Framework for development of clean coal: consultation response

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Executive summary

We welcome the broad thrust of the draft framework for the development of clean coal. We are particularly pleased to note the emphasis on a diverse range of measures for mitigating climate change, the recognition that both market-based and regulatory approaches to encouraging the deployment of CCS are valuable, and the suggestion that the proposed requirement to demonstrate CCS should apply immediately.

We make several suggestions on matters of detail in response to the consultation questions. Specifically, we suggest the establishment of a process of continual review of the realistic capacity of carbon dioxide storage reservoirs. We further suggest that, to allow for the rapid rate of generation of new scientific information, the following are needed. First, an explicit, quantitative statement of the timescale that government considers sufficient for a reservoir to store carbon dioxide securely. Second, an explicit, quantitative statement of the level of leakage risk that government considers acceptable. Third, the publication of plans to accelerate the release into the public domain of seismic, borehole log, well injection test, and drilling record data generated by the private sector. Fourth, an explicit statement of government's view on the extent to which bio-fuel power stations should be covered by regulations requiring carbon capture readiness. Finally, the production of a companion document establishing similar principles for the retrofit of carbon capture and storage systems at existing power stations. We also note the importance of potential CCS operators having robust plans for monitoring their storage reservoirs, using monitoring technologies that have been thoroughly demonstrated to be of sufficient accuracy and precision.

In addition to these technical matters, we make several suggestions about the financial and regulatory aspects of the path to CCS deployment. First, we urge the early production by government of detailed criteria for deciding whether CCS is technically and economically proven. Second, we suggest the adoption of measures to counter any disincentives to private-sector funding of carbon capture and storage research. Third, we point out that the judgement as to whether CCS is technically and economically proven may need to be a continual and site-by-site process, starting as soon as reasonably practicable. Fourth, we propose that the starting date for the requirement to retrofit be left open (but certainly no later than 2025). This will allow for flexibility should CCS be technically and economically proven in advance of 2020. Fifth, we suggest that the proposed levy on electricity suppliers could be linked to carbon emissions. Sixth, we urge further consideration of the relative positions of coal and natural gas, with respect to the requirement to retrofit. Seventh, we ask for a more detailed definition of the crucial phrase "best attainable standards" for judging the efficiency of existing power stations proposed as CCS demonstration sites. Eighth, we suggest that it may be helpful if public funding for demonstration projects is protected from late-stage withdrawal through the spending review. Ninth, as an alternative to the proposed requirement to cease operation of power plants that fail to operate the CCS chain, we propose a mechanism for government to take over the running of such plants. Tenth, we urge extra care to be taken over the equity implications of co-location of demonstration projects. Finally, we note that it may be useful to address the rôle of perceived risk in suppressing private CCS investment as part of a wider review of how government can influence levels of risk aversion in the investment capital markets.

1 About us

The Institute of Theoretical Geophysics is a research group within the Departments of Applied Mathematics and Theoretical Physics and Earth Sciences, in the University of Cambridge. The various members of the Institute of Theoretical Geophysics are involved in developing nonlinear mathematical models and comparing the results with specially designed laboratory experiments. They then aim to extrapolate these new concepts to describe quantitatively large-scale natural events, such as volcanic eruptions, melt migration in the crust of the Earth, sedimentary structures, hazardous rock falls, ice propagation and formation in polar seas, and natural hazard prediction and assessment. In recent years, one of our key theoretical and experimental research themes has been the fluid mechanical behaviour of captured carbon dioxide, following its injection into geological reservoirs.

The contents of this document have been discussed among members of the Institute of Theoretical Geophysics working in research related to carbon capture and storage (CCS), namely Prof. Herbert E. Huppert FRS, Madeleine J. Golding, Dr. Mark A. Hallworth, Dr. Daniel C. Hatton, Dr. Jerome A. Neufeld, and Dr. Dominic Vella. All co-authors contributed valuable insights, and all their responses to the document as a whole were generally favourable, but the latter did not constitute approval in detail of the document. Hence, any errors or fallacies herein should be considered purely my own (Dr. Daniel C. Hatton, lead author).

2 Introduction

We welcome the draft framework for the development of clean coal [8]. This is an important step towards the deployment of a suite of technologies with the potential to make the largest single contribution, in the short and medium term, to decarbonizing Britain's, and the world's, energy generation [43]. More generally, we are pleased to see the commitment in paragraphs 2.4 and 2.14–2.19 of the draft framework to a mixed approach to energy sustainability, involving demand-side efficiency savings, renewables, CCS, *and* nuclear new build. Multiple technologies in combination can achieve a level of carbon abatement that would be impossible with any single technology in isolation [43]. We congratulate the Secretary of State, and everyone involved in producing the draft framework, on their high-quality work.

In the remainder of this document, we will address a number of more specific aspects of the draft framework, which will correspond closely with the issues raised by the consultation questions.

3 Question 3.1: What are your views on how effective the proposed framework of financial and regulatory measures will be in supporting delivery of our vision for clean coal at home and abroad?

3.1 Two-pronged approach

We are pleased to note, from paragraphs 1.2, 2.5–2.13, 3.4–3.11, and 4.54 of the draft framework [8], that government recognises the value of both financial incentives and regulatory measures, and has not fallen into the trap of believing that one must choose either market-based mechanisms or state regulation, to the exclusion of the other (cf. [51]).

3.2 Timing of committing public funds

It is unfortunate to mention, in paragraph 3.1 of the draft framework [8], the need for 'a stable regulatory and financial framework', then, in paragraph 3.3, to declare that final funding approval for the demonstration project chosen in the competition launched in 2007 depends on the results of a future spending review. If, as government appears to believe, there is a serious public policy need for CCS demonstrations, then a particular tool of public policy, even one as useful as the spending review, should perhaps not be allowed to stand in the way. This is especially true given the uneven temporal distribution of funding requirements mentioned in paragraph 5.9 of the draft framework.

4 Question 3.2: How do you think the proposals might impact on decisions to invest in new coal power stations and CCS demonstration in the UK?

4.1 Implications for research funding

Before commenting on this issue, we should declare that, as geophysics researchers, we have a particular interest in funding research on the geophysical aspects of carbon dioxide storage, a subject with which we have already gained significant experience.

The proposed obligation, in paragraph 4.31 of the draft framework [8], to apply CCS to 100 % of flue gas by 2025 is dependent on the technology being technically and economically proven by 2020. We assume that applying CCS will cost money (cf. [49, 26, 22]). This might mean that power station operators stand to gain financially from the technology *not* being proven. We are concerned that this will act as a disincentive to the electricity industry funding research relevant to the technical and economic feasibility of CCS. A simple, but somewhat extreme, solution would be to impose the obligation irrespective of whether the technology is proven. In effect, this would mean forcing plants to shut down if the technology is not proven; this, of course, would have potentially damaging implications for security of supply, and paragraph 3.34 of the draft framework considers and rejects a similar option. A less draconian approach would be to use the legislation implementing the draft framework as an opportunity to introduce a structure of incentives for the private sector to fund CCS research, in addition to the direct public funding outlined in the 2009 budget [18] and in paragraphs 5.6 and 5.25 of the draft framework; one possibility would be to take the need for these incentives into account in setting the level of any general carbon tax, or the number and/or price of EU emissions trading scheme (ETS) permits, applying from 2025 onwards. In this context, we should note that it is not only field-scale demonstrations that are likely to be relevant to the technical proof of CCS: laboratory experiments and theoretical studies will have a rôle to play as well (e.g. [35, 36, 46, 54, 21, 40, 31, 23, 57, 41, 27, 42]).

5 Question 3.3: What are your views on the proposed objective of the UK CCS demonstration programme, including the scale of individual demonstration projects?

5.1 Energy usage of CCS system

The estimate of the energy consumption of a CCS system, implied by paragraphs 3.19 and 4.2 of the draft framework [8], is towards the pessimistic end of the range of IPCC estimates [52] (cf. also annex 4 to the draft framework; [37, pp. 157–158]). Since the draft framework makes it clear in paragraph 5.30 that only highly efficient power stations will be considered for demonstration projects, an estimate towards the optimistic end might be more appropriate.

6 Questions 3.4 and 5.1: What are your views on whether and how an emissions performance standard (EPS) could support our policy objectives? What are your views of the proposed mechanism for providing financial support to CCS demonstration projects? Does it strike the right balance between attaining value for money from public funding while addressing the needs of potential investors? Do you agree with our initial view that a CfD is the most appropriate model for a disbursement mechanism?

6.1 Direct linkage of performance measures with aims

The most appropriate performance measures for a project are those that most directly reflect the aims of that project [11, p. 17]. The aim of the project under discussion is to reduce carbon dioxide emissions from electricity generation. Therefore, we welcome the emphasis, in paragraphs 3.22–3.24 of the draft framework [8], on 'considering the amount of carbon dioxide that is released for each unit of electricity generated'. For the same reason, we also welcome the tentative selection of a contract for differences on carbon abated (CfD) as a means of disbursing subsidies, in paragraph 5.25 of the draft framework.

In the same spirit, it may be useful for the levy on electricity suppliers under paragraph 5.6 of the draft framework, to be a levy per unit of carbon dioxide emitted, rather than per unit of electricity generated.

Another relevant performance measure is the total carbon dioxide emissions of the EU. In this context, we think it excessively pessimistic to declare, in paragraph 4.54 of the draft framework, that 'a requirement to retrofit would have no net effect on EU emissions, which would continue to be determined by the EU ETS cap'. A requirement to retrofit would reduce the regulatory impact of rapid reduction of the EU ETS cap, and would therefore improve the prospects of rapid reduction in the cap being implemented when the European Commission conducts its review of the rate of cap reduction under article 9 of EU Directive 2003/87/EC [4].

6.2 Distinction between coal and natural gas

In paragraph 4.10 of the draft framework [8], government states its intention to apply the obligation to demonstrate CCS on a portion of output from start-up only to coal, not to natural gas. The tenth paragraph of the executive summary of the draft framework makes a robust case, in terms of the lower carbon emissions per unit of electricity output from unabated natural gas, as compared with unabated coal, for this decision. Essentially, the draft framework is correctly pointing out that this is equivalent to applying an emissions performance standard to coal which natural gas is already bettering (cf. [33]).

However, the case for not placing obligations on natural gas facilities is weaker with respect to the subsequent 100 % CCS obligation. Some may perceive it as inequitable that coal power station operators are required by the draft framework to capture and store 100 % of their carbon emissions by 2025, while no obligation to capture or store CO_2 is placed on natural gas power station operators, who will therefore be able to continue to produce approximately 50 % of the carbon emissions associated with unabated coal [33]. This is equivalent to applying a more rigorous emissions performance standard to coal, while allowing natural gas to continue to violate it (cf. paragraph 4.63 of the draft framework). If the draft framework is to be enacted unaltered, there is a need to make an explicit case, perhaps in a preamble to eventual legislation implementing the draft framework, to counter any claims of inequity at the 100 % CCS stage of the regulations.

As an alternative to making this case, a way may need to be found to re-balance the obligations between coal and natural gas operators, without diminishing the overall reduction in carbon emissions achieved. One possibility might be to apply the requirement for 100 % CCS by 2025 to natural gas as well. If government wishes to take this path, it should announce this well before 2025, to allow natural gas generators to prepare for the deployment of CCS.

7 Question 4.1: Do you agree, in principle, that new coal power stations should be required to demonstrate CCS?

7.1 Timing of the commencement of regulation

We welcome the suggestion that the requirement, in paragraphs 4.10–4.12 of the draft framework [8], to demonstrate CCS on a significant fraction of the output of any new coal power station, should apply immediately. As far as mitigating climate change is concerned, we have reached a stage where readiness is no longer sufficient, and the time has come for action [28, 34, 17, 29].

8 Questions 4.2–4.3: What additional planning conditions do you think an operator should have to meet to show that they would be able to meet a requirement to demonstrate CCS? What are your views on the best approach to monitoring the operation of CCS demonstrations?

8.1 Types of data taken into account in DTI study of reservoir suitability

Under paragraph 4.7 of the draft framework [8], the planning element of the new regulatory framework will be incorporated in a final version of the draft guidance document on carbon capture readiness [9] (reproduced in annex 3 to the draft framework). Paragraphs 30–31 of the draft guidance document suggest that the standard way an applicant might demonstrate that a proposed CO_2 storage reservoir is appropriate, in order to meet the planning condition of carbon capture readiness, is to note that the reservoir was found to have a suitable "realistic storage capacity" in an earlier DTI study [30]. In this section, we will suggest a number of ways in which this aspect of the planning requirements could be extended. These will be similar to comments we made in response to the earlier consultation on the draft guidance document.

We are pleased to see that the DTI study includes, in its assessment of realistic storage capacity, consideration of permeability, porosity, and heterogeneity of the reservoir, as well as quality of the cap rock. We will argue that scientific knowledge in this area is evolving rapidly. We will therefore suggest that it would be useful to initiate a process of continual review of estimates of realistic capacity of reservoirs. We will also note some particular types of field data and modelling studies that may be useful in that review process.

This evolution of scientific understanding is a process of completing finer details, starting from the outline narrative of the motion of CO_2 subsequent to its injection into a reservoir discussed in section 5.2.1 of the DTI study. Briefly, this outline narrative is as follows: the CO_2, being lighter than the surrounding interstitial fluid, rises through the reservoir rock under gravity, gradually spreading horizontally as it rises. This continues until the CO_2 reaches the impermeable cap rock overlying the reservoir. If this material is an effective cap rock, the CO_2 cannot rise further (this is known as "stratigraphic trapping"), but continues to spread horizontally (cf. also [14], where these ideas are applied to the specific, real situation at Sleipner). Subsequent to this, some of the the carbon dioxide undergoes dissolution trapping. Dissolution trapping is a process whereby carbon dioxide dissolves in formation water as carbonic acid, forming a heavy product which would sink to, and be stably stored at, the bottom of reservoirs (cf. also [46, 26]). In addition, some of the CO_2 that has not dissolved in the formation water can be held by surface tension, in bubbles within pores that also contain water, a process known as "residual trapping" (cf. also [35, 46, 23]). At a still later stage, the dissolved carbonic acid resulting from dissolution trapping can react with rock materials, to form either solid metal carbonates (a particularly secure form of storage) or dissolved metal hydrogen-carbonates, a process known as "mineral trapping" (cf. also [44, pp. 92–93,108]; [46, 26, 21]).

Scientific understanding has evolved particularly rapidly in the understanding of reservoir heterogeneity, and in characterizing the quality of cap rocks for secure CO_2 storage. There have been several recent advances concerning the effects of reservoir heterogeneity. Specifically, our (and others') new research published in the open domain suggests that vertical heterogeneity in reservoir permeability can be a controlling influence on the motion of injected CO_2 prior to the CO_2 reaching the cap rock, enhancing horizontal spreading [40, 31, 57, 41]. Whether enhanced horizontal spreading increases or decreases the security with which CO_2 is stored will depend on the details of reservoir geometry and cap rock heterogeneities.

One of our research projects also raises the possibility of a method by which vertical heterogeneity in reservoir permeability can be used to enhance rapid dissolution trapping. The more rapidly injected CO_2 mixes and dissolves with the host brine, the less one is reliant on the long-term containment capability of the cap rock. The proposed method consists of injecting CO_2 rapidly, near the bottom of a low-permeability sub-layer, underlain by a higher-permeability sub-layer; this enhances spreading at each sub-layer, encouraging convective mixing and increasing the CO_2/water contact area at which dissolution trapping can take place [31].

New evidence is also emerging on what constitutes a cap rock of sufficient integrity for purposes of secure carbon dioxide storage. Specifically, recent research suggests that, where the cap-rock is dipping (there is a dipping cap rock, for example, at the Otway Project site, [13]), horizontal spreading of CO_2, during an initial period subsequent to the CO_2 reaching the cap rock, is reduced by the dip. In this initial period, the spreading takes a symmetric form, but afterwards, the CO_2 starts to spread preferentially up the slope of the dipping cap rock and the spreading rate in the preferred direction is enhanced by the dip [54]. The length of the "initial period" depends on the permeability of the reservoir, the slope of the cap rock, and the injection rate, and may range from 11 days to 14 years. This (in common with the existence of dissolution trapping) suggests that the "capacity" of a reservoir may not be a fixed number, but may depend on how fast the CO_2 is injected. Whether the initially restricted horizontal spreading increases or decreases the security with which CO_2 is stored will depend on the details of reservoir geometry and cap rock heterogeneities.

In addition, new experimental data and quantitative theoretical models confirm a hypothesis mentioned in sections 5.1.1 and 5.5.1 of the DTI study, that the presence of faults (i.e. two-dimensional, high-permeability features) and/or boreholes in the cap rock will lead to CO_2 leakage towards the surface, on a timescale determined by the ease of flow through these faults [42]. Importantly, our current work suggests that the presence of faults could lead, in the later years of deployment, to almost all of the injected CO_2 escaping through the faults [42]. This highlights the importance of geological studies assessing the integrity of geological storage sites both before injection, and during the injection process.

Recent research further suggests that the presence of channel-like features in the base of the cap rock can enhance the horizontal spreading of CO_2 subsequent to the CO_2 reaching the cap rock [27]. Therefore, models assuming a smooth basal topography for the cap rock (cf. [36]) provide a lower limit on the horizontal spreading distance. Whether this enhanced horizontal spreading increases or decreases the security with which CO_2 is stored will depend on the details of reservoir geometry and cap rock heterogeneities.

Given the rapid rate of generation of new scientific information outlined above, we suggest that the estimates of realistic capacity from the DTI study are likely to need a process of continual review over the next several years, and that the planning conditions for new power stations should take into account the results of such a review process. This uncertainty is reflected in the substantial number of reservoirs where the DTI study notes that there is theoretical capacity, but not yet realistic capacity, and we envisage the results of the review process being, for the most part, a gradual conversion of some theoretical storage capacity into the realistic storage capacity category, as discussed in chapter 6 of the DTI study.

The review process will need access to field data (seismic studies, borehole logs, and results of well injection tests) showing the vertical heterogeneities in the permeability of reservoirs, the presence of any compartmentalizing faults in the reservoirs (the importance of this is noted in section 5.2.2 of the DTI study), and the locations of faults and other high-permeability routes to the surface in the cap rocks, including records of where boreholes have been drilled through the cap rocks. Given the existence of a leakage timescale in cases where the cap rock has fault-like features, it may also be sensible, either in the final version of the guidance document or in the legislation implementing the draft framework, to quantify the timescale that government considers sufficient, for a particular reservoir and cap rock system to secure injected CO_2. A minimum figure, for a useful contribution to mitigating climate change, of a few hundred years has been mentioned [49]. However, a "useful contribution" is not necessarily as large a contribution as government or the public at large may like; hence, the thousand-year timescale for unassisted dissolution trapping may also be relevant [26].

Seismic data have insufficient resolution to determine whether the basal topography of the cap rock contains channel-like features smaller than around 8 m [14], so it will be necessary either to rely on the lower limit to horizontal spreading provided by modelling for a smooth cap rock base, or to use ensemble modelling for various basal topographies.

8.2 Securing the release of data obtained during oil and gas exploration

It is clear from the above (section 8.1) that detailed field data, from seismic studies, borehole logs, well injection tests, and records of drilling, will be an essential component of the review process, both for continual re-assessment of reservoirs covered in the DTI study [30] and for assessment of new reservoirs. Because undertaking new field campaigns has the potential to introduce considerable additional financial costs, it is important to take advantage of data already gathered in the course of oil and gas exploration. We understand that government and the oil and gas industry have already been working on moving data into the public domain, with exploration and development licences being conditional on data release after a multi-year confidentiality period [1]. However, there may be a need to speed up the process: sections 4.1.1.2 and 5.4.2.5 of the DTI study mention that some data potentially relevant to carbon capture and storage have not yet been released. Perhaps it would be useful for the legislation implementing the draft framework [8] to state how government and the oil and gas industry will work together in future to make these and other relevant data available to carbon capture and storage planners.

8.3 Monitoring during and after injection

In addition to their plans for the capture and injection process itself, it is important that applicants outline how they will monitor the carbon dioxide during and after its injection into a reservoir, to make sure that the CO_2 stays buried, both in the immediate aftermath of its injection and throughout the period that government considers sufficient for CO_2 to remain securely stored (cf. [26], section 8.1). It is also important that the technologies used for this monitoring have been thoroughly demonstrated to have sufficient accuracy and precision. This is true both of the demonstration phase and of the 100 % CCS phase.

Time-lapse seismics have proved successful, at Sleipner, in confirming that CO_2 is present in the reservoir, and where in the reservoir it resides over time [14]. Hence, applicants will need to commit to a programme of time-lapse seismic studies over a long period.

However, seismics will not tell the whole story: their resolution is insufficient to quantify with reasonable precision the volume of CO_2 that remains in the reservoir at any given time [14]. Therefore, applicants will need to consider additional monitoring techniques to complement their seismic studies. One possibility is drilling test wells to sample interstitial fluid in the reservoir (cf. [20]), subject to the availability of a suitably acid-resistant cement to prevent the test wells themselves from becoming leakage pathways (cf. [12, 26]). Gravity surveys can also help to locate stored CO_2 [26]. In addition, for the detection of some types of leakage, one can monitor CO_2 concentrations in the sea or atmosphere at the surface [26]. It may also be important to keep logs of pressure and flow rate at the injection well(s), allowing continuous re-assessment of reservoir permeability, and its heterogeneity and anisotropy (cf. [55]).

We also note that, in addition to the monitoring programme itself, having a clear plan for dissemination of monitoring results might be crucial in securing public acceptance of (particularly onshore) CCS [56].

Much of what we have said above tends towards option "2", in paragraph 4.20 of the draft framework [8]. However, the options "1", "2", and "3", in paragraphs 4.19–4.23 of the draft framework, are not mutually exclusive, and an effective monitoring régime may need to include elements of all three.

8.4 Relationship to the Draft Guidance on Carbon Capture Readiness and Applications under Section 36 of the Electricity Act 1989

Prior to the present consultation, government consulted on draft guidance [9] on carbon capture readiness and applications under section 36 of the Electricity Act 1989. In our response to that consultation, we outlined a few respects in which we believed the guidance document would need to be updated to take account of the likely contents of the draft framework [8] being consulted on here. In the following sub-sections, we reiterate some of those points.

8.4.1 Treatment of different combustion fuels

The draft guidance document [9] treats all combustion fuels alike. The requirements in the draft framework [8], however, apply only to coal, not to natural gas or bio-fuels. For consistency with the draft framework, if the latter is to remain unchanged in this respect, the guidance document should perhaps, at least in those respects directly related to the draft framework (see section 8.4.2 below), mention different fuels separately.

8.4.2 Redundancy of paragraph 35 concerning post-start-up changes of proposed storage site

Paragraph 35 of the draft guidance document [9] says that applicants need not, by the beginning of power generation, commit themselves to using a particular storage reservoir. This will need editing in the light of the requirement of the draft framework [8] to demonstrate CCS from the start-up of a new power station, which will mean that, in practice, applicants have to commit themselves at the start of power generation by beginning to inject CO_2 into a particular reservoir.

9 Question 4.4: Under which circumstances would you consider it acceptable and/or necessary for power station operators to switch off the CCS chain?

9.1 Health and safety

In addition to its climatic effects, carbon dioxide in high, or even moderate, concentrations can cause serious, sometimes fatal, respiratory illnesses [47, 25, 19, 48]. Hence, one can readily imagine circumstances where the discovery of a leak, or of the potential for a leak, in the CO_2 transport and storage systems, means that there is a health and safety requirement for temporary shutdown of the CCS chain; this health and safety requirement should, of course, be respected. There is an assumption implicit in the question that this temporary shutdown of the CCS chain will not be accompanied by a temporary shutdown of the power generation facility itself. We note that it does not have to be this way: one could instead look to the nuclear industry, where the protocol for responding to the discovery of cracks in cooling pipes involves shutting down the reactor until the pipes have been repaired [16].

10 Question 4.5: Do you agree that new coal power stations should be required to cease operation if the operator cannot demonstrate that they are making reasonable efforts to operate the CCS chain?

As we understand it, the possibility of a chronic failure to make reasonable efforts to operate the CCS chain is being raised as a wholly separate issue from temporary shutdowns of the CCS chain associated with, e.g., acute health and safety risks.

10.1 Unforgiving nature of the climate system

Sadly, the climate system does not give marks for effort. Earth's surface temperature is not affected by the intentions of power station managers, only by whether the carbon dioxide from their power stations is vented to the atmosphere. Hence, it may be preferable to phrase any regulations in this area in terms of failure securely to sequester carbon dioxide, rather than in terms of failure to make reasonable efforts to operate the CCS chain.

10.2 Mechanisms for public control of failing electricity generation facilities

A requirement to cease operation would be one rigorous way of enforcing the CCS requirements, but might have harmful consequences for security of supply. A less drastic alternative might be a procedure whereby government can take over the operation of a power station if its private sector operator fails in its obligations, analogous to the powers of government to terminate rail franchises the terms of which are not being met [6], and subsequently operate rail services itself under section 30 of the Railways Act 1993 (as amended) [3]. Unlike any of the three options in paragraphs 4.28–4.30 of the draft framework [8], this would ensure operation of the CCS chain was restarted as soon as reasonably practicable without loss of electricity supplies.

We note also that, for plants funded through the CCS demonstration programme, the linkage of ongoing revenue funding to operation of the CCS chain mentioned in paragraph 4.14 of the draft framework is likely to be helpful as an enforcement measure.

11 Question 4.6: Do you agree, in principle, that there should be requirement to retrofit?

11.1 Timing of the commencement of the 100 % capture obligation

As we pointed out above (section 7.1), deployment of CCS and other climate change mitigation measures is a matter of some urgency [28, 34, 17, 29]. As such, we not only agree that there should be a requirement to retrofit, we suggest that the eventual legislation implementing the draft framework [8] leaves open the possibility of commencement of the 100 % CCS obligation prior to 2025, if the technology is proven (either generally, or for a particular site) prior to 2020.

12 Questions 4.7–4.10 and 4.13: What are your views on the criteria that should form the basis of an assessment of when CCS is technically and economically proven? Do you agree that the Environment Agency should be tasked with assessing when CCS is technically proven? Who do you think should be tasked with judging when CCS is economically proven? Should the decision of when CCS is proven be one for an independent body to take, or for Government on the basis of independent advice? Do you agree, in principle, that there is a need for a contingency measure?

12.1 Definition of "proven"

There is an important requirement that transcends the detailed content of the criteria, and the identity of the body that decides whether they have been met. This requirement is that the criteria are explicit, transparent, and democratically formulated; in addition to its intrinsic value, having published criteria with these characteristics will help to avoid any suspicion that the government in 2020 faces a conflict of interest between the need to decarbonize electricity generation and the receipt of revenues from any carbon tax or sale of EU ETS permits. The scientific community, whether organized into an "independent body" or not, can only estimate risks and benefits. Deciding what risks are acceptable and what benefits are valuable is a matter for the public, either directly (cf. [56]) or through their elected representatives. As such, we suggest that, well before 2020, government (or some other representative body such as a special select committee of the House of Commons), preferably with a high level of engagement with the general public, provides a much more detailed definition of "proven". To achieve strong public engagement will require a campaign of broad dissemination of technical information to start soon. This definition will be useful not only as input to a regulatory decision in eleven years' time, but also to inform the design of research and development programmes in the interim, which will provide the data that determine whether CCS is proven for any particular class of sites. The earlier the definition of "proven" is clarified, the better these research and development programmes can be focused, and the more likely it is that CCS will be proven and there will be decisive action on its deployment.

A good start on this has been made in paragraph 2.43 of the draft framework [8], in which government calls for an end-to-end demonstration, including both separation of CO_2 from flue gas and underground injection of that CO_2 at the same, commercial-scale power station. We share the view that such an end-to-end demonstration will be helpful, both for building public confidence in CCS and for better understanding the impacts of CCS. We also thank government for providing a quantitative definition of "commercial scale", in paragraphs 3.16 and 3.19 of the draft framework, although this definition could be clarified further by specifying whether it is measured in megawatts of electricity or of primary heat.

We mentioned above (section 8.3) one piece of information from government that may form a useful part of the criteria for judging whether CCS is technically proven: a quantitative value of the timescale that government considers sufficient, for any particular reservoir and cap rock system to secure injected CO_2. Similarly, it would be useful for government to quantify what it considers an acceptable level of risk of CO_2 leakage.

Another possible next step is to be more specific about the senses in which government considers CCS not to be "proven" already, since there are a number of senses in which one could argue that CCS is already technically and economically proven. Injection of CO_2 into underground reservoirs in the field has been in progress since the early 1970s [49]. Injection partly or wholly for the purpose of long-term disposal of waste CO_2, at rates comparable with the CO_2 production of a power station, has been in progress at one site (Sleipner) for over a decade [49, 14], and at two other sites (Weyburn-Midale and In Salah) for several years [20, 49]. Of these, the Weyburn-Midale Project is an end-to-end demonstration of CCS on flue gas from a synfuel plant, at a scale equivalent to about 220 MW e [20, 49]. This is not too far from government's ambition of an end-to-end demonstration of CCS at commercial scale on a power station. By 2005, the IPCC [49] was able to give quantitative estimates of the financial cost, per unit of electricity generated, of CCS at fixed sources. This cost is inexpensive compared with other supply-side methods of carbon abatement (cf. [38]); if government intends to insist on these cost estimates falling even lower, to consider CCS economically proven, then it should say so explicitly, and quantify how much lower. As early as 2004, Pacala and Socolow [43] felt able to include $3\,\mathrm{Gt/\,yr}\ C$ of geological carbon dioxide storage in the package of measures described in a paper entitled "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years *with Current Technologies*" (our italics).

Given this low financial cost, we are surprised by the pessimism of the statement in paragraph 4.9 of the draft framework that 'we would expect only those power stations able to secure financial support to move to construction'. Instead of simply accepting this outcome, government could make some comments on whether and how it could act to create a favourable macro-economic and monetary climate for CCS to be demonstrated on wholly privately-funded power stations, either simultaneous with, or shortly after, start-up of the four publicly-funded demonstration projects mentioned in paragraphs 3.3–3.4 and 5.1–5.2 of the draft framework.[1] One possibility is for government to ensure that the carbon price is high enough for the private

[1]There is some room for confusion about the number of demonstration projects. Paragraph 5.1 of the draft framework

sector to fund CCS. In the light of the comments in paragraph 5.8 of the draft framework, concerning the rôle of perceived risk in suppressing private CCS investment, government may also like to consider action to reduce the general level of risk-aversion in the UK investment capital market (cf. also [32, pp. 133–134, 298–303]; [15]; [10, annex B]).

Finally, in the spirit of the DTI study by Holloway et al. [30], we note that CCS will not become technically proven for all sites in a single, sudden event. An essential part of CCS being technically proven will be that the storage reservoir has what Holloway et al. call "realistic capacity" — a scientific assessment of the quantity of CO_2 which the reservoir has the appropriate stratigraphic, mechanical, and chemical properties to store securely. Holloway et al. envisage a process whereby realistic capacity is gradually assigned to more reservoirs as scientific understanding improves. As we noted in section 8.1 above, scientific understanding has been evolving particularly rapidly with respect to the likely rôles of heterogeneous reservoir permeability, localized flaws in cap rocks, and cap rock slope and topography in the security of CO_2 storage. It is not only geo-technical risks that can vary from site to site: there are also "social risks" associated with (particularly onshore) CCS, which differ between different communities [56]. Hence, the judgement as to whether CCS is technically proven must be a continual process, not a one-off decision as suggested in paragraphs 3.8 and 4.81 of the draft framework. Government needs to give some thought to how the 100 % CCS obligation will apply in a situation where CCS is technically proven for some types of storage reservoir, but not for others. This geographical variation of risk also suggests that local, as well as national, government may need to be intimately involved in designing the technical criteria.

13 Question 4.12: What are your views on how the requirement to retrofit should apply to existing coal power stations?

13.1 Retrofit to existing power stations

The draft framework [8] is primarily designed to implement CCS at new power stations. However, one of the most exciting CCS proposals in the UK today, for the sheer scale of its ambition, is the Yorkshire and Humber Carbon Capture and Storage Partnership (cf. [45]), which is based on retrofitting CCS technology to existing plants. This proposal is also in the spirit of paragraph 6.10 of the draft framework concerning pipeline networks. Therefore, we suggest it might be useful to produce a companion document alongside the legislation implementing the draft framework, to outline similar processes for implementing CCS at existing power stations. This companion document will be useful whether or not government, at some later date, decides to introduce legislation requiring retrofit of CCS technology to existing power stations (cf. paragraph 4.70 of the draft framework); such legislation would seem to follow naturally from the Committee on Climate Change's recommendation of 'establishing a clear and publicly stated expectation that coal-fired power stations will not be able to generate unabated through the 2020s and beyond the early 2020s' [5, p. 199].

14 Question 5.2: What are your views on the proposed arrangements for selecting and managing CCS demonstration projects? Are there any additional or alternative arrangements we should consider?

14.1 Clarity of conditions for demonstration projects at existing plants

The requirement, in paragraph 5.30 of the draft framework [8], that demonstration projects involving pre-existing coal plants that have 'not been refurbished to bring their generation efficiency up to best attainable standards should not be considered for financial support', is a sensible one. Geological storage space is finite

proposes up to four including the project that wins the 2007 competition, whereas paragraph 5.27 proposes up to four funded through the new mechanism, which suggests up to five including the project that wins the 2007 competition.

[49, 30], and it does not make sense to use it for emissions generated at a higher carbon intensity than necessary. However, government needs to provide a detailed definition of "best attainable standards". Is this the same as the tightly-specified concept of "best available techniques" (cf. box 4.2 of the draft framework)? Alternatively, does it relate to the concept of reasonable practicability, as defined by thirty-five years of case law under the Health and Safety at Work etc. Act 1974 [2]?

15 Question 6.2: What are your views on how can we best ensure that CCS business clusters are encouraged, maximising the future opportunities for UK business?

15.1 Distribution of risks

In deciding whether to pursue co-location of CCS demonstration projects under paragraph 6.13 of the draft framework, government needs to consider how co-location would interact with the differentials of geo-technical and social risks studied by Wong-Parodi and Ray [56]. While the risks of climate change are distributed over the whole population, the risks associated with CCS are localized, and co-location may exacerbate the potential inequity associated with this localization

16 Question 6.3: Are there any other actions that the Government should consider taking at this stage to prepare for the full commercial deployment of CCS?

16.1 Position of bio-fuels

One could argue that a wholly bio-fuel-based power station has, through the growth of its fuel, already to some extent captured its CO_2 emissions before it produces them, which might mean that there is less danger of perceived inequity in a decision not to apply the obligations of the draft framework [8] to bio-fuels than in a decision not to apply them to natural gas (cf. section 6.2).

On the other hand, the "some extent", to which CO_2 is captured before it is produced, varies greatly between different bio-fuels, and in some cases may even be less than zero [24, 50, 53]. The existence of co-firing plants that burn both fossil fuels and bio-fuels complicates the situation further. Also, the possibility that bio-fuels have already achieved some carbon capture before arriving at the power station does not diminish the potential for CCS at bio-fuel-based plants to achieve further decarbonization of electricity supply. Further, we note that the forthcoming EU directive on the geological storage of carbon dioxide [7] specifically mentions the need to build experience of CCS at bio-fuel plants.

Given the existence of these competing arguments, we suggest that, alongside the legislation implementing the draft framework, government might like to make an explicit statement on the extent to which it believes bio-fuels should be subject to the same CCS regulations as fossil fuels.

17 Concluding remarks

We compliment government on its draft framework for the development of clean coal. The emphasis on a diverse range of measures for mitigating climate change, the recognition that both market-based and regulatory approaches to encouraging the deployment of CCS are valuable, and the suggestion that the proposed requirement to demonstrate CCS should apply immediately are all important advantages of government's approach.

We have made several suggestions on matters of detail in response to the consultation questions. Specifically, we suggested the establishment of a process of continual review of the realistic capacity of carbon dioxide storage reservoirs. This review would imply a need for the following. Firstly, an explicit, quantitative statement of the timescale that government considers sufficient for a reservoir to store carbon dioxide securely. Secondly, an explicit, quantitative statement of the level of leakage risk that government considers acceptable. Thirdly, the publication of plans to accelerate the release into the public domain of seismic, borehole log, well injection test, and drilling record data generated by the private sector. Fourthly, an explicit statement of government's view on the extent to which bio-fuel power stations should be covered by regulations requiring carbon capture readiness. Finally, the production of a companion document establishing similar principles for the retrofit of carbon capture and storage systems at existing power stations. We also made some comments on the importance of potential CCS operators having robust plans for monitoring their storage reservoirs, using monitoring technologies that have been thoroughly demonstrated to be of sufficient accuracy and precision, and for dissemination of the monitoring results.

As well as our technical remarks, we made several suggestions about the financial and regulatory aspects of the path to CCS deployment. Firstly, we suggested the early production by government of detailed criteria for deciding whether CCS is technically and economically proven; the development of these criteria may provide a unique opportunity to communicate and engage with the general public on CCS. Secondly, we proposed the adoption of measures to counter any disincentives to private-sector funding of carbon capture and storage research. Thirdly, we noted that the judgement as to whether CCS is technically and economically proven may need to be a continual and site-by-site process, starting as soon as reasonably practicable. Fourthly, we suggested that the starting date for the requirement to retrofit be left open (but certainly no later than 2025). This will allow for flexibility should CCS be technically and economically proven in advance of 2020. Fifthly, the proposed levy on electricity suppliers could be linked to carbon emissions. Sixthly, we believe there is a need for further consideration of the relative positions of coal and natural gas, with respect to the requirement to retrofit. Seventhly, we urge government to provide a more detailed definition of the crucial phrase "best attainable standards" for judging the efficiency of existing power stations proposed as CCS demonstration sites. Eighthly, we suggest that it may be helpful for public funding for demonstration projects to be protected from late-stage withdrawal through the spending review. Ninthly, as an alternative to the proposed requirement to cease operation of power plants that fail to operate the CCS chain, we proposed a mechanism for government to take over the running of such plants. Tenthly, we cautioned that care needs to be taken over the equity implications of co-location of demonstration projects. Finally, we suggested that the rôle of perceived risk in suppressing private CCS investment may need to be addressed as part of a wider review of how government can influence levels of risk aversion in the investment capital markets.

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