How ready is ‘capture ready’? - Preparing the UK power sector for carbon capture and storage

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Executive summary

Background - climate policy, fossil fuelled plants and ‘capture readiness’

Steep reduction of carbon dioxide (CO_2) emissions is a repeatedly stated core goal of UK policy for energy and climate change. Limited progress has been made since 1990, and forecast pathways of CO_2 reduction show that strong additional policies are needed to enable reduction. These could include stronger policies for carbon capture and storage (CCS) deployment. A potential conflict with policies for CO_2 reduction is the wish to build new power plants in the UK fuelled by coal or gas; this would increase emissions now and risk high-carbon lock-in for many decades.

As CCS on power plants is not fully commercially proven, a concept of ‘capture readiness’ (the ability to retrofit capture equipment onto existing plant) has been used in the UK to legitimise the construction of new power plant. Such a condition has also been used by the Government in consents for new gas-fired plants, but in an unsatisfactory way as it appears to be unevenly applied, and less robust than it could be since it does not regulate rapid conversion to full CCS operation. This issue is now brought to a head in the UK by the new unabated coal-fired plant proposals, e.g. Kingsnorth, Kent.

There are three basic alternatives, firstly ‘capture ready’ (CR) investments can be avoided by hoping that current plant designs enable future retrofit; secondly construction of new plant can be prohibited until CCS is ready to be installed from the outset; thirdly varying degrees of CR can be stipulated by regulation. The challenges of this approach include regulating a technology under development, before its actual properties are well known, developing the skills to build and operate the technology, and to guarantee future retrofitting once the new generation capacity is built and entrenched.

It is also possible to mix these strategies, by giving planning consents to a small number of plants, explicitly for the purposes of CCS demonstration. By limiting the number of new-build fossil-fuelled plants now and in the future, the risk of carbon lock-in (in case CCS fails) is reduced.

The main aim of this study is to identify the choices regulators face when specifying what ‘capture readiness’ should mean. There are many dimensions to the concept that deserve consideration, and risks of carbon lock-in that need to be avoided.

This report examines the ‘capture ready’ concept and its application, and concludes that to be credible in enabling rapid reduction of CO_2 emissions the scope of ‘capture readiness’ needs to be extended. These extensions fall under five headings as shown in tables 7 and 8 on pages 34-36:

- Modifications to power plant, enabling easy conversion and operation with capture
- Planned methods and routes to transport CO_2 from plant to storage site.
- Storage sites of sufficient volume and performance, available when required.
- Skills development in CCS operation, and coordination of value chain.
- Stringent regulatory criteria to enforce early conversion to full capture, transport and storage.

What does 'capture ready' include: equipment, connections and skills?

The core idea of the concept of 'capture ready' seems simple, but the analysis shows that it is a complex notion, with many dimensions. For example, CR is not just a technical problem, in the sense of being able to fit new equipment onto an existing plant (or connecting the capture plant to a transport network, etc.). It is also a matter of organisation and coordination, for example building the skills necessary to operate the capture plant and to coordinate the actors involved in the CCS value chain (the providers of capture, transport and storage services).

'Capture ready' should be defined by its outcome, the possibility of converting to full CCS, rather than the intention behind the CR investment. From the point of view of climate change policy, only the outcome matters.

Moreover, CR is not a simple "either–or" decision, but rather can be defined at different points along a scale of readiness (which varies for particular power plant-capture technology configurations). These points can range from the simplest provision of footprint land space for capture equipment, through to, for example, complex plant design changes. A more difficult requirement to comply with is not always better in terms of avoiding lock-in.

Examples of necessary pre-investments in plant design include additional space for future pipes and equipment, tie-ins for future extraction of steam, expansion of support systems like electricity and cooling water. Skills, expertise and operating procedures also need to be developed within power companies. To encourage this, we propose that any new coal and gas-fired plant construct and operate 1-25 MW pilot capture plant immediately upon start-up as part of the CR condition.

It is profoundly important that CR includes not just the power plant, but also assessments of the routes for CO_2 transport, and the availability and capacity of a storage site. Detailed plans for CO_2 transport also need to be prepared, up to a level suitable for acceptance by the local Planning Authority and information provided to any affected publics. Geological storage can be appraised in outline, using existing data around the UK, to assure timing, volume and performance and obtain outline approval by regulators.

The full CCS value chain also needs to be identified and a model for the participants' coordination agreed. This will require the power company to build new skills, and to create credible new business relationships with specialist partners, for example pipeline operators and oil and gas companies, as early as the 'capture ready' investment.

Conversion of capture ready to operating CCS

The timing of conversion to full CCS will be constrained by the technical availability of proven CCS technology. However, technical maturity is not independent of economic aspects, and the degree of financial viability will also in practice matter for retrofit timing.

Clear regulatory criteria are needed to enforce conversion to CCS, with periodic re-assessments benchmarked against worldwide progress. The UK Government should make a clear ruling to close plants that have not fitted full CCS by a pre-agreed date. We suggest conversion within three years of a full CCS chain (of the appropriate capture type) being built and operated at any world site, and full CCS should be required from 2020 in any case. This strong regulatory signal will enable developers of fossil fuelled plant to see CCS as inevitable and unabated coal as unacceptable.

The history of flue gas desulphurisation (FGD) in the UK illustrates the reluctance of the utilities of investing in technology that is not profitable per se, and some of the difficulties in imposing such investments through weak regulation. We may expect resistance to regulation making capture retrofitting mandatory, and need to learn from the FGD case in terms of the stringency and enforcement of regulation needed. We should also learn about the specifics of how to formulate an effective policy, including for example the avoidance of merit-order loopholes diluting the benefits of fitted carbon capture.

We judge that the most difficult and/or least well-understood actions involved in preparing for future CCS are for utilities to prepare for storage (or induce another organisation to do that) and system integration, and for policy-makers to implement stringent and timely retrofit regulation.

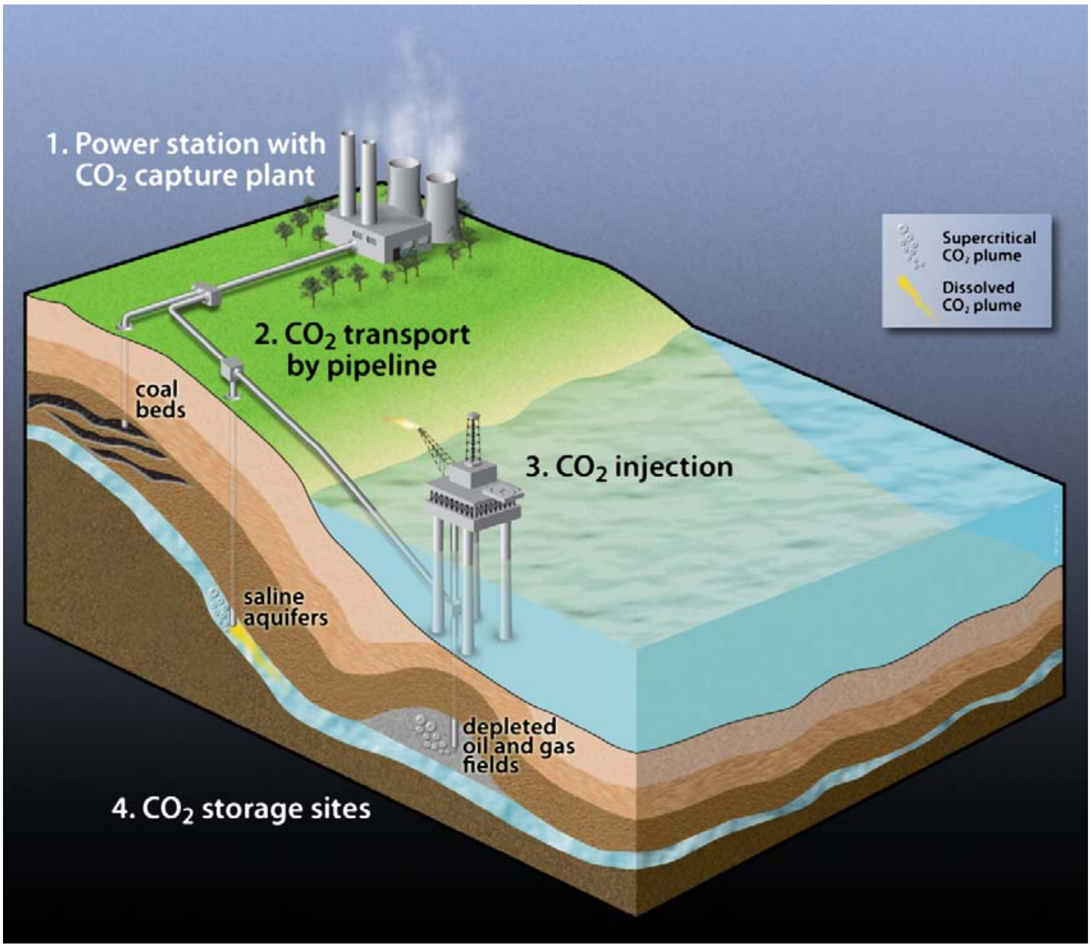
1. Introduction

Background and aims

Carbon Capture and Storage (CCS) technology has emerged over the last fifteen years[1] as a potential option for reducing CO_2 emissions from power generation fuelled by coal or gas. Developments within the last five years that lend credence to future of CCS technology include a review report from the IPCC[2] and a draft EU Directive setting out a regulatory framework[3].

The component technologies needed are in many cases in use already in other applications, but need to be adapted for CCS use, which involves up-scaling and cost reductions for capture technologies, and the integration of the different component technologies into a functioning CCS system.

Figure 1 Schematic of a CCS system, including different storage options



1 The report IEA/GHG/SR3, *The disposal of carbon dioxide from fossil fuel power stations*, June 1994, can be seen as marking the starting point of CCS development.

2 IPCC (2005) *Carbon dioxide capture and storage*

3 EC (2008) *Proposal for a Directive of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006.*

CCS holds out the promise of continuing to use fossil fuels whilst significantly reducing the carbon dioxide (CO_2) emissions from such power generation. It is expected that it will also be possible to use CCS on the flue gases of other industrial activities (such as biofuel manufacture, coal to liquids, cement making, or steel manufacture), which would further reduce carbon emissions, or even (if applied to power generation based on biomass) result in a net carbon sink. IEA analyses predict that world use of fossil fuel will continue to increase to 2050, and that CCS could account for 12-50% of CO2 reduction by 2050.[4]

Recently, there has been renewed interest in building coal-fired power plants in the UK. This has raised the temperature in discussions about if and when CCS can deliver on its promises. An important question is whether to license new unabated coal-fuelled plants at a time when CCS has not been demonstrated to work (at full scale and as an integrated system). The spectre to avoid is 'carbon lock-in' where new (or retrofitted) fossil fuel generating plant is built during the time span when climate change imperatives to reduce greenhouse gas emissions are known, but before a fully functioning CCS system becomes available for addition to new plants.

For example, if new fossil fuelled plant is built now, the world could be locked in to unabated emissions from this plant for the next 30 to 50 years. This problem is apparent and debated in the UK, but also exists on a far greater scale, in China, India and the USA from where most world CO_2 emissions are anticipated to derive during the forthcoming 30 years. Finding the key to avoid carbon lock-in from these countries is a problem pivotal to worldwide climate integrity.

The notion of a 'capture ready' (CR) power plant has been launched as a proposed solution to this dilemma. The core of the notion is that unabated fossil fuelled power plants be designed and built now in such a way as to ensure that they can be retrofitted later when CCS technology becomes available, and the necessary regulatory and financial conditions are in place.

However, there is as yet no agreement or standard for what capture readiness is to mean, or whether the approach will work. This report makes a contribution to illuminating this question, with special focus on the UK situation.

The main aim of this study is to identify the choices Government, regulators and companies face when specifying what 'capture readiness' should mean. There are many dimensions to the concept that deserve consideration, and risks of carbon lock-in that need to be fully assessed and avoided.

The study sets out to identify the principles a definition for capture readiness (CR) should rest on, the dimensions of the concept, and - as far as possible - the criteria a regulator and Government could apply. The analysis has drawn on existing literature on capture readiness, literature on lock-in effects in large technical systems, as well as the wider literature on CCS. The material reviewed also included different actors' published statements on what capture readiness means.

A subsidiary aim of this study is to compare capture readiness with the recent history of the introduction of flue gas desulphurisation (FGD) technology, as enforced by the EU Large Combustion Plant Directive. There are lessons to be learned from comparing capture-readiness with another regulation-driven implementation of abatement technology in the power industry.

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4 IEA (2006) World Energy Outlook 2006

The power generation sector in the UK and recent CCS proposals

The UK power industry is dominated by several large companies, reflecting the large-scale investment needed for most current generating technology. [5] The industry was privatised in 1990, and there have been many changes in the industry structure since. Currently, the 'big six' companies are: Centrica, EdF, E.ON, RWE npower, Scottish Power and Scottish and Southern Energy, all of which are now foreign-owned apart from Centrica and SSE.

The main fuels used for electricity production in the UK are gas, coal and uranium (nuclear). After the ‘dash for gas’ in the early 1990s, there has been little investment in new fossil fuelled generation plant. Considerable coal-fired capacity is also to be decommissioned soon, from 2015 due to old age and also the EU Large Combustion Plant Directive (LCPD). After 2020, most of the established nuclear powered electricity generation will also close due to old age of the nuclear plants. There are therefore concerns about a potential shortfall in electricity generating capacity.

The UK renewables sector is growing rapidly, but starting from a low base of generating less than 5% of UK electricity at present. According to the terms of the recent EU energy package legislative proposals (announced January 2008 by the European Commission) one of the UK’s new legally binding targets is to achieve a 15% share of renewables in the final energy demand by 2020.

Some estimates have predicted the UK’s 15% renewables energy target could equate to 35-40% of electricity coming from renewable sources by 2020. The Government has stated it will consult on how to reach the UK’s renewable energy target later in 2008, and will produce a UK renewables strategy in 2009. Thus, the UK has much to do and achieve with renewables in order to get from 4.6% to 35% electricity sourced from renewables by 2020. But if the UK meets its EU 2020 targets for renewable energy then the percieved electricity gap will be prevented as the new renewable capacity will be constructed before the aging nuclear and/or coal plants are retired.

However, as the Government and others expect a shortfall in generating capacity and because of renewed interest in coal as a fuel (due to high gas prices), a large number of proposals for new build of coal and gas-fired plants have been made.[6] Many of the schemes currently proposed include reference to some CCS aspects, ranging from capture readiness, to small scale capture, to full CCS system – at varying time-scales.

In the UK both coal and gas-fired plants are being proposed. Because CCGT gas plant is cheap to build and operate (although more expensive on fuel), that is the default power industry option and several of these plants look set to be built and commissioned before 2012. By contrast, new coal plant remains conceptual, as it is more expensive to build, and because of the perception that full CCS will be required at some future time although the full size capture equipment, regulatory and financing aspects have not yet been sufficiently clarified. The single exception to this in 2008, is the Kingsnorth coal-fired plant application from E.ON, where it is proposed that a site of a former coal plant will be redeveloped to form a new 1600MW supercritical coal fired plant with efficiency of 45% or more. If given the go ahead by Government this would be the first coal-fired plant to be built in the UK for more than 20 years.

5 The industry description draws on KeyNote, *Market report 2006, Electricity Industry*.

6 An interactive world map of CCS projects is available at www.geos.ed.ac.uk/sccs.

UK climate change and CCS policies

UK energy and climate policies are now interlinked. The current Government ambition is to reduce CO_2 emissions by 60% of 1990 levels by 2050. A more onerous target of reducing emissions by 80% by 2050 is the first major item the new UK Climate Change committee will be examining and it will report on its decisions by the end of the year. An intermediate target of 26-32% reduction has been proposed for 2020 in the draft UK Climate Bill. A short-term target of 20% reduction by 2010 is also in place. Forecasts indicate that current Government policy is not enough to meet the 2010 or 2020 targets, unless robust new policy measures are introduced.[7] Supporting the development and deployment of CCS is a policy option that could contribute to meeting the CO_2 emissions reductions targets set by Government and derived from climate change imperatives.

A main activity of the UK Government in the area of CCS to date is a procurement-based competition for (the economic support for) a full-scale CCS demonstration project.[8] The competition has two main objectives. Firstly, to demonstrate the full CCS chain at commercial scale; secondly, to demonstrate technology that is relevant and transferable to key global markets – with a view especially to retrofitting coal-fired plants in China and India with post-combustion CCS.

The competition was launched in November 2007, and reached the first of many stage deadlines on the 31st of March 2008, with company consortia[9] expressing interest in the competition by submitting pre-qualification questionnaires. The preferred bidder is expected to be announced in early summer of 2009. The competition memorandum sets out a phased approach with a system capable of processing 50-100 MW by 2014, and the full 300-400 MW 'as soon as possible thereafter'. This appears to leave the option open for companies to delay a full capture operation until end of 2019, after which they may be subject to EU rules on CCS from 2020.

In terms of technology, the competition is limited to post-combustion capture and oxyfuel, on a coal-fired power plant in the UK. The competition excludes pre-combustion capture, because this cannot be retrofitted to existing pulverised fuel coal plant.

As shown in table 1, the industry schemes proposed are all of the scale that require formal consent from the Government in order to go ahead (under section 36 of the Electricity Act 1989). This raises the issue whether the UK Government should consent new fossil fuel-fired, and especially new coal-fired generation capacity, when the UK has new emissions reduction targets to meet. Issues related to what 'level' of carbon capture and storage to require, ranging from nil to capture readiness, to full CCS are also of interest now.

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7 Press release from Cambridge Econometrics, 140308

8 BERR (2007) *Competition for a Carbon Dioxide Capture and Storage Demonstration Project – Project Information Memorandum.*

9 At the time of writing, the total number of company consortia to enter the competition was not known, but media reports claim 8 entrants. Three consortia, led by E.ON, RWE npower and Scottish Power, were known to have entered the competition.

Table 1 CCS-related power plant investment plans

Name/location	Actors	Power plant investment	CCS investment [1]	Project stage	Cost [2]
Aberthaw, Wales	RWE Innogy	(FGD retrofit on existing plant. Coal.)	Post-combustion: first experimental 1 MW (then demonstrator >25MW at Tilbury or Blyth).	Decided, 2010	£8.4m (then £50m)
Tilbury, Essex	RWE npower. May be the site chosen for the competition. Consortium with BOC, Shaw Group, Tullow Oil, I.M. Skaugen, Cansolv Technologies.	1000MW supercritical plant. Coal.	Post-combustion plans. Use of Didcot power station as test facility.	Feasibility study. Scoping report submitted. Ready 2012-2016	£700m
Blyth, Northumberland	RWE npower	3x800MW supercritical boiler. Coal.	Post-combustion plans.	Feasibility study. Scoping report submitted. Ready in 2014.	
Kingsnorth, Kent	E.ON. Competition consortium with Arup, EPRI, Fluor, MHI, Penspen and Tullow Oil.	Two 800MW supercritical plants. Coal.	Post-combustion plans.	Applied for consent.	£1000 m
Longannet, Fife and Cockenzie, East Lothian	Scottish Power (Iberdrola)	Retrofit of supercritical boilers at both plants. Max 3390MW. Coal.	Post-combustion plans. Developed at Longannet.	Feasibility study.	
May have been shelved after competition announced?					
Chequers Lane, Dagenham	Barking Power	CCGT extension. CHP ready.	Capture ready.	Consent.	
West Burton	EdF	CCGT. CHP ready.	Capture ready.	Consent.	
Drakelow	E.ON	CCGT. CHP ready.	Capture ready.	Consent.	
Uskmouth, Newport	Severn power	CCGT. CHP ready.	Capture ready.	Consent.	
Westfield, Fife	Global Energy	Re-development of gasification plant. Coal, but also biomass/waste.	Pre-combustion	2008 (CCS later?)	£420m
Eston Grange, Tees Valley, Teesside	Centrica, Progressive Energy, Coots and Coastal Energy. Development agency Renew Tees Valley involved.	New-build 800MW IGCC. Coal.	Capture with hydrogen production. Pre-combusion, pipeline, EOR/ saline aquifer.	Building start planned for 2009	£750m
Killingholme, Humberside	E.ON & Powergen	New-build 450MW IGCC. Coal.	Pre-combustion	Feasibility study.	
Immingham, Lincolnshire (Humberside)	ConocoPhillips	New-build 450MW IGCC. CHP. Coal.	Pre-combustion		
Hatfield, Yorkshire	Shell and Powerfuel (Kuzbassrazrezugol)	New-build 900MW IGCC. Coal.	Pre-combustion	Consent. FEED [3] study starting.	
Probably shelved before competition announced					
Peterhead, Aberdeenshire; Miller North Sea oil reservoir	Scottish and Southern Energy. Project abandonded by BP in 2007.	Original plan: 350MW power station.	Pre-combusion, transport, off-shore storage. Hydrogen.	SSE still going ahead, but without the CCS?	>£300 m
Ferrybridge, Yorkshire	Scottish and Southern Energy, Siemens, UK Coal, Doosan Babcock.	Retrofit of 500MW advanced supercritical boiler. Coal.	Capture-ready		

Notes: 1) It is not always clear from the sources available how concrete the CCS-related parts of the investments are.
2) Investment cost
3) Front End Engineering Study. A relatively early stage study, setting out the requirements on an engineering project, and allowing for budget to be set.
Sources: company websites, media reports and BERR consent information.

In the consents to four gas-fuelled power plants (three new builds and one extension), Government has already specified a capture ready condition (and also specified a CHP readiness condition in some cases). Compilation of these conditions (see table 2) shows that there is no uniform requirement for CR.

Table 2 CCGT consents including capture or CHP readiness conditions

Date	**Name/Place**	**Investment type**	**Company**	**Capture ready**	**CHP ready**
19/12/07	Chequers Lane/ Dagenham	Extension	Barking Power	Yes	Yes
16/10/07	Drakelow	Construction	E.ON	Yes	Yes
03/10/07	West Burton	Construction and operation [1]	EDF	Yes	Yes
13/07/07	Carrington, Trafford	Construction	Bridestones Developments	No	Yes
21/08/06	Uskmouth/ Newport	Construction	Severn Power	Yes	Yes

1) This consent specifies that it allows not just construction but also operation, whereas this goes unsaid in the others.

Sources: Government News Network and BERR website.

The consent for the proposed West Burton plant given by Government formulates its capture ready conditions as follows:

> "The layout of the Development shall be such as to permit the installation of such plant as may reasonably be required to achieve the prevention of the discharge of carbon and its compounds into the atmosphere."

It further specifies regarding 'CHP readiness' that:

> "[t]he commissioning of the Development shall not take place until the Company has installed the necessary plant and pipework to supply waste heat to the boundary of the Site. Reason: To ensure that waste heat be available for use to the benefit of the local community."[10]

We will discuss below that a robust capture readiness requirement needs to also include, for example, the acquisition of expertise, and the timing of (or circumstances triggering) the transition from CR to full CCS operation.

No 'capture readiness' condition has as yet been given to any proposed coal-fired plant, although this very issue has caused debate in relation to E.ON's recent Kingsnorth proposal.[11] A central concern is whether capture readiness offers any

10 BERR (2007). *Electricity Act 1989. Construction and operation of a combined cycle gas turbine generating station at West Burton, Nottinghamshire*, Our ref GDBC/001/00255C

11 See for example BBC website 060208 *Greenpeace protest over coal use*, and Monbiot, G. 180308 *Carbon capture is turning out to be just another great green scam*, The Guardian.

guarantee of reducing carbon emissions, or if it is just a ‘carbon-correct’ excuse to build new unabated coal-fired plants in the UK.

The Government department for Business, Enterprise and Regulatory Reform (BERR) is currently planning a public consultation on the concept of capture readiness, to be launched within the next few months of 2008. Furthermore, BERR is also planning a consultation on a licensing regime for storage of CO_2, within the same approximate time frame.[12]

Summary

Reduction of CO_2 emissions is a repeatedly stated core goal of UK policy for energy and climate change, but forecasts show that additional policies are needed to meet UK emissions reduction targets, which could include stronger targets for CCS deployment. The UK is attempting to play an international role by making some public funds available through a competition to procure a full post-combustion CCS system on a commercial coal-fired power plant.

Additional coal and gas plant, being constructed now and in the future outwith the competition, is being subjected to a capture ready test, which is implicitly attempting to enable avoidance of locked-in CO_2 emissions throughout the lifetime of the plant. However, the CR test appears to be unevenly applied, and omits any statement on conversion to full CCS operation at a set deadline.

12 Communications with CCSA and BERR.

2. Reviewing and investigating capture readiness

The first section in this part of this report sets out a basic structure for addressing the problem of how to define capture readiness. This structure includes a brief discussion on 'lock-in' and a precautionary approach to manage lock-in risks. Moreover, the section will describe different perspectives: such as, environmental regulation, company investment, technology development, etc., from which different actors see and judge capture readiness.

The second section discusses different approaches to defining the concept, and – based on a two-level ‘headline and detail’ model – sets out some of the issues for a headline definition for CR. These include what type of object is actually to be assessed to be 'capture ready' or not, and what 'ready' might mean at the aggregate headline level.

The third and last section outlines the more detailed part of potential definitions of capture readiness. The section covers, in turn, plant design and operation, downstream and system integration and regulatory issues. For each of these areas, the section further specifies the aspects to be considered for inclusion in the concept, and – where possible – sets out the criteria recommended for use in an operational definition.

2.1 The structure of the problem

Lock-in - Decision-making in large technical systems under technological uncertainty[13]

The basic issue at stake here is one of lock-in. It is therefore worth discussing briefly what lock-in is, and what it means in the specific case of decisions about building capture-ready power plants.

Lock-in has been discussed especially in the context of so-called large technological systems, for example electricity production[14] and other infrastructural systems. The basic notion is that these systems consist of many separate components that are interdependent, so that changing one part may require also changing many or all of the other parts. This is thought to make change more difficult, since it is not enough to change the one component, but also necessary to coordinate change across the system.

It is worth noting here that these components are not just pieces of equipment and materials, but also institutions, skills, contracts, etc. For example, an electricity distribution network is useless without the people who design, operate, maintain and use it, and norms and standards for how this is to be done.

There are interdependencies also between technical and social components. For example, between equipment and the skills to operate it, or between equipment and companies who have invested in equipment and skills, or between regulatory regimes and existing technology. Lock-in is about how the complete socio-technical system,

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[13] This section is based mainly on literature from Science and Technology Studies, a social science field that includes, among other things, studies of large technical systems and the management of technological risk.

[14] Hughes , T. P. (1983) Networks of Power Electrification in Western Society, 1880-1930, Johns Hopkins University Press, Baltimore.

including companies, skills, equipment, etc., is difficult to change (at least in a planned, intentional way), because of the dense network of interconnected parts, social and technical.

Carbon lock-in is therefore not just about how different pieces of equipment fit together, but also about how equipment fits with social phenomena like companies, skills sets, regulations, etc. Innovation (for example the introduction of CCS) may be hampered not only by existing equipment (for example capture un-ready power plants), but also existing actors, regulatory regimes, etc. (for example no or little cost attached to CO_2 emissions).[15]

CCS is often presented as a technology that is easy to fit onto the existing energy system. The lock-in perspective prompts us to ask whether the existing system may also hamper the introduction of CCS, in the form of plans that cannot easily be retrofitted with capture equipment, or regulations that does not take the specificities of CCS into account, or actors who lack incentive to invest in CCS if not legally obliged to.

The interconnected nature of the energy system means that such barriers may be difficult to remove, and that they need to be addressed together rather than separately.

The complexity of large technical systems also means that change to one component may propagate through the system, in ways that are complex and sometimes very difficult to predict. This makes governance of such systems difficult. The 'dash-for-gas' is an example of such dynamics.[16]

In the case of capture readiness, a core lock-in issue is that if we build new unabated fossil-fuelled power plants before CCS technology has been proven viable[17] we risk finding ourselves in a situation in the future of having invested a lot of resources into a system that is very difficult (technically, economically, organisationally, politically, etc.) to add the new CCS component onto. Will it be possible to just add on the new component? Or will the new component be interdependent with existing components (power plants, networks, fuel suppliers, etc.) in such a way that adding CCS entails major changes to existing components, making the change somehow impossible or prohibitively difficult? And can we avoid this problem, by being clever about the design of the power plants and by making other preparations, that is build the plants capture ready?

A further complicating factor is that CCS technology (and power plant technology) will change over time. CCS is under development, and has not yet been demonstrated to work. The technologies involved will evolve further before they may be retrofitted onto power plants. This causes technological uncertainty, that is, we do not fully know what CCS technology will look like in the future when it is to be used, and what consequences introducing it will have for the wider system.

In general, this is one of the reasons why technology can be difficult to regulate. On the one hand, before a technology is fully developed and implemented, it is difficult to know the impacts of its use and to specify the rules for whether and how to use it. But

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15 Of course, introduction of CCS would also build upon existing companies, skills, equipment, etc. – the point here is that this might be difficult to do for lock-in type reasons.

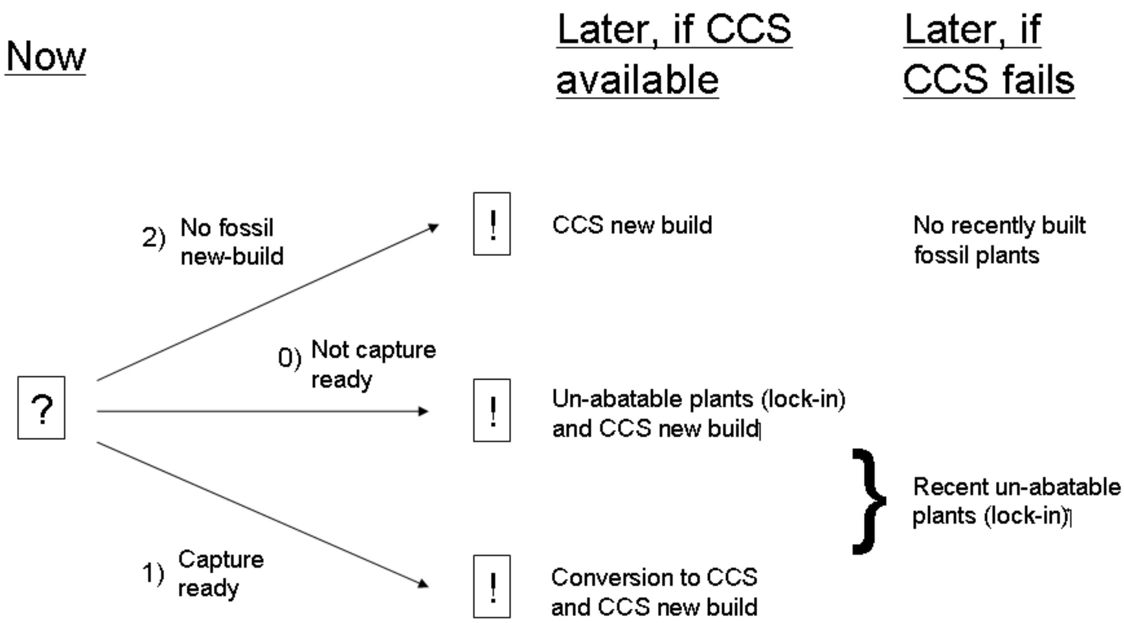
16 Winskel, M. (2002) "When Systems Are Overthrown: the 'Dash for Gas' in the British Electricity Supply Industry", Social Studies of Science, 32(4): 563-598.

17 That is, as an integrated system, at full operational scale.

on the other hand, when it is fully developed and deployed, it may be entrenched as part of a system that is by then difficult to change.[18] This is especially the case with technologies for large technical systems, which may exhibit large degrees of inertia and path-dependency.[19] Technological uncertainty is a core challenge to the idea of designing capture ready plants.

When considering capture readiness, we also need to recognise that there is more than one lock-in scenario to consider. Figure 2 illustrates some of the choices to be made now and later. Capture readiness has been promoted (for example by utilities) as a solution to choice (1) in the figure, that is to make new fossil plants capable of later capture retrofit to avoid stranded assets in case of future tougher CO_2 regulation/higher CO_2 price. (Given the technological uncertainty, we should recognise the risk that capture ready plants will not, down the line, be technically capable of retrofitting, or, conversely, perhaps even the possibility that un-ready plants will in fact be possible to retrofit.)

Figure 2 Lock-in scenarios



Note: The figure sets out three options to illustrate the choice we can make now, the possible later outcomes under different assumptions of what happens with CCS technology development. The figure intends to illustrate the existence of two different lock-in risks, one following from not doing CR, and one from building new fossil-fired plant now, with or without CR, in case CCS technology fails.

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18 This dilemma was articulated in Collingridge (1992) *The Management of Scale: Big Organizations, Big Decisions, Big Mistakes*, Routledge, London.

19 Sauter, R. and Watson, J. Micro-Generation: A Disruptive Innovation for the UK Energy System, chapter 6 in Murphy, J. (ed) *Governing for sustainability: environment, society and technological change*, Earthscan, London.

By contrast, the conservation organisation WWF-UK argues that there is a risk of another lock-in situation.[20] There is also the option (2) of not building new fossil plants without CCS in the short term, until the technology has been proven. This is to avoid the risk of building more fossil plants that will never be retrofitted with CCS, in case CCS technology does not deliver on its promises.

Furthermore, capture readiness will later be discussed as something that can be assessed on a scale rather than as a yes/no choice. We will discuss the risk that a high degree of capture readiness might represent a third type of lock-in, that due to technology developments old capture-ready modifications may, in a worst case, make a plant less amenable to capture retrofitting.

It is thus worth being careful about what lock-in scenario we are discussing, and also noting that different actors will highlight different lock-in risks depending on how they assess the probabilities of the different scenarios involved.

The literature also gives us a hint about possible strategies to pursue in the face of technological risk and uncertainty. Stirling proposes three main strategies: resilience, flexibility and diversity.[21] Resilience is about managing the internal structure of the technology, and could be interpreted here as building capture-ready plants. Flexibility is about keeping options open, and may be illustrated by a delay in building new fossil plants, but also that there is the less desirable possibility of building new plants now and decommissioning them later.

Lastly, and perhaps most interesting, diversity is here about pursuing different strategies in parallel. It may be worth considering mixing the different strategies. For example, one option would be to build a limited number of fossil plants now for CCS development and demonstration purposes, but fewer than what might be commercially attractive. This would limit the impact of locked-in capacity if CCS were to fail, but meanwhile allow for CCS development to be pursued (on a limited number of plants).

Another option would be to make some fossil plants capture-ready and others not in case the modifications actually end up making things worse, given the uncertainty of technological developments as mentioned above. However, this leaves a larger risk of carbon-lock-in, in case CCS fails.

Either option would require a new regulatory approach. Criteria would be needed to choose which plants to give consents for demonstration purposes, or which plants to release from the capture readiness requirement. There would no doubt be competitiveness complaints made against either approach.

Contexts

It is clear that different authors have seen capture readiness as being part of different contexts, and for that reason given the concept different meanings. For example, there is a difference between authors who see capture readiness as part of an investment strategy for utilities, those who see it as part of a regulatory strategy, and those who see it from a technology development point of view. In the sections below these

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20 WWF (2008) *A Review of the various meanings of and definitions for 'Carbon Capture Ready' in the UK - including views from investors, industry and government*, Terms of Reference/'Spec'.

21 Stirling, A. (1999) *On Science and Precaution In the Management of Technological Risk,* Institute for Prospective Technological Studies, Seville.

different contexts will be briefly described, and the different meanings attached to capture readiness compared.[22]

Firstly, we may see capture readiness as part of a regulatory strategy to reduce the CO_2 emissions from fossil-fuelled power generation. Here, capture readiness may be a way of ensuring that in the future regulators will be able to legally oblige utilities to fit capture on to the plants already built. Capture readiness is thus here an insurance policy and part of a carbon abatement strategy[23] to keep regulatory options open, and is consequently part of a long-term regulatory strategy. In this perspective, capture readiness is a means of extracting promises from companies, and the more binding and specific the better. (It is also part of a tradition in environmental regulation of explicitly prescribing technologies for use, as opposed to other regulatory avenues like emissions standards or emissions markets).

Secondly, other authors see capture readiness as part of company investment strategies.[24] The emphasis here is on life cycle costs, that is, an investment in a capture-ready plant is seen as part of a (potential) sequence of investments including a later retrofit. The challenge then is to minimise the costs over the lifetime of the plant. Economic aspects of capture readiness are here emphasised. (On a more aggregated level, this is also about fleet modernisation. Urgency is here added to the concept in the UK or EU context, by arguing that many important investment decisions will be made in the near future.[25])

As part of debates about regulation of the technology, Centrica also stress the financial and competitive risks involved in being a first mover.[26] (Whilst this is a real risk, the literature also suggests that there may be first-mover advantages to early investments in a technology[27]).

Thirdly, there is the position from within the CCS paradigm, from those intimately involved in developing and promoting the development of the technology. Capture readiness is here part of a plan for establishing CCS technology, as a way of buying time for developing the technology so that it can be deployed[28], and as a way of making sure companies are prepared to receive the technology.

From this innovation viewpoint, it is also worth considering what a requirement for capture readiness might have on the development of the technology. Firstly, a clear regulatory signal of capture readiness may serve to boost post-combustion capture relative to other capture technologies, insofar that it is today thought to be the easiest

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22 These different meanings have not necessarily been codified into formal definitions, but are present as connotations (related meanings) of the concept.

23 Drage, E., BERR

24 The Energy Institute, for example, stress that capture readiness is inherently linked to the risk associated with investment decisions requiring significant capital investments. EI (2006) *EI response to HM Treasury – May 2006. Carbon Capture and storage: a consultation on barriers to commercial development.*

25 EC (2007) Communication from the Commission to the Council and the European Parliament – Sustainable power generation from fossil fuels. Aiming for near-zero emissions from coal after 2020.

26 WWF (2007) *UK Power giants – Talking climate change*

27 Porter, M.E. and van der Linde, C. (1995) Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives* 9 (4), 97-118.

28 Lucquiaud, M., Chalmers, H., Li, J., Gibbins, J., Liang, X. and Reiner, D. (2008) *Capture-ready principles and design for pulverised coal plants*, Presentation at UKCCSC project meeting, March 2008. www.geos.ed.ac.uk/ccs/

retrofit option. Secondly, a capture readiness requirement may also generate a need for companies to prepare for and learn about CCS, and thus boost the development of CCS-related skills and experience in firms.

Above, we have set out three distinct perspectives on capture readiness. Reality is likely more nuanced and complex than this, but these three positions have been presented in a somewhat stylised manner for the sake of clarity. The point being to illustrate that different meanings are invested in the concept of CR to make it useful for different purposes.

These outlined perspectives also illustrate that capture readiness is a coming together of different perspectives and interests. It is a solution that fits with the different interests of (at least some) actors.

Finally, we note that the quality of 'capture readiness' definitions depends on their intended purpose. Our primary task in this report is to set out a definition that would be suitable for regulation in order to improve the level of confidence that carbon lock-in is avoided.

Summary

Carbon lock-in is not just a technical problem, in the sense of being able to fit new equipment onto an existing plant (or connecting the capture plant to a transport network, etc.). It is also a matter of organisation, coordination, legal agreements and financial provisions, for example, the building the skills necessary to operate the capture plant and to coordinate the actors involved in the CCS value chain.

'Capture ready' is used with different meanings and purposes by the range of organisations involved with CCS in the UK power sector. For example, some see CR as a hedge against future stranded (inoperable) assets; others see CR as an insurance strategy for governance to reduce emissions; and CR can also be viewed as a bridgehead mechanism to establish CCS in the future. At the present time, CR investments can be avoided by hoping that current plant designs enable future retrofit, or construction of new plant can be prohibited until CCS is ready.

Alternatively, CR can be stipulated by regulation. The challenges of this approach include regulating a technology under development, before its actual properties are well known, and to guarantee future retrofitting once the new generation capacity is built and entrenched.

It might also be possible to mix these strategies. For example, by giving permits to a limited number of plants, for the purposes of CCS demonstration, but not to others, so as to limit the risk of carbon lock-in, in case CCS fails.

2.2 Approaches to defining the concept

Previous work on capture readiness includes reports from the IEA GHG on retrofitting[29] and capture readiness, culminating in a prominent report in 2007, IEA

29 IEA GHG (2005) *Retrofit of CO2 Capture to Natural Gas Combined Cycle Power Plants*.

GHG (2007) *CO_2 capture ready plants*, 2007/4 – henceforth referred to as the IEA GHG report. There is also some academic literature on the concept.[30]

Definition types

There are different formats for a definition of capture readiness. The most common one is one or a few sentences that attempts to cover the essence of the idea. In the IEA GHG report[31] this corresponds to the headline summary definition given[32], which is then complemented by what is basically a list of more detailed aspects. This corresponds well with a model for regulation where a headline permit definition is elaborated and given further substance by more detailed guidelines.

When attempting to pinpoint the meaning of capture readiness, another option is to define what the opposite - capture un-ready - would mean. We will return to the use of such a 'negative definition' below.

It is also worth pointing out that capture readiness is not always seen as a binary – yes or no – property, but something that can be measured on a scale from not capture ready to “very capture ready”, as it were.[33]

Liang et al[34] also make a distinction between ('broad') flexible, open-ended definitions that easily allow for technological change over time, and (“narrow”) more fixed and comprehensive standards. The latter may be more suitable for regulation purposes since it would be easier to judge whether a plant complies or not.

We propose that a good definition format for the purposes of regulation encompasses headline and detail levels, allows for degrees of capture readiness – whilst defining the degree required, and sets down a fixed standard.

What is the object that is to be ‘capture ready’?

Interestingly, different proposed capture readiness concepts refer to different objects. That is, they give different answers to the question of what the thing is that is or isn't

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30 Including Bohm, M., Herzog, H., Parsons, J. and Sekar, R. (2007) “Capture-ready coal plants - Options, technologies and economics”, *International Journal of Greenhouse Gas Control*.

31 IEA GHG (2007) *CO_2 capture ready plants*, 2007/4.

32 “A CO_2 capture ready plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture ready is to reduce the risk of stranded assets and 'carbon lock-in'.

Developers of capture ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO_2 capture have been identified and eliminated.

This might include:
o A study of options for CO_2 capture retrofit and potential pre-investments
o Inclusion of sufficient space and access for additional facilities that would be required
o Identification of reasonable route(s) to storage of CO_2

Competent authorities involved in permitting power plants should be provided with sufficient information to be able to judge whether the developer has met these criteria.”

33 Skarbeck, A., Climate Change Capital.
Arguably, one also needs more than one scale to assess capture readiness.

34 Liang, X., Li, J., Gibbins, J. and Reiner, D. (2007) *Financing Capture ready Coal-Fired power Plants in China by Issuing Capture Ready Options*.

capture ready. The common sense option here is that it is a power plant, but that is not the only plausible option.

Firstly, there is a distinction to be made between an investment[35] (a set of decisions about plant design, etc.) and a power plant (a complex configuration of equipment). This reflects a distinction between the intention behind the investment and its outcome. The engineering challenge of capture readiness is exactly this, whether the intention of capture readiness can be built into the plant or not.

There may be different intentions behind a capture-ready investment: regulatory compliance, avoiding stranded assets, etc. From an environmental point of view, what matters is only the outcome, in terms of suitability of retrofit (and ultimately the amount of emissions). Therefore, the purposes of the investment apart from preparing for retrofit should not be included in a definition to be used for regulatory purposes.[36]

Secondly, the boundaries of the system that can be assessed as capture ready varies between different versions of the concept. Capture readiness can be seen to affect more or fewer components of the power plant. It can be a relatively marginal thing involving mainly the availability of land and space in and around the plant, but it can also involve core technological components, like turbine design, and so affect most or all components of the plant.

Moreover, capture readiness usually includes transport and storage (and should therefore perhaps rightly be called CCS readiness), but most of what has been written on the subject in practice focuses on the plant end of the CCS system, whilst briefly mentioning that transport and storage should be included. The downstream boundary of capture readiness is in this sense blurred.

From an environmental point of view, capture without storage is pointless, and readiness also for transport and storage matters profoundly. This point opens up several potentially difficult issues. For example, one of the things that have not been demonstrated yet is the integration of the full system (that is, power plant, capture, transport and storage), and we therefore know comparatively little about the technical challenges of integrating the full system (more about what we do know later).

Furthermore, whilst it seems clear that utilities would take the responsibility for capture operations, it is less clear which organisations will provide transport and storage. This makes the task of coordinating preparations for transport and storage as part of the full system difficult. A capture readiness requirement that has emissions reductions to mitigate climate change as its main aim (as in the UK), would have to place an equal responsibility for ensuring that transport and storage capabilities will be available with some plausible organisation.

This could be the utility, who could then acquire new capabilities for transport and storage (very far away from core business) or contract that responsibility out to others, although it is unclear who would provide that service.[37] Experience with the Peterhead project as well as current consortia partaking in the Government demonstration competition, suggest that there will be willing actors, and that new

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35 Bohm, M., Herzog, H., Parsons, J. and Sekar, R. (2007) "Capture-ready coal plants-Options, technologies and economics", *International Journal of Greenhouse Gas Control*.

36 As is done in the IEA GHG report definition cited above.

37 Mitchell, J., Scottish and Southern Energy

organisations may emerge to meet these commercial needs.[38] A capture readiness requirement could be used to give the utilities the role of system builders, that is to mobilise the value chain and ensure that preparations are on-going across the system.

What this also illustrates, is that capture readiness is not just a technical issue, but also a matter of coordinating efforts across a complex, interconnected socio-technical system, with potentially and probably many different actors involved.

Based on this discussion, we recommend a definition based on outcome rather than intention, and one that is inclusive of downstream components and actors, as a fundamental and necessary - but perhaps difficult to achieve - condition.

The timing of retrofitting

The purpose of capture readiness is to be able to retrofit capture technology at a later date. The concept is therefore about plants/investments at two points in time: the current status of a plant, and a modification to it in the future. A credible definition therefore needs to specify conditions for both times.

The short, headline, definitions suggest different criteria for when the time is ready for retrofitting. Some commentators suggest that it is about technical maturity, that is, when the technology is well enough proven it should be retrofitted. Others suggest that it is also/instead about economic viability (costs of technology low enough, CO_2 price high enough, etc.).[39] Climate change imperatives would suggest that retrofitting occurs at the earliest opportunity, even if sub-optimal economically. Finally, some include regulatory requirements as a basis for retrofit timeliness.[40]

There are models for assessing technology readiness expressed in purely technical terms. (See for example NASA's 'technology readiness levels' model.[41]) It should be clear, however, from our discussion above regarding downstream issues that an important aspect of technology readiness in practice is the coordination of different actors in the socio-technical system of CCS. Another potential criterion for retrofit timing is therefore that there are organisations in place with the capacity to operate all components of the system, and a business, legal and financial model for coordinating their activities.

It is in practice difficult to separate out technological maturity from not only organisational (coordination) aspects, but also from regulatory and economic factors. Regulation is needed to ensure for example the safety of the technology in operation, and the technology can not be considered ready unless such a framework is in place. And a part of the coordination challenge among the actors involved is to find a model for the sharing of risks and rewards, that is, an overall business model for CCS. Without such a model, the technology cannot deliver.

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38 If the utilities are made responsible, the responsibility ends up by default with the government itself, who would then have to farm out this responsibility to, say, oil and gas companies, or coordinate the system itself.

39 For example, "[a] plant can be considered 'capture-ready' if, at some point in the future it can be retrofitted for carbon capture and sequestration and still be economical to operate". Bohm, M., Herzog, H., Parsons, J. and Sekar, R. (2007) "Capture-ready coal plants - Options, technologies and economics", *International Journal of Greenhouse Gas Control*.

40 The IEA GHG report, for example, includes both economic and regulatory factors. See definition cited above.

41 Presented at http://en.wikipedia.org/wiki/Technology_Readiness_Level

An existing assessment of the readiness of CCS technology using a simple scale, which emphasises both apparently technical and the economic aspects of maturity is given by the 2005 IPCC report.[42] This is summarised as Table 3.

It is worth repeating here, though, that system integration presents challenges in itself, and it has therefore been added to the table. We would estimate the readiness of CCS system integration to be approaching demonstration phase.

It will thus be difficult to specify sensible criteria for the required timing of retrofitting, in terms of 'purely' technological maturity. In practice it comes down to specifying a credible scenario (or several) for the future plant + CCS system. That is a big task, with many dimensions, riddled with many uncertainties.

A more practicable approach would be to wait for the first successful, full-scale demonstrated CCS system, as a more reliable indication of the maturity of the technology, and choose that as the starting point for mandatory retrofitting requirements. Such a demonstration need not be in the UK.

A more fundamental question is whether the regulator ought to specify such criteria. The arguments for are that it would reduce the regulatory uncertainty (insofar as suitable criteria can be specified) for the actors involved, and that this would be a commitment on behalf of government to press ahead with CCS when possible (and it would generate at least some pressure on future Governments to live up to it).

We recommend that the UK Government does commit to future mandatory retrofitting, and sets out a criterion (deadline date) for when retrofitting will be mandated. A practicable approach may be to set out a series of stage posts, being dates when government will re-assess the maturity of the technology, and based on this require retrofitting, or revoke permits. More about this later.

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[42] IPCC (2005) *Carbon dioxide capture and storage*

Table 3 The maturity of CCS technologies

CCS component	CCS technology	Research phase	Demonstration phase	Economically feasible under specific conditions	Mature market
Capture	Post-combustions			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced Oil Recovery (EOR)				X [1]
	Gas or oil fields			X	
	Saline formations			X	
	Enhanced Coal Bed Methane recovery (ECBM)		X		
System integration		X			

1) CO_2 injection for EOR is a mature market technology, but when this technology is used for CO_2 storage, it is only economically feasible under specific conditions

Source: Adapted from IPCC 2005 /Carbon dioxide capture and storage.

Summary

The basic, minimum idea of the concept of 'capture ready' seems clear, but the means to define and measure CR show that it is not a simple "either–or" decision, but rather can be defined at different points along a scale of readiness (which varies for particular plant-capture configurations). These points can range from the simplest provision of footprint land space for capture equipment, through to complex plant design changes. Furthermore, a more difficult and heavy requirement to comply with is not always better in terms of avoiding lock-in.

What matters is not the intention (avoiding carbon lock-in, avoiding stranded assets, etc.), but the outcome – the ability to convert to a low emission plant including capture and storage of carbon dioxide (and Government's ability to enforce that).

It is profoundly important that CR includes not just the power plant, but also assessments of the routes for CO_2 transport, and the availability and capacity of a storage site. These aspects lie outside the plant site, and will require the power

company to build new skills, and to create credible new business relationships with specialist partners as early as the CR investment.

The timing of conversion to full CCS will be constrained by the technical availability of proven CCS technology. Technical maturity is not independent of economic aspects, and the degree of financial viability will also in practice matter for retrofit timing. Clear regulatory criteria are needed to enforce conversion, with periodic re-assessments benchmarked against worldwide progress.

2.3 Detailed level specifications

The discussion so far has been held at an overall "headline" level, and we will now delve into more detailed considerations (corresponding to a regulatory guideline level). We have grouped these into four main dimensions:

- plant technology and operations,
- downstream issues,
- systems integration and
- regulation of retrofitting.

This section will, then, provide what is basically a structured list of issues to consider for a detailed definition of capture readiness. Such a list is unavoidably open-ended; it is not possible to exhaustively predict all aspects of the future CCS system. This section will be guided by what can be identified from the capture readiness literature, and from the preceding discussions in this chapter.

This section will also set out, where possible, criteria to judge capture readiness. We will also compare and discuss different statements about how stringent criteria to apply.

It is worth pointing out here that such criteria relate to current plans for investment in equipment, but also – perhaps less obviously – to information provision, promises about future investments, coordination of actors, etc.

Plant technology and operations

As discussed above, headline definitions suggest technical or economic criteria to judge whether a plant is capable of retrofitting. A fundamental question is whether it is possible to separate technical from economic criteria. This can be clarified by asking the reverse question of what would constitute an un-ready plant. It is clear that if capture is technically feasible on new build, then retrofit is also technically possible on any plant. It would be possible to set up a separate capture plant operating on the flue gases from the power plant, and with its own supply of steam, power, etc. (depending on what capture technology is used).[43] Such a solution would be (perhaps prohibitively) expensive, but not technically impossible. Such a scenario would also require the least in terms of modifications to the power plant. In fact, no modifications would be absolutely necessary.

Such a plant would be less efficient and less profitable, compared to a plant where a capture system had been designed and its performance optimised, as part of the building of a new plant. The best technical option of all, would be to build new power

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[43] Mitchell, J., Scottish and Southern Energy; IChemE (2007) *Capture ready study*.

plant integrated with capture and to operate both systems together from the start-up of the new plant. What drives the notion of capture ready plant design is the possibility of (future) integration of power plant with capture plant so as to increase the efficiency and the profitability of the plant. In practice, therefore, technical and economic feasibility are un-separable.

This is also why it is not entirely clear what a dichotomy between essential and optional plant modifications (pre-investments) means. The IEA GHG report presents this distinction, and suggests that economic considerations only apply to the optional modifications. The report, however, does not explain clearly what criteria are to be used to classify modifications as essential or optional, and since economic concerns drive integration economic factors will always play a role. A dichotomy between essential and optional modifications is exactly what a detailed definition of capture ready plants needs to establish, but it cannot be based solely on technical factors without any regard to economic viability.

In the literature, then, there are necessary plant modifications suggested ranging from core technology, for example altered steam turbine designs, via modifications to pipe-work and ancillary systems like cooling water, to entirely plant-external features like road width on the site for the purposes of retrofitting operations.

Table 4 Power plant type – capture technology matches

	Post-Combustion	**Pre-Combustion**	**Oxyfuel firing**
Pulverised Coal Steam Plant	*Feasible*	Not Applicable	*Feasible*
Fluidised Bed Steam Plant	*Feasible*	Not Applicable	*Feasible*
IGCC [2]	*Feasible*	*Feasible* [1]	Non compatible technology: not feasible
CCGT [3]	*Feasible*	*Feasible* [1]	*Feasible*

1) New gas turbine design necessary in order to burn H_2. Shift reactor and CO_2/H_2 separation are needed. Gas conversion and CO_2 remediation (capture) are necessary.

2) Integrated Gasification Combined Cycle

3) Combined Cycle Gas Turbine

Adapted from EPPSA (2006) *EPPSA's CO_2 Capture Ready Recommendations.*

It is worth noticing that even the basic choice of what power plant type (and fuel) to choose is related to the choice of planning for a retrofit. Table 4 sets out what combinations of power plant and capture technology are currently seen as feasible.

Table 5 summarises the main essential modifications to different power plant – capture technology combinations, as suggested by the IEA GHG report.

Table 5 Summary of main areas for capture-readiness modifications

Configuration	Modifications
PC [1] + post	Add/upgrade FGD Modified design of steam turbine (with ancillaries)
PC + oxy	Avoid in-leakage to boiler Design air ducts and fans for re-use for flue gas recycle FGD design that copes with different gas flows and compositions Modified design of steam turbine (with ancillaries)
IGCC	Addition of shift converters Modification of acid gas removal plant for CO_2 separation Conversion of gas turbines to hydrogen combustion Changes to steam system
NGCC [2] + post	Stream extraction as for PC
NGCC + pre	Addition of natural gas partial oxidation Addition of shift conversion Addition of CO_2 separation plant Conversion of gas turbines to hydrogen combustion Design steam turbine to cope with changes in flue gas flow-rate, composition and temperature

1) Pulverised Coal plant

2) Natural Gas Combined Cycle

Data from IEA GHG report

The IEA GHG report further presents economic estimates which show that essential modifications can be relatively cheap - as compared to overall investment costs for power plant. There are economic reasons (life cycle costs[44]) not to invest heavily in optional pre-investments.

However, there is also a risk that extensive capture-readiness modifications may end up making retrofit more difficult. If technology develops a lot in ways that are not foreseeable, then capture readiness modifications may end up having been useless or even detrimental. This is another argument against heavy pre-investments. This risk is illustrated in figure 3 below. (Again, this argument is based also on economics, rather than any pure technical factors, since as above separate, un-integrated capture would still be possible.)

The trick is, therefore, to invest in the right level of capture ready modifications, which balances current technical knowledge with uncertainty of future technology development. Table 6 gives examples of essential capture readiness investments, and optional investments that are judged not to be necessary for retrofitting (they may

[44] An investment now is more costly than an investment later (of nominally the same amount) because of discounting.

help towards retrofitting, but are costly, and entail a larger risk of having over-modified the plant design).

Table 6 Examples of capture ready design modifications

Configurations	Capture ready design modifications	
	Essential	**Optional**
All	Oversize pipe-racks. Provisions for expansion of control system, on-site electricity distribution and cooling capacity	-
PC + post	Valves and tie-ins for extracting steam, to be used in capture plant.	Modified steam turbine configuration (to optimise operations before and after steam needed for capture).
PC + oxy	Provision for process integration with the air separation unit, boiler flue gas system and CO_2 compression plant.	Steam turbine island equipment sized for optimum performance before and after capture.
IGCC + pre	Space for two-stage shift reactor and supplementary acid gas removal column.	Sizing of gasifier and air separation unit to cope with conditions both before and after capture retrofit.
NGCC + post/pre	Space for new pipes, for example for steam to capture solvent regeneration.	Fitting a bleed onto the gas turbine compressor, to be used in a future air separation unit of the capture plant.

Data from IEA GHG report

Something that has not been mentioned in the capture ready literature, but is worth considering, would be to also require companies investing in new fossil fuel plants to invest in pilot size (1-25MW) slipstream capture equipment. This is a realistic requirement today. It would not reduce emissions, but would enable the companies to build up the skills and experience which could also be seen as a part of being ready for capture. This construction cost is likely to be £8-80M. (The Elsam plant in Denmark cost €16M[45]. This can also be compare with RWE's plans to build such a facility at Aberthaw, at an estimated cost of £8.4M, with a subsequent larger 25MW pilot plant costing £50M, see table 1). This is a small cost compared to the £500-1200M cost of the new plant. As well as directly creating expertise, such facilities will be of future value to trial new and improved methods of solvent or membrane capture. Information also needs to be exchanged between actual and potential plant operators.

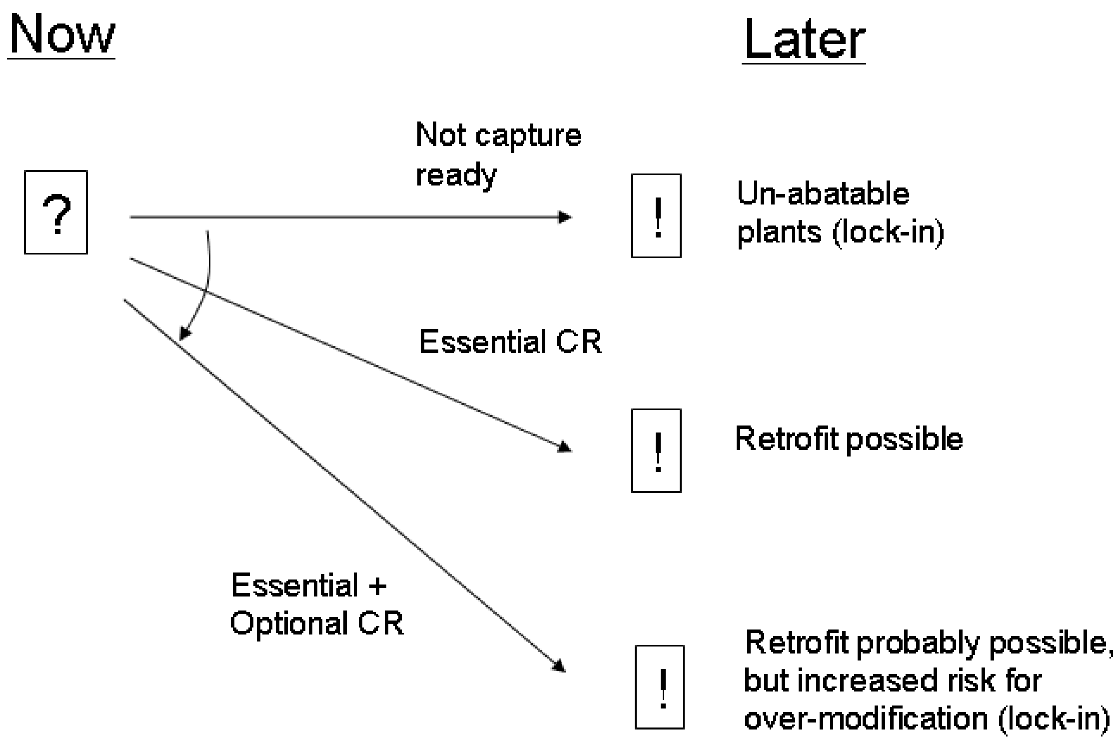
An additional feature common to all options is the availability of ground footprint space adjacent to the existing power plant, and in the correct position to integrate capture with the power plant. A desk-based design study of the proposed site will also highlight generic issues such as vehicle access and storage of material during construction. A related issue is about the layout of the power plant. The layout matters in terms of having space for adding new equipment and pipe-work needed. This is

[45] www.ens-newswire.com/ens/mar2006/2006-03-15-06.asp

also a matter of having enough space during operations and maintenance, as well as during the retrofitting construction. A design study should include these aspects.

Whilst many of the essential modifications are expected to be cheap, it should be noted that they can rely on more or less extensive knowledge and information requirements. Sources differ in terms of at what levels hurdles are to be set. Proposals range from the concept level[46] to a much more labour and knowledge intensive outline design level[47]. Again, this is an issue of judging the technological uncertainty. If it is considered to be high, then current knowledge is less useful, and extensive preparations less meaningful.

Figure 3 The risk of over-modification



Note: The figure intends to illustrate the risk of over-modifying power plants, that investing in so-called optional design modifications may actually increase the risk of lock-in. The ideal is the right level of CR investment.

We also note here that as part of planning for capture readiness, environmental impact analyses[48] as well as hazard and operability studies[49] have been proposed.

An important point is that a regulatory capture readiness requirement needs to include conditions regarding material investments and design choices made, and also regarding information provision. This will be needed to enable regulators to assess the

46 Mitchell, J., Scottish and Southern Energy.
47 IChemE (2007) *Capture ready study*.
48 IChemE (2007) *Capture ready study*.
49 IEA GHG report.

investment plans and the resulting plants, but could also be used as an indicator in itself of how well prepared the utility is for future carbon capture.

As for the operations of the plant, it may be noted that capture readiness is expected to have some impact on the availability and flexibility of the operations of the plant.[50] We will return to this later, when discussing the FGD case.

There is also an organisational dimension to utilities' preparations for carbon capture. A utility needs to have the expertise, skills and the routines for operating and maintaining the capture plant in place in order to have a working capture plant. This would take time to put in place, and the existence of plans for preparing the organisation for operating and maintaining the capture plant is another possible regulatory requirement. Such plans could include recruitment, training and development of operating procedures. Mandatory slipstream capture operations, as mentioned above, would require utilities to build expertise.

We recommend then that a capture readiness requirement should include essential pre-investments, as summarised in table 5. Further, we would argue in favour of stringent information provision requirements regarding plant design and the site, as a way of both assessing and stimulating the companies to prepare for capture. We also recommend that such information provision requirements include organisational aspects.

Downstream issues

Existing headline definitions often (but not always) mention the need for considering downstream arrangements. They often include the expression 'route to storage', which is then taken to include both transport and storage. The EC proposed definition includes "... the availability of suitable storage sites and suitable transport facilities...".[51]

The headline definitions usually have relatively little concrete to say about what needs to be in place regarding downstream arrangements for a plant to be considered capture ready (that is, CCS ready). As discussed above, this is part of the blurring of the downstream boundary of the entire system that is to be capture ready.

For transport, a basic requirement can be to identify a possible route for a pipeline (or other transport options for CO_2 such as shipping since not all plant locations will require an on-shore pipeline). A problem here is that the relevant safety regulation is not yet in place, and it is therefore not possible to know for sure what routes are possible or not (apart from perhaps in areas with very low population densities). Furthermore, it has been suggested that utilities should secure rights of way for the identified routes. A feasible option may be for the planning authority to allocate a protected planning status to the desired route, so that no detrimental development occurs in the intervening period.

Transport planning also opens up the issue of public acceptance of new CO_2 pipelines.[52] This may or may not become an issue, but it is difficult to prepare for this,

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[50] IEA GHG (2005) *Retrofit of CO2 Capture to Natural Gas Combined Cycle Power Plants*.

[51] EC (2008) *Proposal for a Directive of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006.*

[52] IChemE (2007) *Capture ready study*.

since potential protests may not happen until closer to the date when pipelines will actually be built. Applications for future planning permissions may trigger protests though, which is an argument for early applications, to get this issue up on the table.

Routes, permits, etc. also apply to any off-shore pipelines. It is expected, but not certain, that the public will be less concerned with off-shore pipelines. These may be subject to new constraints around or through offshore conservation zones proposed in the 2008 Marine Bill.

For storage, similar requirements regarding identification and permits could apply. A storage site would need to be identified, which can accommodate both the volume of CO_2 anticipated from the power plant, the rate of supply, and which is also available during the correct time frame. The excellent level of geological information available for saline aquifers around the UK will enable a generic predictive appraisal simulation to be made to assess the performance of sealing during the time-scale of storage, injectivity rates, and screen for adverse chemical reactions. Dates when depleted oil or gas fields become available are also known, as is their detailed geological makeup.

Unlike transport, it is here also necessary to consider the long-term consequences of the CO_2. Liability arrangements that set out ownership and responsibility for the stored CO_2 need to be outlined, ready to be put in place, at the start of storage. WWF-UK have further suggested that companies should be required to set aside a sum of money[53] as a 'financial bond' to bolster their credibility in terms of being able to manage any future problems. Because this could well be unpopular with companies, tying up tens to hundreds of millions of pounds for decades at a time, other organisations[54] have suggested that a communal fund would be more appropriate, to spread the risk payments across range of actors.

Large scale insurance, and re-insurance, will need to adapt existing environmental project assessments or will need to develop new markets to handle CCS risks (considered to be of very low frequency but potentially high impact). Large companies (multinational oil majors) could choose to self-insure. Small companies would need commercial insurance, or need the Government to set up and operate a communal bond system.

We recommend that capture readiness should include outline identification of pipeline routes and storage sites. The necessary permits should be acquired as soon as Government regulation is in place. We also see planning to insure risks of stored carbon dioxide as reasonable, the methods for which will have to vary depending on the circumstances for the developers.

System integration

It is worth repeating that capture, transport and storage can not be seen as just independent components, but that integration of the full plant + CCS system is a challenge in itself. This includes technical issues, like CO_2 flow rate and quality, which need to be matched and agreed across the system.

It may also affect plant location decisions, at least insofar as that there must be a possible transport route between plant and storage. Locations in northern and eastern

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[53] WWF (2008) *A Review of the various meanings of and definitions for 'Carbon Capture Ready' in the UK - including views from investors, industry and government*, Terms of Reference/'Spec'.

[54] www.irgc.org

Britain are likely to provide easier access to storage. Location decisions may also be affected by future plans to develop regional networks of CO_2 transport pipelines. It has also been claimed though that location decisions are likely to be decided based mainly on other criteria, for example distance to customers, as opposed to distance to storage.[55]

We now return to the issue of coordinating the actors involved in the full power plant + CCS system. WWF-UK have raised the issue of whether regulation should require utilities to have contracts for transport and storage in place for power plant investments to be considered capture ready.[56] A problem here is that it is not clear who would be willing to provide these services, although with more information becoming available about the consortia bidding for the Government demonstration competition, identification of these actors is becoming easier. It is as yet unclear, however, what degree of commitment they are prepared for.

In contrast, the definitions of the IEA GHG report suggests that utilities should only be required to prepare for capture those things that are under their own control. Contracts can, however, give companies some control over resources that they do not themselves own, and such a distinction is perhaps not necessary. A third option is that Government guarantees the availability of the downstream system.

This discussion illustrates the fundamental lack of a model for coordinating the full system, and how difficult it is to prepare for this as part of a regulatory requirement. Without such coordination, however, no useful capture, and no CCS can occur.

WWF-UK have raised the issue whether to, in line with liability for storage, demand that companies set aside money to guarantee that they are able to invest in CCS at the time of retrofit. For a 400 MW plant this is an investment of at least €430-682m.[57] We would suggest that this ties up capital that could otherwise be invested in other low-carbon generating capacity whilst waiting for CCS.

Capture readiness needs to include a means of coordinating actors across the plant + CCS system. This is expected to be a difficult criterion to achieve.

Regulating the future

The regulatory aspect of capture readiness is about both current actions – having the right permits in place, etc. at the time of the investment, and also an agreement about future actions at the time of the retrofit. This has some important consequences.

It has been suggested that a capture ready requirement must specify the future capture rate or overall emission performance per MWh generated (effectively how much of the CO_2 produced should be captured) of the retrofitted plant, or more generally what will be required for retrofit consents.[58] This seems reasonable as a starting point for the design work. However, it also means that the regulator has made a promise about future regulation. It may then be difficult for a regulator to change the capture rate

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55 EPPSA (2006) *EPPSA's CO_2 Capture Ready Recommendations.*

56 WWF (2008) *A Review of the various meanings of and definitions for 'Carbon Capture Ready' in the UK - including views from investors, industry and government*, Terms of Reference/'Spec'.

57 Source: Climate Change Capital (2007) *ZEP: Analysis for funding options for demonstration plants*.

This is the capital expenditure, to which comes costs of operations and maintenance. Also, costs for transport and storage should be included, but are expected to be small as compared to capture.

58 IChemE (2007) *Capture ready study*.

criterion down the line, should technology development so allow. This could be called regulation lock-in. A regulator should make sure to explicitly reserve the right to impose stricter criteria in the future.

Retrofit consents raise the issue, as introduced above, of the timing of mandatory retrofits, as part of a capture readiness requirement. This has not been discussed much in the literature, however Climate Change Capital propose that a capture requirement is a powerful regulatory signal, and makes a capture readiness requirement unnecessary.[59] We agree that a requirement for future retrofit would be a very strong signal, but that it is worthwhile making sure that companies also prepare in good time, and suggest that a capture readiness requirement is needed, and that it should include regulation of future retrofits.

Current regulation needs to set down a procedure by which future full CCS operation will be mandated. The regulation should also include an option of revoking operating permits and closing the emitting plant, to safeguard against the (worst case) scenario of CCS not becoming available, soon enough or not available at all.

The objective of CCS must be to reduce CO_2 emissions. Consequently, full CCS conversion of CR plant should be mandated after the technology has first been demonstrated. CCS should be mandated three years after the first successful, full-scale, integrated CCS system relevant to the CR plant in question (gas or coal) is up and running (in any world location, not just he UK). This time is needed for the design and construction of new CCS systems. (Learning from the demonstration plants will happen as they are designed and built, as well as in parallel with designing and constructing the new CCS systems).

Since new fossil fuelled plants would increase CO_2 emissions it is necessary to impose a cut-off deadline, in case the first demonstration is delayed, in which case CCS should be mandated anyway. This could mean that if demonstrations fail, CCS is built even if it is very expensive. 2020 is a reasonable deadline for CCS technology to have been tested and proven, if we are to have both fossil-fuelled electricity generation and an effective climate change mitigation policy. If CCS has not been shown to be feasible by 2020, the Government should start revoking operational permits.

To implement this policy, it will be necessary to regularly assess progress towards full scale demonstration (anywhere in the world). We propose biannual stage posts to reflect the expected speed of technology development, starting in 2012 when the first full systems may be nearing completion.

We highlight the risk of regulatory lock-in when regulating in advance future capture retrofits. We recommend a stage-post approach to the regulation of retrofitting, whilst highlighting the risk of early decommissioning this entails. The difficulties of guaranteeing future regulation will be discussed more below.

Overview of actions for utilities and policy-makers

Table 7 gives an overview of the actions a utility should undertake for the investment to be capture ready, as discussed in this report. The table sets out these actions going from little to more effort, from left to right in the table. More effort is not always better though, from the point of avoiding carbon lock-in. Therefore there is also a

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59 Climate Change Capital (2007) *ZEP: Analysis for funding options for demonstration plants.*

classification of the probability of avoiding lock-in, going from lower, through higher, and down to lower again. Finally, the colour coding indicates our judgement of how well-established knowledge and expertise there is to realise each action. This scale goes from green = known, to amber = possible/some uncertainty, to red = difficult/unknown.

Government has a large responsibility to provide regulation, in progressively more detailed stages – much regulation is currently lacking in detail of CCS. Government should retain the option to close plant which have not fitted full CCS by a pre-agreed date, we suggest within three years of a full CCS chain being built and operated, and full CCS from 2020 in any case. This strong regulatory signal will enable plant developers to see CCS as inevitable. Table 8 summarises the policy actions needed from Government for a credible capture readiness regulation that includes retrofitting.

Table 7 ***Actions for utility to undertake to be 'capture ready'*** (see explanation of the table on the preceding page)

	Probability of avoiding carbon emission lock-in			
	Lower	**Medium**	**Higher**	**Medium/Lower**
PLANT				
Space and layout	Statement of capture ready ambition	Land for capture plant identified. (Brown or un-developed land. 0.5 to 1x footprint of main boilers + turbines needed).	Land for capture plant bought. Layout requirements based on design study included in plant design.	
Plant design **(cf. table 6)**	Statement of capture ready ambition	Concept level study.	Design study. 'Essential' pre-investments, without which retrofitting is very hard. (Include routing within plant, pipe-work tie-ins, expanded cooling capacity, etc.)	'Optional' pre-investments, to make retrofitting easier and improve integration with plant.
Organisational learning	Statement of capture ready ambition	Plan for recruitment and training.	Construction and operation, now, of small-scale capture (1-50MW) at every new gas or coal plant. This requires recruitment, training and management of specialist staff.	Acquire full expertise to purchase transport and storage services now.

DOWNSTREAM				
Transport	Statement of capture ready ambition	Desk study identifying boat or pipe route (with expectation of protected planning status from Local Authorities).	Secure way leaves, ownership and planning permission as soon as regulation is in place.	Secure ownership immediately.
Storage	Statement of capture ready ambition	Desk study to identify storage site, capacity, and timing. Outline simulations testing validity.	Full appraisal and simulation. Apply for operation permit as soon as regulation is in place. Financial guarantee (bond or insurance) to cover liability.	Drill boreholes before simulations.
SYSTEM INTEGRATION				
Technical issues	Statement of capture ready ambition	Desk study to match flow rate / capacities, and storage availability.	Agree CO_2 temperature, pressure, contamination flow rates, timing of linkup and beachhead to offshore transport.	
Value chain management	Statement of capture ready ambition	Plan for what capabilities needed. Identify pipeline constructor and operator.	Agree business model with the actors in the CCS value chain. Identify specific sources of components and original equipment.	Contracts exchanged. Set aside capital for CCS now.
RETROFIT TIMING				
Investment	Statement of capture ready ambition	Wait until economically viable.	Transfer to full CCS operation within 36 months after first demonstration (anywhere in the world), or else close and decommission plant by 2020.	Invest in full CCS now.

Table 8 Policy actions needed

What	**When**
CR regulation, as elaborated in this report, and including a schedule for “retrofit or revoke” (see below).	Now
Regulation for transport and storage	
- Complete regulatory regimes	Soon
- More detailed regulation	Continuous
Mandatory retrofits	3 years after first demonstration, or 2020 regardless
- Revoke permits	2020, if CCS has failed

Note: Colour coding as in table 7.

As these two tables illustrate, we judge that the most difficult or least well-understood actions are for utilities to prepare for storage (or induce someone else to do that) and system integration, and for policy-makers to implement a stringent and timely retrofit regulation.

Summary

Examples of necessary pre-investments in plant design are shown in table 6 above; these include additional space for future pipes and equipment, tie-ins for future extraction of steam, expansion of support systems like electricity and cooling water. Skills, expertise and operating procedures also need to be developed within companies. To encourage this, we propose that all new post-combustion coal and gas plant construct and operate 1-25MW pilot capture plant immediately upon start-up as part of the CR condition. Outwith the plant, detailed plans for CO_2 transport need to be prepared, up to a level suitable for acceptance by the local Planning Authority and information provided to any affected publics. Geological storage can be appraised in outline, using existing data around the UK, to assure timing, volume and performance. The full CCS value chain also needs to be mobilised, that is, the actors identified and a model for their coordination agreed.

Tables 7 and 8 give an overview of the action required on behalf of utilities and policy-makers to implement CR. We judge that the most difficult or least well-understood actions are for utilities to prepare for storage (or induce someone else to do that) and system integration, and for policy-makers to implement a stringent and timely retrofit regulation.

3. Comparison with the FGD case

This section will look at the experience of introducing flue gas desulphurisation (FGD) technology into the UK power sector, with the aim of comparing with CCS introduction. It is hoped that an historical case, which is in some ways similar: regulation-driven implementation[60] of environmental abatement technology in the same sector, will offer some insights that can be of use to us here.

The Large Combustion Plant Directive

The process of implementing FGD was shaped by several factors, but the crucial driver was the EU Large Combustion Plant Directive (LCPD) of 1988. The directive regulated several types of emissions, including SOx. It was transposed into UK law in 1991[61], and underwent a major revision in 2001, which will come into effect in 2008. It is still very much affecting the development of the UK fleet of power plants, and is part of the background to why a lot of capacity will need to be renewed within the next 10-15 years.

The regulation offers utilities different options for their plants. They can choose to either abide by emission limit levels, join a national plan[62] – effectively a trading scheme, or 'opt out', which means a restricted number of operating hours before decommissioning before the end of 2015 at the latest. For the utilities, this means that they can do one of several things. They can either burn less coal, burn coal with less sulphur content, close down, or implement FGD.[63]

It is worth noticing that the UK has over the years lagged behind in FGD implementation as compared to for example Germany and Austria. UK Governments have sought to reduce the strictness of the regulation (with arguments including a high dependency on coal[64], and high sulphur contents in domestic coal). Germany, in contrast, had binding national regulation in place before 1988, as well as an industry geared up for supplying FGD equipment.[65]

Privatisation and the dash for gas

The UK electricity generation industry was privatised in 1990, and in the first instance two companies were formed: National Power and PowerGen. Very soon after, the dash for gas occurred, partly as a result of the privatisation.[66]

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60 This is uncertain of course, since it has not yet happened. Also, we here include market-based policy instruments like the EU ETS in 'regulation-driven'.

61 Eames, M. (2000) *The Large Combustion Plant Directive (88/609/EEC): An Effective Instrument For Pollution Abatement?*, SPRU, University of Sussex.

62 Before the revision of the Directive it was a company-level ceiling, i.e. company-internal 'trading'.

63 Blauvelt, E. (2004) "Deregulation: Magic or Mayhem", *The Electricity Journal*, August/September.

64 ENDS Report, February 1995, "Row over FGD rocks the boat for power sell-off".

65 Haq, G., Bailey, P., Chadwick, M., Forrester, J., Kuylenstierna, J., Leach, G., Villagrasa, D., Ferguson, M., Skinner, I. And Oberthur, S. (2001) "Determining the costs to industry of environmental regulation", *European Environment*, 11.125-129.

66 Eames, M. (2000) *The Large Combustion Plant Directive (88/609/EEC): An Effective Instrument For Pollution Abatement?*, SPRU, University of Sussex.

Both developments were important for the introduction of FGD in the UK. The dash for gas was in part driven by the costs of introducing FGD, which may have helped tip the balance from coal combustion with FGD to the then new CCGT technology.[67] Conversely, the build of gas-fuelled capacity in practice reduced the pressure on the utilities to invest in FGD (given the company-level emission ceilings - 'bubbles').

Privatisation mattered in that the Government specified that the two new companies should retrofit 4GW capacity each with FGD over a period of time, which was reflected in the debt level the companies took over from the previous national management.[68] Basically, there was money set aside for the purpose. The first retrofit took place in 1994, but PowerGen especially resisted this stipulation, arguing that its new CCGT capacity reduced the sulphur emissions enough for the company to reach the targets set under the LCPD. Delayed or abandoned plans for FGD retrofit did not lead to money being paid back to Government.[69]

Continuing negotiations and developments

Negotiations between the utilities and government continued. The arguments for delay used by the utilities included the cost of FGD implementation, and its negative impacts on coal-fuelled generation, and indirectly on the domestic coal industry, which supplied high sulphur coal disfavoured by generators seeking a lower sulphur mix, which could be readily imported.

Higher electricity generation costs also led the utilities to move FGD-fitted plants down the merit order, that is, using them less when demand is low.[70] This means that FGD-fitted plants were used less overall, having stood back for unabated plants, which continued to generate electricity cheaply, but with emissions consequences unintended by the FGD policy.

Planned low utilisation of FGD-fitted plant – for reasons of necessary downtime, but also for merit order reasons – was one of the argument topics in negotiations. The planned short remaining plant life was also used as an argument against retrofitting.

Furthermore, varying market shares (and thus active company generating capacity), through decommissioning or selling plants, meant that company emission ceilings were met without amendments to active plants.[71] (Finally, discrepancies between regulations, especially LCPD and Integrated Pollution Control (IPC), also opened up space for new negotiations, potentially further slowing FGD implementation).

Comparison with CCS

Having very briefly set out the FGD history in the UK, we may now compare with the introduction of CCS (as envisioned now). The cases exhibit both similarities and differences. Similarities include, as stated above, the regulation-driven introduction of environmental abatement technology into the UK power industry. Also, neither technology is profitable as such (we note again that sulphur trading – as well as the

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67 Winskel, M. (2002) "When Systems Are Overthrown: the 'Dash for Gas' in the British Electricity Supply Industry", Social Studies of Science, 32(4): 563-598.

68 ENDS Report, September 1994, "Power generators' FGD go-slow".

69 ENDS Report, April 1998, "MPs bash Agency over power station emission limits".

70 ENDS Report, September 1994, "Power generators' FGD go-slow".

71 ENDS Report, February 1995, "Row over FGD rocks the boat for sell-off".

proposed inclusion of CCS into the EU ETS – are both market-based regulatory instruments).

But, there are also differences between the two cases. For our purposes, a core difference is that FGD had already been implemented when the Directive was decided on. Planned FGD readiness, or not, was thus not an issue.

In relation to this, it is also interesting that Germany, in contrast to the UK, had both a more progressive policy stance, and a burgeoning FGD supply industry. The situation looks different for CCS in terms of both comparatively progressive UK policies, and a better chance of establishing a domestic supply industry at an early stage.

It is worth noticing that there are also direct links between the two cases. Firstly, and as mentioned above, the LCPD and the ensuing FGD costs are one of the causes for continued decommissioning of coal plant, which lies behind the urgency for new build in the UK, which has made capture readiness topical. Secondly, the proposed EU Directive for CCS (which focuses mainly on storage) suggests that capture readiness be regulated through an amendment to the LCPD directive (rather than, say, IPPC). Thirdly, the experience with one abatement technology may have prepared the industry to take on another.[72] Finally, the experience of FGD costs being reduced over time as a consequence of roll-out and learning-by-doing, has been used to forecast reduction in CCS costs.[73]

Discussion

The FGD case illustrates the basic point of industry not wanting to invest in technology that is not in itself profitable, unless driven to by regulation.[74] And that implementing regulation requiring such technology may not be easy. An original target of 12GW was reduced to 8GW at the time of privatisation. As of 2006, approximately 8.4GW out of 33.7 GW coal or oil fuelled capacity in the UK had been fitted with FGD.[75] This illustrates the slow progress of introducing the technology, even with regulation.

Furthermore, the costs of abatement were perceived as significant and have had, and are having, impacts on the plant fleet, in ways that have reduced coal burn, but perhaps also caused a risk of under-capacity. It is important to realise that environmental protection will normally cost more than unabated pollution. And if these costs affect choices of generation technology, that is a good thing from an environmental point of view.

The consequences for carbon abatement costs on the merit order of companies are important, and need attention when regulating CCS. If capture ready plants cost more to run, and if full CCS operation is not recompensed to make it profitable, there is a

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72 Mitchell, J. Scottish and Southern Energy.

73 Rubin, E., Yeh, S., Hounshell, D. (2004) "Experience curves for power plant emission control technologies", *International Journal of Energy Technology and Policy*, 2(1/2): 52-69.

74 This is not to say that companies never act proactively when it comes to environmental improvement. An example from the CCS area could be the In Salah carbon storage demonstrator in Algeria. BP, Sonartrach and Statoil are here investing in a project without direct regulatory pressure or any obvious immediate economic benefit.

75 Based on data from *Power UK*, May 2006. The calculation assumes that FGD equipment is fitted for the entire capacity of each station.

risk that such cleaner plants would be used significantly less, unless regulations hinder such moves.

LCPD may have paved the way for CCS in some ways, but there is also an issue of the total abatement costs continuing to add up, and impose extra burden as compared to unabated plant. How capture readiness costs interact with the costs of other abatement is likely to become an issue.

It is interesting to note the difference in policy drivers between FGD and CCS. It may be that concerns regarding export and employment argue in favour of domestic regulation stringency. (This may or may not help the global situation, but is likely to matter in the particular national context).

The comparison of the two technologies also allows a reflection on the pros and cons of flexibility in environmental regulation. The rationales include the arguments that it will allow for cost-efficient abatement, and that regulation needs to be adapted to the specific conditions of particular industries to be effective.

The FGD case illustrates how this flexibility opens up new spaces for negotiations between industry and government, and that these negotiations are affected by the contingencies of the specific situations. Cost-efficient compliance is not a bad thing, but the nature of negotiations does not necessarily guarantee this theoretically optimal outcome. It may be worth proposing rather strict standards, to be modified in the pursuant negotiations.

Summary

The LCP Directive was (and is) a central driver for introduction of FGD. UK has been lagging behind other EU Member States, for example, Germany. The switch from coal to gas reduced the pressure on companies to retrofit FGD. The Directive had to be made stricter in the 2001 revision, to increase the pressure on companies to implement the technology, and to deliver the intended improvements. The FGD case illustrates the reluctance of the utilities to invest in technology that is not profitable per se, and some of the difficulties in imposing such investments through regulation. Resistance can be expected to regulation making capture retrofitting mandatory, and the FGD case provides lessons in terms of the stringency of regulation needed. We should also learn about the specifics of how to formulate an effective policy, including for example the avoidance of merit-order loopholes diluting the benefits of fitted carbon capture, which is of no effect unless it operates as frequently as possible.

4. Conclusions and recommendations

Conclusions

Current pathways of CO_2 reduction in the UK show that current Government policies to combat climate change are not enough to reach interim and longer-term targets. At the same time, there is renewed interest in investments in coal-fuelled power plant. Unless such new-build fossil fuelled plants are built or retrofitted with capture equipment, and integrated into a full CCS chain, the UK faces a risk of carbon lock-in, and increased carbon dioxide emissions for decades to come.

If the Government decides to consent more fossil plants, and especially coal fired plants, whilst living up to its climate change mitigation targets, then a strict and enforced standard for capture readiness requirements is essential, to avoid the risks of carbon lock-in.

Technology, especially technology used in large systems, is difficult to regulate. On the one hand, before the technology is fully developed and deployed, there is uncertainty as to its exact properties and impacts. On the other hand, once the technology is deployed it can be entrenched and difficult to change. Capture readiness regulation is challenging for exactly this reason.

1. *If carbon lock-in due to unabated plants is to be avoided, capture readiness regulation needs to include regulation that ensures future retrofitting. This strategy is associated with a degree of risk, given the difficulty of guaranteeing effective implementation and enforcement of retrofitting regulation in the future.*
2. *A retrofitting requirement can be made more credible by policy-makers committing to including a condition that plant permits be revoked if CCS does not become available soon enough – with clear and fixed deadlines.*[76]

The rate of world progress in development and demonstration of equipment for a range of different capture options is sufficiently rapid, that we consider it is possible that the results of commercial scale demonstration will be available during 2012.[77]

3. *Retrofitting of CR plant can be operational within 36 months of that date.*

The least strict definitions proposed to date require very little, apart from some space around the site. The current headline definitions in consents to gas-fuelled plant do not require much more.

4. *We have identified four directions in which the capture readiness requirement can be expanded to become more robust:*
   a. *deeper into the core technology and organisation of the plant,*
   b. *further downstream to include transport and storage,*
   c. *more systemic by encompassing system integration regarding both technical and organisational challenges, and finally*
   d. *into the future to guarantee retrofitting if and when possible.*

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[76] A similar policy was suggested by the President of the Royal Society, *The Guardian*, 030408.

[77] This, rapidly increasing, list includes post-combustion coal in USA and Australia; post-combustion gas in Norway; pre-combustion gas in Abu Dhabi; and capture from oil shale processing in Canada.

Capture readiness is not just a technical problem, in the sense of a possibility of fitting new equipment onto old. Firstly, it is impossible to separate economic from 'purely' technical aspects. Secondly, being prepared for CCS also involves having an organisation that can acquire and operate capture, and a means of coordinating the full CCS value chain. The full system of power plant and CCS requires equipment, organisations, means of coordination, regulations, etc. to function.

5. *Robust capture readiness regulation should also address non-technical issues, including organisational learning and CCS value chain coordination.*

During 2006 - 2008, the UK has requested that power companies make new gas and coal-fired plant 'capture ready'. This has also been proposed as an EU stipulation.[78]

6. *The variation in existing consents for new gas plant in the UK shows that no suite of uniform CR requirements exists.*
7. *CR requirements need to be more robust. For example, there are no timelines for conversion to CCS. Past UK experience with non-profitable environmental cleanup suggests that additional requirements may be resisted.*

The concept of 'capture ready' power plant is often taken to mean, at its most basic level, design modifications that enable conversion to CCS operation at some future date. If CCS is to be a core policy towards emissions reduction in the UK power sector, then substantive preparations for CCS are essential.

8. *Sufficient academic and industrial work exists to specify what the major issues relating to capture readiness are.*
9. *CR can be specified at different levels of stringency, on a scale from lax rules which leave uncertainty in the ability to convert to capture, to optimum rules promoting maximum ease of future conversion. It is also possible to specify too harsh CR requirements.*
10. *This does not mean that everything is known with certainty. We judge that preparing for storage, and system integration are the most difficult things for the CCS actors. For policy-makers, guaranteeing effective, timely implementation and enforcement of future retrofit is likely to be the main difficulty.*

Lessons can be learnt from the introduction of Flue Gas Desulphurisation (FGD) technology in the UK in the 1990s. This was driven by the EU Large Combustion Plant Directive, and further shaped by the privatisation of the power industry and the ensuing dash for gas. UK has been lagging behind some other EU Member States in terms of enforcing FGD deployment.

The FGD case shows that companies may be reluctant to invest in technology that is not profitable per se (that is, without a special market for emissions created through regulatory fiat), and that it may be difficult for policy-makers to impose such technology. It can be done, but it may take a strong political will to do so.

11. *Robust regulation should be formulated in such a way as to ensure that not only does retrofitting go ahead at the earliest possible date, but also that the generation capacity that is fitted with CCS is used.*

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[78] Article 32 in the recent CCS Directive from the European Commission.

Recommendations

Based on these conclusions, we recommend that:

A. Government should limit the number of new fossil-fuelled, and especially coal-fuelled, plants they give consents to. Building many coal-fuelled plants increases the risk of carbon lock-in, given the risk of CCS failing to be demonstrated. It is not necessary to build a new plant to demonstrate retrofitting of CCS, but it is valuable to demonstrate capture ready plant, which has to be new build. Demonstrating CCS has the potential of greatly benefitting UK skills and expertise, and worldwide climate mitigation efforts.

B. For power plants the essential requirements for consents/permits are i) plant layout enables easy addition of capture equipment, and space is available to build the equipment; ii) plant design permits a range of potential capture equipment to be added within 10 years at most; iii) staff skills and expertise is available. Power companies, project developers and investors should also be required to provide design studies, that is, detailed information about the design decisions made, and show that they have considered the potential impacts of a retrofit on all parts of the plant.

C. If capture is to operate in the UK, it is necessary to have not only the technical hardware, but also expertise and skills in capture across a range of plants, run by large and small power plant operators. We propose an immediate requirement that each new CR plant constructs and operates a pilot capture facility of 1-25 MW size. This may also start development of a UK industry supply chain for components and services.

D. Capture readiness regulations should include safeguards against low planned utilisation of capture ready power plants, and especially of the retrofitted power plants.

E. The standard of CR design and planning must be sufficiently detailed that an outline planning application can be made for the capture addition to the power plant, the transport route can be safeguarded by planners, and the storage site can be appraised to guarantee the required volumes at the required times.

F. Liability and financial arrangements (e.g. insurance against future leakage of CO_2) must be planned and confirmed in outline, to safeguard public and government risk during capture, transport, storage site operation, and handover to government after site closure.

G. A plan for system integration and operation must include the full chain of: capture, transport, and storage operation. This will also specify ranges of CO_2 flow rate, composition/purity, pressures and temperatures.

H. In addition to these technical issues, material evidence is needed that there are preparations on-going for an operating CCS value chain. Documentation identifying potential operators of the planned transport and storage operations, and what relevant competence they have or need to acquire or develop is needed. An indicative business model for the CCS value chain should also be outlined.

I. As a safety net against long-term CO_2 emissions, a requirement that CCS be operational on all UK capture ready plants by 2020 should be introduced. We assess that CCS can be demonstrated in 2012, and so introduced widely from

2015. The 2020 deadline thus leaves a 5 year margin for delays relative to this best case timeline. This harmonises with the EU date for recommended CCS on all plants.

J. If CCS fails to be demonstrated by 2020, or if UK CR plant is not retrofitted and operational by the end of 2020, then government should force closure of that coal or gas plant.

K. To implement this policy, it will be necessary to regularly assess progress towards full scale demonstration (anywhere in the world). We propose assessment every two years to reflect the expected speed of technology development, starting in 2012 when the first full systems may be nearing completion.

END