

Carbon Capture and Storage: Realising the Potential?

‘Pathways and branching points for CCS to 2030’

Work Package 3, Task 6 Working Paper

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Phil Heptonstall, Nils Markusson and Hannah Chalmers¹

Imperial College London and University of Edinburgh

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1. Introduction

Carbon capture and storage (CCS) has been receiving increasingly significant attention in recent years as a promising group of technologies for contributing to mitigating the risk of dangerous climate change. A technical and scientific community developing concepts that could be used for widespread commercial-scale use of CCS has existed for some time, e.g. (Riemer & Ormerod 1995). Awareness of CCS amongst a broader range of actors is, however, a more recent phenomenon. For example, a number of commentators argue that 2005 was a 'landmark' year for recognition of CCS in international communities of actors interested in energy and climate change issues. This was the year that the Intergovernmental Panel on Climate Change published a special report on CCS (IPCC 2005) and also that actions for CCS development were included in the final communiqué of a G8 summit hosted by the UK in Gleneagles (G8 2005).

CCS was recognised as an option that could be relevant for reducing carbon dioxide (CO₂) emissions from the UK energy sector by the Royal Commission on Environmental Pollution in 2000 in an influential report (RCEP 2000) that led to a 2003 White Paper commitment by UK Government that reducing CO₂ emissions should be an integral part of UK energy policy (DTI 2003). Although CCS was not identified as a high priority, further work was undertaken and a 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.

Since then there has been continued and steadily increasing interest in CCS within Government and from other key stakeholders. In 2010 an Office of Carbon Capture and Storage was established in the Department for Energy and Climate Change (DECC 2011a), and a summary of the evolution of the recent policy context can be found in (Heptonstall et al. 2011). The DECC web pages (<http://www.decc.gov.uk/>) also provide a useful overview of many of the recent and ongoing developments that are likely to have a significant influence on whether and when CCS is deployed at commercial or close-to-commercial scale in the UK such as:

- UK Government support for CCS demonstration;
- European schemes that might partially support large-scale CCS projects in the UK;
- Carbon capture readiness (CCR) requirements for thermal plant with capacities of 300MWe or higher; and
- Electricity market reform (often referred to as EMR).

A number of large-scale CCS project concepts have been developed both in the UK and internationally (e.g. see (SCCS 2012)), but at the time of writing very few projects have been able to build successful business cases to allow a positive final investment decision to be made.

This working paper is an output from a project funded by UKERC (the UK Energy Research Centre) that aims to identify and explore some of the key uncertainties that might have a

material impact on if and when large-scale CCS is deployed in the UK. In particular, this paper proposes a number of plausible pathways for CCS progress (or lack of progress) until 2030 and identifies key 'branching points' where a particular trajectory for CCS development may be determined as different pathways diverge from each other. The effectiveness of different criteria to determine which pathway CCS development is following can then be assessed (see the Methodology section for a more detailed explanation of the approach).

Overall, the project aims to make useful contributions to efforts to determine how both the 'viability' and 'maturity' of CCS technology can be assessed more generally. In this context, viability refers to several factors that are outlined in more detail in later sections of this paper, such as whether independent assessments suggest that CCS technology is performing well enough to compete with other options for mitigating the risk of dangerous climate change. Although maturity is related to similar concepts it is more concerned with how far progressed CCS technology appears to be along a continuum of development, rather than the more 'yes/no' assessment that might be expected if only viability is considered. It is, for instance, possible to envisage that a technology be mature in terms of its development but nevertheless not viable unless a set of economic, policy and regulatory conditions are met.

The first work package in this project proposed an assessment framework that identified seven key uncertainties and a number of related criteria that might be used to judge viability and maturity of CCS and potentially also other technologies (Markusson et al. 2012). This was complemented by activity in the second work package, which focussed on exploring lessons learned from a number of case study examples where technology development and/or deployment has faced at least one uncertainty that is in some way analogous to the uncertainties identified for CCS². The third and final work package includes two distinct, but linked, activities. A review of the context for CCS development and deployment in the UK has been undertaken (Heptonstall et al 2011) and this working paper draws together insights from that work with key results from earlier work packages.

As noted above, this working paper uses 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 focussed 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 (typically) higher deployment levels suggested by industry (see further Box 1 in Section 2).

After describing the key features of the methodology in Section 2, Section 3 outlines the pathways and Section 4 presents the branching points analysis. The paper then concludes

² See http://www.ukerc.ac.uk/support/tiki-index.php?page_ref_id=2725 for details of these case studies.

with a summary of key conclusions (Section 5). As with other analysis of this type, 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 the analysis of the conditions for both ‘successful’ and ‘unsuccessful’ CCS deployment by 2030.

2. Methodology

One of the goals of this project was to contribute to the analysis of the conditions for both ‘successful’ and ‘unsuccessful’ CCS deployment by 2030 (which is the agreed endpoint for the analysis in this project) and what actions will influence the outcome. To that end, a set of pathways (and pathway variants) were developed for CCS from now to 2030, drawing on CCS policy documents and research literature, as well as on the case studies from WP2, to explore different possible CCS futures. This analysis also serves as a test of the utility of the analytical framework from WP1, and to identify modifications needed to the set of assessment indicators of CCS uncertainty development proposed there. Finally, the analysis allows the identification of key branching points where CCS pathways might diverge (or merge), which help illustrate which aspects of CCS futures to monitor, and what actions may need to be taken to realise desired pathways. This section sets out the methodological approach used in more detail, and justifies the main choices made when designing it.

The choice of pathways should be seen as relevant and plausible (Voß et al. 2004). However, this analysis needs to acknowledge the possibility of a wide range of different outcomes, to avoid a common pitfall in scenario analysis of focussing only on the futures perceived as most desirable or plausible by the analyst (Bryngelsson & Hansson 2009). Therefore, a set of three endpoints were selected, which differed widely in the amount of CCS deployed. Three endpoints were chosen where we have either (1) reached the more ambitious policy targets for CCS deployment, see Box 1, or (2) CCS has failed to ‘deliver’ completely, or (3) an ‘in-between’ situation with a moderate level of deployment has emerged and the success of the technology ‘hangs in the balance’. The chosen end points do not distinguish between different fuel mixes, not because that does not matter, but since that was not considered to be the main focus as compared to overall deployment levels in this analysis. For a further analysis and justification for this position on fuel mixes, see Appendix 1.

To be able to elaborate the possible sequence of events to each of these three endpoints, what was essentially a back-casting (Robinson 1982) type approach was adopted, tracing possible and coherent pathways from today’s situation – with advanced plans for a first set of large-scale, integrated demonstration projects of CCS on power plants – to each of the three endpoints. Note that while all the pathways are intended to be plausible, no judgement is made as to their likelihood, since we are not in possession of the necessary crystal ball.

The elaboration of the pathways also drew on the insights from the case studies (WP2). This enabled exploration of how the case study results matter for CCS. It also ensured that the pathways descriptions covered the seven uncertainties identified in WP1. The case studies are referred to in the pathway descriptions using the notation described in Table 1 below. The case studies are available on the project web page of the UKERC website at http://www.ukerc.ac.uk/support/tiki-index.php?page_ref_id=2725.

More than one pathway route to a specified end point (level of deployment in 2030) is possible, and the analysis includes such pathway variants. A balance had to be struck between on one hand including pathway variants to incorporate the rich results from the case studies, and on the other hand to limit the number of variants to a manageable number. It was judged that pathway 2 offered the most interesting opportunities to develop variants. For pathway 3, it is enough that one ‘show-stopper’ development takes place (in one area of uncertainty), and a list of such possible developments is enough for the analysis of preconditions for successful deployment. In contrast, pathway 1 provides a future where ‘everything goes right’, and there is a virtuous cycle of improvements across the seven uncertainties. Pathway 2 offers in some ways a more interesting ‘grey area’ of simultaneous positive and negative developments and tensions between them. Therefore, the analysis includes two variants of pathway 2, both of which have the same level of cumulative CCS deployment by 2030.

Box 1 Choosing the highest CCS deployment level by 2030

As we noted in the Task 5 working paper, a wide range of CCS deployment scenarios have emerged in recent years both from analysis undertaken by or for policymakers and from the CCS industry. The most recent of these includes analysis by the UK Carbon Capture and Storage Association (CCSA) who suggest a ‘planning ambition’ of 20–30GW of CCS in the UK by 2030 in their ‘Strategy for CCS in the UK and beyond’ (CCSA 2011). This is described as an ‘ambition’ rather than a projection, and coming as it does from the trade body for the industry would be expected to present a very positive picture, although it is broadly consistent with the aspiration in the 2009 report from DECC’s Advisory Committee on Carbon Abatement Technologies (ACCAT) of 5GW of coal-fired CCS by 2020 (ACCAT 2009). Even so, these numbers do sit at the very top end of the ranges commonly seen in other sources (see below), and possibly inconsistent with plausible CO₂ pipeline build rates, and the concerns raised by some over the time required to accurately characterise potential CO₂ storage sites (Booer 2011;Cooper 2011).

Since the ‘On Track’ pathway is based on policy ambitions rather than the industry ambitions, it is interesting to consider the DECC and CCC views:

- The Poyry (2009) work which was used to inform the DECC 2050 Pathways Analysis (DECC 2010) suggested that 20GW of CCS by 2030 was ‘only just plausible’, with a ‘realistic maximum high deployment path’ of 16.5GW (corresponding to their ‘Level 3 trajectory’. Even the 10GW corresponding to their ‘Level 2 trajectory’ was described as a ‘considerable challenge’ (although it should be recognised that achieving the UK’s long-term carbon reduction aspirations will be a considerable challenge whatever the mix of technologies).
- The CCC’s 4th Carbon Budget report (CCC 2010b) presented a figure of 15.2 GW of CCS by 2030 under their 80% CO₂ reduction scenario.
- The ‘central scenario’ in the CCC’s 2011 Renewable Energy Review (CCC 2011) has a figure of 10.7 GW of CCS plant by 2030.
- The 2011 Carbon Plan suggests a range between 3GW and 20GW by 2030 (DECC 2011c).

These different views do not, on the face of it, appear to represent a trend towards higher estimates for CCS deployment, and are arguably somewhat at odds with the CCSA and (earlier) ACCAT views. If anything, there appears to be a *reduction* in policy aspirations for CCS deployment by 2030. The endpoint for the ‘On Track’ pathway therefore assumes a level of CCS deployment of *up to* 15GW by 2030.

To choose these variants, we drew on the analysis of the case studies from WP2 and the analytical framework from WP1. The seven uncertainties are related in multiple ways, and the analytical framework set out linkages (Markusson et al 2012). The linkages either represent synergies between uncertainties, where improvement in one makes improvement in another more likely (or conversely deterioration in one dimension leads to problems relating to another uncertainty). As well as these virtuous (and vicious) cycle (Hekkert et al 2007) type dynamics, there are also instances of tensions between uncertainties, where improvement on one creates problems somewhere else. This kind of linkage is especially important to analyse, as it indicates situations where trade-offs have to be made between different lines of action, and therefore is especially challenging for decision-makers. Three trade-offs were identified from the case studies:

1. Early or late selection (lock-in) among technology variants
2. Choosing the cheapest or the safest storage
3. Early public engagement or 'letting sleeping dogs lie'

Of these, the first one offered the best possibility of integrating results from the case studies, and was chosen for the variants for pathway 2. The pathways and variants are presented in the next section.

Table 1 ‘Uncertainties’ case studies

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

For the characterisation of the different pathways and variants, it was necessary to strike a pragmatic balance between including all possibly relevant kinds of events (incl. for example cost developments, public acceptance or protest, regulatory developments, etc.) and keeping the task manageable. Moreover, the pathways need to characterise not just CCS technology in itself, but the context in which it develops, including primarily the development of the energy system and of energy and climate policy (Geels 2004; Winskel et al. 2008). The pathways were elaborated in terms of the following limited set of key characteristics:

- technology choices (capture technologies and share of retrofitting, transport technologies and infrastructure designs, storage options used)

- technology performance (energy penalty/costs and accumulated experience of reliable operation)
- relation to wider energy system development (mainly the development of other – competing and complementary – energy supply technologies, incl. nuclear and wind)
- energy and climate policy development

Much of the case studies concern events that happened in different governance contexts: state-owned regimes, regulated monopolies etc. This analysis includes pathways where the state takes on a more interventionist role than is currently the case, extrapolating from current Energy Market Reforms, but not futures that include far-reaching nationalisation and or very strongly centralised planning of the energy system.

The set of pathways and variants was used to further develop the set of assessment indicators presented in WP1. For each uncertainty and assessment indicator of the framework, the pathways were compared to see where they differ. Where two pathways diverge with respect to any of the indicators, this was identified as part of a branching point (Foxon et al. 2012) between the pathways. The branching points can occur at different times in the period to 2030, and the project team chose to carry out the comparison at five year intervals. This way, a set of four key branching points were identified, with implications for choices to be made by policy makers and other decision makers. The branching points analysis helped identify a few further assessment indicators that can usefully be added to the framework developed in WP1.

This methodology allows the analysis of the conditions for both ‘successful’ and ‘unsuccessful’ CCS deployment by 2030. The indicative cumulative deployment of CCS in the UK for the pathways and variants are shown in Figure 1 below. Note that these deployment levels are not an output from a modelling exercise – they result from the construction of credible assumptions about deployment within narratives for each pathway and variant, to provide a context in which the lessons from the WP2 case studies can be assessed.

The final set of pathways selected for the analysis were as follows:

Pathway 1 – ‘On track’. A broadly successful but not improbably high level of CCS deployment, where CCS has, by 2030, an established position as a technically proven and financially viable option in the suite of low carbon electricity generation technologies.

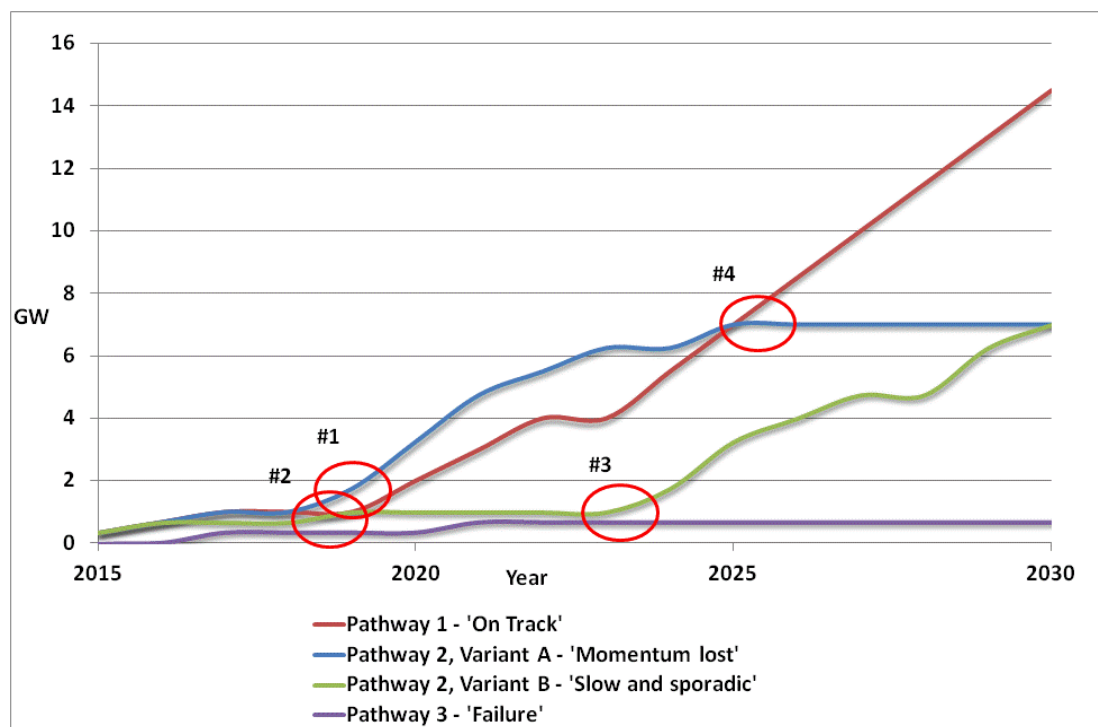
Pathway 2, Variant A – ‘Momentum lost’. Commercial scale demonstration of CCS does go ahead, and is followed relatively quickly by further deployment up to the mid-2020s. By this time, CCS has established itself as technically viable, but from the mid 2020s onwards it is not generally a preferred option 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, and that this is 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 niches only.

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

Figure 1 Indicative cumulative CCS deployment under the four pathways/variants



In the next section, the pathways and variants will be presented and described in more detail, to be followed by a section on the analysis of branching points and revision of the assessment indicators.

3. CCS Pathways

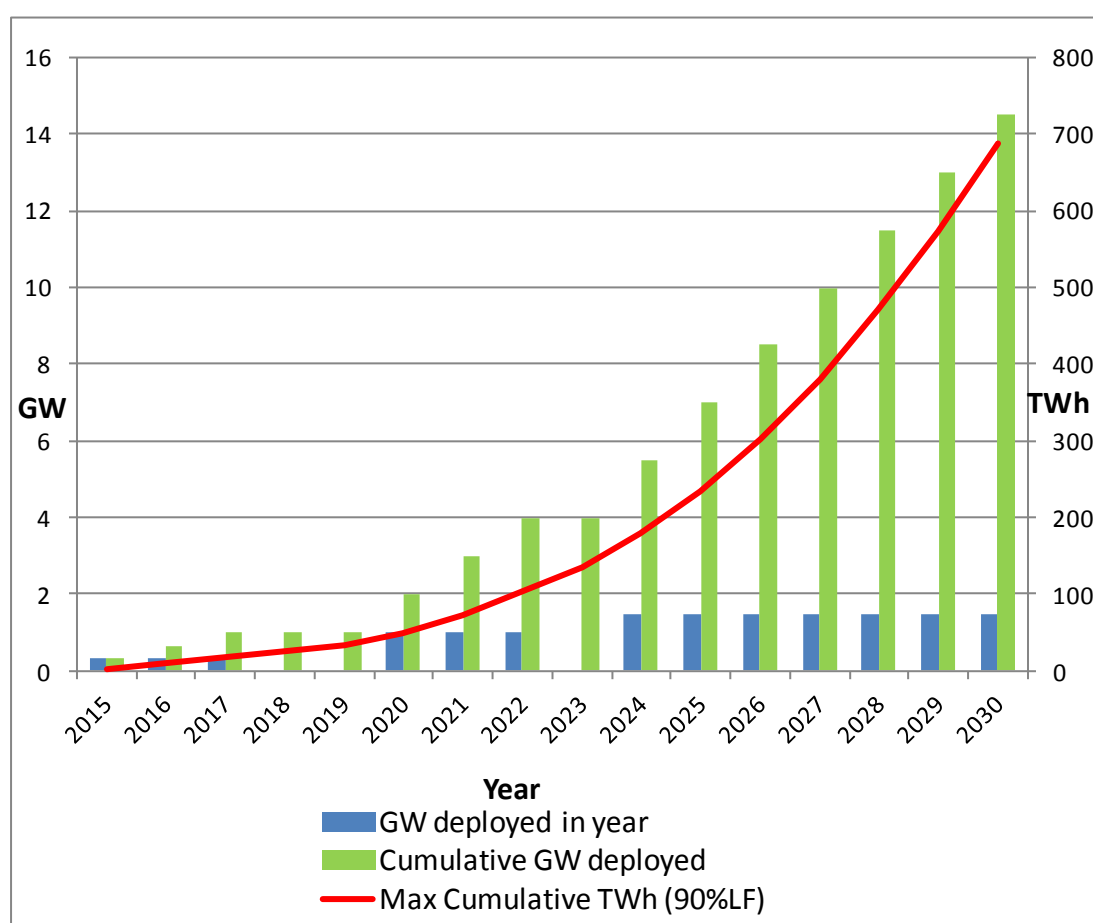
Pathway 1 – ‘On Track’

‘A high but plausible level of CCS deployment by 2030, based on policy ambitions’

Key features

‘On Track’ suggests a broadly successful but not improbably high level of CCS deployment, where CCS has, by 2030, an established position as a technically proven and financially viable option in the suite of low carbon electricity generation technologies. The indicative deployment of, and maximum cumulative electricity generation from, CCS plant is summarised in Figure 2 below. The pathway characteristics are described in the sections that follow.

Figure 2 ‘On Track’ deployment and annual electricity generation from CCS plant



Our definition of ‘technically proven’ is taken to mean that CCS technologies have been shown to work reliably at commercial power plant scale, and that Original Equipment Manufacturers (OEMs) are willing to provide performance guarantees which are acceptable to prospective customers. Implicit in this is that:

- The UK demonstration programme has been successful, and/or that experience in other countries has been positive. Part of this is good judgement and part is luck. The choices made to focus on a limited range of promising technology varieties turned out to be justified and their technical difficulties manageable. Up-scaling is facilitated by modular designs (see *Scaling & speed, US FGD*).
- Sufficient potential storage sites have been identified and characterised.
- A storage liability regime has been 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.).
- CO₂ pipeline routes have been successfully built and operated, and any required new routes identified. This is facilitated by re-use of natural gas infrastructure (see *System integration, UK NGG*). Early project designs have taken the possibility for regional hubs, as well as international inter-connections into account (ibid).
- The permitting process for CCS projects has proceeded relatively smoothly, and all necessary permits have been granted without undue delay.
- Early engagement with local communities have led to modified projects and allayed fears (see *Public acceptance, UK NGG*) and highlighted local benefits.

It is recognised that these technical issues also bear upon the financial viability issues described below, since any technical concerns will have a direct effect on financiers’ and project developers’ willingness to invest in CCS projects (Heptonstall et al 2011). In addition, ‘financially viable’ is taken to mean that CCS projects can be funded through normal project finance avenues e.g. they do not require companies to finance such projects wholly ‘on balance sheet’. Implicit in this is that:

- The cost of CCS technologies (after taking account of policy support mechanisms) is competitive with the alternatives. As we know, competitiveness is not just about having comparable costs per unit of output – support mechanisms must also take account of differences in the timing and nature of costs between different forms of low carbon generation (Gross et al. 2010). This will likely require targeted support until technology is more mature – likely at least during the first decade after first large scale operation (see *Scaling & speed, US FGD*). Competition among manufacturers also contributes to costs being kept in check (see *Scaling & speed, UK CCGT*).
- The policy support may take the form of selective incentives (see *Policy, politics & regulation, UK FGD*) or contracts (see *Economics & finance, UK LFW*) (Alternatively, the power market could be seriously reformed towards a much more dirigiste mode.)
- Any remaining cost differential can be justified by the additional system-wide benefits which CCS may provide over other low-carbon generating options, such as flexibility, and the electricity market is structured so that operators of CCS plants can be rewarded for these additional benefits.

- Generating companies actively choose CCS to complement their other low carbon generation assets.
- Government and regulators build up internal expertise on CCS (see *Scaling & speed, US FGD; Economics & finance, US FGD; Policy, politics & regulation, UK FGD*), and facilitate the exchange of information about the technologies (see *Scaling & speed, US FGD*).

Developments in the electricity market, and the financial and political context

This pathway makes the following assumptions about developments in the UK electricity market during the 2010s and 2020s, and the wider financial and political context:

- Following the financial crises of the late 2000s, the UK economy returns to 'normal' growth levels during the latter half of the 2010s.
- The UK continues to remain within its carbon budget, with the further implication that the international context is broadly supportive of CO₂ emissions mitigation action.
- The policy support mechanisms for renewables and nuclear described in the EMR White Paper are translated successfully into legislation during 2014 as planned.
- The transitional arrangements for renewables do not create a significant hiatus in investment for these technologies, and a number of Round 3 offshore wind developments are underway by 2020, although the technological challenges of going further offshore and into deeper water are substantial and the cost reductions envisaged are not delivered as quickly as anticipated.
- The two new EPR nuclear plants currently under construction (Olkiluoto 3 and Flamanville 3) experience continued delays and further cost overruns and do not come into operation until the second half of the 2010s. Nevertheless, construction work begins on new nuclear projects in the UK around 2015, with the first two plants operational by the early 2020s. Whilst these first new nuclear power stations in the UK for nearly 30 years represent a significant step, there is no sense of a nuclear 'gold rush', and investors remain cautious.
- There is clear and continuous policy support for the '2nd tranche' CCS projects from the late 2010s onwards (see *Economics & finance, US FGD*) as positive experience from the demonstration projects increases political confidence that CCS can play a significant role, and in spite of utility industry resistance to the 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. The supportive political, policy and financial environment allows CCS projects to be financed through a combination of debt and equity.
- Deployment could be driven through a mandate or emissions performance standard, but would have to be combined with financial incentives (see *Policy, politics & regulation, UK FGD*).
- By the early 2020s, the continued high costs of offshore wind and nuclear, coupled with a successful CCS demonstration programme and cost reductions beginning to emerge from '2nd tranche' CCS projects, mean that CCS technologies are considered to be

competitive with other low-carbon options – reinforcing the case for policy support for ‘3rd tranche’ projects, and allowing these projects to be funded through the EMR Contract for Difference (CfD) support mechanism, in the same way as nuclear and renewables.

- An increased diversity of UK gas delivery mechanisms, storage options (and possible contributions from unconventional gas reserves) reduces concerns over medium to long-term gas supplies.

Timing of CCS deployment up to 2030

The current DECC plan is to review the demonstration programme in 2018, to inform decisions on the appropriate support for CCS deployment (DECC 2011b). It is recognised that some of the measures in the EMR White Paper may support CCS demonstration projects, in addition to the support available through the demonstration programme and the NER 300 process. However, for this pathway we assume that the value of support under the Feed-in Tariff for medium term (and beyond) commercial deployment of CCS may not be finalised until the operational experience from the demonstration projects is available. This would suggest that it is very unlikely that any ‘2nd tranche’ CCS plants will be under construction or operational before 2018, on the premise that the final investment decision for these plants will not be possible until the support available is fully understood. We would however expect developers to have a number of projects in earlier stages of development during the mid to late 2010s (‘development’ in this context means the process of putting together the technical and financial plans for a project). This suggests that the earliest any ‘2nd tranche’ plants might be operational is by the early-to-mid 2020s, with ‘3rd tranche’ plants following in the period up to 2030, as described in the table below:

Table 2 ‘On Track’ timeline

Year(s)	Progress	Cumulative deployment
Mid-to-late 2010s	1GW of demonstration plants operational.	1GW
Late 2010s	‘2 nd tranche’ projects in early stage of planning, but no final investment decision.	1GW

Year(s)	Progress	Cumulative deployment
Early-to-mid 2020s	3GW of '2 nd tranche' plants operational. '3 rd tranche' plants in development.	4GW
Mid 2020s – 2030	1 or 2 '3 rd tranche' plants with combined capacity of around 1.5GW comes into operation each year over a period of 6 or 7 years.	Up to 15GW
2030	Plans for further CCS plants are actively under consideration by generating companies.	Up to 15GW

The 'On Track' pathway therefore represents a CCS deployment level of up to around 15GW by 2030, with gas-fired plant dominating (see Appendix 1 for the rationale for this dominance). This also seems consistent with an assumption that strong progress is made in deploying renewables and nuclear which limits the use of fossil fuels in power generation – which seems a reasonable view given that many commentators suggest that the EMR appears to be focussed on these technologies (Heptonstall et al 2011). Of course, it is possible that if renewables and/or nuclear deployment does not proceed in line with aspirations then there may be very strong incentives to increase CCS deployment above the level suggested here (for example by fitting CCS to capture-ready CCGT plants) in order to meet the 2030 carbon reduction aspirations, assuming of course that political commitment to these targets does not weaken.

Nevertheless, even achieving up to around 15 GW by 2030 will require very strong policy support, and it is not clear at this stage if the EMR will deliver this for CCS. It is certainly the case that the CCSA don't appear to think that it sends a strong enough message (CCSA 2011), although there are still some important details of the support mechanism that have yet to be decided upon which could have a significant impact, either positive or negative (Heptonstall et al 2011). Another important point to note is that if CCS is deployed successfully at this level (particularly at the upper end of the range), it may increase the likelihood that some of the CCS plants will run at mid-merit (which we have not attempted to reflect in the 'maximum generation' line on Figure 3). This would in turn increase cost per unit of output and also perhaps drive technology choice since some technologies may be better suited (either technically or economically) to part-load running. Policy must therefore explicitly consider where CCS plants will sit in the merit order because that will drive the support and market structure required.

Pathway 2, Variant A – ‘Momentum lost’

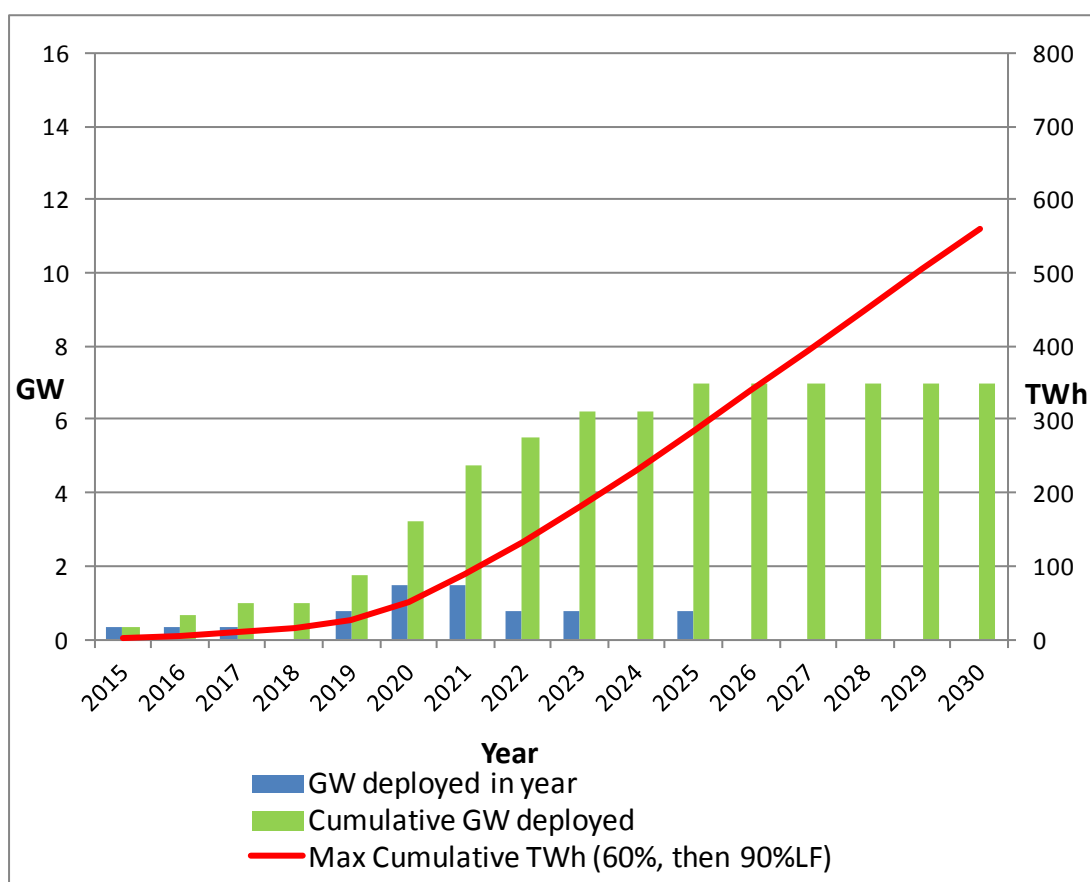
‘Timely CCS demonstration and follow-on deployment, then peters out’

Key features

‘Momentum lost’ suggest that commercial scale demonstration of CCS does go ahead, and is followed relatively quickly by further deployment up to the mid-2020s. Early focus on one or a few technology variants turns out to be fortunate (see *Economics & finance, FGD US; Variety of pathways, FR NP; Scaling & speed, UK CCGT*). 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 remains marginal.

Whilst the UK Government remains supportive of CCS, technical challenges encountered during the scaling up for ‘2nd tranche’ projects raise fresh concerns, and opposition to the resultant increased cost. Concerns over public acceptance of further pipeline routes (after very limited consultation on early ones, see *Public acceptance, UK NGG*) and storage sites (after an event with limited leakage), make political support for CCS less emphatic – which in turn increases investor concerns over policy risk (see below). The indicative deployment of, and maximum cumulative electricity generation from, CCS plant is summarised in Figure 3. The pathway characteristics are described in the sections that follow.

Figure 3 'Momentum lost' deployment and annual electricity generation from CCS plant



One outcome to note is that whilst both Pathway 2 variants arrive at the same 2030 endpoint in terms of GW deployed, and 'Momentum lost' suggests that CCS is moribund by that date, this pathway does actually deliver more cumulative CCS-derived TWh by 2030 than 'Slow and sporadic' (560 TWh vs. 307 TWh), because of the initial earlier deployment.

Our definition of 'technically viable' for this pathway variant is taken to mean that CCS technologies have been shown to work at power plant scale, although OEMs are cautious about providing normal performance guarantees. Implicit in this is that:

- The UK demonstration programme has been generally successful, and experience from demonstration plants in other countries has also been positive.
- However, scale-up of the components in the full generation and CCS chain encounters more technical challenges than anticipated. The overall impact is that '2nd tranche' CCS projects incur higher costs and lower availability than originally envisaged, increasing investor concerns (see below). Note that this is reflected in Figure 3 by reducing average plant load factors to 60% up to 2020, although this makes very little difference to the cumulative CCS generation by 2030.

- A range of potential storage sites, sufficient to support several GW of CCS generation have been identified and characterised. However, identification and characterisation of further sites is very limited.
- Some CO₂ pipeline routes have been successfully built and operated, albeit in UK regions which may take a relatively 'more accepting' view than the norm. As the number of CCS projects increases, pipelines are required in 'less accepting' regions, leading to increased public opposition.

'Marginal financial viability' is taken to mean that prospective CCS projects do not generally offer a compelling investment opportunity (particularly when compared to other power generation options). Implicit in this is that:

- The experience of '2nd tranche' project costs increases and reduced plant availability means that the cost of CCS technologies (after taking account of any technology-neutral low carbon support mechanisms) is not generally competitive with the alternatives.
- Any additional system-wide benefits which CCS may provide over other low-carbon generating options, such as flexibility, are not yet required as existing unabated plant continues to fulfil this role, so the market is not structured to allow operators of CCS plants to be rewarded for these benefits. The limited level of CCS deployment in this pathway (see below) does at least mean that all CCS plants are typically running at or near baseload (where technical availability allows) so there is no specific concern over how CCS plants could be rewarded sufficiently when running mid-merit.
- Deriving business models which provide appropriate incentives to all the actors in the CCS chain, and contractual arrangements which ensure the necessary cooperation and risk-sharing between actors, is more challenging than anticipated.
- Whilst generating companies continue to assess potential CCS projects as part of their medium and long term strategy, any such projects considered from the early 2020s onwards fail at a relatively early stage in a company's internal project review process as costs and risks (both technical and policy) outweigh prospective returns.

Developments in the electricity market, and the financial and political context

This pathway makes the following assumptions about developments in the UK electricity market during the 2010s and 2020s, and the wider financial and political context:

- Following the financial crises of the late 2000s, the UK economy returns to growth (albeit subdued) during the latter half of the 2010s.
- The UK continues to remain within its carbon budget, with the further implication that the international context is broadly supportive of CO₂ emissions mitigation action.
- The policy support mechanisms for all low carbon generation (including CCS) described in the EMR White Paper are translated successfully into legislation during 2014 as planned.
- The transitional arrangements for renewables create something of a hiatus in investment for these technologies, and the two new EPR nuclear plants currently under construction (Olkiluoto 3 and Flamanville 3) are not operational until the late-2010s. The combined

effect is to prompt policy makers and investors to consider CCS more quickly and more aggressively than would otherwise be the case.

- Relatively bullish early policy, planning and project management sidelines any public protests, but the protests snowball and eventually reach parliament undermining policy support (see *Public acceptance, UK NGG*).
- Too strong push also leads to premature choice of technology, leading to poor performance and high costs (see below) (see *Variety of pathways, FR NP; Scaling & speed, UK CCGT; Scaling & speed, US FGD; Economic and finance, US FGD*). Also site selection turned out to have been hasty, with instances of CO₂ leaking, further eroding public support (see *Reliable storage, UK NP*).
- The relatively aggressive roll-out and scale-up of '2nd tranche' projects encounters technical problems which result in cost increases and reduced reliability (availability) of these plants in their early years of operation. This has the effect of reducing policy makers and investor confidence, and the general view from 2025 onwards is of the need to 'take stock' of CCS deployment to date and allow the '2nd tranche' plants to 'prove themselves' before further policy support for any '3rd tranche' plants.
- The increased diversity of UK gas supplies, delivery mechanisms and storage options that are in place by the early 2020s reduces exposure to gas price volatility, so reducing the perceived value of coal-fired CCS as a hedge against gas price volatility. Generators remain largely able to pass the marginal cost of electricity generation at NGCC plants through to consumers. Hence, gas price increases are passed through to consumers, as are any significant increases in costs for emitting CO₂, so unabated gas remains competitive in the market and continues to provide a balancing role.

Timing of CCS deployment up to 2030

This pathway assumes that two or three demonstration plants secure funding from DECC (and possibly NER300 funding), agree contractual terms and proceed, and come into operation by 2017. Clear support for '2nd tranche' plants through the EMR policies encourages progress with further, larger projects, and a further 5–6GW is deployed by the mid 2020s. The rapid scale up required for these '2nd tranche' plants creates a range of technical issues which whilst not insurmountable, do increase costs and affect the availability of these plants in their early years of operation. This leads to a reduction in enthusiasm for further CCS plants, and no more plants are in development during the second half of the 2020s. The result is that total CCS deployment by 2030 is around 6–7GW.

As far as the fuel and technology mix is concerned, this pathway is based on the same observations and logic as for the 'On Track' pathway (see Appendix 1). At the time of writing, current UK Government policy for commercial-scale demonstration at power plants is that a range of CCS (and especially CO₂ capture) technologies will be included in the early stages of this programme, potentially including both coal and gas-fired power plants. As in the 'On Track' pathway, it does not seem sensible to make specific assumptions about the technology mix e.g. whether pre- or post-combustion capture dominates, particularly given the relatively limited deployment of post-demonstration plants envisaged in this pathway.

Table 3 ‘Momentum lost’ timeline

Year(s)	Progress	Cumulative deployment
Mid-to-late 2010s	Up to 1GW of demonstration plants operational.	Up to 1GW
Early-to-mid 2020s	Up to 5–6GW of ‘extended 2 nd tranche’ plants operational.	Up to 6–7GW
Late 2020s	No further plants in development	Up to 6–7GW
2030	No ‘3 rd tranche’ plants in development	Up to 6–7GW

Whilst this pathway variant ‘peters out’, 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, 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 technology variants that turned out to work well (see *Policy, politics & regulation, UK FGD; Variety of pathways, FR NP*). It is debatable how useful it is to start investing seriously in CCS as late as in the 2030, if it is intended to be a stop-gap solution to buy time to develop other low carbon technologies. If, however, CCS is seen as a longer-term solution, for fossil based production, biomass CCS, air capture, then it makes sense.

Pathway 2, Variant B – ‘Slow and sporadic’

‘CCS demonstration delayed and deployed relatively slowly thereafter’

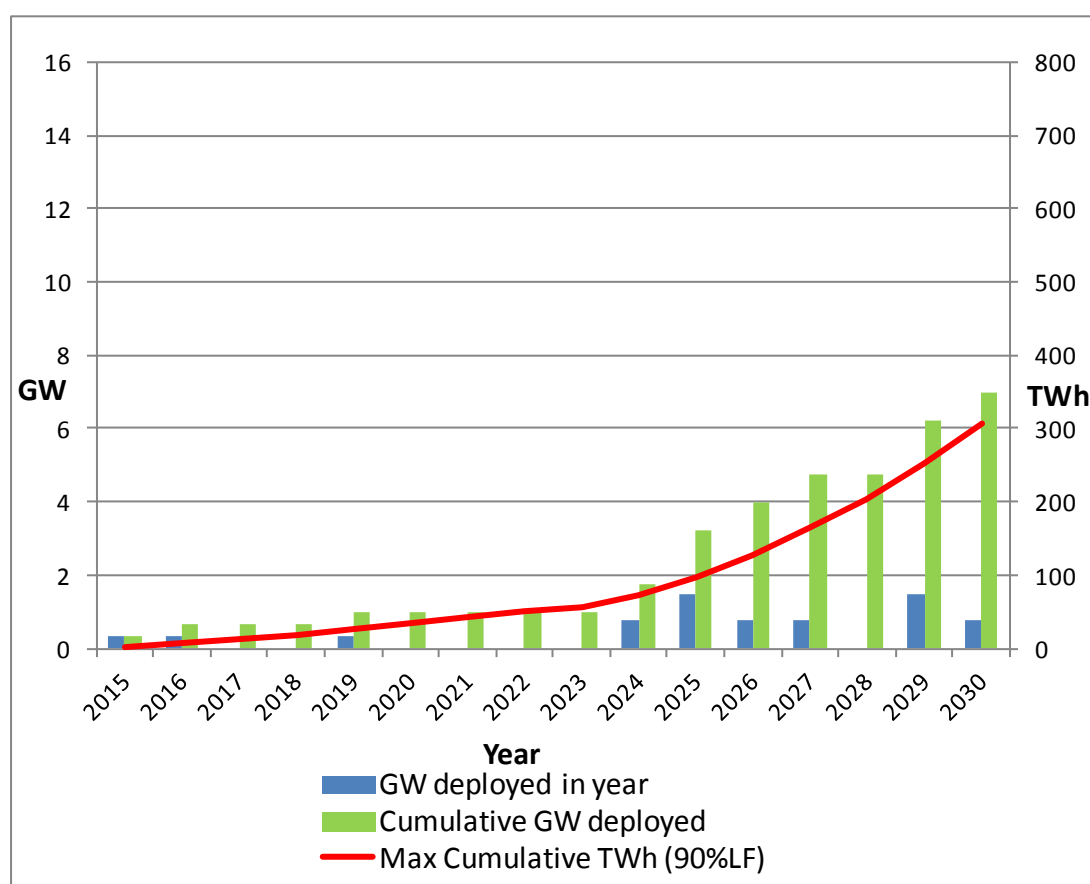
Key features

‘Slow and sporadic’ suggest that commercial scale demonstration of CCS does go ahead, and there is limited further deployment up to 2030 following the initial demonstration programme. 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.

Whilst the UK Government remains supportive of CCS, opposition to the cost (of CCS and other low carbon options), and issues of public acceptance over pipeline routes and storage sites, makes political support for CCS less emphatic – which in turn increases investor concerns over policy risk (see below). The indicative deployment of, and maximum cumulative electricity generation from, CCS plant is summarised in Figure 4 below. The pathway characteristics are described in the sections that follow.

Figure 4 ‘Slow and sporadic’ deployment and annual electricity generation from CCS plant



Our definition of ‘technically viable’ is taken to mean that CCS technologies have been shown to work reliably at power plant scale, although OEMs are cautious about providing normal performance guarantees. Implicit in this is that:

- The UK demonstration programme has been generally successful, albeit progress has been slower than hoped for. Experience in other countries has also been positive, but as in the UK, slower than hoped.

- Integration, scale-up and optimisation of the components in the full generation and CCS chain encounters more technical challenges than anticipated. The overall impact is that early CCS projects incur higher costs than originally envisaged, increasing investor concerns (see below).
- A contributing factor is also 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*).
- A range of potential storage sites have been identified although the fraction that is sufficiently well-characterised is limited.
- Some CO₂ pipeline routes have been successfully built and operated, but progress is slower than expected possibly due to delays with permitting, in some areas characterised by poorly executed public engagement (see *Public acceptance, UK NGG*) and resourceful communities, rather than technical problems. Delays may have also resulted from insufficient policy support to facilitate collective planning and sizing for pipeline networks.

‘Marginal financial viability’ is taken to mean that prospective CCS projects do not generally offer a compelling investment opportunity (particularly when compared to other power generation options). Implicit in this is that:

- Current estimates about costs turn out to have been 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. The cost of CCS technologies (after taking account of any technology-neutral low carbon support mechanisms) is only competitive with the alternatives in certain (relatively rare) niches or project-specific circumstances e.g. a particularly fortuitous combination of site availability, connection to a revenue-generating enhanced oil recovery project, suitability for retrofit, availability of regional policy support. Depleted hydrocarbon fields might also be more attractive than saline formations, because CO₂ storage could delay any regulated liabilities from earlier hydrocarbon exploration, and so offset moderate storage related liabilities (see *Economics and finance, UK LFW*). It may also be that CCS is used mainly where there are fewer options, like on industrial processes.
- Niche deployment may have an impact on the technical variety of CCS solutions as some variants may fit better to the prevailing project-specific circumstances. This may mean that the CCS technology adopted by such projects may not be the same as those adopted in other countries with different national policies or circumstances, which in turn may have important implications for learning, standardisation and cost reduction.
- Whilst this project focuses on CCS on fossil fuelled power, it is worth noting that a niche dominated deployment could perhaps be dominated by niches outside power production. CCS may face less competition as a mitigation option in some industrial processes, or needed in CO₂ negative systems together with biomass based production.
- Any additional system-wide benefits which CCS may provide over other low-carbon generating options, such as flexibility are not yet required as existing unabated plant continues to fulfil this role, so the market is not structured to allow operators of CCS

plants to be rewarded for these benefits. The limited level of CCS deployment in this pathway (see below) does at least mean that all CCS plants are typically running at or near baseload so there is no specific concern over how CCS plants could be rewarded sufficiently when running mid-merit.

- Deriving business models which provide appropriate incentives to all the actors in the CCS chain, and contractual arrangements which ensure the necessary cooperation and risk-sharing between actors, is more challenging than anticipated. (Cf. liability risks above, potentially making saline formations especially financially unattractive, (see *Economics and finance, UK LFW*).
- Whilst generating companies continue to assess potential CCS projects as part of their medium and long term strategy, such projects often fail at a relatively early stage in a company's internal project review process as costs and risks (both technical and policy) are expected to outweigh prospective returns.

Developments in the electricity market, and the financial and political context

This pathway makes the following assumptions about developments in the UK electricity market during the 2010s and 2020s, and the wider financial and political context:

- Following the financial crises of the late 2000s, the UK economy returns to growth (albeit subdued) during the latter half of the 2010s.
- The UK continues to aspire to remain within its carbon budget, with the further implication that the international context is broadly supportive of CO₂ emissions mitigation action.
- The policy support mechanisms for renewables and nuclear described in the EMR White Paper are translated successfully into legislation during 2014 as planned.
- The transitional arrangements for renewables do not create a significant hiatus in investment for these technologies, and a number of Round 3 offshore wind developments are well underway by 2020, with the offshore wind supply chain reaching a sustainable critical mass, with clear evidence of cost reductions emerging.
- The two new EPR nuclear plants currently under construction (Olkiluoto 3 and Flamanville 3) are completed and operational by the mid-2010s, reducing investor uncertainty, and giving fresh impetus to the new nuclear programme in the UK.
- 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 and further demonstration plants are under construction so it is too early for cost reductions to emerge). The result is that the policy support required for '2nd tranche' CCS projects becomes politically challenging during the latter half of the 2010s. Whilst support is forthcoming, it is only sufficient for a limited number of '2nd tranche' projects (i.e. those that benefit from the fortuitous combination of project-specific characteristics described above). 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 and delay (see *Policy, politics & regulation, UK FGD*).

- In the absence of a policy context to the contrary, most of the ‘big six’ UK electricity generators continue to be preoccupied with new build of nuclear, renewables and (unabated but relatively low carbon) CCGT, and do not prioritise investment in CCS.
- An increased diversity of UK gas delivery mechanisms and storage options reduces exposure to gas price volatility, so reducing the perceived value of coal-fired CCS as a hedge against gas price volatility. Generators remain largely able to pass the marginal cost of electricity generation at NGCC plants through to consumers. Hence, gas price increases are passed through to consumers, as are any significant increases in costs for emitting CO₂, so unabated gas remains competitive in the market and continues to provide a balancing role.

Timing of CCS deployment up to 2030

This pathway assumes that one or two demonstration plants secure funding from DECC, agree contractual terms and proceed, albeit delays mean that they are not operational until 2015–2016 (two years later than planned when the demonstration programme was announced). Progress is hampered by difficulties in coordinating the demonstration programme and NER300 funding with as yet unclear UK policy support. Later demonstration projects are also brought to financial close but construction work does not begin until 2014 (again, two years later than planned). These plants are not operational until 2018 or later so there is little accumulated operating experience on which to base plans for the ‘2nd tranche’ of CCS until the early 2020s (although if other countries are able to move more quickly their experience may be useful). Construction work on the first of the ‘2nd tranche’ plants does not begin until the early-to-mid-2020s. The ‘2nd tranche’ phase is extended throughout the late 2020s (in comparison to the ‘On Track’ pathway) since there is insufficient intensity of activity to move the industry to the ‘3rd tranche’ stage until the very end of the 2020s or the early 2030s. The result is that CCS plants are being built throughout most of the 2020s but the project pipeline is sporadic, meaning that total deployment by 2030 is around 6–7GW.

Whilst no further CCS projects having reached financial close at that time, we would however expect developers to have a number of projects in earlier stages of development during the late 2020s, so that projects are in position for final investment decisions during the 2030s (as before, ‘development’ in this context means the process of putting together the technical and financial plans for a project). Of course, if CCS costs were to fall by the early 2030s then such projects may go on to be approved and built during the 2030s.

As far as the fuel and technology mix is concerned, this pathway is based on the same observations and logic as for the ‘On Track’ pathway (see Appendix 1). At the time of writing, current UK Government policy for commercial-scale demonstration at power plants is that a range of CCS (and especially CO₂ capture) technologies will be included in the early stages of this programme, potentially including both coal and gas-fired power plants. As in the ‘On Track’ pathway, it does not seem sensible to make specific assumptions about the technology mix e.g. whether pre- or post-combustion capture dominates, particularly given the relatively limited deployment of post-demonstration plants envisaged in this pathway.

Table 4 ‘Slow and sporadic’ timeline

Year(s)	Progress	Cumulative deployment
Late 2010s	Up to 1GW of demonstration plants operational.	Up to 1GW
Mid-to late 2020s	Up to 5–6GW of ‘extended 2 nd tranche’ plants operational.	Up to 6–7GW
2030	Some ‘3 rd tranche’ plants in the early stages of project development, prior to final investment decision.	Up to 6–7GW

Pathway 3 – ‘Failure’

‘Zero CCS deployment (excluding demonstration plants)’

Key features

Since this pathway has no CCS deployment beyond a limited demonstration programme, the key features are focussed on the possible reasons for failure, and these can be broadly categorised as being either specific to CCS or related to wider developments in the electricity market, and the financial and political context. The CCS-specific reasons are dealt with in this section and the wider context issues are dealt with in a following section. This ‘Failure’ pathway may result from either one of the following issues becoming a ‘show stopper’ or, perhaps more likely, a combination of acute problems in a number of areas having the same cumulative effect:

- The first project(s) from the UK demonstration programme are delivered significantly later than planned. These delays mirror experience from CCS projects in other countries.
- 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 so there is limited scope for learning from the first project (see *Variety of pathways, FR NP* – the early years of focus on gas cooled, graphite reactors).

- It proves very difficult to devise a business model which can provide appropriate incentives and contractual safeguards whilst ensuring the necessary cooperation and risk-sharing between all the actors in the CCS chain (which is also a contributing factor in the demonstration project delays).
- Although some potential storage sites have been identified, very few have been sufficiently well characterised (or have been characterised and found to be unsuitable) to give confidence to project developers and investors.
- Those CO₂ pipeline routes that are built encounter significant public opposition. People react against the uncertainties of the novel CO₂ transporting phenomenon, as well as against clumsy attempts at consultation without any real engagement with or influence offered to local communities (see *Public acceptance, UK NGG*).
- The anticipated cost of future CCS projects (relative to alternative low-carbon generation options, and after taking account of support mechanisms) is not competitive.
- Potential investors view the technical, financial and policy risks (see below) around CCS as being too high to make further projects attractive.

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 (*Reliable storage, UK NP*), the analogues selected for study in Work Package 2 did not generally have a final outcome of failure. Indeed, whilst several of the analogues encountered significant difficulties and challenges, most eventually resulted in a more or less successful outcome. This is perhaps an important lesson in itself, in that it demonstrates that significant technical, financial and public policy issues *can* be managed provided there is sufficient collective will, over a sufficiently long period of time (although it may also reflect a bias in the selection of case studies).

Developments in the electricity market, and the financial and political context

This pathway makes the following assumptions about developments in the UK electricity market during the 2010s and 2020s, and the wider financial and political context:

- The UK continues to aspire to remain within its carbon budget and the international context remains broadly supportive of CO₂ emissions mitigation action. However, climate targets are not universally seen as being fully binding and it is not clear whether failure of CCS simply means meeting our emissions targets through other means, or it (partly) reflects a relaxation of these targets.
- The policy support mechanisms for renewables and nuclear described in the EMR White Paper are translated successfully into legislation during 2014 as planned.
- The transitional arrangements for renewables do not create a significant hiatus in investment for these technologies, and a number of Round 3 offshore wind developments are well underway by 2020, with the offshore wind supply chain reaching a sustainable critical mass, with clear evidence of cost reductions emerging.
- The two new EPR nuclear plants currently under construction (Olkiluoto 3 and Flamanville 3) are completed and operational by the mid-2010s, reducing investor uncertainty, and giving fresh impetus to the new nuclear programme in the UK.

- During the 2010s, continued slow or non-existent UK economic growth focuses attention on the costs to consumers and the impact on industrial competitiveness of relatively high cost and unproven CCS, meaning that improved policy support for CCS becomes politically challenging. Crucially, by this time the UK government is committed to support for renewables and nuclear because that was legislated during 2014, but details of support for CCS were not made clear at this time so CCS support is a ‘new ask’ of politicians and the electorate, and CCS appears to offer no clear and compelling advantages over the incumbent generating technologies.
- 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.
- 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. There is also a continuing strain on companies finances which means that ‘on balance sheet’ financing of large-scale CCS projects is not possible, compounded by the anticipated low returns (which rules out equity finance) and riskiness (which rules out debt finance).
- Decreased use of fossil fuels contributes to declining enthusiasm for CCS demonstration deployment (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 reduces exposure to gas price volatility, so reducing the perceived value of coal-fired CCS as a hedge against gas price volatility. Generators remain largely able to pass gas price increases through to consumers, so unabated gas remains competitive in the market and continues to provide a balancing role, even if relatively low gas prices do not sustain.

Timing of CCS deployment to 2030

This pathway assumes that a first commercial-scale demonstration plant does get funding approval from DECC and goes ahead, albeit continuing delays mean that it is not operational until between 2016 and 2018, several years later than planned. Progress on further demonstration plants is hampered by increasing concerns over delays to the first project. The result, summarised in the table below, is that only one more demonstration plant is built, giving an installed CCS capacity of less than 1GW by the early 2020s, with no appetite amongst generating companies for any more CCS plants.

In terms of fuel and technology mix, this pathway is based on similar assumptions to the other two pathways (insofar as they apply) i.e. current UK policy for commercial-scale demonstration at power plants is that a range of CCS (and especially CO₂ capture) technologies will be included in the early stages of this programme, potentially including both coal and gas-fired power plants. It does not seem sensible to make specific assumptions about the technology mix e.g. whether pre- or post-combustion capture dominates, particularly given the very small number of plants envisaged in this pathway.

Table 5 'Failure' timeline

Year(s)	Progress	Cumulative deployment
Mid-to-late 2010s	One <500MW demonstration plant operational	<500MW
Early 2020s	2 nd demonstration plant (<500MW) operational	<1GW
Mid-to-late 2020s	No further plants in development	<1GW
2030	No further plants in development.	<1GW

4. Branching points

Identifying branching points

We have here analysed the pathway and variants in section 3, with respect to key developments relating to each of the seven uncertainties, over the period studied. See tables 6–11 below. Note that the tables do not explicitly refer to all the indicators from WP1 analytical framework. Items marked in red and underlined indicate where branching points between pathways occur. Typically only one of the pathways is marked red for a given branching point between them.

Table 6 Uncertainty 1: *Variety of pathways*

	2015	2020	2025	2030
On track (PW1)	early choices are made		early choices pay off	
Momentum lost (PW2A)	<u>early choices are made</u>		<u>early choices were dear</u>	
Slow and sporadic (PW2B)			some variety, in niches	
Failure (PW3)				high variety remains

The variety of pathways uncertainty is a key differentiator between the pathways and variants. Firstly, in PW1 and PW2A early choices are made to focus on specific technology variants, but not in PW2B and PW3. Secondly, the early choices in pay off in PW1 in terms of good technology performance in the 2025 period, but not in PW2A. In PW2B, the variety is somewhat limited in the 2025 period by the viability of CCS being limited to specific market niches, corresponding to particular technologies.

Table 7 Uncertainty 2: *Safe storage*

	2015	2020	2025	2030
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On track (PW1)	<u>full speed ahead with characterisation</u>			
Momentum lost (PW2A)			<u>limited char.</u>	
Slow and sporadic (PW2B)		some char., variety of options	focus on oil/gas (?)	
Failure (PW3)		<u>very limited char.</u>		

The safe storage uncertainty also has an early branching point, where PW1 makes the most early progress with site characterisation. PW2A also makes early progress, but this peters out after the technology runs into problems (relating to costs, leakage etc.) in the 2025 period. In PW2B the progress is slower but does not stop, but may be limited to some storage options.

Table 8 Uncertainty 3: *Speed of scaling and deployment*

	2015	2020	2025	2030
On track (PW1)	0.3	2, modular	7	15
Momentum lost (PW2A)	0.3	3.5	<u>7, cost hikes</u>	7
Slow and sporadic (PW2B)	0.3	<u>1, moderate cost hikes</u>	3.3	7
Failure (PW3)	0.3	<u><1</u>	<1	<1

This uncertainty is closely linked to uncertainty 1 ‘Variety of pathways’. In PW1 rapid upscaling and deployment works out, facilitated by, among other things, a modular approach to upscaling. In PW2A, early technology choices turn out to be unfortunate and cause sharp cost rises in the 2020s, leading to a loss of momentum. In PW2B there are more moderate problems with costs.

Table 9 Uncertainty 4: *System integration*

	2015	2020	2025	2030
On track (PW1)	<u>designs modified from start</u>			
Momentum lost (PW2A)			<u>collaboration difficulties</u>	
Slow and sporadic (PW2B)		some collaboration difficulties		
Failure (PW3)		<u>technical integration issues</u>		

In PW1, early foresight in terms of planning for CCS development and deployment means that CCS designs and practices are modified to facilitate system integration. This could include technical things like over-sizing of pipelines, development of storage hubs, as well as non-technical things like arrangements to share storage sites between multiple operators. In PW2A, collaboration arrangements crumble, as the political support and financial viability is eroded. In PW2B, collaboration is difficult, but not unmanageable. A failure scenario, PW3, could include also serious technical problems emerging regarding the operation of CCS systems.

Table 9 Uncertainty 5: *Economics and finance*

	2015	2020	2025	2030
On track (PW1)			costs have peaked and start to fall; targeted support & flexibility valued	
Momentum lost (PW2A)			<u>large cost hikes, flagging support</u>	
Slow and sporadic (PW2B)		moderate cost hikes	niches with EOR	

Failure (PW3)			
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In PW1, good early technology choices pay off in terms of costs peaking relatively early, and thereafter improving. In PW2A, choices were less fortunate and costs still rise well into the 2020s, due to technical problems. Similar issues, but less severe problems occur in PW2B. EOR is here a potential life-saver niche for CCS.

Table 10 Uncertainty 6: *Politics, policy and regulation*

	2015	2020	2025	2030
On track (PW1)	early choices, smooth permitting, gov. builds expertise	support for 2nd tranche		
Momentum lost (PW2A)	early choices	support for 2nd tranche	<u>support falters</u>	
Slow and sporadic (PW2B)	<u>not early choices, patchy permitting, weak planning</u>	support for 2nd tranche, policy learning kicks in		
Failure (PW3)	<u>no support</u>			

PW1, again, represents an ‘ideal’ case of extensive policy learning and strong early support, In PW2A, early action is less well considered (and lucky), eventually leading to practical problems, as well as eroding support. In PW2B, policy learning is slower than in PW1, but gets there eventually.

Table 11 Uncertainty 7: *Public acceptance*

	2015	2020	2025	2030
On track	<u>early, real engagement</u>	public largely silent		

(PW1)				
Momentum lost (PW2A)	little engagement	some reactions against routes and costs	<u>snowballing protests</u>	
Slow and sporadic (PW2B)	patchy engagement	some reactions against routes and costs	motley reactions	
Failure (PW3)		<u>opposition to CO₂ transport and bad consultations</u>		

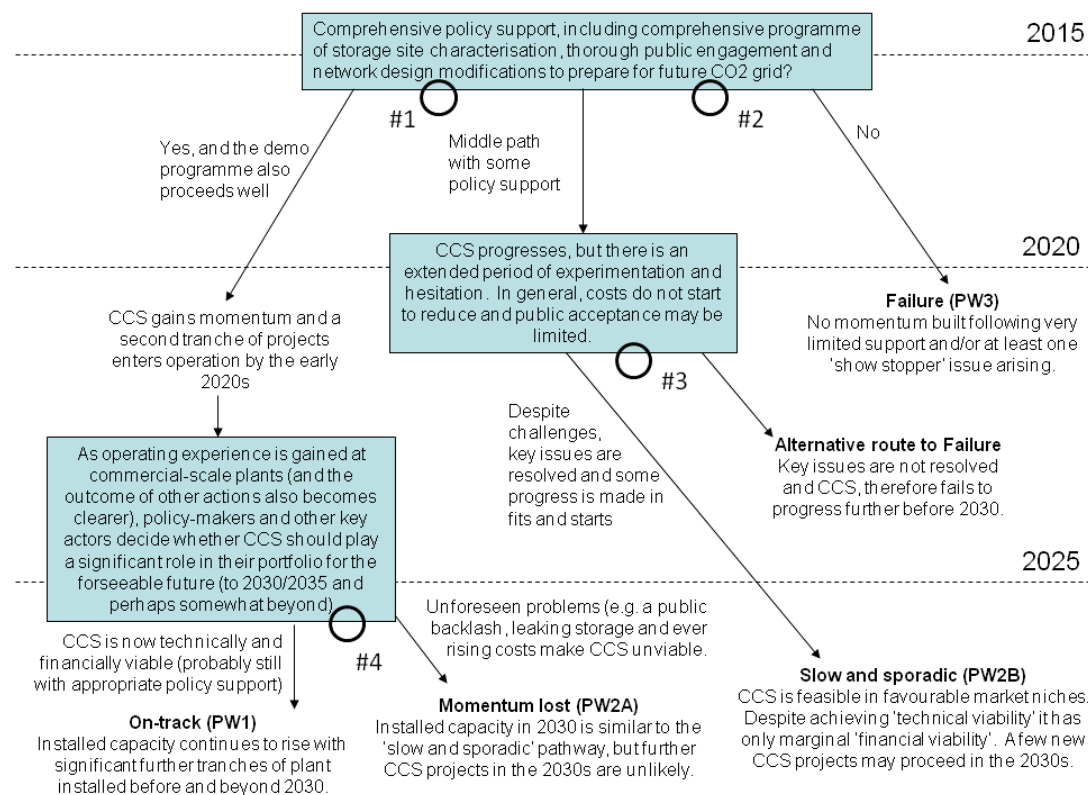
In PW2A, weak early engagement – especially with regard to onshore pipelines – contributes to a backlash against the technology. Rising costs contribute to reduced acceptability. This is avoided in PW1, by early engagement, giving local communities real influence (as well as better outcomes in terms of technology costs). PW3 illustrates the fact that public opposition could be a severe problem, especially if consultation and engagement efforts are done badly.

Reading tables 6–11 by time period, it is clear that the ‘key developments’ (marked red and underlined above) are related. Overall, four distinct branching points can be identified. See table 12, figure 3 and the following description.

Table 12 Branching points

	2015	2020	2025	2030
PW1			#	
PW2A	#		4	
PW2B	#	#		
PW3	2	3		

Figure 5 Pathways and branching points



2015

#1 CCS gets off to a really good start, or not. A good start ('*On Track*') would be due to early, comprehensive policy support, including a comprehensive programme of storage site characterisation, a sensible and reassuring liability regime, and thorough public engagement giving real influence to local communities and network design modifications to prepare for a future CO₂ grid and European interconnections.

Development momentum is here built up (or not) in a virtuous circle of improvements on one uncertainty making progress on another easier. For example, progress with designing strict (but workable) regulation of storage helps reassuring publics about the safety of storage, which in turn paves the way for faster permitting and deployment. Similarly, good progress with a number of technology variants demonstrated means experience accumulates on performance and costs, which in turn could make the making of supportive policy more palatable.

#2 CCS could get going, or not stand a chance at all ('*Failure*'). The latter would happen through no (or very limited) policy support: no incentives provided, no site characterisation done, no public engagement, etc. This means no momentum at all gets built.

Note that there is a middle path here with some policy support ('*Slow and Sporadic*').

2020

#3 A longer period of experimentation and hesitation. If the policy support is of middling strength and there is little selection among technology variants early on, the '*Slow and Sporadic*' pathway may run into some problems around 2020. A range of problems mean that costs are still rising (or at least not coming down), and public support is also patchy. CCS however, is feasible in favourable market niches. (CCS may thereafter develop better in the 2030s, but that is outside the scope of this analysis).

But, if we add to this hesitant start a history of badly done consultations on CCS and the technology may come to face widespread opposition. If that happens, it may be rather hard to get back 'on track'. CCS could then still fail (this would be a slightly different version of the '*Failure*' pathway).

2025

#4 Early good progress could hit a dead end if it is revealed that bad choices were made early on ('*Momentum Lost*'). Early choice of (lock-in to) technology variants may turn out to be mistakes, with ever-rising costs and declining public support. It could be that early, strong policy push helps to mobilise and coordinate actors, which could facilitate system integration, and support the establishment of a strong design consensus. Any negative effects of this may not be evident until some time has passed, say until the mid 20s.

Strong policy push could also result in giving in to the temptation of neglecting public engagement and 'letting sleeping dogs lie', which could make for good progress with early projects. There is a risk for public opposition snowballing, and leading to a general backlash. Again, this could take some time and lead to a loss of momentum and even a stop in deployment. Moreover, if in a strong push to get CCS going, corners are cut with site selection and characterisation, and the storage sites turn out to not be as safe and reliable as expected, this can contribute to the public backlash, as well as cause (expectations about)cost increases through growing remediation expenditure and liability payouts.

Considering all the branching points, it is worth noting that there are more of them early on in the period studied than late. This may reflect the relative difficulty in telling credible, detailed stories the further we go into the future.

Revising the indicators

The next step in the analysis is to compare the branching point descriptions above with the assessment 'indicators' from WP1; see table 13. The questions here are 1) whether have not covered some of the indicators (and if that matters) and 2) if we could and should suggest new ones?

A comparison suggests that there is scope for adding a few more useful indicators:

- Network design modifications (for the uncertainty *public acceptance*) and

- Dominance of market niches (*scaling up and speed of development*)
- They have been added to table 13 and underlined in red.

Table 13 Indicators (from WP1)

Key uncertainties	Indicators
1. <i>'Variety of pathways'</i>	<ul style="list-style-type: none"> - 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 <i>'Safe storage'</i>	<ul style="list-style-type: none"> - 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. <i>'Scaling up and speed of development and deployment'</i>	<ul style="list-style-type: none"> - Unit size, capacity and efficiency - Speed of unit scaling - Cumulative investment / installed capacity - <u>Relative importance of market niches</u>
4. <i>'Integration of CCS systems'</i>	<ul style="list-style-type: none"> - 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. <i>'Economic and financial viability'</i>	<ul style="list-style-type: none"> - 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. <i>'Policy, political and regulatory uncertainty'</i>	<ul style="list-style-type: none"> - 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. <i>'Public acceptance'</i>	<ul style="list-style-type: none"> - Levels of public awareness / acceptance of risks - Specific manifestation of public opposition (or support) - <u>Quality of public engagement</u>

Furthermore, a few indicators have not been covered so far in the branching point analysis:

- Relative importance (of technology variant) for technology developers (*variety of pathways*)
- Role of system integrator firms (*system integration*)

This does not prove that they are not relevant to CCS, but may just reflect choice of analogues and the choice of focus in our analysis of them. Therefore, they will be kept as part of the framework. It should be noted though that the evidence supporting them comes from the literature review (in WP1) and not the case studies.

5. Conclusions

Methodological conclusions

The pathways analysis can usefully serve as way of analysing the conditions for ‘successful’ and ‘unsuccessful’ CCS deployment by 2030 and what actions will influence the outcome.

The analysis has also been helpful for the application of case study findings (from WP2) to CCS, and thus to illustrate how these are relevant to CCS.

The framework from WP1 was reasonably robust. The set of criteria should be revised slightly, and we have suggested adding a few new criteria, which emerged from the cases and the pathways analysis.

Policy conclusions

We have identified a set of key branching points that show things that policy makers should be monitoring for with regard to possible CCS futures.

Good progress towards 2030 targets presupposes comprehensive policy support now. This needs to include:

- Financial support that recognises the unique characteristics of CCS plant
- A large programme of site characterisation
- A sensible and reassuring storage liability regime
- Thorough public engagement, giving real influence to local communities and other stakeholders
- CCS project, system and network designs that are modified in preparation for a future CO₂ grid and European interconnections

Whilst strong policy signals and support would be required to give CCS a good start, there are also risks associated with accelerated innovation and the cutting of corners:

- It is tempting to focus efforts and resources on one or a few technological varieties early on. This may help to speed up development, but comes with increased risks of picking weak technology
- 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
- 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.

Appendix 1, Fuel and technology mix

The 'On Track' pathway assumes that the UK plays a significant role in commercial-scale demonstration of CCS and that the first commercial-scale integrated power plant CCS project in the UK demonstration programme (and also early projects in other countries) is successfully storing CO₂ by 2016. As yet it is too early to say whether a particular CCS technology will emerge as a clear winner. In fact, it can be argued that a range of technologies could prove to be both technically and financially viable depending on a number of factors including sensitivity to site-specific factors (e.g. access to markets for potential co-products from pre-combustion capture that would not be produced by other CO₂ capture technologies) and potential diversity in the role that plants using CCS might play within the broader electricity/energy system (e.g. demand for flexible operation or provision of baseload power) (Chalmers et al. 2009).

Another important factor in determining if and how CCS is used at all and, to some extent which particular technology choices are made, is the fuel mix in the power generation sector (and any other industrial sectors where CCS could or is being deployed). In particular, although much of the discourse has focussed on CCS being used to 'clean up' coal there has been increasing interest in if, how, and when CCS might be applied to natural gas-fired power plants. This reflects both a response to significant reductions in natural gas prices and also climate change policy developments suggesting that more significant reductions in CO₂ emissions may be required in the UK power generation sector than was typically expected by most stakeholders even only 2–3 years ago (CCC 2009;CCC 2010a;DECC 2009). It is, therefore, useful to make a number of observations that bear upon the fuel mix question, and we have grouped these under two scenarios – gas dominated and coal dominated:

Gas-dominated scenario

- The latest cost estimates (on a levelised £/MWh basis, and allowing for carbon costs) suggest that gas-fired CCS will be cheaper than coal-fired CCS, across the spectrum of technologies (2010;Mott MacDonald 2011). The higher CO₂ intensity of unabated coal does of course mean that policy support through carbon pricing rewards coal-fired CCS relatively more than gas-fired CCS but the most recent estimates suggest that this is not enough to offset the higher costs of coal-fired generation, at least for new-build plant.
- On a whole-plant basis (base power plant plus CCS plant) gas-fired CCS technologies (certainly post-combustion) also offer significantly lower capital cost than for coal-fired CCS (ibid), which prospective investors prefer even if the lifetime costs per MWh are similar.
- Given the current market structure, policy and regulatory environment, unabated CCGT is the clear preferred choice for new build power generation in the UK (Gross et al 2010), notwithstanding the significant renewables deployment which has been driven by strong policy support. Furthermore, the EMR White Paper (DECC 2011b) makes clear provision

for new unabated gas plants – and there is a strong political ‘push’ to make sure that investors in unabated gas are not put off by low carbon policies that are too stringent, see for e.g. oral evidence by Hendry to the ECC Committee on energy security (Hendry 2011). From an industry perspective, gas-fired generation is already ‘on the table’ whereas new coal is clearly not (and there have been no new coal-fired plants in the UK for almost 40 years). Arguably therefore, it may seem a smaller step for the electricity generation industry to move to gas-fired CCS rather than coal-fired CCS.

Coal-dominated scenario

- There may be system and societal benefits in having a proportion of coal-fired CCS (e.g. increased diversity of fuel sources and reduced exposure to gas price volatility), although the market would need to be structured and regulated so that operators of coal-fired CCS plants could be rewarded for providing these benefits. There may also be foreign policy rationales for a focus on coal (which have clearly driven this emphasis to date (DECC 2009), such as the need to demonstrate CCS in a way that is relevant to countries like China, India and the US which have coal-dominated electricity systems.
- It may be that there are other commercial considerations which would encourage companies to build coal-fired CCS over gas-fired CCS, such as to provide a hedge against future gas prices, although the experience of the UK electricity market is that wholesale gas price rises can be passed through to consumers anyway (Gross et al 2010).
- Coal-fired CCS may be cheaper than gas-fired CCS in terms of cost per tonne of CO₂ abated, which may be significant if that is the metric on which policy support is based. This is also linked to the issue of retrofitting CCS to existing power stations because in these circumstances the lower abatement cost (and the possibility of extending the life of an existing asset) may favour coal plant (Gibbins et al. 2011).

Gas-dominated versus coal-dominated scenarios

Whilst there may not be enough information to come to a firm conclusion as to which fuel will dominate, it does seem reasonable to ask what would drive coal-fired CCS projects in the UK if the investment proposition for gas-fired CCS is apparently more convincing. In the absence of policy support or regulation which specifically targets coal-fired CCS, it is difficult to see the compelling investment proposition for a generating company who would be expected to favour the lower capital cost and lower costs per MWh of gas-fired CCS options in a market such as the UK where they can pass through fuel costs to consumers. The possible exception is the special case of retrofitting to existing coal-fired plant. There may also be a case for firms to undertake ‘hedging’ strategies given uncertainty about future gas prices – but this may not be a strong case since electricity prices are strongly linked to gas prices now. The pathways therefore assume that gas-fired plant will predominate in CCS deployment.

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