Carbon Capture and Storage

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Realising the potential?

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Executive summary

This report summarises the findings of the two-year UKERC research project: Carbon capture and storage: realising the potential?

The aim of the research is to assess the technical, economic, financial and social uncertainties facing carbon capture and storage (CCS) technologies, and to analyse the potential role they could play in the UK power sector between now and 2030. CCS technologies are often highlighted as a crucial component of future low carbon energy systems – in the UK and internationally. However, it is unclear when these technologies will be technically proven at full scale, and whether their costs will be competitive with other low carbon options.

The important contribution that CCS technologies could make to reducing global carbon emissions has been recognised by the UK government for several years. There has been a plan to build at least one full scale demonstration project since 2006. But, at the time of writing, this has not yet resulted in a firm agreement to fund a specific project. Last autumn, the planned Scottish Power demonstration at the Longannet power plant became the latest CCS project to be cancelled. Despite continuing public commitments to CCS from Ministers, policy, economic and financial uncertainties remain a particular concern for investors in the UK – and in many other countries where CCS demonstrations are planned. The re-launch of the £1bn fund for CCS demonstration projects in April 2012, alongside a roadmap for the commercialisation of CCS technologies, may signal a decisive turning point in UK policy. However, it remains to be seen whether the measures within the roadmap, and the generous package of financial support that is now available, will be sufficient to make CCS a commercial reality.

Against this policy background, this report systematically examines the uncertainties facing CCS technologies in the UK. It uses historical evidence to explore these uncertainties, and the conditions under which they can be at least partly resolved. The historical evidence base comprises nine case studies, each of which focuses on a technology that is partly analogous to CCS. The report draws on this evidence to develop potential pathways for CCS in the UK to 2030, and uses this analysis to draw conclusions for current policies and strategies.

The important contribution that CCS technologies could make to reducing global carbon emissions has been recognised by the UK government for several years.

The report reaches three general conclusions. First, our historical case studies show that uncertainties can be reduced sufficiently for progress to be made. In some cases, they can be resolved entirely. This offers some optimism that, given the right set of circumstances, the uncertainties that affect CCS can also be dealt with. However, care is needed when learning from historical contexts that differ widely from the current situation in the UK. Second, interactions between uncertainties matter. They can reinforce each other, both positively and negatively. There can also be tradeoffs between uncertainties where attempts to resolve one uncertainty could result in the exacerbation of others. Third, the resolution of all uncertainties is not required for CCS to be financeable in the UK. Similarly, the derailing of plans to realise the potential of CCS may not require everything to go wrong – but this could be caused by a 'critical mass' of uncertainties persisting for too long.

A regulatory approach will only work if technologies are sufficiently well developed and the additional costs can be passed on to consumers.

The report also concludes that if CCS is to be a low carbon option for the UK in future, comprehensive policy support is required now to reduce the uncertainties we have identified. In particular, the re-launched demonstration programme needs to yield firm commitments to build several projects as soon as possible. Even if such progress is made, there will be difficult choices for government and other decision makers. Our research has highlighted four areas where such choices need to be made:

1. Keeping options open or closing them down?

Whilst strong policy signals and support are required for CCS, there are also risks associated with accelerated innovation and deployment. It is tempting to focus resources on one technological variety early on as the French government did with the PWR for its nuclear programme. This may help to speed up development, but comes with increased risks of picking inferior technology. It is too early for government and industry to close down on a particular variant of CCS technology. Several substantial demonstration projects are needed, for example so that uncertainties associated with scaling up and system integration can be tackled.

2. Which public policy incentives for CCS demonstration and deployment?

A menu of options is available for public policy support of CCS technologies. A regulatory approach will only work if technologies are sufficiently well developed and the additional costs can be passed on to consumers. CCS technologies are not yet at this stage. In the meantime, the government is right to emphasise the need for demonstrations. Public finance for these demonstrations should be designed to maximise performance rather than novelty. Since not all demonstrations are likely to perform as expected, systematic learning and evaluation by government is also essential.

3. CCS deployment as a marathon, not a sprint.

Our historical case studies show that developing new energy technologies can take a long time. Their costs do not necessarily fall from the first day they are deployed. Whilst learning can bring costs down, costs can rise for several years first as technologies are scaled up. Whilst this requires some patience, it is therefore important to monitor progress carefully to inform decisions on whether to continue with public funding – or, if there is little sign of positive progress over a prolonged period of time, when to divert resources to other options.

4. Dealing with storage liabilities

Our case study of UK nuclear waste management policy has highlighted how complex liability arrangements for CO_2 storage could be. For CCS, a balance needs to be struck between limiting liabilities for investors (so that they will be able to invest in full scale CCS plants) and protecting the interests of future taxpayers (who should not be un-necessarily exposed to liabilities). Agreements are therefore needed about how liabilities should be divided, when a privately run storage site should revert back to the State, what arrangements are needed to fund potential liabilities, and what insurance site operators may require. The nuclear experience suggests that an independently managed fund may be required for carbon storage liabilities.

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Introduction



Carbon capture and storage (CCS) technologies are often highlighted as a crucial component of future low carbon energy systems – in the UK and internationally. However, they are still being developed and demonstrated.

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However, they are still being developed and demonstrated. It is therefore unclear when these technologies will be technically proven at full scale, and whether their costs will be competitive with other low carbon options.

CCS technologies are conceptually straightforward: they are designed to remove up to 90% of the carbon dioxide (CO_2) from fossil fuel power plants or industrial facilities such as steel mills, and to store the CO_2 underground. Carbon dioxide is therefore prevented from entering the atmosphere and contributing to climate change. A carbon capture and storage system consists of three main components: 1) a capture plant to remove CO_2 from a power plant or industrial facility before or after fuel is burned; 2) infrastructure such as a pipeline to transport the captured CO_2 to a storage site; and 3) an underground storage site which will typically be a depleted hydrocarbon field or a saline aquifer.

For their supporters, CCS technologies offer a crucial way to square the continued use of fossil fuels with climate change mitigation. According to the International Energy Agency (IEA) World Energy Outlook in 2011, fossil fuels will continue to supply the majority of the world's energy to 2035, even if climate change mitigation is taken very seriously (IEA, 2011).

This report summarises the findings of the two-year UKERC research project: 'Carbon capture and storage: realising the potential?'. The aim of the project is to conduct an independent, inter-disciplinary assessment of the technical, economic, financial and social uncertainties facing CCS, and to analyse the potential role CCS could play in the UK power sector between now and 2030. The report summarises the main findings of the project, and complements other more detailed outputs[1] . It is designed to fulfil one of the main project rationales, which is to inform UK government policies for CCS as well as the strategies of investors and other stakeholders.

The report addresses four main questions which were agreed early on following discussion with the project's stakeholder steering group:

1. **What are the key uncertainties for CCS technologies?**
2. **How can these uncertainties be analysed effectively?**
3. **What can experience from history tell us?**
4. **Applying this knowledge, under what conditions are CCS technologies likely to be 'financeable' in the UK?**

The report is structured as follows. The remainder of section 1 sets out the global context for CCS technologies, and analyses the recent history of UK policies to support these technologies. Section 2 then explains how the main uncertainties for CCS were identified by the project team, their scope, and how they can be assessed. Section 3 draws on the nine case studies that were used to explore these uncertainties, each of which focuses on a technology that is partly analogous to CCS. The section reflects on the lessons these cases have for CCS policies and strategies, and identifies important interactions between the different uncertainties. Based on the insights from the case study analysis, section 4 develops a number of potential CCS pathways for the UK to 2030. It also suggests a number of important branching points, where decisions could make a significant difference to the contribution of CCS plants to the future UK electricity mix. Section 5 concludes by summarising the main insights from the project and by setting out some important implications for policy and for other decision makers.

[1] For these more detailed outputs, see the UKERC website **www.ukerc.ac.uk**

The promise of carbon capture and storage

For their supporters, CCS technologies offer a crucial way to square the continued use of fossil fuels with climate change mitigation. According to the International Energy Agency (IEA) World Energy Outlook in 2011, fossil fuels will continue to supply the majority of the world's energy to 2035, even if climate change mitigation is taken very seriously (IEA, 2011). The IEA '450 scenario' considers a global energy system trajectory that has a significant chance of limiting average temperature increases to 2°C. Under this scenario, CCS would be fitted to 32% of the world's coal fired power plant capacity (410GW out of 1270GW) by 2035, and 10% of global gas fired capacity (210GW out of 2110GW) by the same date. CCS technologies would therefore account for 22% of the reduction in CO_2 emissions by 2035 when compared to the IEA's alternative 'new policies scenario' in which global greenhouse gas emissions would continue to rise.

Whilst the IEA's scenarios only represent one view of the future, many other scenarios that limit global average temperature rises to 2°C include a prominent role for CCS technologies (German Advisory Council on Global Change, 2011). However, whilst many governments and companies are now funding and developing CCS technologies, there is a long way to go before we know whether such a role for CCS will be technically and economically feasible. Pilot scale capture plants are in operation in several countries, CO_2 is routinely transported across large distances in the United States, and CO_2 is being injected successfully at a number of storage sites. But full scale CCS plants are thin on the ground. A recent survey by the Global CCS Institute identified eight large scale integrated CCS projects that are already in operation around the world (Global CCS Institute, 2011). These focus on gas processing, synthetic fuels and fertiliser production – applications that are less technically demanding and more economically attractive than CCS in the power sector. According to the IEA, 'incorporating CCS into a power plant increases the levelised cost of the electricity produced by between 39% and 64%, depending on the technology and fuel source' (IEA, 2011: 378). This increase is expected for two main reasons. First, the incremental capital costs of adding CCS to a fossil fuel power plant are substantial. A recent Mott Macdonald study estimated that the direct costs of adding carbon capture to a coal-fired plant could be £335-£900/kW, depending on the capture technology used (Mott MacDonald, 2011). This would take total capital costs to £2500-£2800/kW. For a gas fired combined cycle plant (a CCGT), the direct cost increase would be around £480/kW (taking the total capital cost to £1000/kW). The gas CCS capital costs are lower than those of any other power plant technology assessed by Mott MacDonald, whilst the coal CCS costs are higher than the estimate for onshore wind, but lower than estimates for offshore wind and nuclear power. The second reason for an increase in the cost of electricity from fossil plants with CCS is that the energy penalty of including carbon capture in a power plant is significant. Mott MacDonald's report states that this is around 10 percentage points. For example, this would reduce a coal-fired plant efficiency of 42% to 32%.

Given these economically unattractive attributes, it is not surprising that there are currently no full scale CCS demonstrations in operation at coal- or gas-fired power plants. The first two are currently under construction in the United States and Canada, underpinned by substantial government financial support. Plans for a number of other CCS power plants have recently been cancelled, including the Longannet plant in Scotland and the Jänschwalde plant in Germany. Whilst economic and financial factors were significant in the decision to cancel the Longannet plant, the cancellation of Jänschwalde followed public protests against the planned use of onshore storage. As the Global CCS Institute emphasises economic and policy factors in its most recent report on large scale projects:

'The most frequently cited reason for a project being put on-hold or cancelled is that it was deemed uneconomic in its current form and policy environment. The lack of financial support to continue to the next stage of project development and uncertainty regarding carbon abatement policies were critical factors that led several project proponents to reprioritise their investments, either within their CCS portfolio or to alternative technologies'

(Global CCS Institute, 2011: 13).

The UK policy context

The important role that CCS technologies could play in achieving global carbon emissions reductions has also been recognised in recent UK policy debates. Successive governments have emphasised a potential role for CCS technologies since the early 2000s (eg DTI, 2003). The 2005 Carbon Abatement Technology Strategy (DTI, 2005) suggested a potentially substantial role for CCS in the UK if fossil fuels were retained in the energy mix. This was followed in November 2007 by the launch of a competition to build the UK's first full-scale demonstration plant, which would be operational by 2014. The aim was to 'make the UK a world leader in this globally important technology' (DECC, 2009; DTI, 2007:15). The competition was narrowly defined, and specified that it would only fund a demonstration of post-combustion capture on a coal-fired power station. Nevertheless, nine competing projects were proposed. At the pre-qualification stage, the number was reduced to four. By November 2009, just two bidders remained (NAO, 2012).

The 2010 Comprehensive Spending Review confirmed that the newly elected Coalition Government would provide up to £1bn for the successful demonstration project. But on the same day as this announcement was made, E.ON withdrew from the competition on the grounds that the economic conditions were not right. This left Scottish Power's Longannet project as the only remaining competitor. The Spending Review also confirmed that the government reaffirmed the commitment made by the previous Labour administration to expand the CCS demonstration programme to include up to four projects including the initial demonstration. However, it also cast doubt on the 'CCS levy' on consumer bills that Labour had introduced to pay for these further projects.

As part of the policy process of reviewing financing arrangements for the demonstration programme, the Department of Energy and Climate Change (DECC) completed a market sounding exercise. This was designed to 'help the Department to explore workable options for the CCS demonstration project selection and funding processes, and learn about projects being considered by industry' (DECC, 2010b). A key development was the decision to make gas-fired generation eligible for the competition, following recommendations by the Committee on Climate Change (CCC, 2011a). In addition, a decision was made to shelve the CCS levy on consumer bills. This meant that CCS funding would be bound up with the broader Electricity Market Reform (EMR) process that was being developed to improve the incentives for low carbon generation investment. In common with support for CCS itself, this broader process of market reform has had cross-party support, and was inherited by the current Government from its predecessor.

Support for CCS is also planned from the European Commission via the new entrant reserve within the EU emissions trading scheme (EU ETS). This funding is commonly referred to as the 'NER 300', and is planned to be made available from the EU-wide auctioning of 300 million EU ETS allowances. At the time of writing, decisions have not yet been made about which projects the Commission intends to support through this scheme, and the due diligence assessments of projects that have applied for funding are not public.

At the time, DECC's aspiration was that the demonstration projects would facilitate CCS technologies being ready for commercial deployment by 2020, and in particular, that the further three projects would assist in the 'transition to commercial viability' after the 'initial demonstration at commercial scale' provided by the first project (DECC, 2010c:17). This position reflected the UK Government's view that CCS had the potential to make a major contribution to meeting the UK's CO_2 reduction targets:

'By 2020 well over half of the UK's electricity generation will still be fuelled by coal and gas. That is why CCS is such a crucial element of this Government's energy and climate change agenda. It is the only technology that can significantly reduce CO_2 emissions from fossil fuel power stations - by as much as 90%. IEA analysis has shown that without CCS, halving global emissions by 2050 will be 70 per cent more expensive. And it will play an important role in balancing the electricity system - underpinning intermittent and less flexible contributors like wind and nuclear.'
(DECC, 2011c)

However, in October 2011, Scottish Power confirmed that it had decided to withdraw the Longannet project from the first demonstration plant competition. DECC cited increased costs and the inability to reach a commercial agreement as the reasons. In a critical report on lessons for the government from the competition, the National Audit Office cited a number of contributory factors to the collapse of the project (NAO, 2012). These included poor commercial awareness within government, a lack of capacity to procure such large, complex projects, a lack of flexibility with respect to project specifications and the lack of a business case for the competition.

[2] Updates on the NER 300 process are available on the website of the European Commission Directorate General for Climate Action: http://ec.europa.eu/clima/funding/ner300/index_en.htm.

The Energy Minister Charles Hendry MP confirmed this longer term perspective in a recent speech. He emphasised 'the UK Government's firm commitment to Carbon Capture and Storage (CCS) and our determination to see the technology ready to be commercially deployed in the 2020s' (Hendry, 2012).

DECC moved quickly to confirm that the £1bn set aside for the first demonstration would be 'available for a new process' (DECC, 2011b). In the 2011 Carbon Plan, the government stated that it foresees up to 10GW of CCS plants in the UK by 2030 (DECC, 2011d). This is significantly lower than the 20-30GW called for by the CCS industry by 2030 (CCSA, 2011). The government's view is perhaps more dependent on what happens to other low carbon options. The Carbon Plan states that the overall objective is to 'run a low carbon technology race between CCS, renewables and nuclear power' (DECC, 2011d: 72). The Energy Minister Charles Hendry MP confirmed this longer term perspective in a recent speech. He emphasised 'the UK Government's firm commitment to Carbon Capture and Storage (CCS) and our determination to see the technology ready to be commercially deployed in the 2020s' (Hendry, 2012). This was reinforced in April 2012, with the re-launch of the demonstration programme – which has now been renamed 'CCS Commercialisation Programme' – and the publication of a CCS roadmap (DECC, 2012b).

As the CCS roadmap has confirmed, current financial support available for CCS projects is a combination of the £1billion available in capital funding, incentives from the package of policies under EMR, and additional funds from the NER300 process. According to DECC's roadmap, eligible projects for this financial support do not necessarily need to include all components of a full CCS system. They can be 'full-chain or part-chain that can demonstrate the prospect of being part of a full-chain project in the future' (DECC 2012b: 28).

At the heart of the EMR package are long-term contracts for low-carbon electricity. These contracts are designed to stabilise and top up the revenues of low-carbon generators such as CCS, transferring electricity price risk from generators to consumers, through a Contract for Difference (CfD). It is intended that the precise design of the CfD will evolve as CCS matures, moving from demonstration to commercial baseload deployment, and then potentially to flexible operation (DECC, 2011a). In addition to these contracts, a carbon price floor is proposed. This is a fiscal instrument that aims to reduce uncertainty for investors and incentivise low-carbon generation by topping up the EU ETS carbon price. However, it should not have a direct impact on total revenues received by CCS and other plants through the contracts for difference. Enacted through reform of the Climate Change Levy, the floor will begin at £15.70/tCO_2 in 2013. It is envisaged that it will rise gradually to £30/tCO_2 in 2020, and then to £70/tCO_2 in 2030 (real 2009 prices). CO_2 that is captured and stored via CCS will be exempt from the tax (HMT, 2011).

Two further mechanisms are proposed as part of the EMR package. The first of these is an Emissions Performance Standard (EPS), intended to be a regulatory backstop which puts an annual limit on the amount of CO_2 that a plant can emit, equivalent to 450gCO_2/kWh for plant operating at baseload. In this way, the EPS reinforces the current government's policy that no new coal plant can be built without demonstrating CCS, but does not prevent the construction of new unabated gas fired CCGT plants. Existing plants are fully grandfathered, meaning that they are not subject to the 450gCO_2/kWh level. Plants consented after the EPS comes into force will be subject to the 450gCO_2/kWh level, but will receive protection from future changes to the EPS for a specified time period. The government has recently confirmed that gas plants built once the EPS is in force will be grandfathered until 2045 (DECC, 2012). This leads to significant questions about the compatibility of this policy with the UK's climate change targets. Applying this rule to a large number of gas fired plants could take up a significant proportion of the UK's carbon budgets.

The 2010 Comprehensive Spending Review confirmed that the newly elected Coalition Government would provide up to £1bn for the successful demonstration project.

DECC has signalled that the EPS might be lowered in the future, as a means to requiring full CCS on new fossil fuel plant. Finally, DECC has indicated that a capacity mechanism will be introduced to target the problem of resource adequacy, ie how to secure sufficient reliable capacity to cover peak demand. However, a firm decision has not been made on its design; instead, the White Paper launched a further consultation on this instrument (DECC, 2011a).

In addition to challenges associated with the current financial climate, there are a number of factors which potentially limit the 'financeability' of CCS in the UK (and in other countries with liberalised market structures). These factors are summarised below. The project team assessed them through a combination of an analysis of stakeholder responses to consultations and inquiries (DECC, 2010a; DECC, 2010b; ECCC, 2010; ECCC, 2011; HMT, 2011) and stakeholder interviews carried out during Summer 2011 (Jones, 2011).

1. Technology and construction risk:

Stakeholder interviews revealed technology and construction risk to be a particularly important factor deterring investment at present. The multiplicity of CCS technologies, each of which has differing technological characteristics, makes this factor especially difficult to tackle. Stakeholders expressed concerns that delays to the Demonstration Programme and the EMR's emphasis on performance-related support are exacerbating this risk.

2. High capital cost:

As noted earlier, CCS has high up-front capital costs. These estimates are also associated with significant uncertainty due to CCS's status as a new technology. A recent review of cost estimates for CCS technologies over the last ten years shows that there are large differences between studies (see Figure 1.1). Whilst recent design studies funded by the UK government for the proposed demonstration projects at Longannet and Kingsnorth argued that they had reduced uncertainty about costs, more generic cost estimates do not show such convergence. The importance of this factor to stakeholders is reflected in their concerns about the level of additional revenue they will receive through a future contract for difference, and their emphasis on securing NER 300 co-funding for demonstration projects.

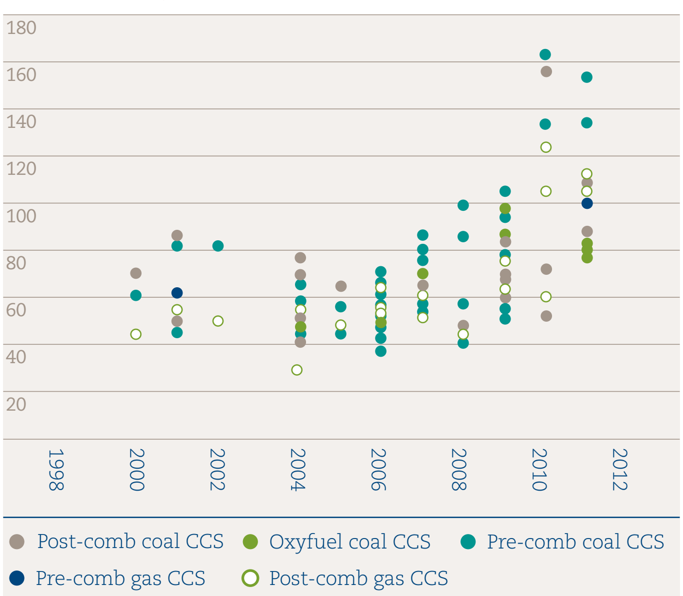
3. Infrastructure constraints:

Stakeholders discussed a number of infrastructural barriers to CCS investment. These include widespread first-of-a-kind costs associated with developing a CO_2 transportation network, and the lack of a systematic approach to optimising the network through a co-ordinated approach and pipeline oversizing. There are also more general uncertainties about storage infrastructure, the capacity of storage sites and the associated legal liabilities for CO_2 storage.

4. Fuel price risk:

CCS has significant and variable fuel-related operating costs which are exacerbated by the high 'energy penalty' that means a significant reduction in power plant efficiency. Fossil fuel plants are typically 'price makers', with the ability to pass fuel price increases on to consumers. This is because fuel prices and electricity prices tend to rise at the same time. However, there are clear stakeholder concerns that the contracts for difference support mechanism that is planned under EMR may remove this natural hedge for CCS plants to rising fuel prices, for example by placing an upper limit on the income they can receive for each kWh of power they produce.

1.1 CCS costs



Source: Jones (2012)

5. Load factor risk:

CCS has relatively high operating and fuel costs, which may mean that load factor risk could become important in the 2020s. In particular, CCS plant might be required to operate flexibly when there is increased deployment of very low marginal cost nuclear and wind power plants. This has the potential to increase the unit costs of CCS generation, thus undermining the attractiveness of CCS investments. This risk is potentially greater for coal CCS than gas CCS, due to the higher capital intensity of coal.

6. Storage risk:

CCS requires the storage of CO_2. A pilot project or a full-scale commercial project will not proceed without guaranteed storage for the entire project lifetime output. There have been several compilations of potential storage capacity in the UK. All these have assessed this capacity at a preliminary level, and are optimistic about the size of UK storage resources. As of 2012, there are few proven or validated storage reservoirs for CO_2 storage in the UK. Stakeholders with expertise in the subsurface development of hydrocarbon resources point out that there are unsolved issues of reservoir connectivity.

Where projects are partly dependent on borrowing to finance them, they must also compete with a broader range of potential investments – including investments outside the UK and in other sectors of the economy.

For utility companies considering very large investments in very long-lived assets, many of these characteristics are unattractive. CCS projects must compete internally within these companies for capital, and must therefore be competitive with alternative investments in electricity generation in the UK and abroad. Where projects are partly dependent on borrowing to finance them, they must also compete with a broader range of potential investments – including investments outside the UK and in other sectors of the economy. Taken together, these factors may constrain the investment available to CCS projects. Over the long-term, investors will require that fuel price risk and load factor risk are addressed. Yet the crucial factors limiting CCS 'financeability' at present relate to the early-stage nature of CCS; in particular, technology and construction risk, capital cost, infrastructural constraints, and uncertainties about the extent and sharing of legal liabilities are the key barriers to investment. Thus, the most important conditions in the near-term are (1) that CCS is successfully demonstrated at commercial scale, and (2) that '2nd tranche' projects receive support in the transition to commercial readiness.

On paper, it would seem that these two most significant conditions are being addressed. The CCS Commercialisation Programme should help to reduce technology risks, to provide greater certainty over capital costs, and develop infrastructure, via commercial-scale projects. Following this, the EMR package of policies could continue to offer support for '2nd tranche' projects, assuming that the CfD strike price is high enough. The basic framework for widespread CCS deployment by 2030 is thus in place. Yet the CCS investment climate remains fragile. Investors are dependent on government support to co-fund CCS demonstration, and have been concerned that in the current challenging financial environment, funding might be constrained or postponed. These concerns were particularly high following the shelving of the CCS levy, the delays in the demonstration programme, and the precedent set by postponed projects abroad.

The key omission at present, then, is perhaps not so much an adequate policy framework, especially now that the CCS roadmap has finally been published. It is rather the confidence that this framework will be implemented with mechanisms that recognise the unique characteristics of CCS and within the timescales required. As one industry stakeholder explained, there has been a lack of 'a sense of urgency'3. Given that the extent of CCS deployment in the 2020s depends on the pace of demonstration in the 2010s, these concerns could have significant implications for future decarbonisation. It remains to be seen whether the measures within the CCS roadmap, and the generous package of financial support that is now available, will be sufficient to significantly boost the confidence of investors.

[3] This resonates with a much earlier observation which, although not specifically aimed at investment in CCS, seems particularly apt: 'If governments wish to stimulate investment, perhaps the worst thing they can do is to spend a long time discussing the right way to do so' (Dixit & Pindyck, 1994).

Analysing the key uncertainties for CCS technologies



The identification of key uncertainties for CCS technologies was an iterative process. The aim was to identify which aspects of CCS are perceived as most uncertain, and which uncertainties were thought to be important for the future development of the technology.

The identification of key uncertainties for CCS technologies was an iterative process.

The aim was to identify which aspects of CCS are perceived as most uncertain, and which uncertainties were thought to be important for the future development of the technology. The research aimed to address a practical problem for policy makers and other decision makers: how to deal with uncertainties for CCS innovation. With this in mind, an initial list of uncertainties across a range of technical, political, financial, legal and social aspects was drafted by the project team. For this, and throughout the research process, the work drew on the inter-disciplinary expertise on CCS and innovation within the research team, which includes geology, engineering, legal and financial and innovation studies.

The draft list of uncertainties was further refined and tested in an iterative process with several steps. In line with contemporary technology assessment practice emphasising engagement with practitioners (Schot and Rip, 1997; Guston and Sarewitz, 2002; Genus, 2006), the list was revised after consultation with the project's steering group, which included a range of experts from industry, policy and academia[4]. The preliminary list was also presented at the largest international CCS conference, Greenhouse Gas Control Technologies (Markusson, Kern et al., 2011). The list of uncertainties was also revised reflecting the insights from a literature review and an investigation of technology assessment practice as described below.

> The research aimed to address a practical problem for policy makers and other decision makers: how to deal with uncertainties for CCS innovation.

A social science literature review (including literature on CCS economics) was undertaken in June 2010 to establish what is known about CCS uncertainties, as well as more fundamental insights about how to conceptualise and understand them (Markusson, Kern et al., 2012). Exclusion of papers that are not relevant (eg because they were purely technical or only mentioned CCS in passing) yielded a set of 74 social science papers. This enabled the review of some of the CCS uncertainties, for example public understanding, as they have been more extensively studied by social scientists. Where there was little social science research, for example on system integration, general innovation studies and policy literature were used. This literature has codified the experience from other technologies, which is of potential use for the analysis of CCS. It also offers a way of relating the results of this work to wider research on technological innovation.

To further focus and ground the framework in an understanding of how actors assess new technologies in practice, 14 interviews with technology stakeholder representatives were conducted. These were individuals from different relevant industries and organisations including utilities, engineering consultancies, finance, insurance, legal professionals, regulators and policy makers that are knowledgeable about how new technologies are assessed in their organisations and sectors. A list of the organisations that were interviewed is provided in an appendix to this report. The interviews were further complemented with a review of technology assessment documents. This included general assessment methods, including procedures for determining Best Available Technology and Technology Readiness Assessments, as well as CCS specific assessments and roadmaps.

During the process of refining the list of uncertainties, a large number of uncertainty candidates were identified and discussed. The most important uncertainties were selected by the research team – and the precise definitions and delimitations of the uncertainties were revised – again in consultation with the project's stakeholder steering group. The resulting robust list of seven key uncertainties for CCS innovation is as follows:

1. Variety of pathways

2. Safe storage

3. Scaling up and speed of development and deployment

4. Integration of CCS systems

5. Economic and financial viability

6. Policy, politics and regulation

7. Public acceptance.

Each of these uncertainties will be described very briefly below. For a more elaborate analysis of the different uncertainties, see Markusson, Kern et al. (2012).

Uncertainty 1: Variety of CCS pathways

There is technological diversity for each of the components of the CCS chain – for example in types of capture, in modes of CO_2 transport, and in types of storage facility. Competition among technologies is normal and good for learning, but will most likely be reduced as widespread deployment approaches. There is uncertainty as to what technologies will win out, and when that will happen. This raises dilemmas for the relevant actors (eg investors and government) in terms of what technologies to invest in at different points in this development. Early selection may get outdated quickly, stranding actors with uncompetitive assets, and/or locking CCS into inferior technologies. Governments need to balance the need for experimentation with the need for fast development and deployment and perhaps premature closure of technological choices.

[4] See the Acknowledgements section of this report for a full list of steering group members

Uncertainty 2: Safe storage

One of the key uncertainties with CCS is whether storage will prove to be secure over long periods of time. While some of the components of CCS have been applied in industrial settings, geological carbon storage represents new challenges. Storage risk has two dimensions: local environmental, health and safety risks and the global risk of carbon dioxide re-entering the atmosphere undermining climate change goals (Pollak and Wilson, 2009). There is uncertainty about probabilities and risks and a lack of experience with geological storage by developers, regulators and researchers. These risks vary across storage options and settings. Developing appropriate, credible and long term mechanisms to deal with risks and their associated liabilities is therefore essential for the deployment of CCS to be successful.

Uncertainty 3: Scaling up and speed of development and deployment

CCS should ideally be ready for implementation within the next decade. This includes having the required knowledge, but also the skills, industries, institutions, etc. Key technologies also need to be scaled up. The complexities involved include if and when we will see dominant designs emerge; how much competition there will be among competing technologies (eg capture variants and storage options), and if components can be developed and scaled in parallel with each other. There is a need to know how we can assess whether development and scaling up will be possible and if it can happen fast enough. It is also important to assess whether top-down, government steering could speed this up.

Uncertainty 4: Integration of CCS systems

CCS exists today as sets of components, types of expertise, etc. Integrating these into working CCS systems raises technical issues, for example limiting the impurity concentrations allowable for transportation. It also brings social challenges in terms of coordinating the actors that are developing and operating CCS systems. These technical and social aspects are likely to be related (Hughes, 1983). System coordination is also complex in that the different activities involved are likely to require different modes of coordination and organisation. Examples include the operation of CCS systems, supporting R&D, and verification of storage for CO_2 trading. Also, coordination may differ at the component versus system levels. Possible models of coordination of CCS development and operation vary with regard to the degree of market orientation, centralisation, fragmentation, participation, etc.

Uncertainty 5: Economic and financial viability

One of the key uncertainties of CCS is its future economic and financial viability for investors. A technology is economically viable if it has a positive cost-benefit ratio. Even if a technology is economically viable, that does not necessarily mean that it is financially viable because the expected pattern of cash-flows is not easily defined, thereby increasing the cost of capital. The technology may have associated risks which make it less attractive than investing in alternative low carbon forms of energy (Gross, Blyth et al, 2007). Economic and financial viability is therefore a key uncertainty for businesses as well as policy makers, and will determine their willingness to invest in CCS. Improving economic and financial viability is an important rationale for policy support.

Uncertainty 6: Policy, politics and regulation

Uncertainty about CCS development is not only due to economic or technical factors, but is also due to political factors. In this context, specific policy instruments which could help CCS to develop, and the political processes of getting acceptance, legitimacy and continued support for CCS are all important. There are also related questions about regulatory frameworks that are required to deal with liabilities, safety rules and so on. These factors are important because in part the future development of CCS will depend on explicit political and policy choices. As James Meadowcroft and Oluf Langhelle argue, 'a strong regulatory push and/or a significant price for carbon emissions will be required to develop commercial applications' (Meadowcroft and Langhelle, 2009: 9).

Uncertainty 7: Public acceptance

Another key uncertainty around the development of CCS is whether CCS will be seen as a legitimate technology for climate change mitigation. The existing literature stresses that societal acceptance is widely recognized as an important factor influencing the successful development and diffusion of new technologies (Huijts, Midden et al., 2007; van Alphen, Voorst et al., 2007; Shackley, Reiner et al., 2009). It also highlights that such acceptance partly depends on the 'fairness of processes governing decisions' (McLaren, 2011: 2) about new technologies, which can help to take divergent views into account. There are examples, such as genetically modified organisms in the United States, where a technology has been deployed in spite of some public resistance – and fair processes do not necessarily resolve such controversies. Public acceptance is not just a matter of individual preferences, but is also the result of social interactions.

Existing social science CCS publications tend to focus on a particular uncertainty such as public acceptance (eg Shackley, McLachlan et al., 2005) or costs (eg Rubin, Chen et al., 2007). They do not tend to analyse CCS uncertainties across the board and their interactions over time. However, the uncertainty dimensions studied are clearly not independent of each other, and the broader framework developed here allows interactions between them to be identified.

Finally, to guide the assessment of CCS uncertainties with more precision, qualitative and quantitative indicators were identified (see Table 2.1). The identification and selection of assessment indicators drew heavily on the interviews with technology stakeholder representatives with practical experience of assessing technologies and the document and literature review.

The indicators are not designed to be comprehensive, but were chosen to aid the analysis of the project's historical case studies in a systematic and comparable way (see Section 3 of this report). Since the uncertainties are related to each other, some indicators are used for multiple uncertainties.

Table 2.1: List of uncertainties and indicators

Key uncertainties	Indicators
1. Variety of pathways The diversity of technological options represents an uncertainty for investors and policy makers. Early selection might accelerate development, but risks locking in weak technologies.	- Number of technology variants - Relative importance of variants for technology developers - Market share of technology variants - Extent of lock-in / dominance of particular technology variant
2. Safe storage There is uncertainty as to whether geological storage of CO_2 will be secure over long time periods, as well as if and how the associated risks can be reliably assessed and managed.	- Availability of storage site data, including agreed robust estimates of their capacity - Nature of legal / regulatory framework to share risks / liabilities - Levels of public awareness / acceptance of risks
3. **Scaling up and speed of development and deployment** There is uncertainty about whether and how fast CCS technologies can be scaled up and developed to maturity.	- Unit size, capacity and efficiency - Speed of unit scaling - Cumulative investment / installed capacity - Relative importance of market niches
4. Integration of CCS systems It is unclear how CCS systems will be integrated. Integration is a technical challenge, as well as an issue of organisation and governance.	- Whether full chain integration has been achieved? - The allocation of responsibility for integration - Presence, role and importance of 'system integrator' firms/ actors - Nature of development, including roles of key actors and the relative importance of 'bottom up' / emergent and 'top down' / directed development
5. Economic and financial viability The future cost and financial risk of implementing CCS are very uncertain. The economic and financial uncertainty is heavily dependent on policy.	- Costs, including assessment of quality of cost data - Key financial risks and 'financeability' - Role of subsidies, other forms of economic / financial support, and other sources of finance (shared with uncertainty 6)
6. Policy, politics and regulation CCS development is strongly influenced by uncertainties about extent of political support, as well as the choice and design of policies and regulations.	- Nature of legal / regulatory framework to share risks / liabilities - Role of subsidies, other forms of economic / financial support, and other sources of finance (shared with uncertainty 5) - Role of other forms of policy support - Extent of political commitment / legitimacy
7. Public acceptance Public acceptance may be crucial to CCS development, but is uncertain. Attitudes to CCS are shaped in social interaction.	- Levels of public awareness / acceptance of risks - Specific manifestation of public opposition (or support) - Quality of public engagement

Historical analogues for CCS

3

Faced with the inherent uncertainties about the future of a new technology, it is common to draw on our experience of previous technologies that are analogous in some way. This happens both informally in discussions as well as through formalised, explicit comparisons in the development of designs, policies and strategies.

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This happens both informally in discussions as well as through formalised, explicit comparisons in the development of designs, policies and strategies. For example Reiner and Herzog (2004) have explored regulatory analogues for CO_2 storage.

A few previous studies have sought to use historical analogues to assess the potential future development of CCS technologies. Studies of CCS learning rates have tried to quantify the rate of learning experienced by mature technologies such as flue gas desulphurisation (FGD). They use this evidence to argue that CCS might develop similarly, with costs falling as CCS technologies are progressively deployed (Rubin et al., 2004, Rubin et al., 2007). There is also some qualitative research that compares CCS with other technologies, which is useful for exploring a wider range of innovation processes than can be compressed into a learning rate. This report adds to this second tradition of qualitative research. In comparison with previous studies (e.g. Chalmers et al, 2009; Rai et al, 2009), the report includes a more in-depth analysis of a wider range of analogue case studies.

The historical analogues included in this study were chosen to be similar to CCS with respect to one of the seven uncertainties outlined in Section 2 of this report. It is important to note that any analogue is necessarily different in some ways and can only ever be a partial analogue. In fact, Giacomini (2005) stresses that the quality of an analogue lies not in being similar in as many ways as possible, but in being very similar in one aspect that is of interest. This means that learning from analogues is never perfect because the 'fit' is never perfect. Not only will there be technical differences, but important contextual factors may also differ significantly between the analogue and the policy, market and institutional environment for CCS in the UK. In this section of the paper, we explicitly draw attention to some of the limitations of the analogue case studies, particularly where they relate to a lesson that is being drawn for CCS.

The analogues were chosen to explore all the seven project uncertainties for CCS. To make sure that the analogues were well chosen, a long list was first drafted, drawing on existing literature, stakeholder interviews and the inter-disciplinary research team. The draft list was further developed through a stakeholder workshop which had attendees from industry, government and academia. The workshop also included a prioritisation process to help the team identify the most promising analogue cases, taking into account factors such as their relevance, coverage of the project uncertainties and research team resources. The analogues were also selected to cover the whole CCS chain from capture to transport and storage

In this section of the paper, we explicitly draw attention to some of the limitations of the analogue case studies, particularly where they relate to a lesson that is being drawn for CCS.

The project team subsequently used the workshop outcomes to agree a final shortlist of nine analogue case studies, each of which covers a defined time period. The shortlist is shown in Table 3.1 alongside the uncertainties they relate to. The research for each case study was carried out using a combination of literature reviews and, in some cases, a few expert interviews to fill gaps in the published data and analysis. The case studies were written up using a standard template which includes sections on the context for the case, the case analysis with respect to the uncertainty concerned, interactions with other project uncertainties, and lessons from the case – both in general, and with respect to CCS.

Table 3.1: Analogue case studies

Uncertainty	Historical analogue case studies
1. Variety of pathways	The French Nuclear Programme, 1950s-1980s
2. Safe storage	The management of radioactive waste in the UK, 1956-2011
3. Scaling up and speed of development and deployment	The UK 'Dash for Gas', 1987-2000 Flue Gas Desulphurisation in the USA, 1960s-2009
4. Integration of CCS systems	Natural Gas Network in the UK, 1960-2010
5. Economic and financial viability	Flue Gas Desulphurisation in the USA, 1960s-1970s Investments in landfill in the UK, 2001-2011
6. Policy, politics and regulation	Flue Gas Desulphurisation in the UK, 1980s to 2009
7. Public acceptance	Natural gas infrastructure development in the UK, 2000-11

This section of the report presents brief results of each of the nine cases. For each uncertainty, the section summarises the case(s)[5] that were carried out and their key features. It also sets out the lessons for CCS policies and strategies, together with any limitations of these lessons.

Variety of pathways

This uncertainty has been analysed with the help of a case study on the *Development and deployment of nuclear power in France from the 1950s-1980s* (Kern, 2011b). The French nuclear programme is widely seen as a successful example of a large scale, rapid roll-out of a standardised design (Grubler, 2010). In the 1950s, a variety of different reactor designs were available internationally (Cowan, 1990). The case analysed the process by which this initial variety was reduced to one dominant design in France by the 1980s.

This case is a partial analogue for the possible development of CCS as there is currently technological diversity for each of the components of the CCS chain. According to insights from the innovation studies literature, competition among technology variants is normal and beneficial for learning, but will most likely be reduced as technologies get nearer wide deployment. There is uncertainty as to what technologies will win out and when that will happen. For policy makers and other stakeholders, this uncertainty raises questions about when to support a diversity of designs and when to prioritise specific variants.

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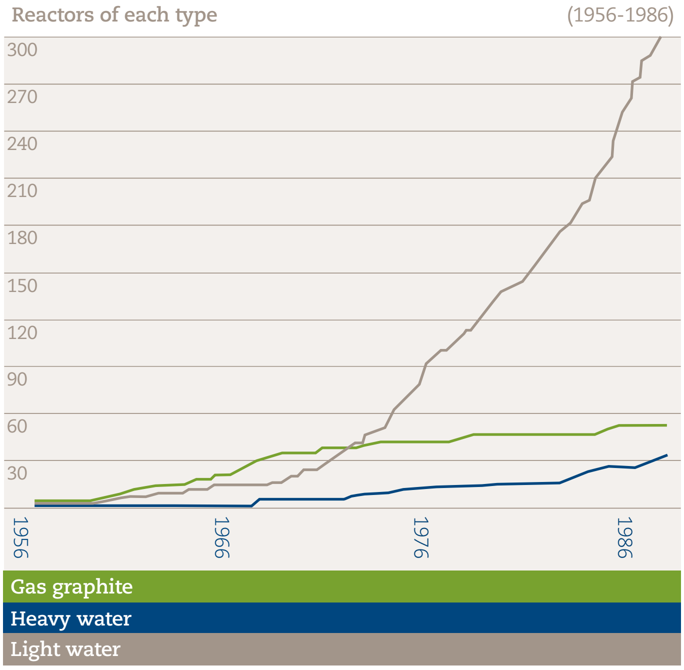
Initially, in France, a domestic design of gas-cooled graphite reactors (GCR) was developed, but subsequently the French opted for an American pressurised water reactor (PWR) design, which also became dominant globally (see Figure 3.1). Later, France also invested significant resources into the development of a fast breeder reactor (FBR), which was never commercialised. The history of the French nuclear programme illustrates that technological variety can be reduced by policy, albeit with significant risks if it is not possible to identify which variant is the 'best'. A number of technical and political rather than economic factors played a key role in the process of choosing the 'best' design for the French nuclear roll-out. Thereafter, standardisation contributed to lower costs and shorter construction times compared to other countries.

[5] Full case study reports are available on the UKERC website – www.ukerc.ac.uk

3.1 Global number of nuclear reactors by type



Source: Cowan (1990: 549

Lessons for CCS policies and strategies

The French nuclear programme illustrates both the advantages and drawbacks of selecting a specific design early on. The decision to pursue the gas-cooled design at the start of the programme and the subsequent support for the fast breeder reactor were not successful. Deployment was very limited, and the costs were substantial. By contrast, decisive government support for the roll-out of the Westinghouse PWR design in the 1960s led to standardisation, learning effects and cost advantages. Its subsequent 'frenchifying' led to the development of an independent nuclear industrial capability in France.

The history of nuclear power illustrates the risks involved in choosing a technology design in the absence of sufficient information about its costs and performance. Whilst the decision to choose the PWR paid off due to France's substantial investment programme in the 1970s and 1980s, it is important to remember that light water reactors such as the PWR were considered at the time to be interim technologies. The expectation was that it would be succeeded by more advanced and cheaper technologies such as the fast breeder reactor – a technology that has since failed progress (Cowan, 1990).

The reason for the UK's initial focus on post-combustion CCS on coal-fired power plants was partly due to industrial lobbying, and the possibility that it could be sold as a retrofit technology in international markets – especially China and India. It was also due to environmental NGO campaigns against unabated coal plants (Watson and Scrase, 2009). Many analysts think that pre-combustion technology is potentially more efficient, elegant and cheaper. But as with nuclear at the time of the French decision to adopt the PWR, there is a lack of empirical evidence on whether post- or pre-combustion CCS will be more economically attractive (see Figure 1.1 in the introduction to this report for an illustration of this). It is therefore important that public policies recognise this uncertainty. Supporting just one variant of CCS, as the original UK CCS demonstration plant competition aimed to do, has high risks.

In contrast to what might be expected with regard to CCS, nuclear power decision-making processes about which reactor design to pursue were not based on economic considerations. Rather these processes had strong political components due to the strategic status of nuclear power and close relations to the military use of nuclear technology, the wish to provide orders to French equipment firms, long lead times and fears of technological exposure (Thomas, 1988). CCS development and deployment is also being shaped by government policy in a major way because of its climate policy rationale and there would be limited commercial interest in CCS technologies in the absence of strong policy drivers (apart from enhanced oil recovery). At the same time, economic considerations remain important. There are clear limits on the amount of public funding available for CCS, and competition is favoured as a mechanism to identify the 'best' projects to support.

It is clear that the UK government's commitment to CCS has its limits. In the Carbon Plan 2011, the government states that its overall aim in the power sector is to 'run a low carbon technology race between CCS, renewables and nuclear power.

The unique institutional set-up allowing centralised decision-making which enabled the roll-out of the French nuclear programme is considered to be one of its key success factors (Hadjilambrinos, 2000; Grubler, 2010). A repeat of this kind of governance arrangement, with a central role for a monopoly state-owned utility, is unlikely for CCS in the UK. The Electricity Market Reform (EMR) process is likely to mean a more co-ordinated approach to investment choices in the UK than has been the case since liberalisation started over 20 years ago. But it is clear that the UK government's commitment to CCS has its limits. In the Carbon Plan 2011, the government states that its overall aim in the power sector is to 'run a low carbon technology race between CCS, renewables and nuclear power' (DECC, 2011d: 72). Therefore, whilst the EMR process will mean significant change, the UK's electricity market context remains fundamentally different to the context for the French nuclear programme.

The history of nuclear power illustrates the risks involved in choosing a technology design in the absence of sufficient information about its costs and performance.

Safe storage

This uncertainty has been analysed with the help of one case study: *The management of radioactive waste in the UK from 1956 to 2011* (Gross, 2011). Radioactive waste (RW) management is used as an analogue for the secure storage of carbon. In both cases, the indefinite management or disposal of waste poses long-term environmental risks.

The case study focused on four aspects of RW management: site selection, operational and accident liability and public acceptance. The study found that two previous attempts at selecting sites for the geological disposal of RW foundered, while a third attempt is ongoing. The initial approaches were almost exclusively based on expert judgement of the technical feasibility with little public input and transparency and they faced substantial public opposition. The ongoing third attempt uses an approach suggested by the Committee on Radioactive Waste Management where local communities volunteer to host the repository, and continued public engagement is seen as key in building trust in the selection process. Operational liability refers to the financial costs of RW management and decommissioning of nuclear facilities. Liability arrangements changed over time as the nuclear industry changed from public to mainly private ownership. Whereas under public ownership no particular arrangements were made, segregated, external funds have been established under private ownership to cover the long-term liabilities (MacKerron, 2012). Arrangements for liabilities for nuclear accidents in the UK differ from those of traditional 'tort liability'. Tort liability is based on fault, is unlimited and insurance is voluntary. Nuclear liability, in contrast, is strict and channelled to the operator. Liability insurance or financial security is mandatory and the overall liability of operators is capped (ie it is underwritten by government). Safety perceptions have a major impact on acceptance of nuclear energy. Many people feel poorly informed about RW and have little trust in government and the nuclear industry (Eurobarometer, 2008).

Lessons for CCS policies and strategies

A number of implications for CCS can be identified from the historical experience with radioactive waste management. First, site selection methodologies should be carefully structured to ensure that financial concerns cannot compromise site safety. Any additional expense associated with exploiting safer sites must be balanced against the potentially greater costs of subsequent leaks and the loss of a licence to operate the site, as well as the damage to public confidence in CCS such leaks might cause. Site selection needs to be a transparent and open process with stakeholder input in order to boost public trust. Second, the case suggests that engaging the public in a dialogue over carbon storage through an organisation which is independent of the CCS industry and government could reap benefits in terms of increasing public acceptance of CCS and confidence in safe carbon storage. This may also help to ensure that 'procedural justice' is followed – ie that there is confidence in decision making processes about carbon storage in general, as well as particular storage sites (McLaren, 2011). The experience of the Committee on Radioactive Waste Management suggests that location specific engagement processes may also be required (CoRWM, 2006).

Third, the nuclear experience suggests that strict, capped and channelled liability for carbon storage operators will afford advantages over tort liability. It can facilitate swifter resolution of compensation claims. However, it is important to bear in mind that restrictions on nuclear liabilities faced by electric utilities are underwritten by governments. By contrast, an unlimited, open-ended liability is likely to deter private investment in CCS plants. However, implementing a cap on liabilities that is too low could expose taxpayers to too much risk – and site operators to too little risk. Not channelling liability to the storage operator could also lead to 'double-insurance' by suppliers and therefore increase overall costs.

An important limitation of this case is that most studies of the potential for carbon storage in the UK point to the exploitation of offshore sites (DEFRA, 2008; Gough & Shackley, 2005). This contrasts with the disposal of RW, where - since the London Dumping Convention permanently outlawed RW dumping at sea in 1994 - the principal focus for a repository has been onshore. Therefore, the current process for siting a deep underground repository, in which local communities volunteer to host the facility, presents no direct lessons for carbon storage projects. However, it can still be argued that when specific CCS projects are at the planning stage, a broad public dialogue about the storage options (eg saline aquifers; oil and gas fields) and possible locations should take place in order to gain public confidence.

The nature of the waste product itself is different in the case of carbon storage. In one respect, CO_2 is less immediately dangerous than nuclear waste which might help public acceptance of safe storage. CO_2 is directly toxic only at concentrations of 100,000 parts per million (ie 10%). However, the long-term storage of CO_2 is undertaken specifically to reduce concentrations of atmospheric greenhouse gases. Thus, while the storage of carbon and the disposal of RW both involve financial risks, the leakage of carbon will pose an additional climate risk. Therefore the considerations applicable to RW management and CO_2 storage are different. Liability provisions for CCS plants will need to take site specific issues into account such as potential leakage and injection rates, and the range of possible carbon prices that could be used to value the impact of any CO_2 that is emitted.

Scaling up and speed of development and deployment

This uncertainty was explored with the help of two case studies: *The development and rapid deployment of combined cycle gas turbine (CCGT) power plants in the UK from 1987 to 2000 (Kern, 2011a); and the development and deployment of flue gas desulphurisation technology (FGD) in power plants in the US between the 1960s and 2009* (Markusson, 2011a). Both technologies have been substantially scaled up in terms of the size of individual units and they have also been rolled out at a substantial magnitude.

The analysis of the *combined cycle gas turbine* case showed the long time frame involved in scaling up the technology to a size of relevance for the power sector. The development from the first industrial CCGT plants to a competitive power sector technology in the 1990s took about 30 years. It required long-term, sustained R&D investment by the heavy equipment manufacturers (General Electric, Westinghouse, Siemens and ABB). Sales

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in niche markets enabled re-investment of revenues in R&D. The technological development also profited from substantial and prolonged public R&D investment in the development of jet engines. The analysis showed how a variety of factors contributed to the surge of deployment of the technology in the 1990s which was previously not expected to play a large role in the electricity sector in the UK. The rapid roll-out is explained by changes in economic conditions (eg the availability of cheap gas), policy and regulatory factors (eg lifting of the ban on using natural gas for power generation; stronger environmental regulations; introduction of competition in the electricity sector) and technological developments (efficiency improvements and scaling up). Competition between the manufacturers led to downward pressure on costs which also helped drive the 'dash for gas'.

The analysis of *FGD in the US* showed that the technology went through a period of relatively rapid scaling up and development in the 1970s, and has later exhibited bursts of rapid investment activity and wide roll-out. FGD systems went through a fivefold scale up over a period of 30 years. A modular approach facilitated the relatively rapid early scaling of the overall FGD plants of 2.5 times over 5 years – and even faster for some technology variants, with scrubber unit sizes increasing more slowly. Deployment was driven by a range of different policy approaches over time, including emissions performance standards, (implicit) technology mandates and sulphur emissions trading. After the initial series of investments in the 1970s, a markedly uneven rate of build can be observed in the 1980s onwards, with peaks of several 10s of GWs installed in some years. At times, this caused worries about the ability of industry to scale up its capacity quickly enough. Part of the reason why this has worked is the international nature of the FGD equipment market that has smoothed out overall demand. Towards the end of the period studied, there were however signs of FGD 'booms' in several markets coinciding in time, with renewed worries about industry capacity bottlenecks forming.

Lessons for CCS policies and strategies

In terms of overall lessons from the two cases about scaling up and rolling out a technology, several points seem important. First, scaling up gas turbines to the size required for a CCGT plant (from 5MW to about 200MW) took about 30 years; FGD systems also went through a 30 year period of scaling up of the maximum scrubber size (by a factor 5). The modular nature of both technologies required some scaling up for the use in power generation, but not unit scaling up to the size of a full power plant. Governments played an important role in this process – for example through R&D support for the development of military jet engines (a source of technologies for CCGTs), and through US government networking and R&D support for the FGD industry. In both cases the rapidity of scaling up processes led to significant reliability and efficiency problems which slowed down development and deployment, and were also expensive to rectify.

In terms of the speed of roll-out, the CCGT case showed that during the 'dash for gas' in the 1990s an average of 2.1GW per year of new capacity was installed in the UK. This can be contrasted with government and industry expectations for CCS deployment in the UK to 2030. The Carbon Capture and Storage Association has called for 20-30GW of CCS capacity by 2030, whilst a recent government statement includes a figure of 10GW for 2030 (Hendry, 2012). For FGD in the US, build rates were higher, albeit in a much larger market. The US power system is approximately ten times bigger than that of the UK. Within a decade of the first large-scale FGD system being retrofitted onto a power plant in 1968, 5GW FGD capacity was added in the US annually. Later, rates of up to 30 GW were reached, but only for short periods.

As with scaling up, this process of rolling out was driven partly by government policies. For example the UK roll out of CCGTs was facilitated by electricity market liberalisation and, subsequently, by strengthened environmental regulations. The US government played a key role in facilitating technology development and deployment of FGD by imposing challenging regulatory standards on sulphur emissions from power plants. The FGD case illustrates how a range of different policy approaches were used at different times. Emissions performance standards, mandates and emissions trading have been used, sometimes in combination, to drive deployment.

There is a similarity to the package of financial and other measures that are currently envisaged by the UK government to support CCS technologies. Furthermore, the development and deployment of FGD technologies in the United States was motivated by similar concerns, ie the need for policy action to deal with environmental pollution. However, in the FGD case, policy makers and regulators had more leverage because of the market

structure in place at the time. Electricity was provided by private and public monopoly utilities. With the consent of regulators, the additional costs of pollution control technologies like FGD could be passed on to their customers. The UK 'dash for gas' is different since it did not occur due to planned policy action. Instead, it was an outcome of a variety of factors which included policy developments – though none of these policies were specifically designed to promote the adoption of this particular technology (Watson, 1997).

A final lesson from these cases is that CCGT deployment in the UK profited from experiences elsewhere (mainly in the US) while FGD deployment in the US also drew on earlier experience with wet limestone scrubbing in the UK, Japan and elsewhere. In both cases technology transfer from other applications/sectors played a major role in technology development (from jet engines in the case of gas turbines and other chemical plants in the case of FGD absorbers). This latter point has important implications for CCS technologies. Whilst some components of CCS systems (particularly capture plants) have only been deployed at 'pilot' scales so far, some of these components are in use at larger scales in other applications (Chalmers, 2012). Therefore, in addition to some scaling up, there is potential for technology transfer from these other applications – though this will come with significant challenges of technological adaptation and integration into CCS systems.

Integration of CCS systems

This uncertainty was explored with the help of one case study: *The transition of the system for gas provision in the UK from town gas to natural gas from 1960 to 2010.* The study was chosen as an analogue for the challenges of integrating large, infrastructural technical systems (Arapostathis, 2011). From 1960 to the mid-1980s, the gas infrastructure was under nationalised governance with the Gas Council as the dominant actor. The introduction of liquefied natural gas (LNG) from 1964 facilitated the later conversion from town gas to natural gas, by providing a 'back bone' pipeline up the middle of England. The introduction of LNG created several challenges, including the higher pressure needed for natural gas, the conversion of burners in domestic appliances and the need for new expertise. The introduction of North Sea gas from the late 1960s drove a change process, in which resilience and flexibility were sought, and provided by interconnections, storage and new control technologies.

The period from the mid-1980s brought privatisation and market liberalisation, and a multitude of actors contributing to the development of the system. From the late 1990s, the depletion of North Sea resources led to a renewed emphasis on gas imports – and a simultaneous rise in political debate about the security of UK gas supplies. The need to expand imports led to large-scale investments in new pipeline interconnectors and LNG import terminals.

Lessons for CCS policies and strategies

One important lesson from the early period covered by the case is that the development of the national gas grid pre-dated the switch to natural gas. The introduction of liquefied natural gas (LNG) facilitated the later development of the natural gas network by providing a driver for the construction of the 'back bone' of this network. With respect to CCS, this suggests that the first UK demonstration projects could be an opportunity to develop a new CO_2 pipeline network. Unlike natural gas, however, CO_2 networks for CCS do not have to be integrated nationally, and will not extend to millions of final consumers.

It is more likely that regionally integrated pipeline systems will be developed for CCS. CO_2 pipeline networks for CCS could therefore have more in common with the offshore networks of gas and oil that transmit fuel to the shore. In the case of natural gas infrastructure, network design was adjusted as exploration of new fields developed. Thus engineers and network designers promoted flexibility in the network design. Similarly, CO_2 pipeline networks will need to be developed flexibly since it is not yet clear which power plants will fit CCS first, and the order in which storage sites will be brought online. In addition to this, there may also be benefits from international interconnection of CO_2 networks to increase system flexibility and economies of scale. This would be similar to the increasing interconnection of UK gas networks with those in other countries in recent years.

Another lesson from this case is that system integration is more than just a technical issue. There are also social and organisational dimensions to system integration. In the gas grid development case, the switch from town gas to natural gas required the development of new skills, large-scale training programmes, and required changes to equipment in people's homes. Management of the multiple types of expertise necessary for the establishment of CCS projects (including capture plants, pipeline networks and storage facilities) will also be challenging – as will the development of contractual arrangements to enable costs, risks and revenues to be shared in a way that suits all parties. One of the lessons learned from the recent negotiations to establish a full scale CCS demonstration at Longannet is that integrating the different areas of expertise within CCS projects is likely to require significant resources (Scottish Power CCS Consortium, 2011b).

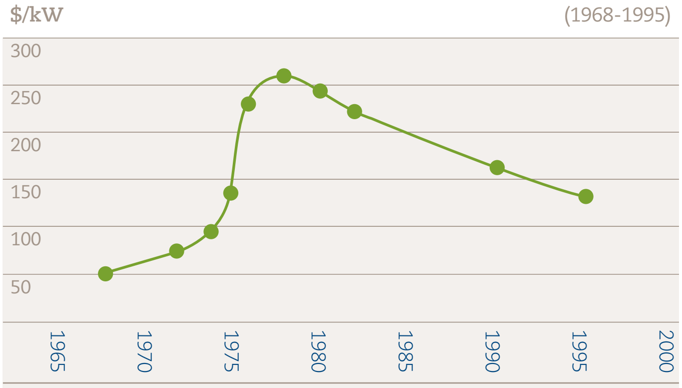
An important limitation of this case is that the natural gas industry and network were developed in a period of nationalisation and centralised control - politically and organisationally. The natural gas infrastructure was already well developed before the more recent period of privatisation and liberalisation, though considerable additional infrastructure development has occurred in the liberalised era. It remains an open question whether CCS will be deployed within a liberalised market context like the current one. Electricity Market Reforms could mean a significant shift to a less liberalised policy and market context, which could have a significant impact on CCS infrastructure development.

Economic and financial viability

We chose two cases to shed light on economic and financial uncertainties: *the storage in landfill sites of waste in the UK from 2001 to 2011 (Kern, 2011c); and flue gas desulphurisation in the United States in the 1960s and 1970s* (Markusson, 2011c).

Landfilling of waste is considered as a suitable regulatory analogue to carbon storage because both activities raise questions about the long-term environmental risks and associated liabilities of dealing with waste streams. Landfilling also has a number of operational characteristics which make it similar to carbon storage (for example a long aftercare phase after operations have stopped). The EU CCS directive was directly modelled on the EU landfill directive (for example, in relation to the rules on financial provisions). Whilst landfill was previously the cheapest waste management solution, it has come under intense regulatory pressure during the last decade because of limits imposed by the EU landfill directive. There have been no investments in new landfill sites since the directive was implemented in 2001. The UK government therefore introduced a number of instruments to reduce the amount of waste being sent to landfill. New void space, where necessary, has been created through an extension of existing sites. The financial provisions for monitoring and aftercare are not perceived as an important obstacle to investment in site extensions by operators. However, they do impact on operators' ability to finance projects and their balance sheets, especially when they operate multiple sites. The focus of the case was widened to include other investments in waste management infrastructure such as recycling and energy-from-waste plants. Key risks influencing the economic and financial viability of such investments include: off-take, waste stream, technology,

3.2 Capital costs of FGD plants in the United States



Note: Figures are in 1997 US dollars
Source: Authors' interpretation of data in Rubin et al (2004)

The landfill case shows that financial arrangements are key to the coordination of the wide range of actors involved in infrastructure technologies.

policy and planning risk. It is argued that carbon storage faces similar risks.

The case study of *flue gas desulphurisation (FGD) technology in the United States* covers the mid-1960s to the late 1970s; the period when the technology began receiving serious attention and investment. The first large-scale FGD plant was built in the late 1960s. Regulators introduced an emissions performance standard in 1971, which created demand for FGD. The government also supported the technology through funding R&D, establishing test centres and sharing data. Litigation created policy uncertainty and delayed investments, but ultimately the standard stood up against the challenges. Subsequent regulation enacted in 1979 was more stringent and effectively mandated FGD. FGD costs rose five-fold in the period studied, and they subsequently fell substantially in the 1980s (see Figure 3.2). The increases were due to unforeseen technical problems and the challenges of technology transfer from other sectors. This rise in costs was much bigger than predicted at the time when the first large plant came on line. Financial risk was not a key problem for the investing utilities, since they operated in regulated, regional monopoly markets and were allowed to pass on abatement costs to their customers.

It is important to recognise that these two cases are different, and they can therefore offer different kinds of lessons for CCS. The landfill case includes lessons about the specifics of policy design under a market-oriented regime, about (some forms of) long-term liabilities, and focuses on a mature technology. By contrast, the FGD case provides lessons about costs and cost data in early stages of technology development, and about what could be done in a regulated monopoly policy regime where financial uncertainty works very differently.

The landfill case shows that financial arrangements are key to the coordination of the wide range of actors involved in infrastructure technologies. The financial provisions for monitoring and aftercare are not perceived as an obstacle for new investment. The most common mechanism for meeting provisions is through bonds. Whilst this experience is relevant to CCS, carbon storage site closure and aftercare monitoring might well incur substantially higher costs than landfill sites, and higher bond premiums.

However, it is important that the liabilities covered by such a bond only cover the costs of site closure and post-closure monitoring in case the operator goes bankrupt before fulfilling the requirements of the environmental permit. Accidental leakage of stored carbon leads to different kinds of liabilities such as the costs of offsetting the emissions released from the storage site, which might be linked to the price of carbon within the EU ETS. These liabilities might need to be covered by some kind of insurance product (EC 2008: 42). For this kind of risk, landfill regulation does not offer a suitable analogue. In this context, the regulatory framework for dealing with nuclear waste might offer some insights (Gross, 2011).

The government has used a variety of instruments to incentivise investment in new waste management infrastructure including long-term contracts, private finance initiative credits and grants. Similar instruments are planned to support CCS investment – including capital subsidies and long-term contracts under Electricity Market Reform. The provision of long-term contracts (with a fixed price) is likely to be important in enabling CO_2 infrastructure investments to overcome key risks, including those relating to policy.

The FGD case shows that 'technology forcing' through the use of regulations can stimulate technology development and early deployment. For CCS, forcing could conceivably be done through different policy instruments, such as an emissions performance standard (EPS) or a mandate. The viability of technology forcing depends on whether companies can pass on the costs, the availability of alternative investments, and on the precise design of the policy instrument. There are a number of reasons why such a regulatory approach may not be appropriate for CCS in the UK – at least not at the present time. These reasons stem from the very different institutional and market context for FGD investment during the period studied. Most US utilities were regulated monopolies which could pass on costs for sulphur abatement to final consumers. FGD technologies were significantly more mature at that time than CCS is today, with the first few full-scale plants already in operation. Potential investors in FGD had comparatively few other options to comply with sulphur regulations – though they could invest in less effective options such as coal cleaning and switching to lower sulphur coals.

Finally, the costs of FGD equipment were a smaller share of overall power plant costs than CCS equipment is expected to be. In view of these differences, regulations to 'force' CCS investment are likely to be less effective than the US approach to FGD – at least until there is more experience of full-scale CCS plant operation and costs.

It is difficult to predict the costs of a technology before full-scale deployment. Even after the first large-scale plant was operating, FGD cost estimates were characterised by 'appraisal optimism'. They turned out to be much too low. The experience of FGD and of low-carbon technologies such as offshore wind (Gross, Greenacre et al., 2010) suggests that significant increases in CCS costs could occur during the demonstration and early deployment phases. CCS technologies are not yet on a 'learning curve' in which costs will inevitably fall with increasing deployment. The FGD experience also shows that costs may subsequently fall once 'teething problems' have been sorted out and experience grows.

It is difficult to predict the costs of a technology before full-scale deployment. Even after the first large-scale plant was operating, FGD cost estimates were characterised by 'appraisal optimism'. They turned out to be much too low.

Policy, politics and regulation

This uncertainty has been explored through a case study of *FGD technology deployment at power plants in the UK between the early 1980s and 2009* (Markusson, 2011b). This analogue was selected because FGD deployment is dependent on policy and regulation, and policies to support FGD in the UK have been subject to significant uncertainty and controversy. During the 1980s international concerns about acid rain began to seriously drive policy discussions about sulphur emissions abatement in the UK. The EU adopted the Large Combustion Plant Directive (LCPD) in 1988, which included limits on these emissions. The LCPD has had significant impacts on FGD investment in the UK, but this has also been a politicised process. Whilst the EU promoted emissions reductions and the use of FGD, the UK government and industry resisted abatement investments that were considered too costly. Therefore, FGD investments were made but were delayed. More recent EU regulations which mandate closure of unabated fossil fuel plants by 2015, together with financial incentives under the second phase of the EU Emissions Trading Scheme, have stimulated a rapid increase in investment. By 2008, power sector SO2 emissions had been reduced by 94% compared to 1980 levels as a result of fuel switching (from coal to gas), the use of lower sulphur coals, and the introduction of FGD. FGD contributed between a quarter and a third of these emissions reductions. The overall UK FGD investment programme cost £1.4-1.8bn in 2011 prices.

Lessons for CCS policies and strategies

An important lesson from this case is that policies to support the reduction of emissions, and the deployment of technologies to achieve this, can be highly contentious and political. The government and the major energy companies (particularly the nationalised utility) were reluctant to invest in FGD technology to help reduce sulphur emissions in the 1980s because of the expected high cost of the technology. The attitude of the UK government and firms to CCS technologies is markedly different. In contrast to the situation for acid rain in the 1980s, recent UK governments have played a leading international role in advocating emissions abatement – and energy companies are actively pressing for public policy incentives to enable investment in CCS technologies (eg CCSA, 2011). However, the costs of CCS technologies have been an important area of debate: not least in the negotiations for the first UK demonstration plant. The developers of the failed Longannet demonstration project concluded that their plant would cost £1.2-£1.5bn whereas only £1bn of public funding was available (Scottish Power CCS Consortium, 2011a). The costs of low-carbon technologies have also become a more prominent area of political debate due to concerns about the impact on household bills (CCC, 2011b).

A second lesson is that the choice of policy instruments may have an impact on the success of efforts to support CCS demonstration and deployment. In the case of FGD, a range of instruments were used at different times including emissions limits and financial incentives (most recently, from the EU emissions trading scheme). For CCS, a similar blend of policy instruments is likely to be used – albeit in a more liberalised market context. These include a general emissions performance standard and long term contracts as part of Electricity Market Reform, and capital grants. Whilst emissions limits led to limited FGD deployment in the 1990s, the implementation of tough regulations on fossil fuel plants under the latest EU Directives covering combustion plant has been far more effective in incentivising widespread deployment. In the intervening period, the costs of installing FGD fell considerably which made it much easier for regulations to have the desired effect. The original UK investments in FGD in the 1990s now look expensive, though there were significant differences between the first plant at Drax and the second at Ratcliffe. Drax was designed by the state-owned Central Electricity Generating Board before privatisation, whilst Ratcliffe was contracted by competitive tender using a performance based contract - and was therefore cheaper[6].

[6]Thanks to Tony White of BW Energy for providing us with some detail on this point.

It is important for government to analyse the potentially complex impacts of policies to promote CCS. In the CCS case, this complexity is compounded by an ongoing process of Electricity Market Reform which represents a significant shift away from a liberalised market structure and towards a more co-ordinated set of institutional arrangements.

The lesson for CCS is that a regulatory approach alone is unlikely to be effective due to the higher expected costs of CCS technologies, and the larger energy penalty of operating capture equipment. As noted in section 1 of this report, the additional direct costs of CCS were recently estimated by Mott MacDonald to be £335-900/kW. By comparison, the costs of FGD plants in the UK have usually been less than £100/kW (Markusson, 2011b). In addition, uncertainties about CCS costs are greater because of a lack of full scale plants in operation.

A third lesson is that policy flexibility can have contradictory impacts on technology deployment. It is useful to distinguish between flexibility in policy making and flexibility in industry compliance with a clear policy goal. Flexibility in policy making can cause a lot of uncertainty. In the UK FGD case, it led to the 'capture' of the policy process by industrial lobbies opposed to action in the early years. Flexibility in compliance can help to reduce costs by allowing industry some leeway in their investment and operational plans. At the time of writing, CCS is subject to both of these varieties of policy flexibility. It is not yet clear when (or if) the technology will be mandatory for new gas plants, or for existing coal and gas plants. Furthermore, the details of the revised CCS demonstration programme are still being developed. The FGD case shows that whilst such flexibility persists, technology deployment will be slowed down.

Finally, it is important for government to analyse the potentially complex impacts of policies to promote CCS. In the CCS case, this complexity is compounded by an ongoing process of Electricity Market Reform which represents a significant shift away from a liberalised market structure and towards a more co-ordinated set of institutional arrangements. As was the case for FGD in the USA, it is important for government to have substantial independent capabilities in the analysis of potential policy impacts and about technology costs and performance. This is especially the case when government is engaged in complex policy reforms, and is involved in difficult negotiations with developers about public funding or the precise design of policy incentives.

Public acceptance

This uncertainty was explored with the help of a case study on *the public acceptance of the development of natural gas infrastructures in the UK between 2000 and 2011* (Marsden and Markusson, 2011). This case was selected because natural gas infrastructure development is similar to the transport infrastructure needed for CCS, particularly pipelines and compressor stations. The study includes the use of salt and brine fields for underground gas storage (UGS), the development of Liquefied Natural Gas (LNG) terminals with above-ground storage tanks and the construction of pipelines (and pressure reduction installations) to connect new facilities with the national gas transmission system. The case is also relevant because recent investments in onshore gas pipeline and storage infrastructure in the UK have been accompanied by local protests and opposition, with some material impacts on project outcomes.

Lessons for CCS policies and strategies

An important lesson from this case is that infrastructure projects such as gas pipelines can change the way that residents identify with their locale and how they feel about the landscape within which they live. For example, if there is a perception that new infrastructures lead to new safety risks, a place that was previously felt to be safe could come to be seen as unsafe. Public protests against such infrastructures may be more likely if the technologies involved are new and unfamiliar. Carbon capture and storage pipelines will be novel for most of the locations in which they are built. However, unlike natural gas, CO_2 is neither flammable nor explosive – and these properties might make such pipelines more acceptable than those for natural gas. The lessons of the case with respect to gas storage facilities may be less relevant to CCS since any CO_2 storage sites that are developed in the UK are expected to be offshore. It is important to note that there is a growing body of literature on public perceptions of CCS. For example, a recent pan-European survey (Reiner, Riesch et al., 2011) shows that members of the public often raise concerns about the risks of CO_2 storage – and that their perceptions of CCS technologies depend on a range of factors including their proximity to potential infrastructure.

The natural gas case study shows that infrastructure developers become visible to the public at two points: the planning stage and the construction stage. The planning stage involves public consultation, but tends to be less visible to the public due to the nature of planning processes, especially if it is large enough to be handled via national (rather than local) planning processes. Of course, protests at this stage can and do happen. By contrast, the construction stage is physically visible and can also produce protest, but then with far less scope for the public to prevent or change the development.

There have been public protests in many of the natural gas pipeline and storage projects we studied. Protests have been particularly visible at underground gas storage projects. The case has also shown that a series of development projects in the same area often lead to sustained opposition. This may be a relevant issue for CCS if a cluster of plants is developed in a particular area. Whilst these protests have led to some substantive delays and a small number of project cancellations, most gas infrastructure projects have not been significantly affected.

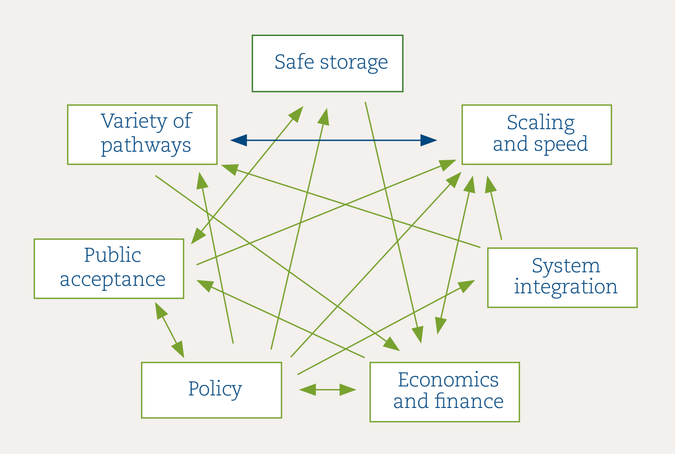
Despite the differences between natural gas and CO_2, the research on public perceptions of CCS suggests that such protests could also affect pipelines and other infrastructure for CCS projects. If they do, delays, costs increases and even cancellations are all possible. The case also shows that it would be unwise to ignore early reactions from small opposition groups. Furthermore, a wide range of local, national and international factors will shape public reactions – so each site needs to be considered on a case by case basis. Areas with low population densities may be affected by less opposition to CCS infrastructure, but clearly the extent of opposition will also depend on whether these areas are seen as important or sensitive for other reasons.

Interactions between uncertainties: virtuous cycles, vicious cycles and trade offs

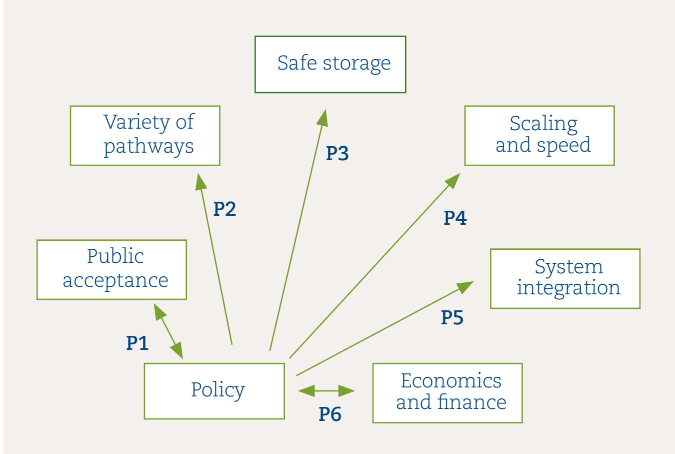
Many of these uncertainties will interact with each other over time. Once the uncertainties had been chosen, a number of these potential interactions were identified (Markusson, Kern et al., 2012). This analysis was subsequently refined as a result of the analogue case studies. The final pattern of interactions is summarised in Figure 3.3.

One example has been highlighted in the Figure to illustrate what we mean by interactions. This shows an interaction between the 'scaling and speed of roll-out' of particular technologies and the 'variety of pathways' available. As the literature review showed, there is a risk that the rapid scaling up of a technology risks locking investors and the governments who support them into an inferior technology by reducing variety too early in the process. Conversely, keeping options open for too long by supporting a range of different technology variants risks spreading the resources too thinly. The case of the 'dash for gas' in the UK showed that the existence of a variety of turbine designs for an extended period of time enabled experimentation and learning. Furthermore, cross-fertilisation with more advanced jet engine technologies enabled the subsequent up scaling and efficiency improvements achieved in power generation gas turbines. The existence of niche markets for different designs sustained variety in this case, and reduced the risks of early lock-in. There was not a deliberate policy push to select one type of gas turbine (and CCGT) design over another. By contrast, the French nuclear case shows how policy did play such a role – and

3.3 Linkages identified between the seven project uncertainties



3.4 Interactions with policy, politics and regulations uncertainty



Despite the differences between natural gas and CO_2, the research on public perceptions of CCS suggests that such protests could also affect pipelines and other infrastructure for CCS projects.

made a clear decision in the face of uncertainty to back the PWR design in the 1960s.

Explaining all of the interactions included in Figure 3.3 is beyond the scope of this report. Instead, the remainder of this section of the report focuses in more detail on the interactions between the policy and economic uncertainties and the other uncertainties identified in the project. These interactions are summarised in Figures 3.4 and 3.5 respectively. The policy uncertainty was chosen as a particular focus because of the central importance of policy in supporting the demonstration and deployment of CCS technologies. Indeed, in the absence of such policy support, it is very unlikely that these technologies would develop significantly at all. The economic and financial uncertainty was chosen because of the focus of our project on the conditions for CCS technologies to be 'financeable' in the UK. Whilst policy support is clearly required for CCS technologies to be deployed, the UK's efforts to date illustrate the difficulties of designing policy mechanisms that provide enough certainty to investors.

The following discussion will provide examples from the case studies which highlight the interactions between the policy, politics and regulatory uncertainty and the other uncertainties. These interactions are denoted as P1-P6 in Figure 3.4.

In terms of the linkage between policy and public acceptance (P1), the literature review for the public acceptance and UK natural gas infrastructure development case highlighted that the absence of credible regulatory regimes can decrease public confidence, and can provoke opposition. A strong regulatory regime might give stakeholders confidence and increase public support. Public acceptance is likely to be necessary for political support, and impacts on policy and regulatory decisions.

The case studies also identified an important linkage between the policy and variety of pathways uncertainties (P2). The French nuclear programme case highlighted the importance of this. In the French case (but also in the other countries developing civil nuclear power including Britain, the US and Germany), governments have played a strong role in supporting the development of nuclear power technologies and in reducing the variety of possible reactor designs. Sometimes political and military concerns, rather than economic or technological criteria have informed these choices. With respect to CCS, political decisions about whether or not to include coal and gas and which technologies to include in the UK government's CCS demonstration competition can also shape technological variety.

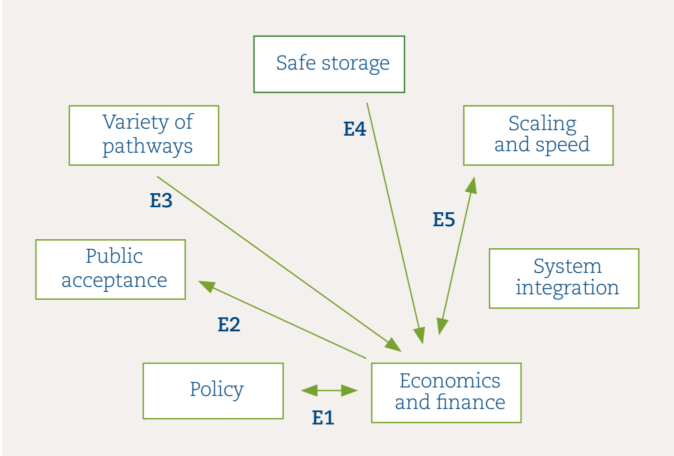
The analysis has also identified an interaction between policy, politics and regulation and the uncertainty around safe storage (P3). The case study of radioactive waste management has stressed the importance of operational as well as accident liability regimes for the development of storage facilities for nuclear waste. In particular these rules shape the risk profile of investments and also impact on public acceptance of storage. The case study also stressed that policy decisions about appropriate site selection methodologies should not prioritise cost factors over safety concerns as any additional expense associated with exploring safer sites must be balanced against the potential costs of leaks and loss of public and investor confidence.

Policy decisions can also impact on uncertainties around the scaling and speed of roll-out of a technology (P4). In the case of FGD development in the US, regulation and policy decisions clearly influenced technology development and drove deployment. This is widely known as 'technology forcing' through regulation or standards. In contrast, the UK FGD case showed how politics between the UK and the EU led to delays in the roll out of FGD technology as UK policy makers were reluctant to impose regulations that would require costly compliance. What is perhaps more surprising is that regulation also shaped the scaling process, in terms of the choice between modular and 'full-scale' scrubber units in the US case. Instead of scaling up FGD units to the full-scale power plant size, modular designs were deployed. This was in part a response to engineering challenges related to the scaling up of the technology, but also a consequence of regulatory requirements. The US Environment Protection Agency only allowed an FGD absorber to be bypassed for the purpose of maintenance if there was a spare absorber to replace it. This means that FGD units were built as sets of modules which included one more module than was needed to operate the plant: for example, 3x50% capacity or 4x33% (Shattuck et al., 2007).

For CCS, the regulatory regime (especially liability rules) will clearly have implications for the technical and organisational forms of system integration that take place.

The case study on the integration of the natural gas network in the UK (1960-2010) pointed to the importance of policy, politics and regulation for system integration (P5). The case study found that network integration in all periods of natural gas development was determined by the political regime, the policy decisions and the relevant regulations and regulatory cultures. The focus on the nationalisation of crucial industrial sectors resulted not only in a nationalised gas industry but also in a centrally controlled industry in which the governance of people and technologies were managed by one institution, the Gas Council. The privatisation and liberalisation introduced since the mid-1980s transformed the structure of the industry and changed the terms of network development. For CCS, the regulatory regime (especially liability rules) will clearly have implications for the technical and organisational forms of system integration that take place.

3.5 Interactions with economics and finance uncertainty



There is also a clear linkage between policy and economic and financial viability of CCS (P 6). As the literature review indicated, a variety of political, policy and regulatory decisions – for example about policy support mechanisms for CCS, carbon prices, carbon reduction goals, and liability rules - will have a large impact on the economic and financial viability of CCS. The case study of economic and financial viability of FGD in the US stressed the importance of policy decisions. For policy-driven, public good technologies like FGD and CCS, policy and regulatory uncertainty will always be of key importance for investment decisions. The policies and regulations introduced under the Clean Air Act (CAA) were crucial to making the FGD a credible investment option, and for creating demand for this technology. The legal challenges against the CAA regulations created uncertainty that delayed investment in the early to mid 1970s, showing the importance of policy and regulatory risk. Public support for R&D, knowledge diffusion, pilot scale tests and investments played a role, although most of the finance for large scale investments was covered by industry themselves. It was regulation rather than subsidies that mattered for 'financeability' in this case. The case study of the economic and financial viability of landfill in the UK emphasised the importance of policy and regulatory decisions that were taken due to pressure from the EU landfill directive.

Now, we will turn to the interactions between economic and financial viability and the other uncertainties as outlined in Figure 3.5. Note that the linkage between economics and finance and policy uncertainties (denoted as E1) has already been covered above (as P6).

The literature review and the case studies identified an important interaction between economics and finance and public acceptance (E2). The case study of the integration of the natural gas network in the UK (1960-2010) shows that this interaction works both ways. While economic factors (eg the cost of a technology passed through to consumers via electricity bills) can have an influence on public acceptance, the lack of public acceptance (eg protests) can impact on the economic and financial viability of a technology. However, in the case of FGD development in the USA, we did not find any evidence to suggest that consumers actively protested against increased costs of electricity due to FGD investment. We therefore conclude that higher costs could lead to a decrease in public acceptance of CCS, but that this is by no means an automatic response. Such a response may be more likely in the current UK political climate, in which there is a fierce debate about the legitimacy of meeting the incremental costs of low-carbon technologies via increases in consumer bills. The case study of the development of natural gas infrastructure in the UK between 2000 and 2011 showed that protest against developments can delay projects and thereby lead to higher costs than anticipated. The case study into the economic and financial viability of investments in landfill sites also confirmed this finding. Siting problems for landfill sites due to public opposition often incur delays, and might reduce the economic and financial viability of a particular landfill site. The nuclear waste management case study also found that opposition to major planned infrastructural works can result in delays to scheduled works which can increase overall costs.

For policy-driven, public good technologies like FGD and CCS, policy and regulatory uncertainty will always be of key importance for investment decisions.

The analysis of the French nuclear programme found that there was an important relationship between economic and financial viability and variety of pathways (E3). In general, costs are an important factor in technology choices. For CCS, this is problematic since knowledge about the costs of different technology variants is currently limited – and the costs of CCS technologies are subject to greater uncertainties than those of some other low carbon technologies. The French nuclear programme was accompanied by an aspiration that increasing rates of adoption of a particular design might foster learning and economies of scale to bring costs down. However, a recent analysis by Grubler (2010) shows that the construction costs of PWRs in France rose steadily from the early 1970s to 1990s – and more than doubled over that period in real terms. In any case, the early momentum and experience gained with light water reactors such as the PWR made it difficult for other technologies catch up. It therefore made this variant look economically favourable when compared to other designs (Di Nucci Pearce, 1986; Cowan, 1990). The case study of FGD in the US also identified links between the variety and economic and financial uncertainties.

There is also an important interaction between safe storage and economic and financial viability (E4). As the nuclear waste management case shows, there is the interplay between the costs involved in developing specific storage sites and operational safety levels. The cost of developing particular sites will need to be balanced carefully against the level of containment offered. If storage safety is not achieved and carbon leaks into the sea or atmosphere, this will impact on the economics of CCS projects by increasing liabilities, damaging investor confidence and impacting on risk perceptions.

Lastly, there is also a crucial relationship between economic and financial viability and scaling and speed (E5). The case studies of FGD technology in the United States emphasised the role of learning by doing through the roll out of the technology. The early stage scaling up and deployment of FGD were associated with rising costs, but interestingly this also reduced uncertainty about costs. The rising costs were primarily caused by the discovery of unexpected technical problems. Continued development and deployment led to the resolution of these problems, and after the late 1970s, costs started coming down (see Figure 3.2). The case study of the UK dash for gas showed that the rapid roll out of CCGTs in the 1990s led to a rapid decrease in CCGT investment prices (Colpier and Cornland, 2002). However, the history of the CCGT also shows that before that period, prices actually increased for some years before accumulated experience from the installed capacity contributed to learning processes which enabled price reductions (Winskel 1998; 2002).

In summary, the analysis of the historical case studies identified a range of important interactions between uncertainties which are relevant to the development and deployment of CCS. Most of these interactions were identified in more than one case. Given that most of them occurred over long periods of time (eg 20-30 years), it is important for decision makers focusing on CCS technologies to not only to consider short term concerns, but also to keep these longer term dynamics in mind.

Another important lesson learned from the historical case analysis of relevance for CCS is that interactions between different uncertainties can take three different forms. On the basis of the data it is possible to distinguish between:

- 'virtuous circles' - where the resolution or management of one uncertainty helps to reduce another uncertainty through a process of positive feedback. For example: increased perception of safety of storage might lead to improved public acceptance
- 'vicious circles' - where the deterioration of one uncertainty has negative impacts on another through a negative feedback process. For example, where rising costs might lead to less policy support and political enthusiasm about the technology
- 'trade offs' - where the resolution or management of one uncertainty leads to more uncertainty in another dimension. For example, we have identified a potential trade off between reducing technological variety in order to speed up the development and roll out of a technology. But this can result in premature lock-in to a particular technology variant which might turn out to be costly compared to alternatives. Conversely, keeping options open and exploring many technology variants to enable learning might impede progress with scaling up and the speed of development and deployment. It might spread resources too thinly to build momentum for any variant. Policy decisions might have a key influence on this trade-off.

These three different kinds of interdependency between the uncertainties have been used by the project team to develop some possible future pathways for CCS in the UK to 2030. These pathways are analysed in the next section of this report.

CCS pathways to 2030



One of the goals of our project has been to contribute to the analysis of the conditions for both 'successful' and 'unsuccessful' CCS deployment, and what actions by policy makers and other decision makers might influence the outcome. To that end, a set of pathways were developed for CCS from now to 2030.

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One of the goals of our project has been to contribute to the analysis of the conditions for both 'successful' and 'unsuccessful' CCS deployment, and what actions by policy makers and other decision makers might influence the outcome. To that end, a set of pathways were developed for CCS from now to 2030, drawing on CCS policy documents and research literature, as well as on the insights gained from the analogue case studies, to explore different possible CCS futures. The analysis allows the identification of key branching points where CCS pathways might diverge (or merge), which help illustrate what aspects of CCS futures to monitor, and what actions may need to be taken to realise desired pathways.

As discussed in section 3 of this report, the seven uncertainties we have identified for CCS are related in multiple ways (Markusson, et al., 2012). The linkages either represent synergies between uncertainties, where improvement in one makes improvement in another more likely. Or they depict how deterioration in one dimension leads to problems relating to another uncertainty. As well as these virtuous (and vicious) cycle dynamics, there are also instances of trade-offs between uncertainties, where improvement in one creates problems somewhere else. This kind of interaction is especially important to analyse, as it indicates situations where trade-offs may have to be made by decision-makers.

A set of three pathway endpoints for 2030 were selected, which differ widely in the amount of CCS deployed. These endpoints represent situations where we have either (1) reached the more ambitious policy targets for CCS deployment (and where virtuous cycles have led to the resolution of many uncertainties; (2) CCS has failed to 'deliver' completely (and where vicious cycles have led to a multiplication of uncertainties); or (3) an 'in-between' situation where a moderate level of deployment has emerged and the success of the technology 'hangs in the balance'. In this third case, there may have been trade-offs between uncertainties. To be able to elaborate the possible sequence of events to each of these three endpoints, a back-casting approach was adopted (Robinson, 1982). This develops possible and coherent pathways from today's situation to each of the three endpoints. An important starting point is the current plan for several large-scale, integrated demonstration projects of CCS on power plants.

Deployment of CCS technologies does not of course take place in a vacuum, and the appetite for investment in CCS generation is at least partially dependent on progress in other low carbon options. For example, CCS may look relatively more attractive if the cost reductions envisaged for offshore wind do not happen as quickly as anticipated or the first new nuclear stations are not delivered to time and budget. Clearly, the opposite could apply and CCS may look relatively less attractive if encouraging progress is made with offshore wind and new nuclear. Once deployed, the actual utilisation of CCS plants may be affected by the mix of other generation on the system. Since plant load factors influence the unit cost of electricity generated, this may have important implications for the financial viability of CCS plants. Full descriptions of the energy system and policy context of each pathway, can be found in a separate pathways report (Heptonstall, Markusson et al., 2012).

This work does not intend to suggest that any particular pathway is more or less probable. Instead, it examines a plausible and analytically useful range of potential futures which can then be used to help understand how far our uncertainties need to be resolved to achieve 'successful' deployment – and also what circumstances might prevent this. In this way, the methodology allows for analysis of the conditions for both 'successful' and 'unsuccessful' CCS deployment by 2030.

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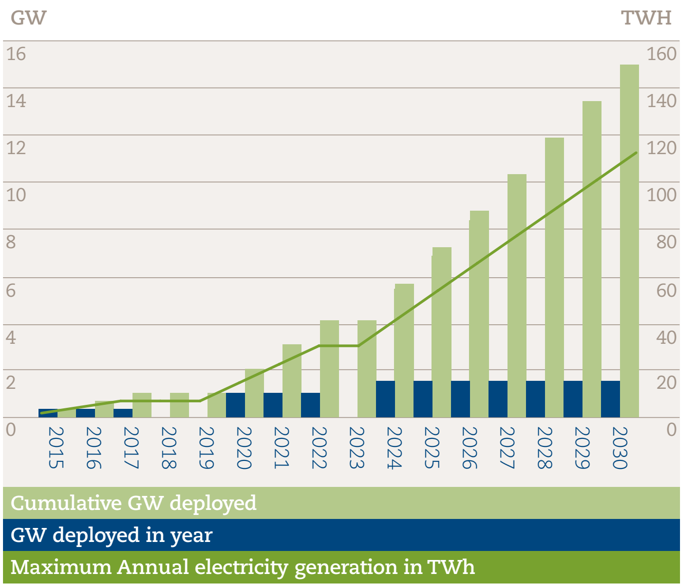
4.1 Pathway 1 on track



The set of pathways was analysed with the help of the uncertainty indicators listed in section 2 of this report (see Table 2.1). For each uncertainty and assessment indicator, the pathways were compared to see where they differ. These differences can be identified as branching points between pathways (Foxon, Pearson et al., 2012). The branching points can occur at different times in the period to 2030, and the comparison was done at five-year intervals. As a result of the comparison, a set of four key branching points were identified, with implications for choices to be made by policy and other decision makers.

As Figure 4.1 shows, the 'On track' pathway envisages a cumulative deployment of up to 15GW of CCS plant by 2030. To get to this point, the pathway envisages that around 1GW of demonstration plant is operational, with a mix of fuels and technologies, by the mid- to late-2010s. Subsequent '2nd tranche' projects are in the early stages of planning by the late-2010s and by the early-to-mid 2020s around 3GW of such plants are operational. By this time, '3rd tranche' projects are in development, which then facilitates CCS plants with a combined capacity of around 1.5GW coming into operation each year over a period of six or seven years up to 2030. In addition, plans for further CCS plants are actively under consideration by generating companies at this point (Heptonstall, Markusson et al., 2012). Whilst Figure 4.1 assumes a 90% load factor to calculate a notional maximum electricity generation from CCS, it is of course possible that some of these plants may be required to run at lower load factors in the future, especially if the alternative is to constrain off low or zero marginal cost nuclear or wind power plants at times of low demand. Such lower load factors could have potentially important financial implications for the CCS plants affected (Heptonstall P, Gross R et al., 2011). They would also face technical challenges. Whilst several strategies have been proposed to improve the flexibility of CCS plants (eg solvent storage or the use of bypass stacks), these have not yet been fully developed and tested.

The pathways

As noted above, the project team used an analytical method based on describing a number of plausible deployment pathways for CCS in the UK and identifying branching points that differentiate these pathways to explore how key uncertainties could affect UK CCS deployment up to 2030. The analysis is primarily focused on deployment of CCS in the power sector since this is aligned with the initial focus of UK Government funding and also much of the CCS literature. It also uses policy ambition as a starting point for defining 'on-track' deployment, rather than the higher deployment levels suggested by some industry representatives (eg Carbon Capture and Storage Association, 2011). The pathways are deliberately agnostic with regard to CCS plant fuel and technology choices, not because such choices are unimportant but because the intention was to focus on the insights available from the case studies (Heptonstall, Markusson et al., 2012).

Three pathways were initially selected, although during the course of the analysis one of these pathways was expanded into two variants in order to illustrate the trade off involved in early or late selection of technology variants (and a number of other closely related issues and choices). The final set of pathways used for the analysis was:

Pathway 1 – 'On track'
A broadly successful pathway, with a plausibly high level of CCS deployment. By 2030, CCS has an established position as a technically proven and financially viable option, and is competitive with other low-carbon electricity generation technologies.

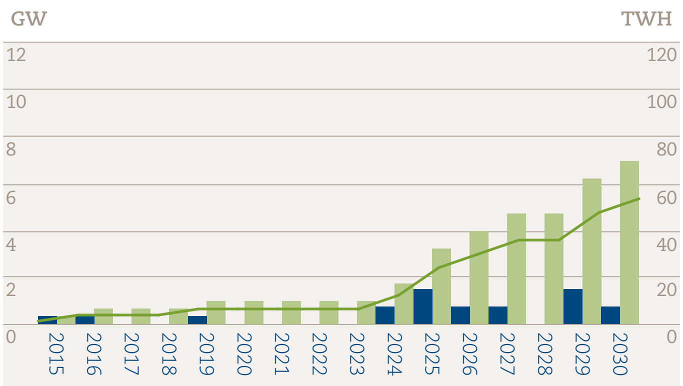
Pathway 2, Variant A – 'Momentum lost'
Commercial-scale demonstration of CCS does go ahead, and is followed relatively quickly by further deployment up to the mid-2020s. By this time, CCS has established itself as technically viable, but from the mid-2020s onwards it is not generally a preferred option as part of the low-carbon generation mix in the UK. Financial viability ends up being marginal.

Pathway 2, Variant B – 'Slow and sporadic'
Commercial-scale demonstration of CCS does go ahead, followed by limited further deployment up to 2030. CCS has established itself as technically viable, but it is not generally a preferred option as part of the low-carbon generation mix in the UK. Financial viability remains marginal with deployment in particular market niches only.

Pathway 3, 'Failure'
No CCS deployment beyond a limited demonstration programme.

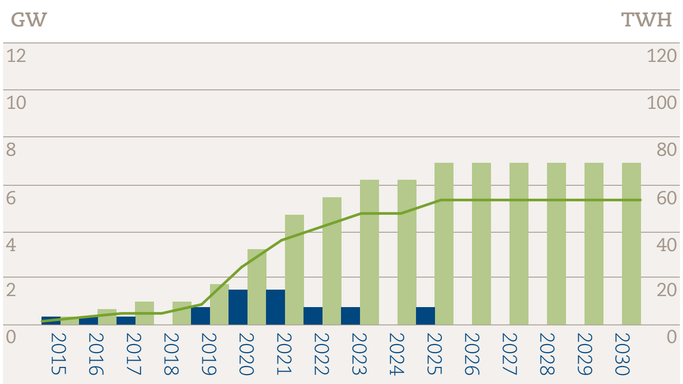
The indicative deployment of, and maximum cumulative electricity generation from, CCS plant under Pathways 2 and 3 is shown in Figures 4.1-4.3 page 34.

4.2 2B Slow and sporadic



Cumulative GW deployed
GW deployed in year
Maximum Annual electricity generation in TWh

4.3 2A Momentum lost



Cumulative GW deployed
GW deployed in year
Maximum Annual electricity generation in TWh

The 'Momentum lost' pathway envisages up to 6-7GW of CCS deployment by 2030. The pathway is characterised by an encouraging start with around 1GW of demonstration plant operational, with a mix of fuels and technologies, by the mid-to-late 2010s. This is then quickly followed up with up to 5-6GW of 'extended 2nd tranche' plants operational by the early-to-mid 2020s. As the name suggests, CCS deployment then comes to a halt (for the reasons described below), so that by the late 2020s there are no further CCS plants in development. Note that Figure 4.2 uses a load factor of 60% during the early years of CCS plant operation, to reflect the technical challenges encountered during the scaling up for '2nd tranche' projects.

The 'Slow and sporadic' pathway also envisages up to 6-7GW of CCS deployment by 2030, but with a different deployment trajectory compared to 'Momentum lost'. The pathway begins with slower progress on the demonstration projects than the two previous pathways with the result that it is the late 2010s before 1GW of demonstration plants are operational. This is then followed by a rather fitful, although not insignificant deployment of a further 5-6GW of '2nd tranche' plants during the mid-to-late 2020s. In further contrast to 'Momentum lost', by 2030 some '3rd tranche' plants are in the early stages of project development, albeit prior to final investment decision.

The final pathway, 'Failure', envisages that only two demonstration plants are brought to completion, with the first being operational by the mid-to-late 2010s, and the second by the early 2020s, representing a total of less than 1GW of CCS plant. Following this, there are no further plants in development in the period up to 2030, and no plans for any CCS plants in the post-2030 period.

Pathways and branching points – Applying insights from case studies to CCS

This section elaborates the innovation dynamics of the pathways in more detail, drawing on insights from the case studies. It uses the notation in Table 4.1 to indicate how the cases have been used to help develop the pathway narratives. The main aim is to highlight key pathway characteristics, especially those that reflect case study insights.

Special attention is devoted to the points where the pathways diverge, here called branching points, since they represent important events to monitor and important choices to make. The four pathways and the branching points between them are depicted in Figure 4.4 (and in Figure 4.5). Please note that where pathways coincide in terms of cumulative deployment, they may well be different in terms of the underlying dynamics and the development in other dimensions. Nevertheless, the focus here is on 'financeability', and the branching points of interest are where the pathways diverge substantially from each other in terms of deployment (for a range of reasons to be discussed below).

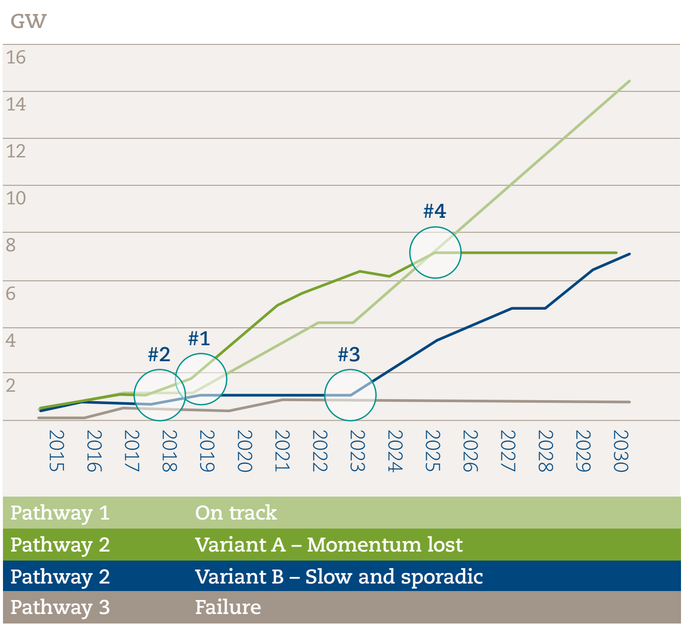
Pathway 1 – 'On Track'

In this pathway all uncertainties are managed successfully, and there are virtuous cycle type dynamics with advances on one front facilitating improvements on others. The key technical features of the pathway include a successful UK demonstration programme and/or positive experience in other countries. Part of this is down to good judgement and part may be sheer luck. Choices made to focus on a limited range of promising technology varieties turn out to be justified and their technical difficulties manageable. The capture technology up-scaling required is facilitated by modular designs (see *Scaling up and speed, US FGD*). As regards to storage, sufficient potential sites are identified and characterised on time for both early and later projects. CO_2 pipeline routes are successfully built and operated, and any required new routes identified. This is facilitated by the re-use of natural gas infrastructure (see *System integration, UK natural gas grid*). Early project designs take the possibility for regional hubs, as well as international inter-connections into account (*ibid*).

Table 4.1 Notation used for the case studies in the pathway narratives

Uncertainty	Country	Notation
Scaling and speed – CCGT	UK	*Scaling & speed, UK CCGT*
Scaling and speed – FGD	USA	*Scaling & speed, US FGD*
Economics and finance – landfill waste	UK	*Economics & finance, UK LFW*
Economics and finance – FGD	USA	*Economics & finance, US FGD*
Variety of pathways – nuclear power	France	*Variety of pathways, FR NP*
Safe storage – nuclear power	UK	*Safe storage, UK NP*
System integration – natural gas grid	UK	*System integration, UK NGG*
Policy, politics and regulation – FGD	UK	*Policy, politics & regulation, UK FGD*
Public acceptance – natural gas grid	UK	*Public acceptance, UK NGG*

4.4 Combined Pathways



This pathway is also characterised by early, comprehensive policy support, which together with technical progress builds up a momentum that in turn facilitates sustained policy support (see Branching Point #1), where the 'On track' and 'Momentum lost' pathways diverge from the 'Slow and sporadic' pathway'). This includes early engagement with local communities, which leads to modified projects and allayed fears (see *Public acceptance, UK natural gas grid*) and highlighted local benefits. A storage liability regime is set up that is both workable for industry (restricted in time and amount, no unrealistic criteria) and which inspires confidence in the reliability of storage (transparent, economic interests kept in check etc). The permitting process for early CCS projects proceeds relatively smoothly, and all necessary permits are granted without undue delay. Deployment is driven by both sticks (a mandate or emissions performance standard) and carrots, in the form of financial incentives (see *Policy, politics & regulation, UK FGD*) or contracts (see *Economics and finance, UK LFW*). Government and regulators build up considerable internal expertise on CCS that is independent of the industry. (see *Scaling & speed, US FGD; Economics & finance, US FGD; Policy, politics & regulation, UK FGD*). This helps with the formulation of effective policy. Government also plays a key role in facilitating the exchange of information about the technologies (see *Scaling and speed, US FGD*).

There was also clear and continuous targeted policy support for the '2nd tranche' CCS projects from the late 2010s onwards (see *Economics & finance, Scaling & speed US FGD*). Positive experience from the demonstration projects increases political confidence that CCS can play a significant role, and in spite of utility industry reluctance in the face of costly investments (see *Policy, politics & regulation, UK FGD*). This is coupled with increasing technical concerns over managing the GB electricity system with very large fractions of non-dispatchable wind power and economically inflexible nuclear power. As a result, specific attention is paid to CCS plant flexibility within the '2nd tranche' – and to overcoming technical, economic and regulatory constraints to such flexibility.

The costs of CCS technologies are competitive with the alternatives. Competition among equipment manufacturers contributes to costs being kept in check (see *Scaling and speed, UK CCGT*). Any remaining cost differential can be justified by the additional system-wide benefits which CCS provides over other low-carbon generating options, such as flexibility. The electricity market is structured so that operators of CCS plants are rewarded for these additional benefits. A supportive political, policy and financial environment allows CCS projects to be competitive and financed through a combination of debt and equity. Generating companies continue to actively choose CCS to complement their other low-carbon generation assets.

Pathway 2A – 'Momentum lost'

The key differentiating factor in this pathway, as compared to the 'On track' pathway above, is that a strong policy push leads to technical and other choices being made – which works well at first but after some time turns out to have been the wrong choices for a set of possible reasons (see Branching Point #4).

Key technical features include commercial-scale demonstration of CCS going ahead, followed relatively quickly by further deployment up to the mid-2020s. Early focus on one or a few technology variants seems to be appropriate at first (see *Economics & finance, FGD US; Variety of pathways, FR NP; Scaling & speed, UK CCGT*). However, whilst the UK Government remains supportive of CCS, technical challenges are encountered during the scaling up for '2nd tranche' projects which raises fresh concerns, including poor performance and opposition to the resulting increased costs (see below) (see *Variety of pathways, FR NP; Scaling & speed, UK CCGT; Scaling & speed, US FGD; Economic and finance, US FGD*).

The relatively bullish early policy, planning and project management also sidelines any public protests, but the protests snowball and eventually undermine political and policy support (see *Public acceptance, UK NGG*).

A supportive political, policy and financial environment allows CCS projects to be competitive and financed through a combination of debt and equity.

Concerns over public acceptance of further pipeline routes grow after very limited consultation on early routes (see *Public acceptance, UK NGG*).

In addition, there has been too little site characterisation, so that the initial tranche of storage sites cannot be followed by the addition of further sites. Alternatively, site selection turns out to have been poorly performed, with instances of CO_2 leaking, further eroding public support (see *Safe storage, UK NP*). This makes political support for CCS less emphatic – which in turn increases investor concerns over policy risk. The outcome is that CCS establishes itself as technically viable, but from the mid-2020s onwards it is not generally a preferred option as part of the low-carbon generation mix in the UK. Financial viability remains marginal.

Whilst this pathway variant loses momentum, it is not impossible that it is followed (after 2030) by a renewed policy push, based on a switch to other technology, and probably with a bigger emphasis of import of technology developed elsewhere, which is successful and leads to further deployment (see Variety of pathways, FR NP).

Implicit in this is that effective international knowledge sharing and well-functioning international supply chains mean that the UK is well prepared to benefit from the import of technology variants which have been proved to work well elsewhere (see Policy, politics & regulation, UK FGD; Variety of pathways, FR NP).

Pathway 2B – 'Slow and sporadic'

In the case of this pathway, CCS gets off to a somewhat hesitant start - see Branching Point #1, where this pathway diverges from the 'On track' and 'Momentum lost' pathways, and Branching Point #2, where it diverges also from the 'Failure' pathway. There is policy support, and experimentation across a wide range of technology variants. The key technical features include the identification of a range of potential storage sites although the fraction that is sufficiently well-characterised in a timely manner is limited. Some CO_2 pipeline routes are successfully built and operated, but progress is slower than expected. Reasons for this include delays with permitting, and in some places poorly-executed public engagement and successful opposition campaigns (see *Public acceptance, UK NGG*) rather than technical problems. Insufficient policy support undermined long-term planning and leads to a failure to facilitate collective, long-term planning and sizing for pipeline networks, which makes them unnecessarily expensive. A further contributing factor is the difficulty in coordinating and organising the different kinds of expertise needed for making a CCS system work, slowing down system integration (see *System integration, UK NGG*). During the 2010s, subdued UK economic growth focuses attention on the costs to consumers and the impact on industrial competitiveness of relatively high-cost and unproven CCS. By the mid-2010s only one or two CCS demonstration plants are operational (although further demonstration plants are under construction), which delays cost reductions from learning-by-doing.

The result is that the policy support required for '2nd tranche' CCS projects becomes politically challenging during the latter half of the 2010s. Whilst some support is forthcoming, it is only sufficient for a limited number of '2nd tranche' projects (ie those that benefit from a fortuitous combination of project-specific characteristics). Continued uncertainty about the market – in the UK and beyond – limits the ability of domestic industry to build and maintain capabilities (see *Scaling & speed, US FGD*). Faltering political will leads to policy capture by reluctant operators of unabated fossil-fuel power plants and nuclear developers, which contributes to delays (see *Policy, politics & regulation, UK FGD*).

CCS had only limited financial viability in the 2020s. Early estimates about costs turn out to be too optimistic. Cost escalation is driven by unforeseen technical problems relating to scaling (see *Scaling & speed, US FGD; Economics & finance, US FGD*) and system integration, as well as by continued controversy about risk sharing and funding. Deriving business models which provide appropriate incentives to all the actors in the CCS

Any remaining cost differential can be justified by the additional system-wide benefits which CCS provides over other low-carbon generating options, such as flexibility.

chain, and contractual arrangements which ensure the necessary cooperation and risk-sharing between actors, is also more challenging than anticipated. The costs and risks of CCS technologies (after taking account of low-carbon support mechanisms) are only competitive with the alternatives in relatively rare niches or project-specific circumstances. For example, this could include a particularly fortuitous combination of site availability, connection to a revenue-generating enhanced oil recovery project, suitability for retrofit, and availability of regional policy support. Depleted hydrocarbon fields are also more attractive than saline formations, because CO_2 storage could delay any regulated liabilities from earlier hydrocarbon exploration, and so offset moderate storage related liabilities (see *Economics and finance, UK LFW*).

As a worst case scenario, the lingering problems may be compounded by mismanaged public consultations on CCS, which lead to widespread opposition. The momentum of development may not be sufficient, and there is no more deployment from the early 2020s (see Branching Point #3).

The comparatively long period of experimentation could lead to improvements accumulating and CCS becoming more and more attractive, but the main deployment effect of that would only be seen after 2030, which is much later than current policy and industry aspirations.

Pathway 3 – 'Failure'

In this pathway, CCS encounters one or more 'show stoppers', and an insufficient reduction in several of the seven uncertainties. One possible mechanism for this is a vicious circle of problems that reinforce each other, and drain the momentum from the innovation process (see Branching Point #2).

The problems encountered include both technical and social ones. Integration, scale up and optimisation of the components in the full generation and CCS chain encounters substantially more technical challenges than anticipated. The overall impact is that the first demonstration projects incur significantly higher costs than originally envisaged. This experience is replayed in subsequent demonstration project(s) since a different suite of technologies are employed, which limits the scope for learning from the first projects (see Variety of pathways, FR NP – the early years of focus on gas cooled, graphite reactors). Moreover, those CO_2 pipeline routes that are built encounter significant public opposition. People react against the uncertainties of the novel CO_2 transporting phenomenon, as well as against clumsy attempts at consultation that do not engage with or offer any real influence and benefit to local communities

(see *Public acceptance, UK NGG*). Appraisal optimism of storage sites becomes a millstone when the true costs of re-engineering and monitoring existing hydrocarbon fields to meet stringent EU performance regulations become apparent. Few additional storage sites can then find commercial investors, and so UK storage resources remain large but commercial reserves are too small for significant impact. This contributes to public confidence evaporating.

The outcome is a failure of CCS to take off. The delays and the revealed poor performance of the CCS technologies erode support for this mitigation option, so that it is dropped from the climate policy agenda given the urgency of achieving emissions reductions. The 'big six' UK electricity generators are preoccupied with new build of nuclear, renewables and (unabated but relatively low-carbon) CCGT, and in the absence of a full CCS demonstration programme and with continued strong policy support for proven alternatives, they do not prioritise investment in CCS. Decreased use of fossil fuels also contributes to declining enthusiasm for CCS demonstration projects (even though a significant proportion of the electricity delivered in the UK is still from unabated fossil-fired plants, with the accompanying emissions which that implies). An increased diversity of UK gas delivery mechanisms and storage options reduced exposure to gas price volatility, and so reduced the perceived value of coal-fired CCS as a hedge against potentially high and volatile gas prices. Generators remained largely able to pass gas price increases through to consumers so that unabated gas remains competitive in the market and continues to provide a balancing role (even though the relatively low gas prices may not last).

It is interesting to note that few of the lessons from the uncertainties case studies appear to connect directly to this 'Failure' pathway. This may be because (with the arguable exception of *Safe storage, UK NP*) the analogues selected for study in Work Package 2 did not generally have a final outcome of failure. But, it also illustrates that quite serious challenges can be overcome with enough political will and societal support, at least over time.

Branching Points

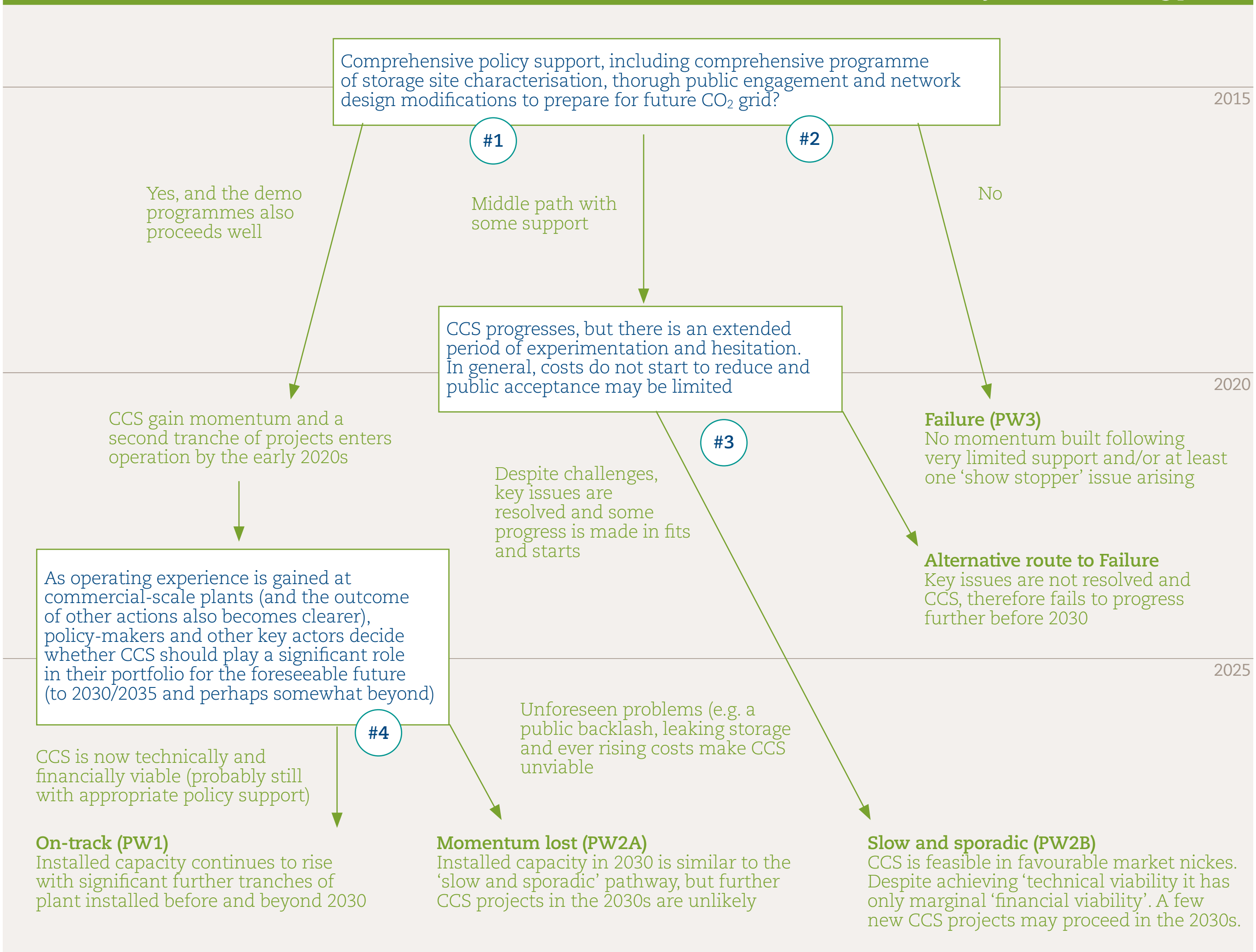
The design of the pathways, as elaborated above, helped the project team analyse the time scales involved, and suggests a set of 'branching points' where the pathways may diverge, as noted above in the pathways descriptions. Figure 4.5 summarises the four key branching points (the blue boxes) analysed. This analysis helps to highlight events that are worth monitoring, and to identify choices that need to be made.

Branching Point #1 represents a choice between strong, comprehensive early policy support or a more limited and partial approach. Branching Point #2 is where a 'Failure' pathway branches off, either as a result of political will being too weak, or through the emergence of a 'show stopper issue' of a technical or social kind.

In between these two branching points, there is the 'Slow and sporadic' pathway with a moderate level of policy support and moderately successful development work, which – with a combination of luck and prudent planning – could lead to a deployment in specific market niches the late 2020s. Branching Point #3 illustrates that there is a need for sustained success and progress unless the pathway is to grind to a halt in the 2020s.

Leftmost in Figure 4.5 is the 'On track' pathway where CCS develops the strongest momentum, through all the uncertainties improving. The final branching point, Branching Point #4, suggests that if early progress is achieved through the cutting of too many corners, and premature selection of technology variants, there is a risk of a backlash in the (late) 2020s and the momentum being lost.

4.5 Pathways and branching points



Conclusions and policy implications

CCS technologies continue to face multiple uncertainties. Events in the UK and abroad since we started our research reinforce the need to analyse these uncertainties, and possible ways in which they could be overcome.

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CCS technologies continue to face multiple uncertainties. Events in the UK and abroad since we started our research reinforce the need to analyse these uncertainties, and possible ways in which they could be overcome.

The UK government has continued its commitment to CCS, and has re-launched its demonstration programme. But at the time of writing, this has not yet resulted in a firm agreement to fund a specific demonstration project.

In autumn 2011, the planned Scottish Power demonstration at the Longannet power plant became the latest CCS project to be cancelled. The government-funded design studies for the Longannet project and a second planned project at Kingsnorth (which was also cancelled) helped to identify uncertainties in more detail. Government and industry argue that some of these uncertainties, such as those associated with capital costs, have been reduced. However, the cancellation of Longannet showed that the anticipated costs were higher than the £1bn available from public funds. Furthermore, as the recent National Audit Office report on the demonstration competition points out, it 'took place against an evolving background of economic, policy and regulatory uncertainty' (NAO, 2012: 8).

The spotlight has now shifted to other CCS projects that are now vying for funds under the new CCS commercialisation programme. Despite continuing public commitments to CCS from Ministers, and the publication of the CCS roadmap, policy uncertainties are likely to remain a particular concern for investors. The coincidence of the demonstration programme with the broader Electricity Market Reform process offers an additional source of revenue for CCS projects. However, there is some way to go before the first projects can proceed to a final investment decision. A further complication is that it is not clear which projects will receive additional funding under the EU NER 300 process.

The problems facing CCS technologies are not just apparent in the UK (Global CCS Institute, 2011). Other countries have also encountered difficulties in realising their potential. In the Netherlands and Germany, public opposition to onshore storage of CO_2 has meant that projects have been put on hold or cancelled. In the USA too, there has been slow progress with many projects, including some of those that have been promised financial support by the Federal government. There have been some positive developments too. The Dutch 'ROAD' project, which is a 250MW power plant with CCS, is coming close to a positive final investment decision. This has funding from the European Energy Recovery Plan and the Dutch government, and has not applied for the EU NER 300 process.

As noted in the introduction to this report, two full scale power plants with CCS are under construction in the United States and Canada, with a planned operational date of 2014 in each case. In both cases, public funding is being provided in the form of capital grants, and enhanced oil recovery will increase revenues.

In view of these persistent uncertainties and the slow progress with many planned projects, what insights can our research offer for policy and other decision makers? There are some important general lessons. **First, our historical case studies show that uncertainties can be reduced sufficiently for progress to be made. In some cases, they can be resolved entirely.** This offers some optimism that, given the right set of circumstances, the uncertainties that affect CCS can also be dealt with over time. However, we have also emphasised that care is needed when learning from historical contexts that differ widely from the current situation in the UK in important institutional, policy and economic respects. It is important to consider the limitations revealed by the analogues in relation to CCS, as well as the lessons they can teach us.

A second general conclusion from our analysis is that interactions between uncertainties matter. They can reinforce each other, both positively and negatively. There can also be tradeoffs between uncertainties where attempts to resolve one uncertainty could result in the exacerbation of others. This reinforces the need for a systemic analysis of emerging technologies such as CCS, to complement more specific research on particular technical, economic, policy and social issues. In the pathway analysis presented in section 4 of this report, we have highlighted how particular tradeoffs between uncertainties can make a significant difference to outcomes for CCS. For example, the variants of pathway 2 explore some of the risks of a strong policy that pushes technology development down a specific route – and how this strategy may lead to a backlash, and an eventual stalling of progress.

The problems facing CCS technologies are not just apparent in the UK (Global CCS Institute, 2011). Other countries have also encountered difficulties in realising their potential.

A third and final general lesson is that the resolution of all uncertainties is not required for CCS to be financeable in the UK. Similarly, the derailing of plans to realise the potential of CCS may not require everything to go wrong – but this could be caused by a 'critical mass' of uncertainties persisting for too long. When discussing technologies like CCS that are characterised by pervasive uncertainties, it is tempting to feel that all risks must be dealt with by government before progress can be made. But that assumption is mistaken, and forgets that the private sector routinely deals with multiple risks. **If new low-carbon technologies such as CCS are to be part of our low-carbon future, the role of policy frameworks is not to remove all uncertainties, but to identify those risks that would not be tackled in the absence of intervention.**

Maximising the probability of an 'on track' pathway to 2030

DECC has recently reframed the main aim of their policies to support CCS. The CCS commercialisation programme emphasises more clearly that full scale demonstrations are a means to an end. In some ways, this encapsulates the approach we have explored through our 'on track' pathway, in which CCS is successfully demonstrated and deployed in the period to 2030. In a recent presentation to the industry, the chief executive of DECC's Office of CCS summarised this aim as follows:

'As a result of the intervention, private sector electricity companies can take investment decisions to build CCS equipped fossil fuel power stations, in the early 2020s, without Government capital subsidy, at an agreed CfD strike price that is in line with the strike prices for other low carbon generation technologies'
(Dawson, 2011).

Our historical case studies show that uncertainties can be reduced sufficiently for progress to be made. In some cases, they can be resolved entirely.

To achieve this aim requires comprehensive policy support now. Whilst the CCS roadmap promises such comprehensive support, the commercialisation programme needs to yield firm commitments to build several full scale CCS projects as soon as possible. Without this progress, uncertainties will persist. UK investors would effectively be relying on taxpayers and/or energy consumers in other countries to support CCS across the 'valley of death' to commercial availability. In view of the difficulties being experienced internationally, this is a highly risky strategy. It would also mean that the UK would be less likely to reap other industrial development benefits.

Table 5.1 summarises some specific actions that could be taken by government and other actors to address the uncertainties we have analysed in this report. We recognise that many of these actions are already being taken as set out in the CCS roadmap. It is important to consider them as an overall 'package' – and to assess whether some of these uncertainties require more attention than they have received so far.

Table 5.1: Recommendations for policies and strategies

Key uncertainties	Recommended actions
1. Variety of pathways	The UK CCS demonstration programme should support a limited number of different technologies and fuels to enable learning about their relative merits (government).
2. Safe storage	Potential storage sites should be characterised in detail (storage site operators; government). An appropriate regime for CO_2 storage liabilities is required that strikes a balance between the public and private sectors (government; storage site operators).
3. Scaling up and speed of development and deployment	Scaling up does not only require an increase in size of individual components, but also their integration and some technology transfer from other applications (CCS equipment suppliers). Government should be prepared for technical problems and cost increases that might accompany scaling up and early deployment. Support programmes should be regularly evaluated (government). Targeted public R&D support and knowledge sharing can help to address scaling up challenges (government, CCS equipment suppliers).
4. Integration of CCS systems	The deployment of CCS should take into account the potential for regional and international pipeline networks (CCS project developers; government; pipeline companies). The social and organisational challenges of CCS system integration require appropriate business models, risk sharing arrangements, and the integration of different areas of expertise (CCS project consortia; government).
5. Economic and financial viability	Several full scale demonstration projects should be supported by public funds, and their costs published (government, developers). Financial support for CCS should include long-term contracts to reduce risks and encourage performance (government).
6. Policy, politics and regulation	A regulatory approach is unlikely to be sufficient to support CCS deployment. Mandating CCS in the near future would be premature, though this option should be kept under review (government). Substantial analytical and other capabilities are required within government to understand the impacts of policy implementation, and to negotiate with industry (government). Some flexibility is needed in the implementation of regulations and funding programmes, but this should be underpinned by a clear commitment to CCS deployment (government).
7. Public acceptance	There should be fair, transparent processes for the siting of CCS plants, CO_2 transport infrastructure and storage reservoirs (government; prospective storage operators, independent bodies).

The pathways analysis in section 4 of this report also provides a more dynamic perspective on some of the actions summarised in Table 5.1. Through this analysis, we have highlighted a number of specific 'branching points'. These are points in time where we have assumed that certain conditions have been met, and actions taken, in order for CCS deployment to continue along our 'on track' pathway. They include:

- By 2015, strong policy support for CCS demonstrations has been provided, and some are under construction. Additional actions that have been taken include thorough public engagement, a comprehensive programme of storage site characterisation and network design modifications to prepare for future CO_2 grid.
- By 2020, lessons from the first demonstration projects have been used to inform the design of policy support mechanisms for a 'second tranche' of full-scale CCS projects. Policy and stakeholder actions are assumed to lead to the initial operation of some of these second tranche CCS plants by 2020.
- By 2025, operating experience has been gained with commercial-scale plants. This has meant significant technical progress, and CCS plants are now financially viable under the prevailing market and policy framework for the electricity sector. Policy-makers and other key actors (particularly consumers) decide that CCS should play a significant role in the UK's climate change mitigation portfolio.

Navigating policy choices and dilemmas

Whilst the 'on track' pathway describes how many of the uncertainties facing CCS could be resolved in future, we have stressed that it is not meant to be a prediction or a prescription for action. The reality of policies to support CCS in the UK is likely to be much less straightforward. Our analysis has highlighted difficult choices that have to be made by government and other decision makers. In many cases, it is unclear what course of action is preferable to maximise the chances that the government's desired outcome will be achieved. Taken together, our historical case studies and pathways analysis highlight four areas where government and other decision makers have such choices to make.

1. Keeping options open or closing them down?

Our research has shown that whilst strong policy signals and support would be required to reduce uncertainty and give CCS a good start, there are also risks associated with accelerated innovation and deployment – especially if this leads to the cutting of corners. For example, it is tempting to focus efforts and resources on one technological variety early on as the French government did when picking the PWR for its nuclear programme. This may help to speed up development, but comes with increased risks of picking weak, unreliable or expensive technology. Similarly, there may be a temptation to choose convenient and cheap storage options for the first projects. If due consideration is not given to ensuring the safety and reliability of storage, there are risks of cost increases from remediation expenditure and liability payouts, as well as a backlash in public opinion. It may also be tempting to try to bypass local opinion and wide stakeholder engagement. Whilst it may well be possible to force through early projects, this strategy means that there is a risk of protests growing over time. This does not mean that strong policy push and brave choices are wrong, but it does mean that stronger push and speedier policy action have significant risks.

Our conclusion on this point is that it is too early for government and industry to close down on a particular variant of CCS technology. The National Audit Office report on the competition to build the UK's first CCS demonstration plant stated that the original focus on coal-fired plants with post combustion CCS was a source of inflexibility in the negotiations with bidders (NAO, 2012). In our view, this specific focus was a mistake. It is therefore welcome that government funding is proposed to support a wider variety of fuels and technologies. The important thing is to make sure that any projects that are supported are substantial, and allow crucial uncertainties associated with scaling up and system integration to be tackled effectively.

2. Which public policy incentives for CCS demonstration and deployment?

As we have seen from some of our historical case studies, there is often a menu of options available for public policy support of emerging technologies. An important lesson from the case of FGD technology in the United States is that a regulatory approach that effectively mandates a technology can be contentious. It will only work if the technology is sufficiently well developed and the additional costs can be passed on to consumers. CCS technologies are not yet at this stage. Any mandating of CCS now is unlikely to be effective – and would simply mean a shift of investor attention to other, less risky power generation technologies. It will not be easy to identify when the time is right to mandate CCS on fossil fuel power plants - a measure that should arguably apply to existing plants too as climate change targets begin to bite. However, the government's recent decision to guarantee that new gas-fired plants will be able to operate without CCS until 2045 is too generous (DECC, 2012). If gas continues to be the technology of choice for investors in the UK, and a large number of new plants are 'grandfathered' in this way, they could use up a significant proportion of the UK's planned carbon budget – especially in the 2030s and 2040s.

In the meantime, our research suggests that the government is right to emphasise the need for demonstration to determine whether and how many of the uncertainties we have identified can be reduced. Within this, two considerations are important. First, there is a need to ensure that any demonstrations that are built have some incentive to maximise performance in terms of costs and efficiency. Otherwise, there is a risk that demonstration becomes the end of the process rather than a step towards the government's aspiration that CCS should be competitive with other low carbon electricity generation options. The proposed UK policy approach that blends capital subsidies with revenue support via contracts for difference is therefore welcome. Second, the support of more than one demonstration will be an important risk management strategy for government and industry. Early projects should be encouraged to test different aspects of CCS including different fuels, capture technologies, and types of storage site. At this stage of development, some CCS demonstrations may not perform as well as developers hope. Failures are inevitable, so it would be very unwise to put all our public finance into one project. At the same time, there is a need to ensure that scarce funding is not spread too thinly. This reinforces the importance of co-ordinating the timing of any funding from the contracts for difference with the availability of capital funding during this Comprehensive Spending Review period. It also underlines the need to pay attention to international efforts to develop and deploy CCS technologies, and to identify the industrial development opportunities for 'UK plc'.

3. CCS deployment as a marathon, not a sprint

Our case studies of FGD and gas-fired power plant technology reinforce a general lesson from the experience of energy technology innovation – namely that innovation can take a long time. This is not a welcome feature of the innovation process given the urgency of energy policy imperatives such as the need for climate change mitigation. In addition to this, our cases have also shown that the costs of new technologies do not inevitably fall from the first day these technologies are deployed. In some cases (eg nuclear power), there is evidence that costs have done the opposite – and have progressively risen (Grubler, 2011). Whilst learning can bring down costs, our FGD case showed that costs rose for a decade in the United States before they started to fall. Technical problems were an important driver of the evolution of costs. They also affected CCGT technology as it was scaled up. It is likely that CCS technologies will also experience some teething problems as they are deployed at scale, and it would not be surprising if this led to costs which are higher than expected.

The implication of this is that there is a need for patience amongst policy makers and industry. International developments may help CCS technologies to overcome any technical problems more quickly, but this is by no means guaranteed. From a public policy perspective, it is therefore important to keep a close eye on costs and technical progress to inform decisions on whether to continue with public funding – or, if there is little sign of positive progress over a prolonged period of time, when to cut our losses and focus resources on other technologies that are more promising. Whilst the plan for an industry-led CCS Cost Reduction Task Force is welcome, it is also important for government to retain a significant independent capability to assess industry claims about costs. After all, committing substantial public funding to a particular technology such as CCS has opportunity costs. It means that less money is available to support other low carbon options – whether they are large scale power plant technologies or investments in energy efficiency and more decentralised energy supply technologies. The branching points we identify in section 4 of this report suggest when some of these important decisions may need to be made.

4. Dealing with storage liabilities

A final dilemma concerns the treatment of liabilities for stored CO_2. Our case study of UK nuclear waste management policy has highlighted how complex liability arrangements can be, and the history in that case of not dealing with liabilities effectively. The current DECC budget is testament to this, and is dominated by commitments to spend scarce resources to deal with the UK's nuclear legacy. For CCS, it is possible to learn from this experience – and to put in place more appropriate arrangements. Liabilities for investors cannot be open ended if they are to be expected to invest in CCS projects. However, future taxpayers need to be protected from an un-necessary level of exposure to these liabilities.

Our research does not provide a specific conclusion on where this balance should be struck – and how liabilities should be shared between project developers and the public sector. However, the nuclear waste management case suggests some possible features of a sound liabilities regime. Some of these features are already incorporated into the EU CCS Directive. There is a need for agreement about the length of time a storage site operator will be responsible for their site, and at what point responsibility should revert back to the state. There is also a strong case for setting up a segregated, independently managed fund which storage site operators would pay into over time. This would help to pay for the costs of long-term management that would otherwise be wholly borne by future taxpayers. In addition, the limits to liability for accidental leakages of CO_2 need to be established, with appropriate collective insurance arrangements for developers. It is therefore important that the government concludes its planned assessment of storage liabilities quickly, and builds on this to develop suitable arrangements to manage them.

Appendix A: Project interviewees

Representatives of the following organisations were interviewed to help identify and select assessment indicators that were used to analyse the historical case studies. The interviews were undertaken during the spring and summer of 2010:

- Department of Energy and Climate Change
- Environment Agency
- Scottish Environment Protection Agency
- Climate Change Capital
- European Investment Bank
- Ecofin
- Scottish and Southern Energy
- Doosan Babcock
- ARUP
- TUV NEL
- Mott MacDonald
- McGrigors
- University College London, Faculty of Laws
- An independent expert with long experience in the insurance industry

6

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