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‘Capture ready’ regulation of fossil fuel power plants – Betting the UK’s carbon emissions on promises of future technology

Nils Markusson*, Stuart Haszeldine

The University of Edinburgh, School of Geosciences, Edinburgh EH9 3JW, UK

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ABSTRACT

Climate change legislation requires emissions reductions, but the market shows interest in investing in new fossil fuelled power plants. The question is whether capture ready policy can reconcile these interests. The term ‘capture ready’ has been used a few years by the UK Government when granting licences for fossil fuelled power plants, but only recently has the meaning of the term been defined. The policy has been promoted as a step towards CCS and as an insurance against carbon lock-in. This paper draws on literature on technology lock-in and on regulation of technology undergoing development. Further, versions of the capture readiness concept proposed to date are compared. Capture readiness requirements beyond the minimum criterion of space on the site for capture operations are explored. This includes integration of capture and power plant, downstream operations, overall system integration and regulation of future retrofitting. Capture readiness comes with serious uncertainties and is no guarantee that new-built fossil plants will be abatable or abated in the future. As a regulatory strategy, it has been over-promised in the UK.

1. Introduction and background

Rapid reduction of CO_2 emissions from power generation is a repeatedly stated core goal of the inter-linked UK energy and climate change policies. Current climate change targets include 20% reduction of national green house gas emissions by 2010 and 80% reduction by 2050 from a 1990 baseline. However, only limited progress has been made to meet those targets, and forecasts indicate that strong additional policies are still needed (UKCCP, 2008; UKPEAC, 2008). At the same time, there is a renewed interest from commercial companies in investing in new coal fuelled plants, which has not been the case since the dash for gas in the 1990s (Winskel, 2002). This raises the policy issue of whether to license new unabated fossil – especially coal – fuelled plants before CCS has been demonstrated (as an integrated system at large scale). There is a risk that new fossil plants without abatement systems implemented from the outset will never be abated, and that the UK is then stranded with these new emission sources for a long time.

‘Capture ready’ (CR, also called ‘carbon capture ready’ or ‘sequestration ready’) power plants have been proposed as a solution for this conundrum. The basic notion is that new plants are built in such a way that capture equipment can be added at a later date. This idea has now been incorporated in industry plans for new fossil fuelled plants in the UK. The idea of CR power plants has also been taken up in policy making.

A review of license consents for fossil fuelled power plants (see Table 1), shows that capture readiness has been used as a regulatory requirement in the UK since at least 2006. In the 2006/2007 licences, the CR criterion was formulated in rather general terms. The license for West Burton states: “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” (DBERR, 2007). Moreover, the CR criterion was not implemented in a consistent manner. Gas fired power stations licensed in 2009 have had to set off land adjacent to the power plant as a capture ready preparation. In contrast, the Combined Heat and Power (CHP) plant in Seal Sands licensed in 2008 has not been required to do so. The CR criterion has mainly been used in licences for gas fired plants, but also for the Hatfield plant which will convert from gas to coal. CR has also been part of the discussions around a licence to the controversial Kingsnorth scheme (Scrase and Watson, 2009), which has not been granted so far.

The use of capture readiness as a regulatory requirement has thus preceded the definition of what the term means, and the use of the term has varied. The Government was earlier prepared to stipulate capture readiness for gas fired plants without specifying the term, and only later specified that space for capture equipment is a core CR criterion.

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* Corresponding author. Tel.: +44 131 650 55 70; fax: +44 131 668 31 84.
E-mail address: nils.markusson@ed.ac.uk (N. Markusson).

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Table 1
Recent fossil fuelled power plant licences.
Source: News Distribution Service (NDS).

Date	Name/place	Plant type	Company	CR requirement?
05/02/09	Hatfield, Yorkshire	CCGT[a] (conversion to IGCC[b] planned)	Powerfuel Power	Yes
05/02/09	King's Lynn, Norfolk	CCGT	Centrica	Yes
05/02/09	Pembroke, South West Wales	CCGT	RWE npower	Yes
28/08/08	Seal Sands, Teesside	CCGT (CHP[c])	Thor Cogeneration	No
19/12/07	Chequers Lane, Dagenham	CCGT (extension)	Barking Power	Yes
16/10/07	Drakelow	CCGT	E.ON	Yes
03/10/07	West Burton	CCGT	EDF	Yes
13/07/07	Carrington, Trafford	CCGT	Bridestones Developments	No
21/08/06	Uskmouth, Newport	CCGT	Severn Power	Yes

[a] Combined cycle gas turbine.
[b] IGCC=integrated gasification combined cycle.
[c] CHP=combined heat and power.

UK policy in this area is developing in close relation to EU policy. In December 2008 the European Union decided on a minimum requirement for capture readiness (European Parliament, 2008), which will be discussed below, and which will have to be fulfilled for UK power plants when relevant. The UK Government has recognized the need to specify further what a CR requirement should mean. A public consultation closed in September 2008 (DBERR, 2008). The Scottish Government (2008) has also consulted on this recently. The UK Government held a second consultation on draft guidance notes for CR in 2009 (DECC, 2009c).

In November 2009, the UK Government set out its decision on what CR is to mean in the UK (DECC, 2009b). The criteria include demonstration of the technical feasibility of CO_2 transport and retrofitting capture technology, the economic feasibility of future full chain CCS operations, the identification of suitable area for storage, and the availability of space on site for capture equipment. Consented plants will be required to retain the space on site as well as to report regularly to the regulator on the technical feasibility of retrofitting capture technology.

Apart from the UK, the only country to our knowledge with an explicit CR policy is Canada, where the domestic regulatory framework for regulating green-house gas emissions includes special rules for new plants that are CR. Although what CR is to mean here has yet to be specified (Government of Canada, 2008).

In addition to complying with EU policy, the UK Government specified that the rationale for introducing CR policy is that it is a preliminary step towards CCS (DECC, 2009b). The CR policy should also be seen against the background of the increased interest in building coal fired power stations in the UK. The Government states that it is reasonable to assume that new fossil fuelled power stations will need to fit CCS technology within their lifetimes, and the Government sees CR as a way to guarantee that there are not any known technical and economic barriers for this. The Government has described CR as a low cost insurance policy against new un-abatable power plants (DBERR, 2008).

CR policy is part of a wider set of UK CCS policies. In 2009, the UK Government also introduced a requirement on new coal fired power plants to demonstrate CCS on at least 300 MW of its capacity, and has repeated its commitment to fund up to four demonstration projects (DECC, 2009a).

CR policy is an example of an attempt to regulate the use of a technology before it is mature. Strictly speaking CR requirements are directed at power plants rather than CCS, but CR modifications of plans for power plant investments reflect our knowledge of CCS technology. However, we know from history that regulating technology undergoing development presents regulatory dilemmas and that the impact of such regulation is uncertain (Collingridge, 1992). CR policy may not be a step towards the realisation of CCS.

The UK energy system is – like the energy systems of many other countries – locked-in to the use of fossil fuels. CCS may become a way of dealing with this, but there is also a risk that power plants will not be fitted with CCS technology in the future, if CCS fails or if the technology develops in ways not anticipated by CR modifications. Investment in new coal fired plants without CCS has been controversial in the UK (Scrase and Watson, 2009). There is a risk that CR policy legitimises investment in new fossil fuelled plants that will in the end not be abated, and thus that CR will fail as an insurance against further carbon lock-in.

This paper aims to explore the risks inherent in UK CR policy, in terms of its contribution to the development of CCS in the UK and its wider effect on the energy system and its lock-in to unabated fossil power. To guide the analysis, the paper will first briefly review the literature on technology lock-in and the regulation of technology undergoing development, and then explain how these concepts relate to CCS and CR. The paper will then discuss what a stringent capture readiness requirement would look like and if it would be effective, based on a review of proposed definitions of CR and a synthesis of a selection of relevant CCS-related literature. In the final section, we will summarise and assess what the main uncertainties inherent in CR are, as well as assess UK's current CR policy and discuss some of its wider implications.

2. Lock-in and regulation of technology undergoing development

In the context of CR, lock-in is sometimes taken to mean companies' interest in avoiding the costs of stranded assets. The idea is here that companies risk investing in plants that will later be impossible to use because of more stringent pressures to reduce emissions, unless they can be retrofitted with capture technology. This is the scenario the UK Government wants to avoid by introducing CR requirements (DBERR, 2008).

'Technology lock-in' is however usually seen as a phenomenon at the technology (Foxon, 2006) rather than the company level. Lock-in is due to the tendency of any technology to develop along trajectories (Dosi, 1982; Arthur, 1989). The development of a technology is cumulative and dependent on previous development – it is path dependent (David, 1985; Arthur, 1994). There are barriers against change to other technologies, and even in the face of new and potentially more efficient or attractive alternatives, established technologies often persist. A classical example is the QWERTY keyboard (David, 1985). More effective keyboard layouts have been launched, but they have been locked-out by the incumbent technology. Lock-in has been observed in the study of many technologies, and especially in studies of large technological systems, like electricity production systems (Hughes, 1983). Technological systems are never completely resistant to change (Winskel, 2002), but they can be entrenched and very difficult to shift.

There are several mechanisms behind technology lock-in (Knot et al., 2001). Often an established technology undergoes further innovation that raises its efficiency or improves its quality in defence against competing alternatives. Technologies may also be inter-related, making change a matter of a more complex transition from one set of technologies to another. The interest in preserving the value of investments in an established technology is another reason (cf. the stranded assets argument above). There are also learning effects, and actors may want to continue to benefit from skills and experience from developing and using an existing technology. Moreover, expectations about the continued future viability of an existing technology serve to reinforce actors' willingness to invest in and use it, and there is thus an element of a self-fulfilling prophecy involved (Foxon, 2006).

To understand technology lock-in it is necessary to understand technology not just as artefacts or as knowledge, but as socio-technical systems (Hughes, 1983; Winskel, 2002; Geels, 2004, 2005) including also specialised actors, organisations, institutions, cultural norms, etc. The creation and alignment of all these different elements is what makes up a well functioning socio-technical system, and at the same time what makes it difficult to change. The more developed and mature a socio-technical system is, the better aligned are the different elements, and the more stable and resilient to change is the system. Technology lock-in is not a problem in itself, but rather a feature of the establishment of any successful technological system. Lock-in becomes a problem only when it locks out alternative technologies that are judged to be more desirable.

Unruh (2000) has coined the term carbon lock-in, referring to societies locked into dependence on fossil fuels. The energy systems of these countries have invested a lot in fossil based technologies, have established strong fossil-related industries, have sophisticated regulations to govern the use of fossil fuels, etc. They have well-established, well-functioning socio-technical systems for the use of fossil fuels. New, alternative energy technologies have to be very good indeed to compete.

Successful socio-technical systems develop along increasingly stable development paths. This does not mean, however, that the end-point is known beforehand. Technologies evolve over time through the emergent interactions between different elements. Early promises about performance and functionality are rarely good predictors of the properties of mature technologies. Future developments are always, and especially at early stages, uncertain.

The combination of uncertainty with lock-in has proven to create difficult dilemmas for policy-makers and regulators of technology (Collingridge, 1992). On the one hand, when a technology is young and comparatively malleable its final properties and its impacts cannot be known with any precision, and it is hard to know exactly what to regulate against or to promote. On the other hand, when the socio-technical system has stabilised and the properties are known, the technology may be so entrenched that it is difficult to modify or abandon. Intentional steering of technologies undergoing development is difficult. Capture readiness is an example of this kind of problem, as will be discussed in the following section.

2.1. *Regulating fossil plants towards CCS abatement*

The concept of lock-in helps us understand the current energy system with its strong dependence on fossil fuels: carbon lock-in. But the concept may also help us explore potential future energy systems with CCS and with CR power plants.

Firstly, CCS has been proposed as a technical fix for carbon lock-in. CCS is in this perspective characterised as an abatement technology analogous to for example Flue Gas Desulphurisation technology. CCS is in the terminology of socio-technical systems theory a not yet stabilised niche technology, which is envisioned as an addition to and modification of the fossil fuel socio-technical system. The CCS solution would leave the energy system locked-in to the use of fossil fuels, but promises to mitigate the CO_2 emissions using add-on, end-of-pipe technology that is expected not to disrupt the existing fossil fuel system (Unruh and Carrillo-Hermosilla, 2006).

Secondly, whilst waiting for CCS to materialise, capture readiness has been proposed as a way to deal with lock-in risks. By designing power plants so as to be ready for envisioned future capture operations, we are said to avoid a future with even more un-abatable power plants.

Table 2 summarises these scenarios and the proposed consequences in the future if and when CCS becomes mature and readily available on the market. The table also includes as a contrast a third option, to not build any new plants until CCS is mature.

It is worth noting here that the lock-in risks referred to in this paper are about the continued use of unabated fossil plants. A successfully CCS-abated fossil fuel system is still locked-in to fossil fuel technology. The question is rather whether a system characterised by carbon lock-in will be cleaned up using CCS, and if CR offers any guarantees of this outcome.

Both CCS technology and CR policy are somewhat controversial, and there are fears that – given that the technology is not ready to use – they may just lead to the continued use of fossil fuels, and further lock-in to unabated fossil power (WWF-UK, 2008). Whilst some component technologies of CCS have been used for other applications, see Table 3, CCS as an integrated technical solution is still undergoing development. Necessary changes include, for example, the scaling up of capture technology and integration of the full chain of power plant, capture, transport, injection and storage. The technology will need to be demonstrated at full scale before wide deployment. The immaturity of CCS introduces technological uncertainty in any predictions of the future of CCS-abated fossil plants.

Experience also shows that adding new elements to an existing system may introduce tensions that cause further change. Changes to components may change the overall design trade-offs of technological systems. Funk (2008) presents examples from the IT sector, including how improvements in integrated circuits in the 1970s made new products including calculators possible, and other products and the corresponding system designs obsolete. CCS on power plants is of course a very different case, but this nevertheless raises questions about what impact the addition of CCS may have on the system of fossil fuelled power production. The integration of CCS with power plants will be discussed in

Table 2
A basic overview of the options.

Action now	Future of fossil plants (if and when CCS ready)
New plants CR	Retrofitting possible, plants abatable
New plants not CR	Retrofitting may be impossible, or very expensive
No new plants now	Possible to build abated plants

Table 3
The maturity of CCS technologies [a].
Source: adapted from IPCC (2005).

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

[a] Maturity here indicates the most mature variety of each technology. For each technology there are also more radical (less mature) varieties.

[b] This technology for producing CO_2 is mature, and typically used together with existing storage demonstration projects, but is not the kind of capture technology that would be useful in terms of abating emissions from power production.

[c] Experience to date mainly from on-shore pipelines.

[d] 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.

more detail below, including the issue of whether CCS is easily added on or not, and whether the fossil energy system will need to undergo any more serious changes to accommodate the inclusion of CCS technology.

The uncertainty about the future of CCS technology and about the future shape of the fossil energy system further complicates any effort of trying to design power plants, so that they will be suitable for future adding-on of capture technology. Regulating technology undergoing development is difficult, and CR regulation faces this problem. To avoid lock-in to unabated fossil power, CR designs should make it possible to abate emissions from power plants tomorrow. The question is whether this can be guaranteed.

And finally, to avoid further lock-in to unabated fossil fuels, it is not enough to know that it will be possible tomorrow to abate CO_2 emissions from power plants built today. The real goal must be that CCS abatement systems will actually be implemented (and continually used) shortly after the technology is proven. What matters in the end is the outcome in terms of CO_2 abatement, not the good intentions or what could have been achieved. Can the promise of abatable and abated plants tomorrow be guaranteed?

Having briefly reviewed the literature on lock-in and the regulation of technology undergoing development, and applied this to CCS and CR, we can re-state the research questions for this paper. Firstly, given the uncertainties of any technology development pathway, will CR regulation now guarantee that future abatement will be possible? Secondly, given a scenario where plants are built CR now, will current regulation guarantee later CCS abatement? In short, will new fossil plants be abatable and abated?

This paper will now discuss what CR regulation might look like, in two ways. Firstly, the paper will review and compare some of the definitions proposed in the literature to date. Secondly, the paper will explore what a robust CR regulation could look like, by synthesizing CCS-related literature. We will give our view of the challenges involved in the CR approach to the regulation of power plants, including our assessment of how well these challenges are understood.

Table 4
Examples of CR definitions.

1. "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" (DBERR, 2007).

2. "…have suitable space on the installation site for the equipment necessary to capture and compress CO_2 and the availability of suitable storage sites and suitable transport facilities, and the technical feasibility of retrofitting for CO_2 capture have been assessed" (EC, 2008).

3. "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 et al., 2007)

4. "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:

- a study of options for CO_2 capture retrofit and potential pre-investments
- inclusion of sufficient space and access for additional facilities that would be required
- 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" (IEA GHG, 2007).

3. Proposed CR definitions

We will here give a few examples of proposed definitions of CR, as exhibited in Table 4. The first example focuses on what is a common, minimum standard of CR: enough space on the site to accommodate capture operations. The second example extends this to include also transport and storage considerations. It is also more explicit with regard to the feasibility assessments that it proposes should be made with regard to capture technology. It thus attempts to specify a procedural requirement, aiming towards a standard of knowledge and information provision, rather than a physical requirement.

The third example provides an example of a definition that explicitly mentions economic criteria, in addition to physical/artefactual ones, and procedural/knowledge criteria. The fourth example adds a regulatory dimension (and would make CR regulation explicitly dependent on other regulation). This also includes the provision of information to regulators. Furthermore, this definition sets out limits to the responsibility of operators, specifying that they are only responsible for known factors, and things that are under their own control.

These few examples clearly show a variation in definitions, and specifically, in what types of criteria are included: physical, procedural and contextual (economic and regulatory drivers). The examples given here are all summary or headline definitions trying to capture the essence of CR in a few sentences. The IEA GHG report on capture ready plants (2007), for example, also provides extensive further specification of what such a definition would mean.

It can be helpful to turn the question around and ask what a not-capture-ready plant would be. IChemE (2007) argue that since we know that there are solvents that can capture the CO_2 from flue gases, it is in principle possible to fit capture onto any power plant already, the only snag being the cost. That is, with a narrowly science-oriented definition, all fossil plants are CR. But this fails to reflect that power plants can be more or less technically easy or economically costly to add capture technology to. As discussed above, there are remaining challenges in terms of scaling up capture technology and integrating it with power plants. Not-capture-readiness also varies by power plant design.

Including economic criteria is inevitable. Retrofitting capture technology at very high costs may not be the cheapest abatement option available at the time, nor easy to mandate through regulation. There will be some limit to how much abatement will be allowed to cost. Including economic criteria can thus make CR regulation more robust, if they are stringent. The problem is that this introduces new uncertainties. We do not know whether they will be delivered through the EU ETS or not, and not what will drive the prices.

Arguably, this will be a problem for the minimum definition decided on by the European Parliament in December 2008 (European Parliament, 2008). It is essentially: to have suitable space on site, if suitable storage sites are available and transport and retrofitting can be shown to be technically and economically feasible. It remains unclear what standard of evidence is needed to judge especially economic feasibility of transport and storage.

It is also important to recognize that firms and governments may have different opinions about what are acceptable costs of CR modifications and of retrofitting. Definition number 4 above mentions stranded assets and carbon lock-in as something CR helps avoid. Stranded assets are primarily a problem for the individual company, whereas carbon lock-in is a wider issue for the energy system and society as a whole. Governments may be willing to accept higher costs for avoiding lock-in than firms would for avoiding stranded assets. This is not an argument for wasting resources, but an acknowledgement that firms can only be held responsible for what is fairly directly linked to their activities, whereas governments need to take the whole system into account – and this may of course have implications not only for what total costs are accepted, but also for who pays the bill.

This section has briefly discussed the variation in proposed CR definitions and discussed some of the underlying principles that have been identified in the literature. The next section will discuss in more detail how the concept needs to be specified and extended from a minimum definition of site layout, to include capture-power plant integration, transport and storage, system integration, and future conversion to CCS.

4. Exploring the dimensions of CR further

4.1. Integrating power generation and capture

The IEA GHG report on CR (2007) represents the most comprehensive attempt at specifying CR plant designs to date from an engineering perspective. As well as recommending setting aside space on the site for capture, it sets out design changes (investments) to be made to make power plants CR. These changes include (depending on different configurations of power generation technology and capture technology), for example, adding or upgrading FGD equipment, modified steam turbine designs and addition of CO_2 separation plant.

There are different levels of plant modifications that could be done to make a plant CR (Bohm et al., 2007; IEA GHG, 2007). The modifications can be more or less radical, and more or less expensive. The range of options stretches from relatively easily accommodated changes like providing space for the pipes that would be necessary to re-route flue gases, to core technology modifications like converting gas turbines to combustion of hydrogen combustion (for IGCC plants). See Table 5.

This challenges the idea of easily adding-on capture to power plants (cf. Stephens, 2005, for the case of IGCC). Depending on the power generation technology, and the specific designs, integrating a capture function can have extensive impacts on plant design. The add-on ideal is most closely approximated for post-combustion capture, but even here, given the size of the capture investment, optimization of power plant and capture plant together will involve modifications to both.

The IEA GHG report makes a distinction between essential and optimal investments, but without being very clear as to what criteria are used to classify investments as essential or optimal. This is a problem, since that distinction seems to be exactly what a regulatory CR requirement would have to do. From a regulatory point of view this is also problematic, since a more arduous specification of CR is not necessarily more effective. Capture (and power plant) technology will develop, and CR modifications thus run the risk of becoming obsolete and even counter-productive. This risk also becomes more costly, the more expensive the CR modifications are. There is thus a risk of exacerbating lock-in risks by over-modifications, by imposing too arduous CR requirements. There is therefore a need to specify a level of modification that

Table 5
Summary of main areas for capture-readiness plant modifications.
Source: data from IEA GHG (2007).

Configuration	Modifications
Pulverised coal (PC)+post-combustion	Add/upgrade flue gas desulphurisation Modified design of steam turbine (with ancillaries)
PC+oxyfuel	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)
Integrated gasification combined cycle (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
Natural gas combined cycle (NGCC)+pre-combustion	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
NGCC+post-combustion	Stream extraction as for PC

strikes a balance between technological, climate and financial risks. But it is not clear that this balance has been sufficiently explored yet and, in particular, that the technological uncertainty involved has been treated in a rigorous enough manner. Indeed, there is genuine uncertainty involved, and even balanced CR modifications are no guarantee that retrofitting will be feasible. CR inevitably leaves us with a residual lock-in risk. There is considerable risk in investing in CR. As Stephens (2005) has pointed out, this is especially true in the case of IGCC where the underlying plant technology is not well proven through extensive use either.

It is also necessary for utilities to have the expertise, skills and routines for investing in and operating capture technology. One could argue that companies should develop such organisational capabilities to be ready for capture. A possible way to regulate this might be to mandate slipstream-scale capture operations, as previously suggested by Stephens (2005) on the 5–50 MW scale. Further considerations with regard to power plants include impacts on availability and flexibility of the plant (IEA GHG, 2005), on environmental impact (IChemE, 2007) and on health and safety (IEA GHG, 2007).

4.2. *Downstream operations: transport and storage*

Preparing for future CCS implies that it should be possible to not just capture but also transport and store the CO_2. A common way to phrase this is: "identifying a route to storage", but this phrase covers a range of more or less thorny issues.

The technology envisaged for CO_2 transport: pipelines on and off shore, alternatively by ships or trucks, is well known for other liquids or hydrocarbons, and has been used also for transport of CO_2, but mainly for on-shore applications. There are also unresolved issues regarding its use. Firstly, securing control of the land needed for on-shore pipelines may not be easy or even possible for all desirable locations (DBERR, 2008). Critical areas may be close to the plant where there are likely to be few routing options and the beachhead where planning issues are difficult in the UK. Secondly, there are as yet no environmental or health and safety regulations in place that could guide authorities to permit the construction of pipelines, on or off shore. This also means that choosing a feasible route is uncertain. A further complicating issue is that the construction of new infrastructure, like pipelines, may open up debates on public acceptance. As part of necessary planning for transport routes, public consultation should be done to reveal the existence of any such barriers.

Also choosing a suitable storage site requires a regulatory framework, and exploration of public attitudes. The regulatory framework also has to include financial arrangements for governing long-term risks of leakage, in the form of for example an insurance policy. A workable balance of responsibility between operator and state needs to be found, which would also vary over time reflecting the limited ability of companies to manage longer-term risks. The properties of depleted gas and oil fields are especially well known, and may therefore be targeted first for storage. However these are generally deeper and thus more difficult to reach, and have more legacy boreholes forming potential leakage points. Large uncertainties remain with regard to storage in aquifers, both with regard to capacities and seals. Even so, generic predictive appraisal simulations can already be done routinely as part of planning for storage when preparing for CR investments.

4.3. *Integration of the whole system*

The integration of the whole socio-technical system of fossil power with CCS is a challenge in itself, and is necessary for the implementation of CCS. All the elements along the chain from power plant to rock reservoir have to be made to work together. This also includes technical elements, as well as the actors, institutions, etc. needed for the system to function. System integration also needs to be prepared as part of planning for CR investments.

System integration involves relatively technical issues like managing impurities and water in the gas that could cause problems for pipeline corrosion, and the sealing of injection wells. There are also matching problems between sources and sinks of CO_2 in terms of the rate of supply of the gas, and the timing of supply and storage site operations (including timing with previous oil and gas extraction operations if off-shore equipment is to be reused). Moreover, there are also coordination problems of a less technical nature. A core question is whether transport infrastructures will be proprietary, or whether there will be shared structures, which would likely require government intervention and support. A strategy is needed setting out expected future CO_2 volumes, to enable planning of transport investment. The lack of a policy for this increases the uncertainty in preparing for CCS.

Furthermore, there is the fundamental issue of who will pay for the abatement of CO_2, and how any profits will be shared among the actors involved. The uncertainty of economic drivers, and the lack of clear business models for the coordination of the actors along the supply chain, further increases the uncertainties involved. There is a need for political leadership on this issue. This also relates to the difficulty of assessing the cost of CCS. Demonstration of the technology is needed also for price discovery.

Finally, integrating CCS with fossil power plants will not leave the existing system unchanged. It will have an impact on power plant technology and operations, as discussed above. It will have an impact on business models in the sector, and change the relationship between the power and the oil and gas industries. Integrating power plants into another infrastructure of CO_2 transport and storage will pose new coordination challenges. The size of capture plants relative to power plants, the fact that an entire new infrastructure is needed and the potentially large cost of CCS are all facts that suggest that CCS may not be a simple add-on solution. Adding in a CCS component may change the design trade-offs and require more fundamental change to the overall socio-technical system of fossil fuelled power production.

4.4. *Regulating the future addition of CCS abatement*

Capture readiness needs to be seen as an investment in two stages: a CR power plant today, and a full CCS investment including a retrofit of capture technology onto the power plant in the future. Both stages of the overall investment would be driven by policy (regulation or policy-generated emissions markets). And the stages should not be seen as separate things. Again, ultimately, the intention behind a CR investment does not matter; what matters is the outcome in terms of CCS-abated power plants as rapidly as securely possible.

Future policy-driven retrofitting matters technically today for CR investments. For example, the capture rate that will be required after retrofitting, matters for what pre-investments are made as part of a CR power plant investment. This means that current CR regulation needs to indicate future performance standards. Similarly, the expected time lag between CR investment and CCS investment matters for CR designs (IEA GHG, 2007). A timeline for future emissions requirements is also needed.

It is difficult for anyone to guarantee what policy makers will do tomorrow, which introduces political uncertainty into the calculation. Efforts should be made when designing a CR policy to make as binding as possible commitments for future policy. Taken together, technical, financial and policy uncertainties mean that there is no certainty that CR investments today will lead to CCS investments tomorrow. CR regulation and CR investments do, however, seem to make CCS investments more feasible as well as perhaps making it easier for policy makers to introduce CCS requirements later.

5. Discussion and conclusions

Summing up, to be stringent CR needs to be extended from “space on the site”, to include core power generation technology, downstream transport and storage, system integration, and future retrofitting requirements. Doing so, however, makes CR regulation a lot more complex, and introduces several uncertainties, some of which may be very difficult to manage.

Firstly, we have seen that adding capture to a power plant may not be a simple operation. This depends – as has been discussed elsewhere – on the choice of power generation technology and capture technology, and may contribute to which technology is chosen. But we could also see the adding on of capture (and certainly full CCS) as potentially introducing a tension in the fossil-fuelled power generation system, leading to more radical change. Secondly, the modified socio-technical system of CCS-abated power generation is in its early days, and there are still uncertainties as to what shape it will take. This introduces technological uncertainty in any effort of trying to design power plants now, so that they will be suitable tomorrow for the adding on of capture technology. It also introduces uncertainty with respect to the vision, design and preparation for the overall system. This includes downstream operations, encompassing both narrowly speaking technological elements and organisational, financial and political elements. Our assessment is that the most difficult and least well understood actions are for utilities to prepare for storage and system integration, and for policy-makers to implement a stringent and timely retrofit regulation, to transfer to full CCS operation. As we can expect from historical experience, regulating technology before it is mature introduces uncertainties in outcome.

Against this background, we can assess UK CR regulation. It covers both up and down stream operations, as well as future retrofitting. It includes an economic assessment of the CCS chain, but does not explicitly deal with system integration. The regulation explicitly requires little physical change beyond space on the site for capture equipment. It does however set up a procedural rule that the companies demonstrate that there are no known technical and economic barriers for future retrofitting of the proposed plant. Companies have to prepare plans for CCS operations that conform to the current state of knowledge, which potentially implies substantial further action improving the chances of future retrofitting. From this we would expect at least learning effects as the companies – as well as government – are required to monitor the technical and economic knowledge on CCS that becomes available. Of course, as our knowledge develops, barriers against retrofitting may arise and the plants would then be un-abatable and remain unabated.

However, the UK CR policy over-promises in presenting itself as a step towards CCS and an insurance against carbon lock-in, and underplays the risks of this not happening. Whilst it does acknowledge the uncertainties involved, the document setting out the policy (DECC, 2009b) also downplays these uncertainties. For example, when discussing the assessment of the feasibility of retrofitting, it states that the aim of such an assessment is “to demonstrate to the consenting authority that the plant has been designed in such a way as to enable the subsequent retrofit of carbon equipment to the entire capacity of the proposed power station”. This cannot be conclusively predicted.

There are clearly technical, economic, political, etc. uncertainties inherent in a CR approach to the regulation of power plant CO_2 emissions. CR regulation may well contribute towards making power plants fit for future CCS retrofitting, but uncertainties remain and abatability cannot be guaranteed. CR design does not guarantee that it is possible to implement CCS. CR policy is therefore not necessarily an effective insurance against un-abatable plants and further carbon lock-in.

Moreover, the promise of CR is not just that this will be possible, but that abatement will happen. Even if the technology works out in engineering terms, there are large uncertainties in terms of policy and public acceptance. There is no guarantee that CCS will actually be implemented. CR policy will therefore not necessarily be a step towards CCS. Table 6 gives an overview of the possible outcomes explored in this paper. Several of these scenarios lead to lock-in risks, even in the cases with CR. The only way to be sure to avoid further carbon lock-in, until CCS is proven, is to not build new fossil plants.

As we have shown, a stringent CR regulation is difficult to implement and may not be effective. A less stringent one is easier to handle. A CR standard will also give climate mitigation legitimacy to investment in new fossil – and especially coal – plants, without strong guarantees of future abatement. A CR policy is therefore likely to be attractive to power companies interested in investing in new coal plants, and a less stringent policy more so than a more stringent one.

As mentioned above, the UK Government included CR requirements in the licences for new fossil – both coal and gas – plants without defining the meaning of the term. This some-

Table 6
A more detailed overview of options.

CCS futures	Action now	Futures of fossil plants
If CCS works	No new plants now	Possible to build CCS-abated plants
	New plants not CR	Retrofitting may be impossible, or very expensive
	New plants CR	
	If CR works	Retrofitting possible, plants abatable
	If CR does not work	Retrofitting may be impossible, or very expensive
If CCS does not work	No new plants now	No un-abatable plants
	New plants not CR	Un-abatable plants
	New plants CR	Un-abatable plants

what rushed CR implementation suggests that the CR label was more important than the content. It appears as if the Government was then motivated primarily by a desire to legitimise new fossil plants rather than to plan for CO_2 abatement. The later clarification of the content of CR requirements and other CCS policies suggest that UK Government is serious about CCS. Especially the requirement to demonstrate CCS on (part of the capacity of) any new coal plants is a rather stronger support for CCS development than CR policy.

The analysis here has focussed on the UK situation. The need for new fossil fuelled plants in the UK is currently contested, and capture ready regulation debates have become linked to that debate. It has, however, been argued that the rapid expansion of fossil fuel in not least China dwarves the UK contribution, and that our main concern should be to develop CCS and CR for application there. On the one hand, it could be said that the UK alongside other affluent countries have an obligation to contribute to the development of CCS and CR if newly industrialised and developing countries are to adopt the technology (Gibbins and Chalmers, 2008). On the other hand, building new coal plants in the UK may also undermine UK's credibility in contributing to new international climate change agreements (Scrase and Watson, 2008). It may be that other affluent countries that are more unambiguously dependent on new coal plants should take a bigger role in demonstrating CR plants, especially coal fired ones, unless UK CCS export opportunities are considered more important than UK CO_2 emissions.

This analysis is intended to contribute to deliberations on policy and regulation. The situation may well look different from a company point of view. Capture-ready modifications to power plants may make economic sense, depending on what assumptions firms make about possible futures. This is different from the point we are making here that capture readiness is an over-promised and not very effective regulatory strategy.

The main novelty of this paper lies in its demonstration of the risks of CR policy, especially in contrast with the presentation of UK CR policy as a step towards CCS and an insurance against carbon lock-in. We have presented an analysis of different possible future scenarios, and shown that the only safe way to avoid further carbon lock-in, until CCS has been developed, is to not build new fossil plants. In terms of CR content, the issue of system integration as an issue that goes beyond technical and economic factors is also a new contribution.

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