers (e.g. [32]), and the communication of CCS will help to determine how CCS is used in the future. Corry and Reiner [13] distinguish gaps in the types of information that are available and in the types of institutions actively providing information on CCS. English is found to be the dominant language for communication of CCS material, and the technologies of CCS are found to be more widely publicised than the social aspects of CCS such as the economics, politics, the regulatory framework and environmental themes [13]. In addition, the least trusted organisations (corporations and Government) are found to be doing most of the communication.

The NearCO<sub>2</sub> project [72] has also investigated perceptions of and attitudes towards CCS by surveying residents of five EU member states (comprising Germany, Netherlands, United Kingdom, Poland and Spain), with the findings that male respondents had a greater familiarity with CCS than females and that whilst the respondents from the UK had the least awareness of CCS, they also had the most genuine knowledge. Public respondents (as opposed to stakeholder respondents) thought favourably of CCS, with respondents from Poland most in support of CCS (72% favourable), although support for local projects was lower than the general case [72]. For CO<sub>2</sub> storage, there is a positively linear relationship between distance from the storage site and the favourable opinion of it. For CO<sub>2</sub> capture, the study found a quadratic relationship between distance from the capture site and the

favourable opinion of it [72].

The focus of CCS demonstration projects has been technical 'learning-by-doing' [70] because the cost to governments of developed countries for the first 100 plants is estimated at £2.2-2.6 billion yr<sup>-1</sup> <sup>10</sup> [45] and therefore cost-efficiency and value for money are highly desirable [70]. Benefits other than technological testing and improvement, and establishment of operating costs, may be gained from CCS demonstration projects, such as social learning, knowledge transfer and greater political support [70]. CCS demonstration projects could be seen as a source of work and industry, and greater social and political acceptance of CCS could be achieved if project developers were to invest in social learning; not to do so may be a lost opportunity [70].

### 3.2 The Capture of CO<sub>2</sub>

The capture of CO<sub>2</sub> is not a new process [68]. Many industrial processes separate CO<sub>2</sub> from other solids or gases, either as a waste product or for further use (for example beverage carbonation, cement production or hydrogen production and the synthesis of ammonia). However, although each of the components is commercially available, the component parts have not yet been united and tested in an integrated system [48]. There are, therefore, a number of uncertainties surrounding the large-scale deployment of integrated CCS capture technologies. Uncertainties are related to technology cost, the method of capture, adverse environmental effects and scale.

Researchers at the University of Cambridge are working on a number of different methods for CO<sub>2</sub> capture and storage or utilisation. CCS technologies need to be applicable to both existing and newly built infrastructure because approximately 80% of the future emissions for 2020 are locked-in, coming from emissions-intensive plants that are already in place or under construction [19]. Topics such as accelerated mineralisation (e.g. [77]), alternative cements (e.g. [51, 58, 59, 78]) and brine sequestration [28, 29] are all active research areas being followed in the Department of Engineering, where technologies for the production of materials that will use CO<sub>2</sub> and reduce emissions are being developed.

The currently available methods of CO<sub>2</sub> capture from power stations comprise both pre-combustion and post-combustion technologies (Figure 2). Pre-combustion technologies such as Oxyfuel with pulverised coal (Figure 2 A), Chemical Looping Combustion (CLC) (Figure 2 B) (e.g. [11, 25, 26, 75]) and Integrated Gasification Combined Cycle processes (e.g. [27, 74]) are not expected to be deployed in the first instance, as each of these technologies requires modifications to be made to the currently used method of energy generation at a power station. Oxyfuel can be retro-fitted to a power station, but with significant difficulties in terms of costs and logistics, and the CLC process requires a new type of power station. Researchers at the University of Cambridge are also investigating the use of alternative solid fuels in the gasification process (e.g. [73]).

Oxyfuel is the process of burning fuel in a mixture of oxygen and carbon dioxide [48]. By combusting the fuel in the absence of nitrogen, the waste gases (CO<sub>2</sub> plus sulphur and steam) can be easily separated and utilised. However, energy is used initially to separate nitrogen from the air (air liquefaction) providing the process with an energy penalty of approximately 15 to 25%. On the other hand, the process of separating the nitrogen can also produce argon which can offset some of the cost. The fuel combustion cannot take place in pure oxygen because the temperatures generated would be too high.

The chemical looping process oxidises a gaseous fuel using metal oxide in the following

<sup>10</sup>Converted from a published estimate using a conversion factor of US\$1 = £0.642.

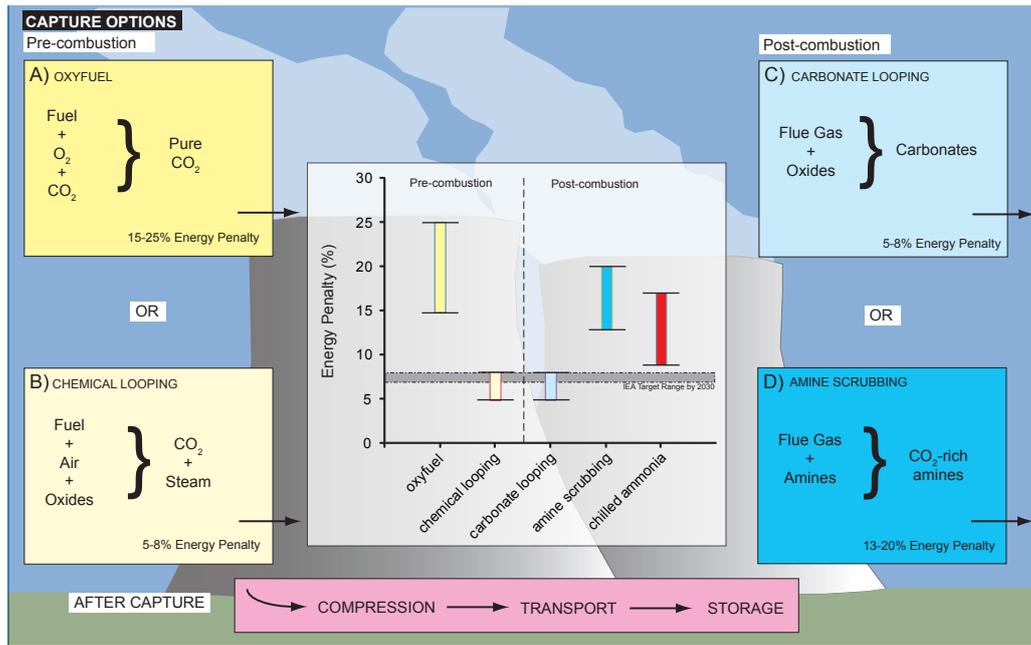
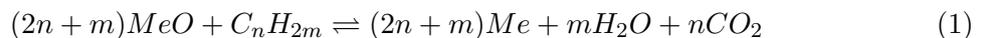


Figure 2: The CCS process with different capture technologies. Post-combustion technologies such as carbonate looping (e.g. [60]), amine scrubbing and chilled ammonia are more likely to be deployed in the first instance. A) Oxyfuel is a pre-combustion technology, burning fuel in oxygen and carbon dioxide (without nitrogen) so that the waste gases are easily utilised. B) Chemical looping is a pre-combustion technology that involves the oxidation and reduction of a gaseous fuel using a metal oxide. Oxidation transfers oxygen from the metal oxide onto the organic fuel producing a metal, steam and carbon dioxide. C) Amine scrubbing uses amines to remove  $\text{CO}_2$  from the post-combustion flue gases. D) Carbonate looping uses calcium oxides to remove  $\text{CO}_2$  from the flue gases. Different capture technologies have different associated energy-penalties. According to the IEA, the aim for all capture technologies is to reduce the energy penalty to the range of 7-8% by 2030 [45].

reaction.



The off-gases are condensed to produce water and pure  $\text{CO}_2$  [27, 74]. The metal can then be passed through a second process where it is re-oxidised by air;  $\text{N}_2$  and unused  $\text{O}_2$  are also emitted [27, 74]. Chemical looping, like oxyfuel, has the advantage over post-combustion techniques where the fuel is burnt in air, that the resulting  $\text{CO}_2$  is not contaminated by nitrogen, and instead can be directly transported to a  $\text{CO}_2$  storage site. The total heat produced by CLC is the same as that produced if the fuel were burned in air [27, 74] except that the  $\text{CO}_2$  has also been separated from the off-gases. The CLC process has an energy penalty of approximately 5 to 8% (Figure 2 B).

Researchers at the University of Cambridge [27, 74] have shown that it is also possible to apply chemical looping combustion (CLC) to a solid-fuel source as long as a gasification agent is included. The gasification agent (e.g. steam) turns the solid carbon to gaseous compounds ( $\text{CO}$  and  $\text{H}_2$ ) that can then be reacted with the metal oxide. An example of a solid-fuel source would be a lignite coal<sup>11</sup> or lignite char [27, 26]. Lignite coal is not typically used in

<sup>11</sup>Lignite, or brown coal, is the lowest grade coal with a carbon content in the range 25-35%.

the UK, instead higher grade coals<sup>12</sup> are used to produce electricity. However, a significant amount of Europe's energy is generated by burning lignite coals (~26% of coal burnt) [25].

Carbonate looping is a post-combustion process, similar to the chemical looping process, whereby calcium oxide (CaO) is used as the metal oxide and the CO<sub>2</sub> in the flue gas reacts to form calcium carbonate (CaCO<sub>3</sub>) (Figure 2 C). The CO<sub>2</sub> is then separated so that the CO<sub>2</sub> can be stored and the CaO can be reused. Carbonate looping has the advantage that it is cheaper than other metals, but large volumes are required and CLC is thermodynamically more efficient. Like carbonate looping, amine scrubbing is a post-combustion process of removal of CO<sub>2</sub> from flue gases using amines (Figure 2 D). Amines are alkaline organic chemical compounds containing nitrogen that react with the acidic CO<sub>2</sub> in the flue gases, capturing it. They can then be heated to obtain the pure CO<sub>2</sub>, and re-used. In this regeneration stage, between 13 and 20% of the power output of the plant can be lost.

One of the issues with the commercial-scale deployment of CO<sub>2</sub>-capture technologies is that of scale. Currently, capture technologies have only been tested on the 1 to 30 MW range [68]. The outstanding question that may be resolvable during the demonstration phase of CCS deployment, is whether capture technologies will work on the large scale (300-800 MW range [68]). A commercial-scale post-combustion scrubbing plant would have a larger footprint than the power station, with a number of different reactors to process the volume of flue gas generated by the power station. The reactors would not necessarily be able to be shut down on a timescale commensurate with the timescale for electricity generation of a power station. This raises questions about whether the power station would have to work as a base load or be able to be more variable, generating according to demand. Also, whilst the three parts of the CCS chain (capture, transport and storage) are not new technologies, they have not been used together in an integrated system. For the commercial deployment of CCS to occur, these three parts need to be deployed so that they are ready at the same time. For any one of the components to be delayed and not be operational whilst the other elements were, would likely incur a large financial penalty and the CCS process may not succeed in meeting financial targets.

Another issue is the production of waste materials and the potential for environmental pollution through the CO<sub>2</sub> capture process. This is especially important for post-combustion amine scrubbing as amines are chemically vicious and volatile, and are highly toxic; some amine is inevitably emitted during CO<sub>2</sub> capture. However, all of the capture processes will produce some waste product. Precombustion chemical looping will produce a large volume of waste oxygen carrier<sup>13</sup>. Like the CLC oxygen carriers, amines will also degrade with continued use and will require periodic replacement. When burning solid fuels, residues such as char and ash can build up and contaminate the CLC process. Drs. Dennis and Scott are currently working on methods for the selective oxidation of the metal and not the char.

### 3.3 The Geological Storage of CO<sub>2</sub>

CO<sub>2</sub> can be stored in a number of geological locations and through a variety of methods. These include the deep ocean, utilisation of crushed rock, reactive rock formations and underground reservoirs such as depleted oil and gas reservoirs or saline aquifers [3]. CO<sub>2</sub> can

<sup>12</sup>Mainly bituminous coal, with some anthracite, is combusted for electricity in the UK. Bituminous coal is higher grade than lignite, with a carbon content in the range 60-80%. Anthracite is the highest grade with about 90% carbon content.

<sup>13</sup>for example: for each 1 kg of nickle oxide, 0.07 kg of coal will be oxidised. This means that large amounts of oxide are required to oxidise each batch of fuel. In addition, the reduction and oxidation process used to separate the CO<sub>2</sub> can only happen a limited number of times before the oxide becomes degenerated and needs replacing.

also be used in active oil reservoirs for Enhanced Oil Recovery (EOR) where a by-product is the storage of  $\text{CO}_2$  in the reservoir. Most of the storage capacity of the UK for  $\text{CO}_2$  is provided by proven (depleted oil and gas reservoirs) and unproven (saline aquifers) reservoirs, predominantly in the North Sea [19] (Figure 3).

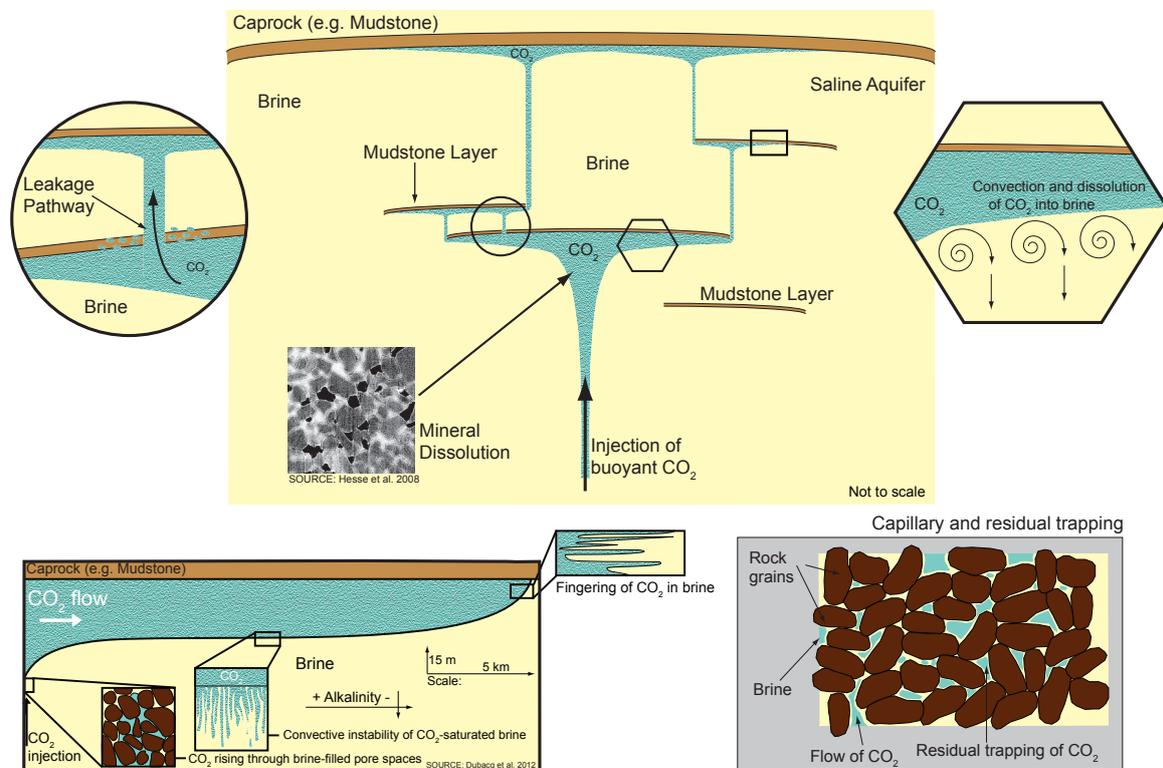


Figure 3: The methods of geological  $\text{CO}_2$  storage in a saline aquifer or disused oil/gas reservoir.  $\text{CO}_2$  migrates buoyantly upwards through a porous reservoir due to density differences until it reaches an impermeable cap. Leakage may occur through fractures in the caprock. A  $\text{CO}_2$  plume will spread laterally along an impermeable interface and become trapped through capillary trapping, residual trapping and solubility trapping due to convective dissolution. Solubility trapping occurs due to the dissolution of  $\text{CO}_2$  into the brine in a reservoir that forms a fluid that is more dense. This causes a convective instability at the interface of the  $\text{CO}_2$  and brine. Capillary trapping retains  $\text{CO}_2$  in pore spaces as the  $\text{CO}_2$  is unable to overcome the capillary force required to escape the pore space. During brine imbibition after  $\text{CO}_2$  injection has ceased, residual trapping occurs as brine re-enters a previously  $\text{CO}_2$ -saturated region and flows around the  $\text{CO}_2$  in a pore space, cutting it off from the rest of the  $\text{CO}_2$  fluid.  $\text{CO}_2$  in solution with brine forms carbonic acid which can dissolve carbonate and silicate minerals in a reservoir. Understanding the kinetics of reactions between the solution and the reservoir rock has important implications for whether dissolution or precipitation will be dominant. This balance may control whether a reservoir will eventually leak or gain a more effective seal. Photograph [40].

Storage in depleted oil and gas reservoirs or saline aquifers can occur at depths greater than about 750 m, where the injected  $\text{CO}_2$  exists as a supercritical fluid. Technology used for compression and injection of  $\text{CO}_2$  is already used in the oil industry for enhanced recovery [3]. Disused reservoirs and saline aquifers are filled with brines, denser than supercritical  $\text{CO}_2$ .

The CO<sub>2</sub> rises through the surrounding brine and is trapped by an impermeable cap rock (structural trapping) in most cases. There are a number of different research groups within the university working on different aspects of the migration of CO<sub>2</sub> within an underground storage reservoir and its consequent trapping. Researchers at Cambridge University have shown that the buoyant rise of supercritical CO<sub>2</sub> through a porous reservoir occurs much more quickly than previously expected [5, 6], and is only halted once it reaches an impermeable interface, along which it spreads laterally [62]. A laterally spreading plume of CO<sub>2</sub> within a reservoir will experience further opportunities to become trapped. Work in Cambridge is conducted on CO<sub>2</sub> migration [56, 62, 38, 39, 65, 67, 69, 79, 80] and trapping in a saline aquifer; the StatoilHydro project at the Sleipner field in the North Sea [4] is frequently used as a case study. The various kinds of trapping in saline aquifers being studied are capillary trapping [38, 39], residual trapping, and solubility trapping through convective dissolution [1, 42, 61, 64] (Figure 3).

Theoretical analytical and numerical models have been developed by researchers at the Department of Applied Mathematics and Theoretical Physics and BP Institute to model the lateral propagation of CO<sub>2</sub> within a porous medium along an impermeable interface. The flow can be modelled as an inverted gravity current driven by the density difference between the CO<sub>2</sub> and the brine. Lyle et al. [62] find that the current spreads axisymmetrically at a rate of  $t^{(\alpha+1)/4}$  ( $t^{1/2}$  for the case of constant volume flux). The volume of fluid injected is equal to the flow rate multiplied by time to the power  $\alpha$  ( $V = Q \times t^\alpha$ ) so larger values of  $\alpha$  signify increasingly larger injected volumes of CO<sub>2</sub>. This is supplemented by the work of Golding and Huppert [38] where topographic trapping in a channel is examined, and Golding et al. [39] where capillary forces are addressed. Vella and Huppert [79] look at the progression of CO<sub>2</sub> along an inclined impermeable interface and find that for constant volume or constant flux injections of CO<sub>2</sub>, the current initially spreads axisymmetrically and at longer times, spreads down slope. Work has also been carried out on the effect of fractures or leakage pathways within the impermeable boundary layer, on the propagation of the gravity current [66, 67, 80] and on the effect of multiple layers [41, 65].

In a porous medium saturated with a brine (e.g. a saline aquifer) into which CO<sub>2</sub> is being pumped, capillary forces exist between the two fluids. Capillary pressures are dependent on the size distribution of the pore spaces, and their regularity. Capillary forces affect the amount of CO<sub>2</sub> saturation achieved, and the permeability of the porous medium to flow through it [38, 39], because the CO<sub>2</sub> needs to overcome the capillary pressure in order to get into a pore space. Therefore capillary forces need to be understood to be able to accurately model the migration of fluids in a reservoir. Capillary forces can also trap CO<sub>2</sub> in the pore spaces.

Residual trapping occurs in reservoirs where CO<sub>2</sub> pumping has stopped and brine imbibition<sup>14</sup> is occurring. Beneath the laterally spreading plume of CO<sub>2</sub>, the brine begins to re-enter a previously CO<sub>2</sub>-saturated region. The brine flows into the pore spaces and will take the easiest path. Rather than forcing out all of the CO<sub>2</sub> in a pore space, the brine may flow around the CO<sub>2</sub> in the centre of the pore space, cutting off that small amount of CO<sub>2</sub> from the rest and leaving it trapped in the pore space. Residual trapping is dependent on the initial CO<sub>2</sub> saturation, and this is dependent on reservoir properties (pore-size distribution, temperature and pressure).

The solubility of CO<sub>2</sub> in the brine can be important for understanding the dissolution or precipitation processes that occur in the reservoir. The dissolution of CO<sub>2</sub> into water within a reservoir forms carbonic acid and reduces the pH of the fluid. The solubility of CO<sub>2</sub> in saline water is pressure-dependent, with greater amounts of CO<sub>2</sub> dissolved at higher

<sup>14</sup>Brine imbibition is the process of reabsorbing brine into the porous medium.

pressures<sup>15</sup>. Once CO<sub>2</sub> is dissolved into the brine, the CO<sub>2</sub>-saturated brine becomes more dense and sinks to the base of the reservoir, thereby trapping the CO<sub>2</sub> (solubility trapping).

An important question to answer is whether the reactions between the CO<sub>2</sub>-brine mixture will cause the precipitation or dissolution of carbonates or the dissolution of silicates in the reservoir and, if they occur, the rates of these reactions. Carbonate dissolution occurs more rapidly than silicate dissolution<sup>16</sup> and the dissolution of carbonate minerals releases CO<sub>2</sub> and increases the porosity of the reservoir, thereby increasing the storage capacity in the area of dissolution, but also possibly the risk of CO<sub>2</sub> escaping elsewhere. Carbonate deposits are commonly found in faults and fissures, forming seals. Dissolution of these carbonates may provide an escape pathway for CO<sub>2</sub> [55]. On the other hand, the rapid dissolution of carbonate in one part of the reservoir may saturate the fluid in calcium (and other cations<sup>17</sup> and encourage mineral precipitation elsewhere, reducing permeability in that area.

The dissolution of silicates is associated with the precipitation of clay minerals (e.g. kaolinite) which may cause an alteration in the permeability in the reservoir, possibly assisting the trapping of CO<sub>2</sub>. The porosity-permeability relationship is non-linear with small porosity changes having a large effect on the permeability. Researchers at the University of Cambridge are trying to constrain the reaction rates within reservoirs [30, 54, 81]. Reaction rates in natural systems are sensitive to the temporal variation of the reactive mineral surface, the porosity and the pH, as well as heterogeneities in mineralogy and fluid chemistry, and hence reaction rates calculated using an analogue system do not necessarily reflect those of the natural system.

Major concerns regarding CCS are the risks associated with storage, the possibility of leakage of CO<sub>2</sub> from a reservoir and whether monitoring processes have the resolution to determine leakages. The injection rate must be limited so that increasing pressure does not lead to fracturing of the reservoir during injection. If a reservoir is confined, then the build-up of pressure due to CO<sub>2</sub> injection may be a particular concern. However, if the reservoir is unconfined, an additional concern is the displacement of saline water by CO<sub>2</sub>, with the migration of this saline fluid leading to contamination of potable water supplies. Additionally, explosions due to CO<sub>2</sub> build-up (e.g. Crystal geyser) may occur and subsequent accumulation of dense CO<sub>2</sub> in low-lying surface areas is a risk that can have varying consequences depending on the location of the leak. Ponding of CO<sub>2</sub> in low topography poses the greatest threat to the general population in terms of suffocation hazards (e.g. Lake Nyos).

To be able to detect leakage from a reservoir, effective monitoring of that reservoir needs to be carried out. Cambridge researchers are using three-dimensional seismic acoustic surveys to image the CO<sub>2</sub> injection into the Sleipner storage reservoir [5, 6]. Boait et al. [5, 6] have investigated the CO<sub>2</sub> plume at intervals, using images of nine discrete CO<sub>2</sub>-rich layers which are separated by thin mudstones and capped by a thick reservoir caprock. The imaging shows that the areal extent of ponded CO<sub>2</sub> in the deepest layers has stopped growing through time and in some cases has decreased in size, whilst the size of the shallower layers has continued increasing through time [6]. This suggests that the observed shrinkage of the deeper horizons is reflective of an actual reduction in size of the deeper layers of CO<sub>2</sub>-rich fluid [6] with the propagation of CO<sub>2</sub> into or around the overlying mudstones [5].

The seismic data, through the calculation of the vertical pushdown of horizons [5], can

<sup>15</sup>The solubility of CO<sub>2</sub> is complicated, and dependent on a number of parameters including temperature, pressure, water salinity, the state of the reservoir water (e.g. liquid, gas or supercritical phase), and whether or not there is already any CO<sub>2</sub> dissolved. Also, the carbonic-acid species produced (H<sub>2</sub>CO<sub>3</sub>, HCO<sub>3</sub><sup>-</sup> or CO<sub>3</sub><sup>2-</sup>) is dependent on the pH of the reservoir, which is spatially and temporally variable depending on the injection of the CO<sub>2</sub>.

<sup>16</sup>The reaction kinetics for the dissolution of silicates is slower than for the dissolution of carbonates

<sup>17</sup>A cation is an atom that has lost electrons from its outer shell.

also be used to estimate the amount (mass and volume) and distribution of CO<sub>2</sub> stored in the horizons of the reservoir [10]. The vertical pushdown can be calculated from the difference in two-way travel times between surveys, from the knowledge of the acoustic velocities of brine-saturated versus CO<sub>2</sub>-saturated sandstones. However, volume estimates are not well constrained; that requires monitoring in observation wells to support the seismic data. Leakage from an offshore reservoir could be detected using an ocean-bottom array for water chemistry, and should CO<sub>2</sub> be leaking, the water column would become acidic. Monitoring of offshore reservoirs is more costly than monitoring reservoirs onshore; monitoring can be carried out more extensively onshore than offshore for a given cost and leakage is more likely to be detected.

## 4 Barriers to Deployment

There are some key challenges facing the deployment of CCS. One of the most significant barriers to deployment is cost. In developed nations technology deployment is somewhat difficult due to cost, although additional energy expenses are economically feasible for the customer base. However in developing nations where a large percentage of the population do not have access to mains electricity<sup>18</sup>, the cost of deploying CCS could be prohibitive. The problem of CO<sub>2</sub> emissions and climate change is a global one, needing a global solution. If the answer is CCS, then it needs to be cheaper. There are some ways of achieving this, for example, ensuring that the storage sites for the captured CO<sub>2</sub> are close to the sites where the CO<sub>2</sub> is generated, improvements in combustion and power-generation technologies, such as those being developed at Cambridge University, so that the capture of CO<sub>2</sub> is more efficient with reduced energy penalties.

Another barrier is that of scale. Capture technologies have not been tested at the scale that would be required to retrofit a currently active, coal-fired power station (300-800 MW range [68]). The different parts of the CCS chain have not yet been used together in an integrated system, but this is required for deployment, otherwise heavy financial penalties may be incurred. The uncertainty surrounding CCS deployment is also a major challenge and is perceived to be mainly due to costs and liabilities should a storage reservoir leak CO<sub>2</sub>. The CCS Directive (2009/31/EC) specifies that a leakage is 'any release of CO<sub>2</sub> from the storage complex' which is the 'storage site and surrounding domain', and corrective measures must be taken if any leakage occurs. This places a financial burden on the operator until the liability is passed to the competent authority. The timescale for the transferral of liability in the UK has not been set, although Directive 2009/31/EC stipulates that it must be greater than 20 years unless evidence is supplied to indicate that the CO<sub>2</sub> has been permanently contained. The right regulatory framework needs to be set so that the financial burden placed on operators of storage sites is not prohibitive, but that negative environmental and health impacts due to leakages are minimised. The key is to generate the right market conditions in order to allow the technology to be deployed and remain viable, and to take a realistic view on the risks of leakage from storage versus the risks of not deploying CCS in the first place.

Lastly, the public communication of CCS is vital for commercial deployment. Previous projects have failed on the strength of public opposition with shortcomings in communication often to blame [36]. Early communication between project developers, stakeholders and the public, is important if a CCS project is to succeed [13].

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<sup>18</sup>In 2009, 19.5% of the world's population did not have access to mains electricity with 99.8% of these people living in developing nations [47]. China has 99.4% electrification, India has 75% [47].

## 4.1 Cost

There are a number of components in the CCS chain with varying costs (Figure 4). The largest cost associated with the deployment of CCS technology is the cost of capturing CO<sub>2</sub> [48, 21, 83]. There is, however, a popular belief that the costs associated with CO<sub>2</sub> capture will decrease with time [48]. Technological developments may add to a reduction in the cost of CCS, although more efficient equipment does not always correlate with a lower cost. However, there are certain areas which will need to be investigated further, where technological advances, optimisation and economies of scale may lead to reduced costs.

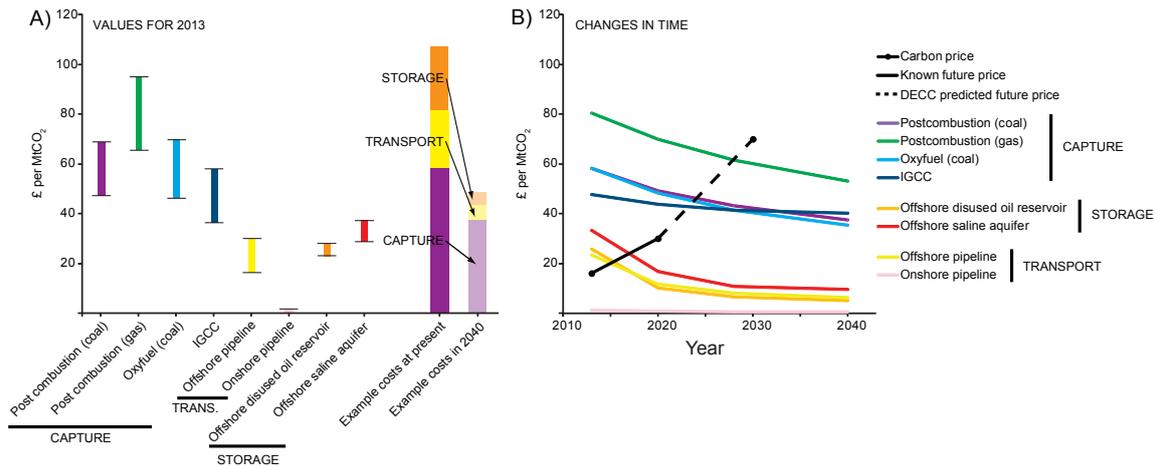


Figure 4: One of the most significant barriers to deployment is cost. A) Additional costs due to CO<sub>2</sub> capture, storage, monitoring and transport in 2013 and predictions of future costs. Capture costs are dependent on the type of power plant. Anticipated storage costs are dependent on the type of storage reservoir and the characteristics of the reservoir. B) Predicted costs to 2040. The Carbon Price Floor (CPF) will provide revenue and will cost £30 tCO<sub>2</sub><sup>-1</sup> in 2020 having followed a linear path of price increase [43]. It is predicted to rise to £70 tCO<sub>2</sub><sup>-1</sup> by 2030 [15]. The CPF is designed as an incentive to encourage investment in low-carbon generation.

The cost of transport will include the costs of construction, maintenance and operation, as well as other costs such as design and insurance [48]. The cost of constructing and maintaining offshore pipelines is between 40 and 70% more than onshore pipelines, and it is not expected that the costs associated with transport will decrease over time [21, 48]. The transport of CO<sub>2</sub> by ship is cost-competitive if the distances are large [48]. The cost of transportation by ship is estimated at £11.7 and £12.9 per MtCO<sub>2</sub> at the demonstration scale (2.5 MtCO<sub>2</sub> per year) and £9.7 and £10.6 per MtCO<sub>2</sub> at the commercial scale (20 MtCO<sub>2</sub> per year) for distances of 180 km and 500 km respectively [21, 83].

Storage costs are affected by whether the intended storage reservoir is on or offshore and the characteristics of the reservoir, for example the depth, permeability and thickness [48]. Estimates of storage costs are included in Figure 4 [21, 83]. The cost of drilling a well is a large part of the capital investment required for storage reservoirs where there has been no previous industry (for example saline aquifers) [48]. The cost of assessing and characterising a reservoir, studying the feasibility and obtaining the correct licensing will also need to be included; these costs are estimated at £1.08 million<sup>19</sup> [7, 48]. The U.K.'s storage capacity is

<sup>19</sup>Converted from a published estimate using a conversion factor of US\$1 = £0.642.

composed of offshore disused oil and gas reservoirs and saline aquifers.

There is a large amount of uncertainty regarding the costs of deployment of CCS. Some of these costs are introduced by the unknown time of availability of storage sites. For example, it may be unknown when a hydrocarbon reservoir will become available for storage as the date for the end of the production of the hydrocarbons may be unknown [20]. In addition, there is a wide range in the estimates made of the cost to deploy CCS on a large scale. There are site-specific issues (for example the transportation distance) that cause the deployment estimates to vary. Cambridge University research on trapping mechanisms within potential storage reservoirs will be an essential guide to field tests of CCS and the assessment of costs.

## 5 Conclusions

This document has outlined the key challenges that face the deployment of CCS in the UK, along with the ongoing research at the University of Cambridge that is resolving some of these challenges. Research into CO<sub>2</sub> capture has yielded progress in developing new capture technologies with greater energy efficiencies (for example pre-combustion chemical looping technology using a solid fuel [11, 25, 26, 73, 74, 75]). Continued testing of these technologies will lead to better prospects for their commercial deployment.

CO<sub>2</sub> storage research has focussed on understanding the physical processes of the migration of CO<sub>2</sub> within a porous reservoir through geophysical observations [5, 6] as well as analytical and numerical modelling [62, 79]. The Sleipner Field in the North Sea has been used as a field area for the study of CO<sub>2</sub> propagation [4, 5, 6]. This, in combination with analogue experimental modelling [38, 39, 41, 56, 62, 69], has led to a better knowledge of the different trapping processes that could occur within the reservoir [1, 38, 39, 42, 64], the rate of migration of CO<sub>2</sub> within a reservoir [38, 39, 62, 66, 67, 69, 80] and the risk of CO<sub>2</sub> leakage [66, 67, 80]. Axisymmetric gravity currents have been found to spread laterally at a rate of  $t^{1/2}$  for a general case before capillary forces or non-horizontal interfaces are considered. Research has also been conducted into the reaction kinetics of geochemical processes occurring in a reservoir using natural analogue sites where CO<sub>2</sub> is leaking from underground reservoirs [30, 54, 55, 81], leading to an enhanced knowledge of the long term effects of CO<sub>2</sub> storage. Carbonate dissolution occurs more rapidly than silicate dissolution. The dissolution of carbonate minerals may increase the porosity of the reservoir locally, but increase the risk of CO<sub>2</sub> escaping elsewhere.

Sending a clear and scientifically grounded assessment of the risks associated with long-term CO<sub>2</sub> burial is vital for commercial deployment, as is the public communication of CCS technologies. Research into the financing, economics and policy of CCS, and the public communication of CCS technologies, has found that CCS technologies are currently not well known or understood by the public and that there are gaps in the types of information that are available and in the types of institutions actively providing information on CCS.

The body of research being accumulated at the University of Cambridge is helping to decrease uncertainty in CCS, increasing the likelihood of commercial deployment of CCS. As large-scale demonstration projects come closer to fruition, what remains to be done is to continue to drive the cost of CCS down through the introduction of improvements to technologies, especially in the case of CO<sub>2</sub> capture, through better understanding of the physics and chemistry of storage, and to continue to increase public awareness of CCS and the role it can play in a greener future.

## Acknowledgements

K. A. Daniels would like to acknowledge an EPSRC Bridging the Gaps grant. JAN is funded by

a Royal Society University Research Fellowship. A. Al-Tabbaa, M. J. Bickle, F. C. Boait, S. S. S. Cardoso, J. S. Dennis, B. Dubacq, M. J. Golding, D. R. Hewitt, N. Kampman, J. P. B. Lovell, D. M. Newbery, S. A. Scott and A. W. Woods are all thanked for their assistance and useful discussion. This manuscript has benefitted from the constructive comments and suggestions of J. P. B. Lovell.

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