



# LOWEST COST DECARBONISATION FOR THE UK: THE CRITICAL ROLE OF CCS

Report to the Secretary of State for Business, Energy and  
Industrial Strategy from the Parliamentary Advisory Group  
on Carbon Capture and Storage (CCS)

September 2016



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## Letter from the Chairman

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*Dear Secretary of State,*

At the start of the year, following discussions on the Energy bill and with the successful and historic Paris Agreement recently completed, but also with the cancellation of the latest CCS Competition fresh in our minds, I was invited by your predecessor to chair an independent joint industry and parliamentary advisory group on CCS. We undertook to report by the end of the summer.

Following many months of work, it is with great pleasure that I am providing you with the final report of that group and commending its content and recommendations to you.

I have had a long association with CCS and the CCS industry as do many members of the group. However, after so many false starts I began this study, as I know a number of my colleagues did, quite prepared to advise you to write-off CCS as a part of UK energy policy. As you will see, our report recommends the opposite of this.

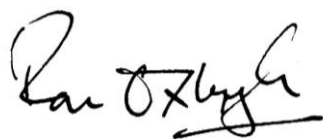
I have been surprised myself at the absolutely central role which CCS has to play across the UK economy if we are to deliver the emissions reductions to which we are committed at the lowest possible cost to the UK consumer and taxpayer.

While some of the recommendations may at first reading appear unconventional, they are absolutely focused on the delivery of least cost solutions.

As we were completing our report, the Committee on Climate Change published its letter to you (6<sup>th</sup> July). It is pleasing to observe that there is a high degree of agreement with the recommendations of our report.

I would like to personally thank all the members of the group, those people who gave evidence to the group, and the excellent members of your department who supported us through what turned out to be a much more comprehensive process than any of us were expecting at the beginning. However, I should like to express my particular thanks to Ian Temperton who in addition to providing his valuable expertise to the Group's discussions acted as our secretary and was responsible for writing much of this report.

A new approach to CCS of the form recommended in this report is urgently needed.



Ron Oxburgh

Chairman of the Parliamentary Advisory Group on Carbon Capture and Storage

# Terms of reference and acknowledgements

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## *Terms of reference of the group*

The terms of reference for the group were as follows:

- To assess the potential contribution of CCS to cost-effective UK decarbonisation
- To recommend accordingly to the Secretary of State by end of summer 2016

## *Acknowledgements*

Particular thanks go to Eva Stepniewska, Will Lochhead and Amy Clemitshaw of DECC for their help facilitating the group's work.

The group would also like to thank the Institution of Mechanical Engineers and the Institution of Civil Engineers for kindly hosting some of its meetings.

A number of people kindly agreed to speak to the group on various topics. These included Peter Atherton (Jefferies Bank), Jo Coleman (Energy Technologies Institute), Mike Thompson and Eric Ling (Committee on Climate Change), Jim Watson (UK Energy Research Centre), Graeme Sweeney (by phone) (Zero Emissions Platform), Paula Carey (Carbon8), Ashley Ibbett (DECC), Ian Ellerington (DECC), Belinda Perriman (Teesside CO<sub>2</sub> Collective), Neil Kenley (Tees Valley Unlimited), Allan Baker (Societe Generale), Stephen Bull and Faisal Bachlan (Statoil), Jonathan Pearce and Michelle Bentham (British Geological Survey), David Rennie (Scottish Enterprise), Stephen Kerr (Caledonian Clean Power) and Paul Sullivan (National Grid).

The group would like to thank all of those who attended meetings for their time and the very valuable insights which they provided to the group.

Some people provided valuable feedback on early drafts of the report. The group would also like to thank them for their time and valuable insight. These included David Hone, Joan McNaughton, Jeremy Oppenheim, Rick Jefferies and the CCSA.

The views expressed in this report are solely those of the Parliamentary Advisory Group and not of any of those who attended our sessions or reviewed early versions of the report.

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***Committee members and report authors are listed on pages 47 - 49***

# Summary

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## ***CCS is essential for lowest cost decarbonisation***

1. This report addresses the policy disconnect that arises between the previous Government's cancellation of the carbon capture and storage (CCS) competition on grounds of cost and the advice it received from a number of independent policy bodies that CCS was an essential technology for least cost decarbonisation of the UK economy to meet international agreements (most recently Paris 2015).
2. The Committee on Climate Change (the "CCC") recently reported the additional costs of inaction on CCS for UK consumers to be £1-2bn per year in the 2020s, rising to £4-5bn per year in the 2040s
3. ***The group agrees carbon capture and storage is an essential component in delivering lowest cost decarbonisation across the whole UK economy.***

## ***CCS works and can be deployed quickly at scale***

4. Current CCS technology and its supply chain are fit for purpose. There is no reason to wait for international projects or for technological progress in either the components or overall system of CCS. Because lead times are long – planning, regulatory and construction – early decisions are needed.
5. ***UK action on CCS now will deliver lowest cost to the consumer. There is no justification for delay. Heavy costs will be imposed on current and future UK consumers by a continued failure to enact an effective CCS policy.***
6. Ample, safe and secure CO<sub>2</sub> storage capacity is available offshore in the rocks deep beneath UK territorial waters and this represents the least cost form of storage at the scale required.
7. CO<sub>2</sub> re-use, such as enhanced oil recovery and the production of materials such as building products, already exists and should continue to be encouraged, however the required large-scale decarbonisation of fossil fuels will create volumes of CO<sub>2</sub> which no market for re-use will be able to absorb.
8. ***The lowest cost CO<sub>2</sub> storage solution for the UK at the scale required will be offshore geological storage in UK territorial waters. There is no reason to delay the development of such storage and associated infrastructure. The state will need to take an enhanced role in managing storage risk if costs are to be minimised.***

***CCS in the power sector has an essential enabling role***

9. CCS has direct or indirect implications for the decarbonisation of all four of the major fossil fuel consuming sectors of the UK economy – industry, power, transport and heating. They need to be considered together so that synergies of a common infrastructure can be exploited. Other routes to decarbonisation are possible but in some important sectors they would be more expensive than using CCS.
10. With some 200TWh/year of new clean power generation needed in the UK system in the 2020s fossil fuels with CCS will play an important role as a cost competitive and potentially flexible power generation technology.
11. There is a widespread view that CCS has to be expensive. On the contrary, the high costs revealed by the earlier UK approaches reflected the design of these competitions, rather than the underlying costs of CCS itself.
12. This poor design led to the lack of true competition and the imposition of risks on the private sector that it cannot take at reasonable cost for early full-chain projects.
13. Previous third party analysis by the CCS Cost Reduction Taskforce and for the Committee on Climate Change as well as analysis performed for this report show full-chain CCS costs at c.£85/MWh under the right circumstances. This report concludes that, under the right conditions as set out in this report, even the first CCS projects can compete on price with other forms of clean electricity.
- 14. To ensure that least cost CCS is developed when earlier approaches have foundered a CCS Delivery Company (“CCSDC”) should be established that will initially be government owned but could subsequently be privatised (Recommendation 1).***
15. This company will have the responsibility of managing “full-chain” risk and will be responsible for the progressive development of infrastructure focused on industrial hubs to which power stations and other emitters could deliver CO<sub>2</sub> which, for a fee, will be pumped to appropriate storage.
16. The CCSDC will comprise two companies: “PowerCo” tasked with delivering the anchor power projects at CCS hubs and “T&SCo” tasked with delivering transport and storage infrastructure for all sources of CO<sub>2</sub> at such hubs.

***A system of economic regulation is needed***

17. The UK CCS industry (including the CCSDC from its creation) will operate under a regulated return style of economic framework. This provides for the lowest cost of capital and hence lowest cost to the consumer and creates the highest prospect of mobilizing private capital at the earliest opportunity.

***18. This regulatory framework should be put in place now, drawing to the greatest extent possible on existing and trusted frameworks in the UK energy sector (Recommendation 2).***

***CCS infrastructure then facilitates decarbonisation in industry***

19. The transport and storage infrastructure developed by the CCSDC will facilitate CCS for other sectors such as industrial processes that cannot support its development on their own.

20. CCS in industry represents some of the cheapest available carbon abatement in the UK economy.

21. However UK industry does not have the incentive, scale or financial capacity to support the development of CCS infrastructure.

***22. A payment scheme will therefore be needed to give industrial emitters an incentive to collect their CO<sub>2</sub> and pay T&SCo to receive it from them. Such "Industrial Capture Contracts" will need to be funded directly by HMG (Recommendation 3).***

23. Early Industrial Capture Contracts will be awarded to those emitters of pure, storage-ready streams of CO<sub>2</sub> who are able to transport and store using existing infrastructure and low cost stores. Industrial emitters with material capture costs or without access to existing transport and storage infrastructure will need more time to develop their systems and may be awarded such contracts later.



***Heat may be the most important sector for CCS in the long-term***

24. The most challenging sector for CCS in the medium term is the decarbonisation of heating. The options for decarbonising the c.20m private gas heating boilers, that contribute a large part of the heating demand as well as the rest of the heating sector, are limited.
25. One possibility is to replace gas boilers by decarbonised electrical heating. In this case, even with widespread use of heat pumps, the maximum demand for grid power in winter would become several times what it is today. There would need to be new generating capacity (nuclear, CCS or renewable), additional on-grid electricity storage and a significant strengthening of the grid to carry the heavy load of the seasonal peak. This extra capacity for both transmission and generation would be needed for no more than a few months a year and so appears costly.
26. Another option is to repurpose the recently renovated natural gas distribution network and use it to supply hydrogen to domestic heating and cooking appliances and industrial users. A switch to hydrogen has the advantage that the seasonal peak heat demand can be met by hydrogen which has been stored through the year and hence without further material change to the distribution network. A key to this is the utilization of a pervasive existing modernized distribution network and a safe and strengthened infrastructure to store and distribute the hydrogen.
- 27. At the moment this is only an option, but the case is sufficiently compelling and the timing sufficiently critical that the government should build on the excellent recent work in this area and initiate further preparatory work without delay through the formation of a “Heat Transformation Group” (Recommendation 4).***
28. Decarbonised hydrogen can be produced by electrolysis of water and could open the way to a future fossil fuel free economy but for the immediate future would be produced from hydrocarbons with CCS. A hydrogen network could also be used for clean power generation and for emission free vehicles (particularly in heavy goods transport).
- 29. Whichever choice is made for heat, CCS will be required whether on plant to generate the additional electricity needed or to generate hydrogen directly from hydrocarbons.***

***CCS Certificates and a CCS Obligation provide the long-term assurance and incentive framework for the private sector***

30. This report recommends a two stage development of the CCS industry. In the first phase involving substantial state sponsorship, the CCSDC delivers both power projects and backbone transport and storage infrastructure at industrial hubs around the UK. This then de-risks the investments for additional capture and transport and storage investments in the second phase.
31. This creates the opportunity to implement an assurance and incentive scheme for an industry operated by the private sector and funded by private capital which has a clear pathway to meeting the UK's decarbonisation goals for the middle of this century.
- 32. A CCS Certification System should be implemented immediately to verify that particular volumes of CO<sub>2</sub> have been securely stored by any valid means including forms of re-use (Recommendation 5).***
- 33. A market-style incentive system in the form of a CCS Obligation on all fossil fuel suppliers to store a growing percentage of the emissions resulting from that fuel could be introduced in the late 2020s (Recommendation 6).***
34. This can guarantee a continued demand for CCS to underpin investor confidence and align demand to achieving the UK's national and international commitments to decarbonisation.

***The government should act now. There is no reason for delay***

35. CCS has the potential to be safely storing 15% of current UK CO<sub>2</sub> emissions by 2030 and up to 40% by 2050.
36. The development of CCS hubs would provide jobs and economic stimulus in parts of the country where they are most needed.
37. While decarbonisation will never be cost free, this report sets out six main recommendations that constitute the foundations of a viable and cost-effective CCS policy.
38. CCS will be required under any choice of options and the cost to the consumer will be minimised if the infrastructure is developed progressively as part of the long-term strategy set out in the report.
- 39. Action is needed urgently if the commitments under the Climate Change Act and the Paris Agreement are to be met at least cost to the UK consumer. The six recommendations of this report should be implemented without delay as shown in the accompanying milestone chart (see page 10).***

# Recommendations

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## ***1. Establish a CCS Delivery Company (“CCSDC”) (paras 195 –252)***

A newly formed and initially state-owned company tasked with delivering full-chain CCS for power at strategic hubs around the UK at or below £85/MWh on a baseload CfD equivalent basis. Formed of two linked but separately regulated companies: “PowerCo” to deliver the power stations and “T&SCo” to deliver the transport and storage infrastructure, the CCSDC will need c.£200-300m of funding over the coming 4-5 years.

## ***2. Establish a system of economic regulation for CCS in the UK (paras 253-290)***

The government will establish a system of economic regulation for CCS in the UK which is based on a regulated return approach. This will draw heavily on existing regulatory structures in the energy system and hence include: a CCS Power Contract based on the existing CfD or capacity contract to incentivise CCS for power; the regulation of T&SCo as other energy network operators; the introduction of an Industrial Capture Contract (see below); and the continued regulation of the energy network industry.

## ***3. Incentivise industrial CCS through Industrial Capture Contracts (paras 291-317)***

The Industrial Capture Contract, will be funded by the UK government and will remunerate industry for capture and storage of their CO<sub>2</sub>. It will be a regulated contract which will have a higher price in the early period in order to deliver capital repayment in a timescale consistent with industry horizons. Industry will have access to transport and storage through short-term contracts. Early projects will use existing infrastructure and pure streams of CO<sub>2</sub>.

## ***4. Establish a Heat Transformation Group (“HTG”) (paras 318-335)***

The Heat Transformation Group will assess the least cost route to the decarbonisation of heat in the UK (comparing electricity and hydrogen) and complete the work needed to assess the chosen approach in detail. The HTG has a likely funding need of £70-90m.

## ***5. Establish a CCS Certificate System (paras 336-342)***

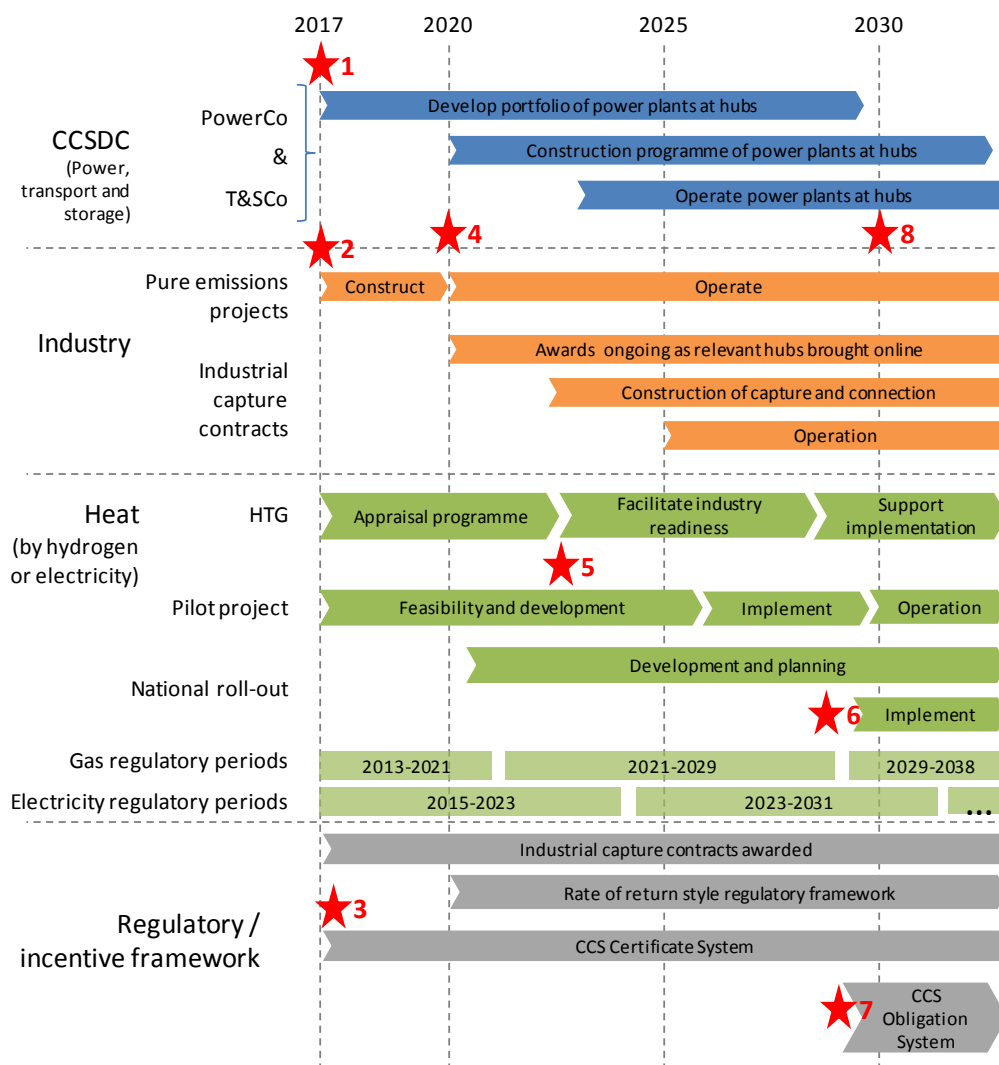
Government will implement a CCS Certificate System for the certification of captured and stored CO<sub>2</sub>.

## ***6. Establish a CCS Obligation System (paras 343-359)***

Government will also implement a CCS Obligation from the late 2020s as a means of giving a long-term trajectory to the fossil fuel and CCS industries. This will put an obligation on fossil fuel suppliers to the UK to sequester a growing percentage of the CO<sub>2</sub> associated with that supply. Proof of storage and hence fulfilment of the obligation being via presentation of CCS Certificates.

# Milestones for lowest cost decarbonisation using CCS

The diagram below shows how the six recommendations and associated milestones in this report deliver a programme of CCS deployment in the UK over the coming decades.



- Key milestones**
- ★1 Funding of CCSDC and HTG; implementation of recommendations
  - ★2 First investment decision on pure stream industrial projects
  - ★3 Implementation of a CCS Certificates System and award of early industrial contracts
  - ★4 First investment decision for a full-chain power project
  - ★5 Role of hydrogen vs electricity in heating determined
  - ★6 Start of roll-out of heat solution
  - ★7 Start of CCS Obligation on fossil fuel suppliers
  - ★8 Potential privatisation of CCSDC or its subsidiaries

# CCS in the UK

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## The case for CCS in the UK

40. The present inquiry was set up in the wake of the cancellation of the latest of several ‘competitions’ that were run with a view to establishing CCS in the UK (see Appendix 1).
41. The only outcome of this earlier activity was the impression that CCS is an expensive and expendable technology for the UK in its programme of decarbonisation.
42. A number of authoritative bodies had claimed that CCS is an essential technology if the UK is to undergo the transformation required to decarbonise its energy sector at least-cost.
43. Making a critical assessment of this conclusion, the group reviewed the evidence and met those responsible for the arguments, and then concluded that they were correct. Based on what we know today the decarbonisation targets we have set ourselves will come at very much increased cost without CCS.
44. The Committee on Climate Change’s recent advice to government on CCS quotes estimates of the additional cost of decarbonisation without CCS as £1-2bn per year in the 2020s increasing to £4-5bn per year in the 2040s<sup>1</sup>.
45. These potential future costs of our inaction today underpin the case to act on CCS now.
46. A more detailed discussion of many of the issues raised below is to be found in the Appendices.

## CCS across the UK economy

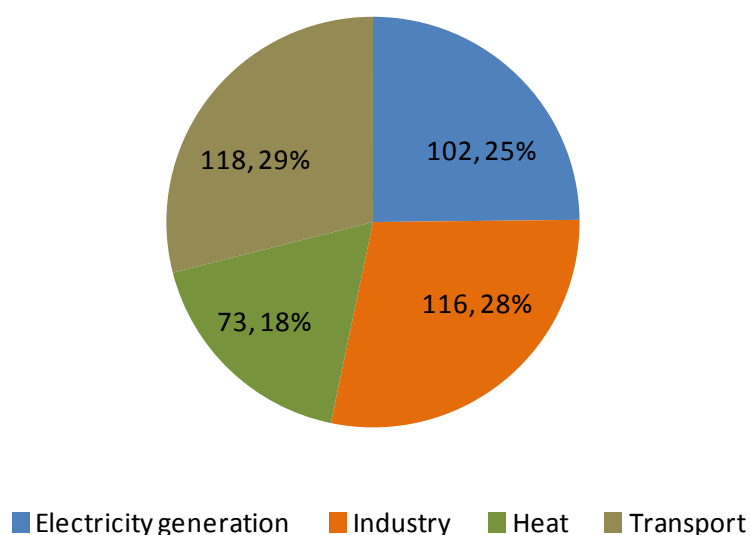
47. Realising the benefits and cost advantages of CCS requires policy-makers to consider the various impacts of technology options across the whole economy. Developing CCS involves thinking across the different sectors of the energy economy, such as electricity, heat and heavy industry, and evolving the application of CCS to these different sectors over time.
48. This highlights both the importance of CCS and the complexity of policy-making for it. CCS is essential across various sectors of the UK energy economy.

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<sup>1</sup> A strategic approach to carbon capture and storage, Committee on Climate Change, Letter to DECC Secretary of State, 6<sup>th</sup> July, 2016.

49. The diagram below shows the current estimated CO<sub>2</sub> emissions for the UK across the major sectors of the economy.

**2015 UK CO<sub>2</sub> Emissions (mt) - c.409mt total**



Based on Provisional estimate of UK greenhouse gas emissions for 2015 (DECC March 2016) excluding waste, agriculture and LULUCF (actual total including all sectors is 405mt CO<sub>2</sub>)

### *Electricity*

50. Electricity generation was the source of 25% or 102m tonnes p.a. of 2015 UK CO<sub>2</sub> emissions<sup>2</sup> from fossil fuels.
51. Many energy systems models, particularly those which include the whole system costs of different technologies show a substantial role for CCS as a cost-effective low carbon power technology.
52. The benefit of CCS in a whole electricity system context derives in part from its ability, with suitable design, to deliver electricity when it is needed.
53. CCS power stations, as with all forms of thermal power, are despatchable as they can change output in response to the grid operator's requests. They also have a property known as inertia inherent in their design which makes an important contribution to the stability of the electricity grid and helps to integrate other low carbon generation technologies.
54. The relative competitiveness of CCS in the power sector also clearly depends on uncertain future fossil fuel prices.

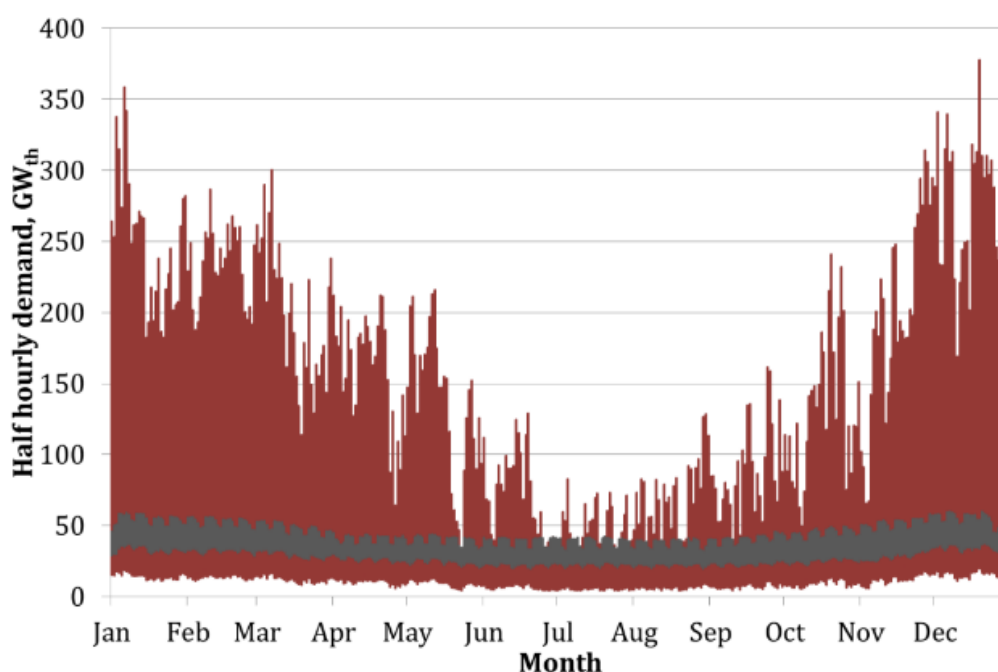
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<sup>2</sup> Provisional estimate of UK greenhouse gas emissions for 2015, DECC March 2016.

55. If decarbonising today's electricity sector were the only challenge, and that sector had sufficient cost-effective flexibility to absorb other sources of low carbon power, then development of CCS might not be so pressing.
56. However, power is a crucial enabling sector for the other sectors that rely on CCS for lowest cost decarbonisation as explained in the following sections.

### *Heat*

57. Residential and public sector emissions which are mostly from heating represented 18% or 73m tonnes p.a. of 2015 UK CO<sub>2</sub> emissions<sup>2</sup> from fossil fuels.
58. The challenge of keeping the UK warm is illustrated by the diagram below which is the work of Robert Sansom of Imperial College. It shows estimated national half hourly heat demand (red) for 2010 and actual half hourly national electricity demand (grey).



59. Decarbonising heat could be achieved through pervasive electrification with installation of heat pumps, resistive heating and / or heat networks (such as district heating), or by using hydrogen as the main energy vector and converting the natural gas grid to carry decarbonised hydrogen (this is explained in greater detail in Appendix 5)
60. Both of these decarbonisation scenarios for domestic heating require CCS. This is either because of the need to produce decarbonised hydrogen or to significantly increase electricity production at the required new power stations, if electrification is the cheaper option.

61. Large-scale deployment of heat pumps, resistive heating or heat networks potentially need massive increases in the scale of electricity generation, as average UK heat demand exceeds electricity demand by a factor of 1.5x and peak heat demand exceeds peak electricity demand by a factor of 5-6x<sup>3</sup>. Given this increase in demand for electricity CCS-for-power is almost certainly competitive with alternative forms of clean electricity generation.
62. An alternative approach to decarbonising heat is to convert the gas grid to carry hydrogen.
63. This could be achieved through a scale-up of electricity for hydrogen production by electrolysis; however this is prohibitively expensive.
64. By a wide margin, decarbonised hydrogen comes most cost-effectively from its production from hydrocarbons with CCS (for instance via reforming natural gas).
65. No heat pathway is without its challenges, and there is much further work to be done, but based on what we know today about clean electricity and clean hydrogen production costs over the coming decades the conversion of the gas grid for hydrogen could be the least cost route for the decarbonisation of heat (see Appendix 5).
66. Such a pathway also has ancillary health and safety benefits such as improvement in local air quality and reduction in accidents related to, for instance, carbon monoxide poisoning, and it potentially minimises disturbance to consumers in the transition as the urban infrastructure is already largely installed.
67. To have the option to begin converting the gas network to hydrogen in the 2030s requires CCS transport and storage infrastructure in place based on a proven and cost-effective model during the 2020s (see milestone chart on page 10).
68. While it is still only an option today, the case for decarbonised hydrogen for heating is sufficiently compelling and the timing sufficiently urgent that action is required now because of the very long lead times involved.

### *Industry*

69. Industrial processes, non-power energy supply and business represented 28% or 116m tonnes p.a. of 2015 UK CO<sub>2</sub> emissions<sup>2</sup> from fossil fuels.
70. The top eight emitting industrial sectors emitted c.80m tonnes p.a. of CO<sub>2</sub> emissions based on 2012 data with 23m tonnes p.a. of potential abatement of those emissions being identified as coming at least cost from CCS<sup>4</sup>.

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<sup>3</sup> Managing heat system decarbonisation. Comparing the impacts and costs of transitions in heat infrastructure, Imperial College, Centre for Energy Policy and Technology, April 2016.

<sup>4</sup> Industrial decarbonisation and energy efficiency roadmaps to 2050, DECC, March 2015.



71. CCS is required for many industries as they use industrial processes where the use of hydrocarbons and the creation of CO<sub>2</sub> as a by-product are practically unavoidable today and for the foreseeable future.
72. Some industrial processes produce relatively pure CO<sub>2</sub> that could be stored without further processing.
73. Subject to its financing challenges industrial CCS has the potential to provide low cost emissions abatement from essential strategic industries and to provide valuable employment in regions with challenging economic conditions.

### *Negative emissions technologies (“NET”)*

74. There is a very great likelihood that to redress the risks associated with atmospheric concentrations of CO<sub>2</sub> rising above safe levels, CO<sub>2</sub> which has already been emitted will need to be extracted from the atmosphere.
75. This requires so-called “negative emissions” which offset current and past emissions of CO<sub>2</sub>.
76. While there are a number of potential negative emissions technologies including NET fuel cells, soil carbon and direct air capture, none of these can be deployed cost-effectively at scale today.
77. Most energy system models assume that negative emissions are delivered by combining bioenergy sources (e.g. forestry and energy crops) to fix the CO<sub>2</sub> from the atmosphere and CCS to permanently sequester it underground after combustion of the bioenergy.
78. Despite the significant reservations of many about the availability and sustainability of bioenergy at the required scale, bioenergy with CCS (“BECCS”) plays a very significant role in both 2°C and 1.5°C modelling scenarios for global warming which are consistent with, for instance, the Paris Agreement.
79. The capacity to deliver negative emissions also has the potential to reduce the overall cost of decarbonisation by compensating for emissions from some hard-to-mitigate sectors (such as aviation, agriculture or some industrial processes). This adds some flexibility into any decarbonisation plan.
80. The ability to deliver many of these negative emissions technologies will require an established CCS infrastructure to be in place, as is needed for emissions reductions in heat and industry.

## ***Transport***

81. Transport represented 29% or 118m tonnes p.a. of 2015 UK CO<sub>2</sub> emissions<sup>2</sup> from fossil fuels.
82. This report has not considered transport in any detail. The sector is diverse in its requirements and its emissions can to varying degrees be mitigated by CCS. The technology to make electrical vehicles (EVs) both convenient and affordable is advancing rapidly. As with heat, a scale-up in the need for decarbonised electricity to power these vehicles is likely to include a role for CCS if it is to be achieved at least cost. This applies equally to rail transport which is substantially electrified on the main lines.
83. Additionally, if the gas network were converted to hydrogen it would facilitate the use of hydrogen fuel cell vehicles and provide an alternative to battery vehicles particularly for HGVs.

## **Implementing CCS**

### ***CCS hubs: a national infrastructure priority***

84. Coastal areas have many attractions for locating power stations; they are similarly good places to make hydrogen from hydrocarbons; and they may already be host to major industrial installations.
85. Combining this with the fact that scale is a very important factor in driving down cost, developing so-called “CCS hubs” with CCS infrastructure concentrated at major industrial coastal locations makes perfect sense.
86. These locations tend also to be a focus for energy infrastructure such as natural gas import pipelines, deep sea ports, facilities for natural gas or hydrogen storage etc.
87. Such locations also provide easy access to offshore storage locations for CO<sub>2</sub>. While the ability to access multiple sources of CO<sub>2</sub> reduces cost and increases resilience at such hubs over time, so too does the ability to access multiple sinks.
88. Properly developed CCS hubs may also be located in some of the least wealthy parts of the UK many of which have suffered from deindustrialisation over recent decades.
89. Developing such hubs will require traditional industrial skills and for the most part these hubs are likely to be in north of the UK.
90. Historical attempts at CCS policy in the UK have pitted one potential strategic hub against another in competition. While they will obviously not all be built at once, there is no compelling reason why a national CCS infrastructure should not include most, if not all, of the UK’s major industrial locations.

91. CCS development therefore has the potential to inject infrastructure spending into the regional economies which most need it and hence contribute to a rebalancing of the economy both geographically and by sector.

### *The crucial facilitating role of the power sector*

92. Not only does CCS have a crucial role to play in the decarbonisation of electricity, this sector also acts as a critical enabler for CCS in other sectors.
93. The case for CCS is most compelling on a whole system, cross-economy basis given the UK's decarbonisation goals.
94. The unavoidable additional costs of power stations with CCS compared to power stations without CCS need to be funded in an economically efficient way over the long-term and the existing funding mechanisms in place for the electricity sector provide the only viable route for this.
95. The infrastructure at CCS hubs needs to be funded through creditworthy initial use at scale and the only sector that can provide that today is the power sector.
96. Hence the development of CCS hubs, with their large-scale transport and storage infrastructure needs CCS to operate first in the power sector because the other sectors where it is important are either not yet fully developed (heat and NETs) or not sufficiently large or creditworthy (industrial emitters).

### *Why now?*

97. These essential sectors need access to cost-effective transport and storage infrastructure and drive the urgency.
98. With 200TWh/year<sup>5</sup> of new electricity production needed in the 2020s according to the Committee on Climate Change work must start now if CCS is to make a meaningful contribution.
99. The option of clean hydrogen with CCS for heating is critically dependent on a proven and cost-effective CO<sub>2</sub> transport and storage infrastructure being established by the second half of the 2020s and a decision to take this pathway in the early 2020s
100. Industrial processes can deliver low cost emissions abatement now, particularly compared to other current forms of decarbonisation if it has access to a cost-effective CCS infrastructure. Small scale opportunities exist using pure streams of CO<sub>2</sub> and existing infrastructure today.

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<sup>5</sup> Power sector scenarios for the fifth carbon budget, Committee on Climate Change, October 2015.

101. Given that it takes many years to build large scale infrastructure projects like CCS networks, the development of cost-effective CCS networks needs to commence immediately (see milestone chart on page 10).

### **Storage and use**

102. There is more than sufficient geological storage in the UK.

103. Over the last two decades some 20m tonnes of CO<sub>2</sub> has been safely stored by Norwegian projects in rocks deep beneath the North Sea. These projects and many others worldwide provide ample evidence that CO<sub>2</sub> storage can be safe, secure and enduring.

104. Storage capacity is no impediment to the development of CCS in the UK and there is now a well-documented portfolio of likely stores at various stages of investment readiness (see Appendix 4).

105. Most of the CO<sub>2</sub> that the UK sequesters through CCS will be stored in geological formations offshore in UK territorial waters where there is ample, safe, secure storage capacity.

106. Onshore storage is less well characterised in the UK and there is some merit in re-appraising that knowledge gap and exploring the possibility of low cost onshore storage projects.

107. Similarly, carbon capture and re-use technologies may have a limited role to play, their development should be encouraged, and they may provide cost-effective pathways for decarbonisation in niche applications. (see Appendix 3).

108. The UK is not alone in having storage potential and there may be circumstances where physically storing in nearby countries is most cost-effective. Where they present themselves, those opportunities should be taken.

109. The UK can proceed with confidence that, at the scale required, offshore geological storage in rocks deep beneath UK territorial waters will be the lowest cost option for the UK consumer over the long-term. There is no reason to wait for an alternative.

### ***Storage responsibility***

110. Any emitter of CO<sub>2</sub> can today emit to atmosphere, pay a minimal charge for doing so (for instance the current EU ETS price) and be expunged of its liability for that pollutant for ever.

111. If the emitter voluntarily elects to sequester that CO<sub>2</sub> in a geological formation then it carries the liability for that pollutant, including monitoring, reporting and provisioning for it over several decades until it is eventually transferred to the state.

112. Such risks are impossible for most private sector actors to elect to take in the absence of significant prior experience or a compelling incumbent reason for doing so.
113. Even those with experience show no appetite for taking this risk at scale in the long-term.
114. This gap has to be bridged if early projects are to be successfully developed.
115. There is no point in developing CCS infrastructure unless there is confidence in the system which ensures that CO<sub>2</sub> is safely sequestered. Energy consumers may reasonably expect that when they pay additionally to safely and permanently store emissions then that is exactly what will happen.
116. If CCS develops, as it must, as a global solution to be applied in many countries then it is imperative that the UK, the EU and others set robust standards for storage which others follow.
117. The provisions of the CCS Directive (or whatever may now replace it) which govern these arrangements are necessary and essential to ensuring value for the energy consumer over time and the integrity of decarbonisation pathways.
118. Wherever storage risk is to reside, the entity responsible must be vested with the skills and resources to manage those risks to the appropriate standards.
119. If that entity is to be state-owned, then the state must manage this as a technical, as well as a financial risk.

## **Industrial readiness**

### ***Required technologies and skill-base***

120. No more fundamental research is needed in order to begin a programme of least cost CCS deployment.
121. There is no case for waiting for technological innovation in the CCS system or the individual components of that system.
122. The required technologies exist at the appropriate scale and are commercially available in competitive markets today. For the most part the component technologies of CCS have been available for decades.
123. Globally, there are 15 large-scale CCS projects in operation, with a further seven under construction. The total CO<sub>2</sub> capture capacity of these 22 projects is around 40m tonnes per annum.<sup>6</sup>
124. There is no need for proof of the technical concept.

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<sup>6</sup> Global Carbon Capture and Storage Institute

125. The component markets are in a state of maturity and transformative technologies are not anticipated to be available at scale in a timeframe or with a degree of certainty that justifies waiting.
126. Incremental improvements are already efficiently absorbed in the supply chains delivering the component technologies of CCS. Research should of course continue to support the long-term cost-effective development of this important strategic industry.
127. The component supply chains for CCS are vast (including oil and gas, power, gas processing, pipelines etc.) and hence a UK CCS programme will not disturb those markets; no scale-up is required; and there is no concern about the physical ability to deliver.
128. The UK is blessed with existing deep domain expertise, skilled people, and companies able to play a significant role in the components of the CCS supply chain.

### *Collaboration*

129. There have been numerous international collaboration initiatives in commercial-scale CCS.
130. The UK already has what it needs to develop its own CCS industry and hence should be wary of diverting scarce resources into international projects without there being clear benefits in the form of cost reduction for the UK consumer.
131. There is no compelling UK case for international collaboration except possibly in the North Sea (see Appendix 2) and to accelerate knowledge transfer into emerging economies and the development of CCS in such economies. In both cases this has the potential to drive the export of UK expertise in CCS.

### *UK infrastructure is a UK issue*

132. The UK has existing infrastructure through its hydrocarbon industries which provides potential cost savings for a UK CCS programme. This should be safeguarded and leveraged where it does genuinely save cost to the consumer.
133. One of the key drivers for cost-effective CCS is the development of infrastructure at scale. This is a specifically UK issue.
134. There is a compelling case for starting now. The UK potentially has an in-built competitive advantage in developing CCS because of its existing infrastructure. This advantage may not last forever as legacy pipelines, potential storage fields and other potentially useful infrastructure is likely to be decommissioned in the absence of a credible pathway for its use in CCS.

## Industrial CCS

135. CCS is essential to the decarbonisation of industry. However there is currently no business case to justify the necessary investment. Industry has neither the incentive, the scale, nor the credit quality to deliver CCS.
136. Generally, industry is exposed to internationally competitive markets in which it has no capacity to pass on the cost of carbon abatement unless all its international competitors carry the same obligation, which they currently do not.
137. While the treatment of different industries varies, the most energy intensive tend now to be largely exempt from, or compensated for, environmentally related costs.
138. Even if they were fully exposed to environmental costs such as emissions trading schemes and environmental taxes, those costs would provide insufficient incentive to pursue CCS.
139. These factors combine to mean that there is no material incentive for UK industry to pursue CCS.
140. Industry therefore will seek to sequester its CO<sub>2</sub> only if it is paid to do so by government, or if an effective international sectoral agreement on CO<sub>2</sub> disposal comes into effect for its industry (and they and their competitors are not immediately exempt from it or compensated for it).
141. The former is in the gift of the UK government. The latter is unlikely any time soon.
142. Without such an incentive there is no case for companies to pursue CCS at industrial locations despite the cost to society being low for capturing and storing this CO<sub>2</sub>.
143. Even if UK industry had the right economic incentive to undertake CCS, for the most part the companies in question have insufficient credit quality to underwrite the financing of, say, a CCS transport and storage infrastructure.
144. While a transport and storage infrastructure might be most cost-effectively financed over decades, most UK industrial emitters will finance investments in their facilities over less than 10 years.
145. This means that industry cannot be expected to underwrite, or give long-term commitments to use, transport and storage infrastructure.
146. It also means that while it may be able to finance capture plant, it will need to be remunerated for doing so in a way which is initially much shorter term than is the norm in other infrastructure-like sectors.
147. Any UK government payment to incentivise capture in industry will therefore need to be front-loaded .

148. Furthermore, any international sectoral agreement would need to place a value on abatement significantly in excess of the long-term economic cost before an industrial player will undertake CCS. This very much raises the threshold for action via this route.
149. Notwithstanding their credit quality, most industrial emitters are of insufficient scale to be able to support the cost-effective financing of a CCS transport and storage infrastructure on their own.
150. Looked at over the long-term the cost of abatement in UK industry is low compared to the cost of carbon abatement which UK consumers already pay in other low carbon sectors.
151. Financed and regulated efficiently UK industrial CCS is likely to represent highly cost-effective abatement. Hence the least cost pathways for decarbonisation for the UK involve acting on these emissions much sooner than is likely to occur by waiting for international sectoral action.
152. If the UK takes unilateral action on industrial emissions it reduces its cost of decarbonisation.
153. There are also small and medium scale opportunities where pure, storage-ready CO<sub>2</sub> is currently vented to atmosphere and where the emitter is close to existing infrastructure which can be used for transport and storage. There are clearly early wins to be had by storing these streams in low cost onshore or near-shore stores.

### **The future of natural gas**

154. Unabated natural gas is often talked of as a bridge fuel from a high carbon to a low carbon energy system. It is lower carbon than unabated coal, but not as clean as renewable, CCS on coal or gas, or nuclear power.
155. However most decarbonisation scenarios for the UK do not have unabated gas for power generation in the energy mix beyond 2050 and some recent work<sup>7</sup> shows that little or no new natural gas capacity in power without CCS can be accepted from now on.
156. Certainly a power station with a notional 20-30 year life constructed in the 2020s risks its life being shortened if it is not fitted with CCS and the UK sticks to its emissions targets.
157. A mechanism for dealing with this risk has been for government to require new emitting power stations to be “capture-ready”.

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<sup>7</sup> The future role of natural gas in the UK, UKERC, February 2016.



158. Capture-readiness is loosely defined and even more loosely applied and there is a concern that the lack of real capture-readiness in investments in natural gas plant in recent years makes them susceptible to stranding as emissions targets become more stringent.

159. Investors are on notice that new gas-fired power stations without CCS will have a limited life. This is a very clear conclusion from the majority of the energy model scenarios for the UK.

160. Mitigating this risk, and hence stimulating investment in gas-fired power generation, requires power station developers to take CCS seriously, and yet we know that there are no full-chain CCS sponsors in the private sector.

161. Investment in new gas-fired power stations in the UK is therefore a very risky proposition in the absence of a clear strategy on CCS.

### **A new commercial approach**

162. There are two facts about CCS which have become very clear in recent years: firstly, there are no companies who make it their business to be full-chain CCS project sponsors, and secondly the individual components of the CCS chain are mature and competitive with multiple private sector players and a range of technological options.

163. Despite these known facts successive governments have insisted on full-chain projects when no private sector sponsor exists.

164. Imposing unfamiliar and potentially excessive demands on multiple private sector actors has led to the unnecessary compounding of risk which has greatly increased the estimated cost of deploying CCS, and has failed to deliver the desired outcome.

165. Failing to deliver CCS or delivering it at excessive cost both impose additional and unnecessary costs on the UK consumer.

166. There has not been sufficiently clear and effective price or cost discovery for CCS for the government to have any basis for discounting CCS as a technology

167. A piece of infrastructure such as Crossrail, the Olympics or a High Speed Rail line is nationally important and unique. It is better therefore to retain that unique overall (“full-chain”) project risk in government, at least initially, while letting private sector companies compete to provide the component parts of the project which they are best placed to deliver at least cost.

168. What this implies is that a CCS development strategy needs to align itself to the very well-established, deep and efficient supply chains which exist in all the components of CCS.

169. From the beginning, a new and successful CCS strategy needs to reflect the absence of private sector full-chain sponsors, while maximising the competition between private sector players in the components at which they excel.

170. This involves realistically allocating risk from the start and hence achieving best value for the consumer where the opportunity exists to do so.

171. Such an approach maximises private sector involvement, maximises competition and minimises the cost to the consumer.

### **Cost-effective CCS from day one**

172. Given the established nature of CCS component technologies and supply chains, CCS can be delivered cost effectively from the first project depending on three critical drivers for cost: effective competition, scale and cost of capital.

173. As noted above, if competition is minimised by asking the market to deliver something that it is not set up to do (a full-chain project) then the likelihood is high cost.

174. If the component markets are addressed separately in the most efficient manner consistent with the usual practice of those component industries then there is no reason that the true efficient cost of each component should not be able to be accessed by the very first project.

175. If private sector competition is maximised, the next major component of minimising cost to the consumer is scale.

176. The capital intensity of CCS means that the unit cost of carbon abated, or energy produced, is minimised by being able to amortise the capital cost of the project over greater capacity (tonnes) and over an extended period (time).

177. Time and tonnes are the key to cost-effective CCS. To be cost-effective, transport and storage infrastructure in particular must be delivered at scale, amortising its initial capital cost over a substantial and reliable long-term stream of CO<sub>2</sub>.

178. It is entirely possible to start big, and as noted earlier, from a component perspective even a big CCS project will not stretch the supply chain.

179. Given this capital intensity the final crucial component of delivering cost-effective CCS from the start is the cost of capital.

180. In previous attempts at CCS the private sector has been exposed to unfamiliar risks which have compounded its required cost of capital. In an efficient approach this would not be the case.

181. The commodity and regulatory risks to which investors are exposed are then the key to determining the cost of capital for such projects in the energy sector.

182.If these can be minimised and a low cost of capital realised from the start then this third component of cost reduction is also available from day one.

183.It is therefore the judgement of this report that the price of CCS in power generation can be roughly halved from the current perceived price produced by successive competitions. Such a reduction is the result of implementing a commercial structure which maximises competition, delivers at sufficient scale, and operates under the right regulatory structure.

### **Mobilising private investment**

184.Keeping the cost of capital low from day one involves providing investors with as familiar a risk and cash flow profile as possible. Being unfamiliar tends to be unattractive and costly.

185.Investment is disproportionately attracted to regulated returns on assets in the energy sector, and the cost of capital for investment in such areas is substantially below that for market / commodity exposed areas. The spread between these two forms of investment is only widening.

186.Particularly in this extended era of low interest rates, the stable long-term dividends provided by regulated assets are prized by investors.

187.Hence if there is a need to attract large volumes of low cost private capital to investment in CCS over time, it makes sense to make those investments are regulated assets, or behave like regulated assets to the greatest extent possible.

### **The state and CCS**

188.Decarbonisation represents a very great challenge to the business model, asset value and the very existence of many companies in the energy business, and hence one might expect given the very clear role CCS plays in many least cost pathways, that the energy industry would be investing in it itself, irrespective of short-term policy.

189.One might also imagine that given the investor focus on stranded assets and the massive destruction of value which has occurred in the European energy market in recent times from a failure to respond to changes in the policy environment, that companies might be under pressure from their investors to develop strategies and capabilities which equip them for pathways involving CCS.

190.They are not.

191. Despite the fact that the business model and physical infrastructure of energy in the UK will be transformed out of all recognition in the coming decade or two, and that CCS is likely to play a significant role in that transformation, if it is to be done at least cost, companies and investors have come to rely on government to lead. There is no indication of their taking meaningful initiatives on their own.

192. This situation is endemic to the structure of the industry and so policy-makers should not expect investor attitudes to change. However, this situation is obviously also exacerbated by the failure of successive governments to effectively execute their declared intentions with respect to CCS

193. Industry and investors expect the state to lead on CCS and there is little likelihood of any speculative investment by the private sector in the next phase of CCS development.

194. To both maximise success and private involvement in that success in the long-term, the state must take a very significant and certainly leading role in the development of CCS in the UK.

# Achieving lowest cost decarbonisation: Next Steps and Recommendations

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## **1. Establish a CCS Delivery Company (“CCSDC”)**

195. The CCS Delivery Company will be a newly formed initially state-owned enterprise tasked with delivering full-chain CCS power projects and associated over-sized transport and storage infrastructure at key strategic industrial hubs.

196. The CCSDC will have a mandate singularly focused on delivering at lowest cost to the consumer. Its projects will receive no more than £85/MWh on a baseload CfD equivalent basis.

197. The CCSDC will likely develop 3-6 strategic hubs through the 2020s; sequestering 15-30m tonnes of CO<sub>2</sub> p.a. from power generation by 2030. It may need of the order of £200-300m of pre-investment decision funding from the government between now and the early 2020s and will bring forward investment decisions early in that decade.

198. The CCSDC will comprise a power company (“PowerCo”) and a transport and storage company (“T&SCo”) which may later be separated and privatised.

199. The CCSDC should be formed and funded as soon as possible and certainly during 2017.

### ***State-owned and financed***

200. The element of this recommendation that will appear the most unusual and present the most difficult political challenge is the initial outright state ownership and financing.

201. It is actually not unusual for either infrastructure or energy.

202. The CCSDC is delivering nationally important, first-of-a-kind energy infrastructure for the UK.

203. In the case of projects with these characteristics in the UK in other infrastructure sectors (Crossrail 1 & 2, HS1 & 2, the Olympics, the Docklands and others) it is entirely normal for the UK government to act as the initial and overall sponsor.

204. Across the energy sector state ownership is the norm in many countries.

205. Even in the liberalised UK electricity sector the large-scale, capital intensive investments most analogous to CCS (nuclear and offshore wind) are dominated by majority state-owned enterprises (of other states).

206. The intention is that the CCSDC and / or its two component subsidiaries will be able to be privatised or attract private finance to a substantial degree once they have developed a track record. State ownership and financing is to be temporary.

### *Why full chain?*

207. The first CCS project simply is a full-chain by definition. There is no getting away from that. However it is developed, a first project will undoubtedly have one major source of CO<sub>2</sub> and one major sink for the CO<sub>2</sub>.

208. Once multiple sources and multiple sinks are developed it is easier to envisage a more flexibly structured CCS industry, but the first project at each hub is a full-chain project.

209. Full-chain risk is a risk the private sector cannot take, or cannot cost-effectively take, on the first projects. Taking early full-chain risk is a key reason for the formation of the CCSDC.

### *Why electricity?*

210. Electricity is the key facilitating sector for CCS. If we review the sectors needing CCS: heavy industry cannot finance an infrastructure; NETs are a long way off; no decision can be made on heat without a functioning CCS infrastructure; and hence that leaves us with power.

211. Only electricity provides a large-scale, creditworthy route to financing the early CCS infrastructure the nation needs at its strategic industrial hubs.

### *Why £200-300m?*

212. The group has not independently assessed the funding needs of the CCSDC and hence this is a very approximate assessment of the need for government funding over the next 4-5 years.

213. For clarity, this budget is for the development of the first hubs to the point of a final investment decision. It is not the budget to construct the power projects or the transport and storage infrastructure. This budget needs to cover further storage appraisal work (likely the largest element of the budget), engineering and design studies for the power station and transport and storage projects, and the formation of an organisation of the scale and quality required to deliver this substantial programme of investment and to be a credible prospect for privatisation in time. Actual construction will require additional funding come the early 2020s and this is the earliest that any form of private capital is likely to be able to be attracted to the CCSDC.

214. The first task for government in the formation of the CCSDC should be to properly assess its funding needs, however this funding should be consistent with the CCSDC's role and level of ambition. The £200-300m estimate in this report is consistent with known costs of similar past work on CCS Competitions.

### *Two companies in one, for now*

215. From its inception the CCSDC will be structured as two separate companies. A power company ("PowerCo") tasked with delivering power station CO<sub>2</sub> at the required scale at strategic hubs, and a transport and storage company ("T&SCo") which provides the transport and storage infrastructure servicing all sources of CO<sub>2</sub> those hubs.

216. As the first projects are full-chain, the CCSDC simply must manage those risks across the two companies. However the two companies will be regulated separately and the intention is that over time they will be separated as the UK develops a network of sources and sinks for CO<sub>2</sub>.

### *Long-term CO<sub>2</sub> storage liability*

217. The CCSDC will take the long-term CO<sub>2</sub> storage liability that the private sector clearly cannot take today. Specifically this will reside in T&SCo.

218. This is both a technical and financial risk which the CCSDC will develop the requisite capability to assess and manage.

219. This will help promote the right standards for the rest of the industry, and enhance the prospects of this risk being privatised in time.

### *Delivering lowest cost at scale (the £85/MWh cap)*

220. The absolute primary focus of the CCSDC is to deliver least cost projects for the UK consumer.

221. This means the price paid by the UK consumer for early projects should be immediately competitive with other forms of clean power generation. Hence the proposed cap at £85/MWh on a baseload CfD equivalent basis for projects reaching financial close in the first half of the 2020s. This cap is chosen, in part, to be at or below the prices for nuclear<sup>8</sup> and offshore wind<sup>9</sup> contracts for difference for projects becoming operational in a similar timescale to the CCS power projects developed by the CCSDC.

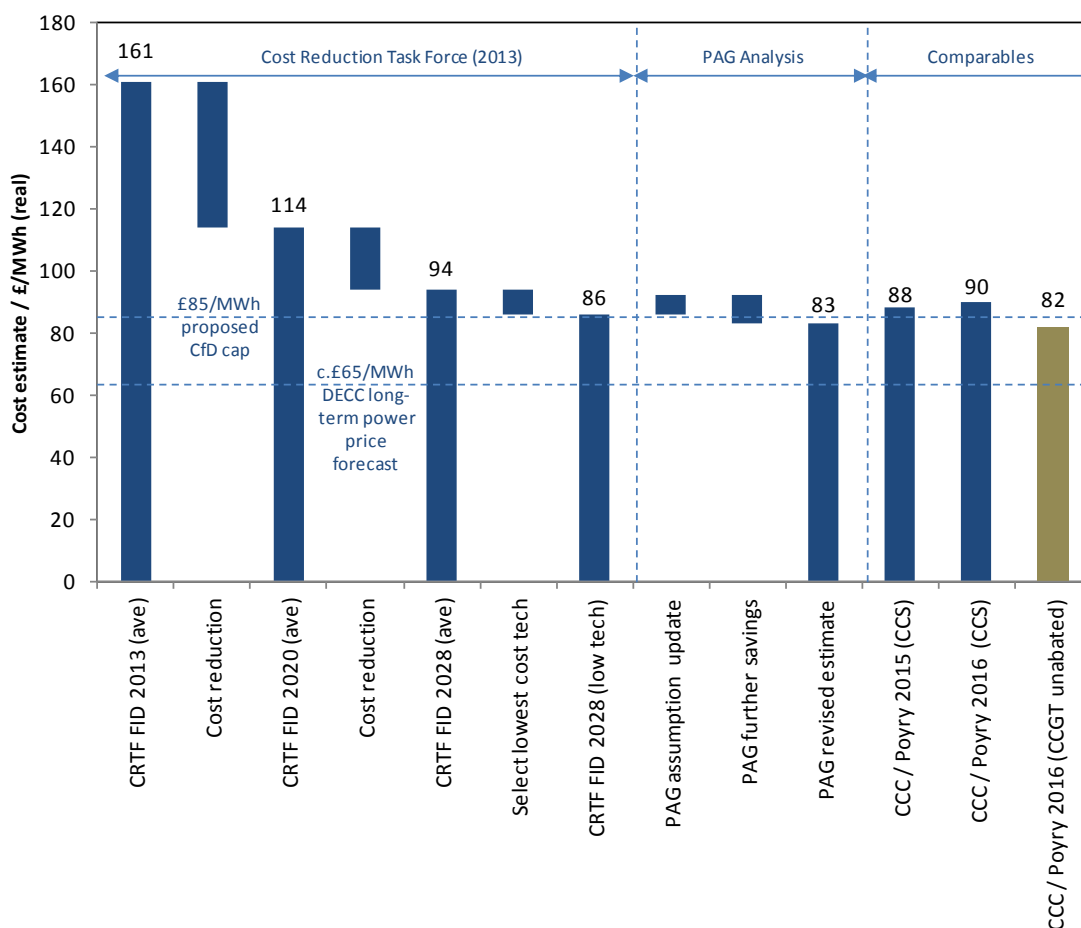
222. The group reviewed the available recent third party work on the costs of CCS to assess the prospects of the industry meeting this cap.

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<sup>8</sup> Hinkley Point C CfD price is £92.50/MWh potentially falling to £89.50/MWh (2011-12 money). Reference: Nuclear Power in the UK, NAO, July 2016.

<sup>9</sup> Future offshore wind CfDs will start at a £105/MWh capped price and this will fall to £85/MWh (2011-12 money) for projects commissioning by 2026. Reference: Budget 2016, HM Treasury, March 2016.

223. The source of the majority of the assumptions for generic CCS cost analysis in the UK comes from a 2012 report for DECC by Mott MacDonald<sup>10</sup>. This report was used to underpin the analysis by the CCS Cost Reduction Task Force (“CRTF”) in 2013<sup>11</sup>. This analysis showed cost reductions driven by scale (especially in transport and storage), financing cost and improved engineering and design. The cost reductions from £161/MWh in 2013 to £94/MWh in 2028 on a technology average basis are shown in the chart below. The lowest cost technology based on the CRTF analysis was £8/MWh below this figure at £86/MWh. The CCSDC would always select the lowest cost technology, and it is the view of this report that the implementation of the recommendations of this report provide the circumstances under which the cost savings shown by the CRTF analysis can be realised for the first projects. Hence in the view of this report £86/MWh is achievable given the CRTF analysis and the conditions set out herein.



<sup>10</sup> Potential cost reductions in CCS in the power sector, Mott MacDonald, May 2012

<sup>11</sup> CCS Cost Reduction Task Force Final Report, May 2013



224. Advice to the Committee on Climate Change in 2015 by Pöyry and Element Energy<sup>12</sup> and in 2016 by Pöyry<sup>13</sup> updates the CRTF work and shows that CCS can achieve costs of c.£90/MWh by the early 2030s. The key drivers of cost reduction from an initial £115/MWh in the mid-2020s are scale, reduction in the cost of capital, and the appropriate allocation of risk (specifically storage and cross-chain or full-chain risk). The recommendations in this report set out how each of these three drivers of cost can be realised in the mid-2020s with the right strategy and regulatory framework. The analysis for the Committee on Climate Change is summarised under “Comparables” in the chart above and is shown on “CfD equivalent” basis.
225. This group has also updated the CRTF work for the purposes of this report in order to accommodate some known changes in assumptions since 2013 and to present the analysis on a CfD equivalent basis. This results in a cost increase from £86/MWh to £92/MWh however further changes related to scale and cost of capital reduce the estimated cost to £83/MWh and hence below the proposed £85/MWh cap. This is shown as “PAG Analysis” in the above chart.
226. Hence while challenging, the £85/MWh cap is consistent with recent assessments for the cost of CCS at scale following a period of “learning by doing”. With the right approach, as set out in this report, the group does not believe such a period of more expensive deployment is needed.
227. The proposed capped price is intended to underwrite both the investment by PowerCo and T&SCo for the anchor project at a hub.
228. Government should prescribe little else but lowest cost in the remit of the CCSDC.
229. Delivering least cost projects for the electricity consumer over the long-term is not inconsistent with delivering and underwriting a large-scale CCS infrastructure at key strategic industrial hubs.
230. Hence the CCSDC should be tasked with ensuring over-sized transport and storage infrastructure appropriate for the potential needs of industry and heat at those key strategic industrial hubs (paid for initially within the £85/MWh cap).
231. The group is of the view that, unencumbered by other objectives, the CCSDC will be able to deliver this under the regulatory framework recommended in this report.

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<sup>12</sup> Potential CCS Cost Reduction Mechanisms: Final Report Summary, Pöyry and Element Energy report to the Committee on Climate Change, April 2015

<sup>13</sup> A Strategic Approach For Developing CCS in the UK, A report to The Committee on Climate Change, May 2016, Pöyry Management Consulting

### ***Why 2020 onwards?***

232. Turning the focus of CCS delivery to least cost involves a shift in mindset and approach which cannot be achieved overnight.

233. Hence while the work done on numerous failed projects to date will provide useful background, the CCSDC must be unencumbered by past approaches.

234. Time is actually relatively short between now and the early 2020s.

235. The CCSDC will deliver a steady delivery plan across multiple hubs preventing stop-start and its associated costs to the consumer.

### ***What to expect of the CCSDC by 2030***

236. Giving the CCSDC a singular focus on least cost means not defining the scale, technology, or location of its projects. However the government will be keen to understand what to expect from the CCSDC.

237. The judgement of this report is that the CCSDC will develop between three and six strategic hubs around the coast of the UK. Cost-effective transport and storage infrastructure at any given hub will need at least 5m tonnes p.a. of CO<sub>2</sub> to underwrite it which, for 3-6 hubs, implies 15-30m tonnes/year of electricity emissions sequestered in total (this represents 15-30% of current power sector emissions).

238. Subject always to optimising the cost to the consumer, T&SCo will likely have a capacity of 2-3x this initial anchor requirement hence providing sufficient additional capacity to sequester all currently identified CCS potential in the UK industrial sector, further independent emissions from the power sector, and the first phases of any large-scale roll-out of clean hydrogen for heating.

239. This is likely to require at least a 1GW power station at each hub and hence 3-6GW in total providing some 24-48TWh/year of new electricity generation on a baseload basis.

240. This is less than the 4-7GW expected by the Committee on Climate Change<sup>14</sup> by 2030 and is between 12% and 24% of the additional 200TWh/year of new low carbon power generation that the Committee on Climate Change say is required to be built in the 2020s.

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<sup>14</sup> Power sector scenarios for the fifth carbon budget, Committee on Climate Change, October 2015.

241. Based on DECC's long-term electricity forecast of c.£65/MWh (quoted in the recent National Audit Office report on nuclear power<sup>15</sup>) then the "subsidy" required on a levy control framework basis for CCS at £85/MWh is c.£20/MWh. For the programme set out in this report for the CCSDC of 24-48TWh/year of new CCS production this therefore requires levy control framework payments of between £0.5bn and £1bn per year.

242. This compares with an existing levy control framework budget of c.£10bn per year in 2020 and with the £1-2bn per year of savings in the 2020s estimated by the Committee on Climate Change for a pathway including CCS compared to one without. It is an additional £6-12 per year on the average household domestic electricity bill<sup>16</sup>.

243. Note also that the recent Pöyry analysis for the Committee on Climate Change quoted earlier shows unabated gas-fired CCGT costs in 2030 as being c.£82/MWh. Hence despite the apparent need for subsidy as calculated under the levy control framework, if delivered at or below the proposed cap of £85/MWh CCS is close to being competitive with what is generally considered to be the lowest cost polluting new entrant (unabated gas-fired CCGT).

### *The central role of the private sector*

244. As with other examples of state-sponsored infrastructure (e.g. Crossrail 1&2, HS 1&2, the Olympics and others), subject to the singular focus on delivering at least cost, the CCSDC will seek to maximise the role of the private sector and maximise the benefits of a delivery structure which promotes competition in the private sector. The CCSDC will address the deep and liquid markets that exist in the components of CCS, providing the private sector with opportunities in CCS in a manner consistent with the sectors in which they already operate.

245. This means that the CCSDC must be free to "build" a capability where it thinks it can achieve lowest cost by doing so, and it should "buy" where there is clearly the capability to deliver a component of its programme via the private sector.

246. The expectation should be that construction of early projects will need to be state financed, at least in part, but the CCSDC will be focused on accessing private capital to the greatest extent possible in the context of its overall mandate to deliver at least cost to the consumer.

247. The long-term expectation is that either the CCSDC as a whole or PowerCo and T&SCo separately will be privatised.

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<sup>15</sup> Nuclear Power in the UK, National Audit Office, 13<sup>th</sup> July, 2016.

<sup>16</sup> Based on total electricity production of 350TWh/year and average domestic electricity consumption of 4MWh/year.

***What if the CCSDC fails to deliver?***

248. The group does not expect the CCSDC to fail to deliver at or below the proposed cap of £85/MWh.

249. However if it does fail to deliver at or below £85/MWh then the government will have two options.

250. The first is to not take the CCSDC's projects forward at all. That would be rational in the presence of more cost-effective alternatives.

251. The second would be to simply build the transport and storage infrastructure (T&SCo). This it would do if it still felt that by then such infrastructure was needed for industry and heat. It would avoid paying for capture over many years while still developing the CCS transport and storage infrastructure that the UK needs for other sectors.

252. The proposed structure of the CCSDC as two companies from the start provides the government with this option in this downside case.

***WE RECOMMEND: Establish a CCS Delivery Company ("CCSDC").***

***A newly formed and initially state-owned company tasked with delivering full-chain CCS for power at strategic hubs around the UK at or below £85/MWh on a baseload CfD equivalent basis. Formed of two linked but separately regulated companies: "PowerCo" to deliver the power stations and "T&SCo" to deliver the transport and storage infrastructure, the CCSDC will need c.£200-300m of funding over the coming 4-5 years.***

## **2. Establish a system of economic regulation for CCS in the UK**

253. The government will establish a system of economic regulation for CCS in the UK which is based on a regulated return approach.
254. The system will draw heavily on existing, established and trusted regulatory mechanisms and institutions with appropriate modifications to ensure least cost delivery of CCS.
255. Initial full-chain CCS projects delivered by the CCSDC will be supported by a modified CfD or capacity contract: the CCS Power Contract.
256. Transport and storage (T&SCo) will be regulated as a network consistent with other regulatory structures for gas and electricity networks.
257. Long-term storage risk will reside with the transport and storage company (T&SCo).
258. An Industrial Capture Contract will be established as detailed in the next recommendation.
259. The existing system of regulation for energy networks will undertake what is needed to deliver decarbonisation of heat in the normal course.

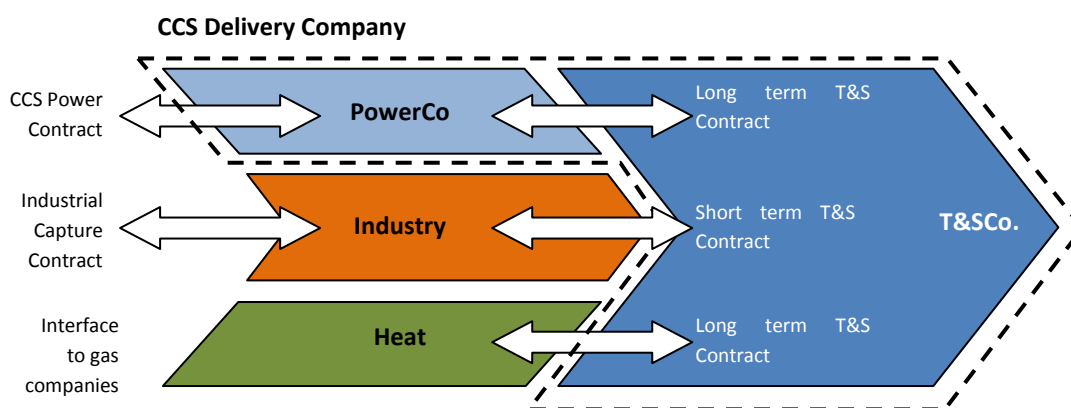
### ***Good for investors; good for consumers***

260. A regulated return approach (with appropriate incentives) is the most likely to attract cost-effective private investment at scale.
261. Hence if one envisages an important role for private capital in the development of the CCS industry over time then this approach makes the most sense for investors.
262. This is also in the interest of consumers for two reasons.
263. Firstly, this will attract the least cost private capital at the right time and given the capital intensity of CCS then the cost will be minimised.
264. Secondly, the cycle of reviewing and reassessing the regulatory settlement and the associated business plans of the companies involved allows for the evolution of the business while maintaining best value for the consumer over time.
265. If a single lifetime settlement, through some form of long-term contract, were instigated for CCS today it would go out of date very quickly; it would over-price risk; it would under-value opportunity; and it would prevent the least cost development of the industry.
266. The periodic ability to revise the business plan in the light of opportunity and changes in the market and policy environment is an essential part of keeping the long-term cost to consumers low.

267. This system of regulation needs to be established from the start so that a track record is developed in the regulatory relationship in the run up to any privatisation of the CCSDC or its subsidiaries. Hence despite initially being state-owned the CCSDC should be regulated as if it were in the private sector.

### *Contractual architecture*

268. The diagram below illustrates the proposed structure of the players in CCS in the UK and the regulated contracts that establish the relationships between them.



### *CCS Power Contract*

269. The CCS Power Contract will remunerate the CCS power projects delivered by the CCSDC.

270. It will have three elements:

- a fuel related payment which is indexed to the market;
- a capacity payment intended to remunerate the capital investment in the power station; and
- a pass-through of the tariff charged by the transport and storage company (T&S Co) which is intended to underwrite the full initial investment in T&S Co.

271. All three elements will involve appropriate incentives.

272. This is the most appropriate and cost reflective structure for a contract for a CCS power station.

273. It is possible to envisage taking either the existing CfD or capacity market contracts currently issued by government as a starting point. The CCS Power Contract has elements of both of these precedents.

274. Contract length should be consistent with the existing CfD at 15 years.

275. This structure gives investors as close to a regulated return on the power asset as is practical.

### *Transport and storage*

276. The transport and storage infrastructure (T&SCo) should be regulated on a rate of return basis with appropriate incentives in a very similar way to the way existing electricity and gas networks are regulated.

277. While being initially state-owned and part of the CCSDC, T&SCo will be regulated as if it were a stand-alone private sector enterprise. This develops the track record needed to ensure private capital can be attracted to the business in time.

278. The premise is that the transport and storage tariff is set in a way which means that the return for T&SCo is underwritten by the power project initially delivered by the CCSDC at each strategic hub. For the avoidance of doubt, this includes its full initial investment in over-sized infrastructure.

279. As additional emitters take up the capacity in T&SCo's infrastructure the additional tariff payments will be passed on, in large part, as tariff reductions to all users of T&SCo's network.

280. T&SCo will be required by its regulator to make capacity available on a short-term basis to industry.

281. The flexibility which comes with regular regulatory settlements is particularly important for T&SCo as its business plan will undoubtedly change over time. It may need to develop more stores; extend its network; add capacity; add resilience; or make other changes or investments, none of which can easily be legislated or regulated for in advance.

282. It will find itself in a monopoly position at some hubs and it may well find efficiencies and opportunities in its business (enhanced oil recovery perhaps) which create unforeseen profits which will, at least in part, need to be shared with the UK consumer through the regulatory process.

### ***Regulation of PowerCo and T&SCo***

283. T&SCo and transport and storage in general would be best regulated by Ofgem as it regulates other network companies with similar roles and economic characteristics.

284. As noted above, little change is needed for heat and Ofgem can absorb CCS into its ongoing regulation of the natural gas network industry if appropriate.

285. The CCS Power Contract would be negotiated with BEIS and be contracted to the existing Low Carbon Contracts Company and hence funded via a levy on the electricity consumer as with all other forms of low carbon power.

286. For the regulator to act in the interests of current and future customers as Ofgem does now works without change for CCS in power and heat.

287. The above system of regulation draws very heavily on the existing proven and trusted regulatory systems which the UK energy industry has developed over time, while making necessary modifications to ensure that CCS is delivered at least cost.

### ***Heat***

288. Energy networks in the UK have a well-established system of regulation and there is no reason to interfere with that for the purposes of CCS.

289. If the decision is made to repurpose the gas network for hydrogen supply then this can be absorbed into the normal regulatory processes of the industry. This would involve the capital and operating costs of the hydrogen supply being accounted for in the appropriate regulatory settlements.

290. In particular, the tariff charged by the transport and storage company (T&SCo) to dispose of the CO<sub>2</sub> from hydrogen production will need to be an allowable cost for the network operators.

***WE RECOMMEND: Establish a system of economic regulation for CCS in the UK.***

***The government will establish a system of economic regulation for CCS in the UK which is based on a regulated return approach. This will draw heavily on existing regulatory structures in the energy system and hence include: a CCS Power Contract based on the existing CfD or capacity contract to incentivise CCS for power; the regulation of T&SCo as other energy network operators; the introduction of an Industrial Capture Contract (see below); and the continued regulation of the energy network industry.***



### **3. Incentivise industrial CCS through Industrial Capture Contracts**

291. The Industrial Capture Contract, will be funded by the UK government and will remunerate industry for capture and storage of their CO<sub>2</sub>.

292. The contract will be regulated with relatively short review periods. The first period will be more highly priced to allow recovery of capture capital investment over a short period.

293. Early contracts will be awarded to projects with pure streams near existing infrastructure which can therefore be implemented without access to the transport and storage infrastructure being developed by T&SCo.

294. Once T&SCo has developed the infrastructure at a hub, industrial emitters in that area will be provided with open third party access to that regulated transport and storage network without the obligation for long-term contracts.

295. Full liability for the CO<sub>2</sub> will pass to the transport and storage company.

#### ***Early deployment of low-cost industrial CCS***

296. Early allocations of Industrial Capture Contracts will facilitate the rapid delivery of medium-scale projects using low cost industrial emissions where this accelerates least cost abatement.

297. This will involve the transport and storage of pure, storage-ready CO<sub>2</sub> emissions from industrial sites around the UK to low cost stores which in some cases may be onshore.

298. Such projects will be of the order of several hundred thousand tonnes per annum and could help fill the knowledge gap which exists for onshore storage. They will utilise existing infrastructure and potentially assist in proving the physical or commercial model at certain hubs.

299. The use of existing infrastructure means that these early projects can be developed without the need for the construction of the infrastructure by T&SCo.

#### ***Access to transport and storage as required***

300. More generally, those industrial emitters with material capture costs or which are not close to existing infrastructure will have regulated third party access to the transport and storage infrastructure as required once it is developed by T&SCo.

301. This reflects the inability of most industrial emitters to make long-term commitments.

302. There will be a requirement on the transport and storage company (T&SCo) to reserve capacity for short-term contracting with industrial emitters.

303. Industrial capture contracts should be awarded to these emitters only when the transport and storage infrastructure is operational at the relevant hub providing an immediate and low risk route to storage for such industrial emissions.

***High initial support delivers low cost in long-term***

304. Similarly, to reflect the short horizons inherent in investment in UK heavy industry the remuneration under the Industrial Capture Contract will, in the first instance, be inflated to allow the full return on investment for the initial capital in the capture and onshore connection investment made by the emitter.

305. Subsequent remuneration can then be lower with capital fully amortised and hence only operating costs to fund.

306. Over a reasonable lifetime of an industrial emitter, the average cost of abatement for many industries will be low and highly competitive with other forms of emissions reduction.

***Regulation of the Industrial Capture Contract***

307. The Industrial Capture Contract is a regulated contract between the UK government and the industrial emitter, the terms of which are renewed on a regular and likely relatively short cycle

308. This ensures that any capital investment can be recovered over a short time period consistent with the investment horizons of industry.

309. It then ensures long-term best value to the UK taxpayer by allowing for regular reassessments of fair costs.

310. While this may appear cumbersome, in industries subject to international market forces, where there are various routes to decarbonisation, and incremental investments may be cost optimal over time, this approach simply reflects the business reality of the type of emitters in question.

311. The transport and storage tariff should be a pass-through cost in the contract.

312. The contract will be funded directly by the taxpayer and will be structured to account for any other environmental measures such as emissions trading schemes and taxes to which the emitter is exposed. The contract may be in the form of a fixed direct payment, a formula-based payment, or a contract for difference.

313. The regulator for the Industrial Capture Contract is less obvious than for PowerCo and T&SCo. There is no case for creating a new regulator and so realistically it is one of BEIS, Ofgem or HM Treasury directly as this contract will be funded directly by the taxpayer.

314. For the Industrial Capture Contract, and the part of regulating transport and storage that relates to that arrangement, the regulator's remit will need to include the additional requirement to deliver least cost industrial CO<sub>2</sub> abatement for the UK taxpayer.

### ***Price discovery and limits***

315. The government will need to assess the best route to efficient initial price discovery for the Industrial Capture Contract.

316. If there are numerous emitters with similar capture costs then auctions may play a role. If there are not, then the government will need to be prepared to negotiate the contracts always remembering the underlying premise that industrial abatement over time should represent value for money for the taxpayer and consumer.

317. Given the structure of the Industrial Capture Contract and the paucity of alternatives for capturing emissions from many industrial processes it is difficult to set a limit on the price at which the government should award these contracts. The cost of an alternative carbon-free process, or of physically offsetting the emissions via negative emissions technologies clearly set two upper limits on the price at which the government should contract.

### ***WE RECOMMEND: Incentivise industrial CCS through Industrial Capture Contracts.***

***The Industrial Capture Contract, will be funded by the UK government and will remunerate industry for capture and storage of their CO<sub>2</sub>. It will be a regulated contract which will have a higher price in the early period in order to deliver capital repayment in a timescale consistent with industry horizons. Industry will have access to transport and storage contracts through short-term contracts. Early projects will use existing infrastructure and pure streams of CO<sub>2</sub>.***

#### **4. Establish a Heat Transformation Group (“HTG”)**

318.The Heat Transformation Group will perform an assessment of the relative costs and technical feasibility of decarbonising heat via electrification or hydrogen.

319.The HTG will then execute a full programme of work assessing the technical and economic issues associated with the chosen route.

320.This will be an independent, cross industry group which will continue the recent work on the challenge of decarbonising heating.

321.Work should be programmed to fit with the established regulatory cycles of the relevant industries. In the case of the natural gas system this means conversion from 2029 onwards, fitting into the existing regulatory cycle for the gas network industry.

322.Capital funding of c.£70-90m will be required from government in the coming 4-5 years and will facilitate a decision on decarbonising heat by either route in the early 2020s.

##### ***Why £70-90m?***

323.The group has not independently assessed the validity of this funding request and the first task of government in forming the HTG should be to do exactly that review.

324.This estimate is based on the proposals for further work in the h21 Leeds City Gate Project<sup>17</sup> for conversion of the gas network in Leeds for hydrogen.

325.It includes both funds required to maintain the momentum behind the Leeds project as an early pilot (c.£10m) and more extensive work required to assess the general issues for that project and a nationwide roll-out (c.£60-80m).

326.The assumption, which the group has not validated, is that if the electrification route is taken then a similar quantum of expenditure will be required for detailed feasibility assessments for that pathway.

##### ***Why action is needed now***

327.The HTG should be established in 2017.

328.Whatever the technological solution to decarbonising heat in the UK, compliance with our national and international commitments requires nationwide implementation of that solution to start around 2030.

329.It is likely to be a programme spanning at least two decades.

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<sup>17</sup> h21 Leeds City Gate, July 2016, Northern Gas Networks, Wales & West Utilities, Kiwa Gastec, Amec Foster Wheeler

330. Taking the hydrogen route by way of example, the gas network industry has regulatory settlements of eight years under the current regime and so to begin implementation work in the 2029-2037 regulated period requires considerable planning and development work to be performed in the 2021-2029 period. Preparation for this planning will need to start no later than 2018 so it can be included in business plans for that 2021-29 period.

331. If the electrification route is taken and distribution network investments are needed to support this roll-out then there might be a need for activity to support this in the 2023-2031 regulatory period for electricity distribution networks.

### ***Role of the regulator***

332. Ofgem currently regulates both the UK gas and electricity industries and we are not proposing that any change is needed to this arrangement.

### ***Broad representation***

333. Transforming the heating system for the UK is a nationwide infrastructure programme and hence requires cross sector co-ordination.

334. While remaining focused and cost-effective, the HTG will have inclusive mechanisms for engagement with all its key stakeholders.

335. This will certainly include senior representation from all the network companies, energy suppliers, government, regulators, consumer groups, equipment and appliance manufacturers, politicians, NGOs and representatives of civil society, and other stakeholders in UK energy and heating supply.

***WE RECOMMEND: Establish a Heat Transformation Group (“HTG”).***

***The Heat Transformation Group will assess the least cost route to the decarbonisation of heat in the UK (comparing electricity and hydrogen) and complete the work needed to assess the chosen approach in detail. The HTG has a likely funding need of £70-90m.***

## **5. Establish a CCS Certificate System**

336. Government should establish a system of CCS Certificates for certifying captured and stored CO<sub>2</sub>. This system should be established immediately so that it is operational before any CO<sub>2</sub> is stored.

337. An infrastructure should be put in place for the creation and trading of CCS Certificates issued under this scheme.

338. CCS Certificates would be issued to those who have physically permanently stored CO<sub>2</sub> for each tonne they have stored and those certificates would then be able to be traded between parties.

### ***CCS Certificates now***

339. A CCS Certificate System should be implemented to establish the commercial infrastructure for the implementation of a market-based system in the next phase (see next recommendation).

340. The CCS Certificate System will certify safe, long-term storage of CO<sub>2</sub> by any means, not just geological storage.

341. Any storage outside of the UK will need to be similarly certified or subject to the same level of certification as in the UK. Arrangements should be made for the fungibility of the certificates and any other consequences which come from international trade in such instruments.

342. At least for geological storage, the Oil and Gas Authority (OGA) may have a role to play in any CCS Certificate System.

***WE RECOMMEND: Establish a CCS Certificate System.***

***Government will implement a CCS Certification system for the certification of captured and stored CO<sub>2</sub>.***

## 6. Establish a CCS Obligation System

343. Government should implement a CCS Obligation from the late 2020s as a means of giving a long-term trajectory to the fossil fuel and CCS industries.

344. A CCS Obligation involves placing an obligation on companies supplying fossil fuels in the UK to prove that they have stored (or bought CCS Certificates from others who have stored) CO<sub>2</sub> equivalent to a given percentage of the carbon content of the fuel they have supplied in a given year.

345. The combination of the CCS Obligation System with the CCS Certificate System provides an exit route for direct government involvement in CCS.

346. Failure to submit sufficient CCS Certificates to meet a party's CCS Obligation would lead to a financial penalty. The percentage of fossil fuel supplied required to be sequestered would increase over time in a manner consistent with the UK's national and international obligations and targets.

### *Good for investors and the planet*

347. The idea of such an obligation to store being placed on fossil fuel suppliers has existed for a number of years.

348. Setting a growing obligation to capture and store CO<sub>2</sub> emissions can directly track the trajectory required to keep warming below the required limit.

349. For investors, a science based trajectory for the sequestration of emissions which is directly embodied in an obligation on fossil fuel suppliers gives the form of long-term certainty that they often ask for.

350. Capital intensive low carbon infrastructure in the UK is now funded through government backed contracts and so a first phase of new approach to CCS needs to start in the same vein.

351. The second phase should start by implementing a CCS Obligation in the late 2020s. At this point the CCSDC will have facilitated the deployment of CCS and its associated infrastructure at meaningful scale; there will already be a supply of CCS Certificates from the activities of the CCSDC; and there will be a transport and storage infrastructure which obligated parties can easily access.

352. It would be possible to set an obligation trajectory that blended the science with the practical reality of delivering CCS.

353. This would then provide the government with an exit route for direct involvement in CCS.

354. Following the initial deployment of CCS infrastructure by the CCSDC a government in the late 2020s will have two choices. The first will be to continue to write regulated contracts for players in sectors of the energy industry to sequester CO<sub>2</sub>. This clearly requires a degree of continued direct involvement. The second and recommended approach is to implement a CCS Obligation System.

355. A well-designed and well-functioning CCS Obligation System provides a single, long-term, economy-wide incentive which removes the government from direct involvement in CCS projects.

356. An eventually privatised CCSDC combined with a CCS Obligation System would align perfectly with the government's declared intention of removing itself from the energy system over time.

357. A CCS Obligation System makes the storage of CO<sub>2</sub> a requisite part of the future fossil fuel supply business. It hence overcomes one of the key issues in CO<sub>2</sub> storage and that is that it is in no-one's business interest to do it.

### *Design considerations*

358. There are a number of other design issues which the government should assess as part of considering a CCS Obligation System.

359. These are not discussed in detail in this report but they include: the level of the obligation; the level of the penalty; the use of the proceeds from penalty payments; the linkage to any other forms of carbon pricing or taxes; and the most efficient system for determining a company's obligation level.

***WE RECOMMEND: Establish a CCS Obligation System.***

***Government will implement a CCS Obligation from the late 2020s as a means of giving a long-term trajectory to the fossil fuel and CCS industries. This will put an obligation on fossil fuel suppliers to the UK to sequester a growing percentage of the CO<sub>2</sub> associated with that supply. Proof of storage and hence fulfilment of the obligation being via presentation of CCS Certificates.***



# Membership

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## *Membership and declarations*

The group comprised the following people all of whom acted in an individual capacity for the purposes of this report and the group's work. The group met seven times over the first seven months of 2016.

Given the volume of material available on CCS, the group has not performed original primary research or analysis, instead we have attempted to understand and synthesise what exists and hopefully to provide new insight. This means that the report represents the judgements of the group.

### **Lord Ronald Oxburgh KBE, FRS, HonFREng**

Ron Oxburgh has a background in geology/geophysics and has researched and taught in those subjects in both the UK and the US. He served as Chief Scientific Adviser to the Ministry of Defence 1987-93 and as Rector of Imperial College from 1993-2001. Having served on the Board of Shell Transport and Trading for a number of years he became Chairman in 2005 and oversaw the merger with Royal Dutch Petroleum to form Royal Dutch Shell. He has been an independent member of the House of Lords since 1999 and has chaired the Select Committee on Science and Technology. He currently chairs several small energy related companies.

### **Peter Aldous MP**

Peter Aldous has been MP for Waveney since 2010. Previously he worked as a chartered surveyor and he is a partner in a family arable and pig farm. Since entering Parliament he has focused on the energy sector, the low carbon economy and the regeneration of coastal communities. He is a member of the Environmental Audit Committee and is Chairman of the All Party Parliamentary Groups for Oil and Gas, Energy Storage and Intelligent Energy.

### **Philip Boswell MP**

Philip Boswell was an experienced Quantity Surveyor and Contracts Manager from the Construction Industry, before moving over to the Energy sector as a Commercial and Contracts Manager for various Onshore and Offshore Projects with BP, Shell, Qatar Petroleum and others. He has managed major projects on most continents, was Shell's Contract Lead on the CCS team moving the project bid from coal fired Longannet to gas fired Peterhead, and was a visiting lecturer at Aberdeen University. Phil is the MP for Coatbridge, Chryston & Bellshill and is on the SNP Treasury Team as well as on various Energy and Finance Bill Committees

### **Chris Davies**

Chris Davies was Liberal Democrat MP for Littleborough & Saddleworth 1995-7 and MEP for North West England 1999-2014. He was European Parliament rapporteur for the 'CCS Directive' 2008-9 and for the Parliament's 2013-4 report on taking CCS forwards. He tabled the legislative proposal that became the EU's 'NER300' funding mechanism intended to support CCS and innovative renewable energy projects, and which has developed into the European Commission's current proposal for an EU Innovation Fund.

### **Dr. Phil Hare, Director, Pöyry Management Consulting**

Phil heads Pöyry's Global Consultancy Practice in Energy Market Analysis & Market Design and he has a long interest in the economic, strategic and policymaking aspects CCS developments in Europe. In recent years he led Pöyry's involvement in the CCS Cost Reduction Task Force and the ETI's CCS scenarios.

Otherwise he specialises in corporate strategy, particularly energy companies entering new countries and building new businesses. His clients range from some of Europe's largest energy companies, to new market entrants, and regulators and policymakers.

Phil is also Deputy Chairman of the BSC Panel, the industry body that governs the UK's electricity market arrangements.

### **Prof. Stuart Haszeldine OBE FRSE C.Geol**

Stuart Haszeldine, University of Edinburgh, is the world's first Professor of Carbon Capture and Storage. He trained as a geologist, and has 40 years research and industry experience in hydrocarbons, fracking, radioactive waste, biochar, energy, climate, and environment. He leads SCCS (Scottish Carbon Capture and Storage), and co-leads UKCCSRC (UK Carbon Capture and Storage Research Centre) research on natural and engineered geological storage and monitoring of CO<sub>2</sub>. This has gradually developed the North Sea subsurface as commercial CO<sub>2</sub> storage for a European sized CCS industry. He was awarded the Geological Society William Smith Medal for applied geology in 2011, and in 2012 was appointed OBE for services to climate change technologies.

### **James Smith**

James is chair of the Carbon Trust, chair of the advisory board of the Grantham Institute on Climate Change at Imperial College and LSE and chair of the Conservatoire for Dance and Drama. He is a former President of the Energy Institute. He chairs the advisory board of the Association for Black Engineers in the UK and the Science Council's strategy group on diversity.

James retired from Shell in 2011 after 7 years as Chair of Shell UK. He has been interested in CCS since his time in Shell and was involved in discussions on the then proposed Longannet project.

### **Ian Temperton**

Ian has worked in the development, policy and financing of CCS for close to twenty years with involvement in projects in the UK, Norway and the Netherlands. He was for 12 years a Managing Director at Climate Change Capital where he advised clients on a wide range of clean energy transactions. He holds degrees in engineering from Cambridge University and finance from London Business School. He has also been a Visiting Business Fellow at the Smith School for Enterprise and the Environment at Oxford University and he currently sits on the advisory board of the UK Energy Research Centre.

### **Dr Anthony White MBE**

Dr Tony White started his career as a research scientist with the Central Electricity Research Board in 1977. He moved to the stockbroker James Capel in 1989 to advise the Government on the liberalisation and privatisation of the electricity industry in England & Wales and has since held a number of senior roles in the utility and finance industries. He currently provides advice on energy finance and strategy. He specialises in understanding the way liberalised power markets operate, how they are financed and the way the associated networks that serve them are best regulated.

### **Baroness Bryony Worthington**

Bryony Worthington graduated in English literature at Queens' College, Cambridge. She worked for Friends of the Earth as a climate change campaigner and then for the Department for Environment, Food and Rural Affairs, implementing public awareness campaigns and helping draft the Climate Change Bill, before becoming head of government relations for the energy company, Scottish and Southern Energy. Lady Worthington was the lead author in the team which drafted the UK's 2008 Climate Change Act. She left DEFRA to form Sandbag in 2008. Sandbag now focuses on researching and suggesting improvements to the ETS, how to phase out coal-fired power stations in Europe, and how governments and the EU can work to support Carbon Capture and Storage. She was created a life peer on 31 January 2011 with the title Baroness Worthington, of Cambridge in the County of Cambridgeshire, and sits on the Labour benches.

## Appendices

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During the seven months of the group's work a number of working papers were produced by members of the group to inform the work of the group and to facilitate the formation of our recommendations. A selection of these is included in the remainder of the report.

We should emphasise that these are stand-alone working papers which were not intended to form a coherent whole and which do not necessarily always represent the final consensus view of the group.

As we have attempted to keep the main body of our report concise, we hope including these, subject to the above health warning, is helpful .

The table below provides a list of the papers.

Appendix 1	History of CCS in the UK, EU and USA
Appendix 2	Innovation, research and collaboration
Appendix 3	Carbon capture and use
Appendix 4	Storage
Appendix 5	Decarbonising heat

# Appendix 1: History of CCS in the UK, EU and USA

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1. The concept of CCS was invented in the 1970's but UK action on identifying storage did not occur until the early 1990s, with high level political support to develop commercial projects only from 2005, and funding from 2007.
2. The UK made very early technology choices to focus on CCS applied to electricity generation, with post combustion capture from coal. High quality regulation and permitting rules were constructed, and a low carbon electricity market created with the intention of supporting industry in a public-private co-funded first project, stimulating market-led development of CCS.
3. That choice excluded other fuels and capture options, ignored decarbonisation of industry and heat, failed to convincingly engage electricity providers, oil companies and politicians, and did not adequately recognize challenges to infrastructure provision, investors and financiers. A focus on capture, with immediate build of commercial projects did not provide support for technology evolution or transition.
4. Three cycles of Competition processes to deliver the first project have been complex, prolonged and divisive. In particular, the allocation of risk away from Government towards developers, the high quality and performance over-engineering required of projects, the lack of any firm plan for incentivised CCS rollout to create a sizeable business, the requirement to fund oversized CO<sub>2</sub> transport infrastructure, and the uneconomic very short durations of project operation, all led to greatly inflated costs, with complex and unfamiliar business partnerships.
5. Along with these cycles of competition, incentives for CCS were provided by Government in the form of an Emissions Performance Standard; the obligation to provide CCS-ready plans for new coal plant development; and the transposition of EU environmental legislation on coal and gas plant greater than 50MW. The Large Combustion Plant Directive requires compliance by end 2015, and Industrial Emissions Directive commences in 2016 requires full compliance by end June 2020, on emissions such as mercury, particulates, SO<sub>x</sub> and NO<sub>x</sub>.
6. These legislative threats, in combination with the perceived cost of fitting CCS, have successfully stopped development of any new coal plant.
7. Funding for CCS in the UK was provided by a "prize" of up to £1 billion of capital support, in combination with (at different times) operational support proposed by Renewable Obligation Certificates, a CCS levy, and Contracts for Difference on the wholesale electricity price.

8. Government support to develop operational CCS on power is constrained by the requirement to stay within the UK Treasury finance limits for green investment using the Levy Control Framework. CCS is also hampered on electricity by the inclusion of electricity generation emissions within the “Traded Sector” where UK rates of GHG reduction are prescribed; exceeding those by one Member State can enable un-used emission certificates from the UK to be transferred to other EU states which continue emitting CO<sub>2</sub>.
9. In spite of more than 15 commercial project proposals and an estimated £500 million being spent by Government and business, no commercial projects using CCS on electricity have been approved in the UK. Minimal progress has been made on applying CCS to industry, or to heat.
10. European heads of government agreed in 2007 to have up to 12 CCS demonstration projects by 2015, but no plan for the deployment of the technology was made. The general assumption was that the cost of purchasing CO<sub>2</sub> emission allowances would alone provide sufficient incentive to encourage private sector initiatives and investment, although in complete contrast the promotion of renewables has been achieved through the payment by Member States of very large subsidies.
11. In addition to some funding for research, the EU later agreed to provide specific incentives for commercial-scale CCS projects: €1 billion was allocated through the European Economic Recovery Programme (EPR), although only half that amount has been taken up; and developers were invited to bid for support from the ‘NER300’ financial mechanism specifically created to support CCS, although in fact no payments have been agreed.
12. It falls upon Member States to develop the policies most appropriate to their specific circumstances, and few have considered what will be needed to achieve the required CO<sub>2</sub> reductions beyond 2030, when deployment of CCS is most likely to be necessary. At the present time, the EU’s only CCS demonstration project still under active consideration is ROAD in the Netherlands.
13. The USA has used the Federal Department of Energy to allocate hundreds of millions of dollars per year over 15 years into a technology development and pull-through programme focused on achieving commercial deployment. This has successfully enacted a 3 stage technology development programme, which has also been funded with \$3.4 billion from the Recovery Act of 2009 to develop a small number of commercial sized 1mt CO<sub>2</sub>/yr pilot injection sites which are currently operating.

14. All current CCS developments in the USA have been co-funded in some way by tax concessions, loan guarantees and Federal grants to individual projects. For a commercial CCS rollout via electricity to be allowed, the commercial regulator of that generating company's infrastructure must be convinced that the increased bills to electricity rate-payers attached to that power plant will benefit financially or environmentally.
15. The very low price of shale-derived gas and oil in the USA has given a political opportunity for Presidential action by using the Clean Air Act to create a Clean Power Plan, based on emissions standards for each State. The method of compliance on reduced emissions is not specified, but the numerical limits fit well to those achievable by fitting CCS on coal plant, with CCS on gas possible at a future date.

## Appendix 2: Innovation, research and collaboration

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1. Under this heading there are two important points to make.
2. First, that both the CCS projects in the cancelled competition were content to proceed using current technology for the capture of CO<sub>2</sub>, its transportation and its storage. The technology is demonstrably mature.
3. Second, experience in heavy engineering shows that it takes around twenty years for a major innovation to be developed, tested and adopted throughout an industry.
4. Given the timescale on which we are committed to decarbonising the UK economy and implementing CCS, there is not enough time for more than incremental improvements in the existing main process of capture at power stations. There is an energy penalty incurred when the solvent used for capture is subsequently heated to drive off and collect the CO<sub>2</sub>. Different research groups make different claims but optimistically there is possibly scope for reducing capture costs by a third.
5. With respect to the second element in the CCS 'chain', transport, in most scenarios this is managed by pipeline or in special circumstances by ship. Both methods are widely used for other purposes and can be considered as mature and seem unlikely to offer major opportunity for innovation.
6. Storage of CO<sub>2</sub> is conventionally considered as injection and retention of the fluid underground in deep porous rocks. Underground storage of CO<sub>2</sub> has been extensively studied in the Norwegian sector of the North Sea at Sleipner. Useful information has been derived by observing how CO<sub>2</sub> displaces existing pore-fluids and permeates the rock.
7. Geology is no respecter of international boundaries and in the long term thinking about reservoir networks may well be best done in collaboration with our North Sea neighbours (storage of CO<sub>2</sub> is dealt with in greater detail in Appendix 4).



## Appendix 3: Carbon capture and use

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1. One potential way in which CCS can be deployed without significant public funding would be to find ways of locking captured CO<sub>2</sub> into useful products rather than transporting it to places where it can be sequestered underground. In nature plants are able to do this by photosynthesis - absorbing CO<sub>2</sub> and water from their surroundings and energy from sunlight to make complex organic molecules that can ultimately end up in oil or gas. Carbon is also naturally sequestered into minerals, soils and oceans. Research efforts have been devoted to artificial photosynthesis with a view to developing it as a commercial process; unfortunately this is still a long way from practical application. Similarly research is underway on enhanced mineralisation and re-use of CO<sub>2</sub> as a chemical component in the chemicals and plastics sector.
2. A great deal of energy is released in the combustion of fossil fuels leading to the production of CO<sub>2</sub>. If that CO<sub>2</sub> is to be incorporated in new fuels or new products, similar amounts of energy are needed to achieve that. From that there is no escape. If that energy is derived from sustainable sources the new products may themselves be sustainable.
3. In practice the main bulk use of CO<sub>2</sub> worldwide has been for enhanced oil recovery. CO<sub>2</sub> is also a traded commodity for specialist manufacturing and use in industrial processes. It is in use by one small UK firm who have developed a process under which it can be made to react with industrial waste products such as some types of fly-ash to produce construction blocks. The transport economics of this process and the need to pay for CO<sub>2</sub> as a feedstock mean that though it is already profitable this is currently the case only in a limited number of locations.
4. In some places market gardeners add CO<sub>2</sub> to the atmosphere within greenhouses to stimulate plant growth. The same principle has been applied in the cultivation of algae to produce a biofuel and protein, the energy for the process being derived from sunlight. This has been amply demonstrated in the laboratory but has proved difficult to industrialise. If as seems likely the practical difficulties are overcome the most attractive sites for this technology will be in the tropics with high insolation that varies little through the year.
5. There is unlikely to be any single potential use for CO<sub>2</sub> that will on its own absorb very large quantities of CO<sub>2</sub>. If CCS is deployed as widely as appears to be necessary, the supply of CO<sub>2</sub> will be substantial and although some of it could be incorporated in products, the greater part would have to be stored. The most plausible large scale use would be similar to the business application mentioned earlier, namely using enhanced mineralisation processes to trap CO<sub>2</sub> in synthetic aggregate and building materials.

6. However, it is worthwhile considering what this means in practice. Cement manufacture for example is currently based on limestone and has a large CO<sub>2</sub> footprint which is hard to mitigate. In the UK, around 7.5 million tonnes of CO<sub>2</sub> is produced each year by cement manufacturers. If 50% of this were allowed to react with the minimum required 7.5 million tonnes of crushed silicate rock, the annual product would be a 11 million tonne mixture of silica sand and limestone (containing the CO<sub>2</sub>). This is equivalent to around 7% of the annual use of mineral aggregates in UK construction.
7. As the price attached to emitting CO<sub>2</sub> increases globally, new ways of re-using CO<sub>2</sub> may emerge and it will be important to give them full consideration. The introduction of a certification system, a clear recommendation of this report, would allow for such innovations to be counted towards the UK's decarbonisation targets. Where it makes commercial and energetic sense CO<sub>2</sub> reuse should be welcomed as a complement to the larger scale use of CCS based on underground storage.

## Appendix 4: Storage

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### Summary

1. The UK has abundant potential to geologically store CO<sub>2</sub> in the deep subsurface, sufficient for 100-200 years of current total emissions, or up to 700 years of current industrial emissions alone, without power, heat, or transport.
2. Natural CO<sub>2</sub> occurrences demonstrate many millennia of secure CO<sub>2</sub> retention deep beneath the North Sea. Storage sites onshore within defined geological structures are very small, totalling less than one small offshore site.
3. Large and secure storage sites have been identified offshore using hydrocarbon exploration and production techniques, but no CO<sub>2</sub> has been injected for storage offshore of the UK.
4. Assessment of offshore storage is well developed, some sites are commercially investable as storage immediately, and are connected by legacy pipes to coast beachheads and low cost industry sources. Storage networks in the Central North Sea and Irish Sea could start immediately, and grow stepwise to become linked to CO<sub>2</sub> Enhanced Oil Recovery.
5. The cost of storage is small, just £12-15/tonne CO<sub>2</sub>, and can expect to fall 30% by use of infrastructure clusters and sharing<sup>18</sup>. However the price within CCS Competition projects has been four times that, consequent on covering of risk being priced-in.
6. Collaboration on storage projects may reduce investment per company, but the benefit of this activity for the company is then not at all clear. Technical knowledge of CO<sub>2</sub> injection already exists in hydrocarbon companies, so a single collaboration would not make an industry

### Outline concepts

7. The conventional concept of CCS relies on long-duration storage of fluid CO<sub>2</sub> in geological pore space of deeply buried sediments. There are abundant localities globally, including offshore of the UK, where this has occurred naturally. Similar geological conditions have been identified and successfully exploited by operational engineered CO<sub>2</sub> storage in 100 commercial operations and 30 scientific tests globally. The common features shared between CO<sub>2</sub> stores are: pore space in sandstone or carbonate rock, connected by micro-scale permeability, sealed above and laterally by less permeable mudrocks, with a large surrounding volume (>30x) of brine in pore space to absorb and disperse transient excess pressure from injected CO<sub>2</sub>.

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<sup>18</sup> Progressing the Development of the UK's Strategic Carbon Dioxide Storage Resource, April 2016

8. However each storage site requires individual identification, appraisal, development and management, and monitoring. Purposeful geological storage of CO<sub>2</sub> in Europe is governed by the CCS Directive, which imposes very tough standards on the high quality of CO<sub>2</sub> retention over many centuries, requires a store operator to demonstrate that storage becomes more stable through time, and stipulates that penalties result if CO<sub>2</sub> leaves the defined 3-dimensional subsurface storage complex, and liability resides with an owner if CO<sub>2</sub> exits the complex to reach the biosphere governed by the EU-ETS.

### Why store CO<sub>2</sub> offshore ?

9. Early in the emergence of CCS in the UK, Government decided that CO<sub>2</sub> storage offshore, rather than onshore, would be a favoured option. This may seem counter-intuitive, as drilling and developments costs onshore are ten times less cost than offshore. Additionally, Bunter sandstone occurs onshore – and is the anticipated good quality reservoir rock for the Irish Sea and Humberstone offshore storage clusters. Choosing offshore storage for the UK is for three reasons.
10. Firstly, the offshore geology is known to include very large geological ‘trap’ structures which hold buoyant fluid – such as oil or methane gas – or liquid CO<sub>2</sub>, for many millions of years. Each of these offshore sites can hold tens of millions (Fig 2), or in some cases hundreds of millions of tonnes of CO<sub>2</sub>. By contrast beneath the onshore landmass of the UK there are no similarly sized structures (Fig 1). The total oil discovered in structures onshore of the UK is 75 million barrels (Fraser & Gawthorpe 1990), about 2% of the total oil in structures of the North Sea. Thus individual onshore fields in secure traps are capable of holding just a few millions of tonnes CO<sub>2</sub> each. This is enough for demonstration purposes, but not for commercial projects (Fig 1).
11. Secondly, public perception is vitally important for permission to operate. However injection of CO<sub>2</sub> will extend many tens of kilometres laterally (Fig 1). Injection is very likely to cause small earth tremors, and there are numerous (false) claims that injected CO<sub>2</sub> has leaked from injected reservoirs.
12. Thirdly, the largest stores for CO<sub>2</sub> are all offshore – with no rival uses of depleted oil or gas fields, and no known rival use of the very large saline reservoir sandstones. The small structures of depleted oil and gas fields onshore (Fig 1) are all under consideration as inter-seasonal methane stores or as geothermal energy heat sources. These can make significantly more profit annually, by cycling the contents, whereas CO<sub>2</sub> storage makes a profit only once, at the point of injection.

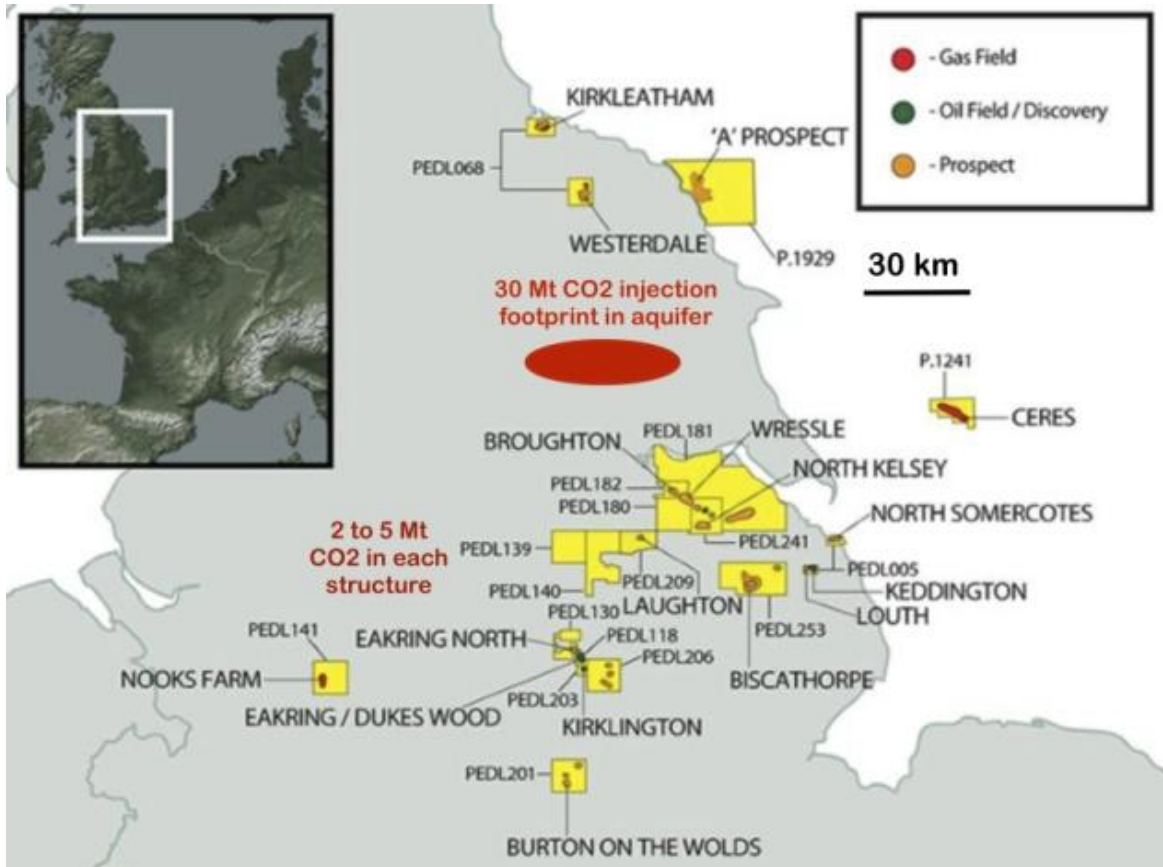


Fig 1 map, from <http://www.energy-pedia.com> shows the locations and footprint of the UK's main onshore oil and gas fields. Also shown (as a red oval) is the comparable sizes of Captain X aquifer offshore CO<sub>2</sub> storage site from the Pale Blue Dot 2016 study

13. The size of a storage site is also important. A medium offshore oilfield proposed for storage, such as Miller, is the size of greater Edinburgh (i.e. 10-15km diameter). Unconfined “open” sandstones with no structural traps could have 30 million tonnes CO<sub>2</sub> underlying the land surface for distances of 50-100 km. A distance of 30 km is shown in Fig 1. Even though the hazards to surface dwellers are minimal, these are potentially very large impacts on public perception

### UK CO<sub>2</sub> storage appraisal history

14. The first studies of UK CO<sub>2</sub> storage tonnages focused on the Bunter Sandstone of East England and the Irish Sea. These were published by BGS in 1996, and by the University of Manchester in 2003 and 2006. A subsequent evaluation, including the entire Northern and Central North Sea, was published by Scottish Carbon Capture and Storage in 2009, which provided the first estimate of entire UK storage at 60 – 80 billion tonnes CO<sub>2</sub>.

- Several studies later, that has led to CO<sub>2</sub>MultiStore in 2015, which has used offshore information from hydrocarbon companies, to make an assessment suitable for commercial quality investment of 460 million tonnes CO<sub>2</sub> injection capacity into the Central North Sea Captain Sandstone. This is the most advanced regional assessment in the UK.

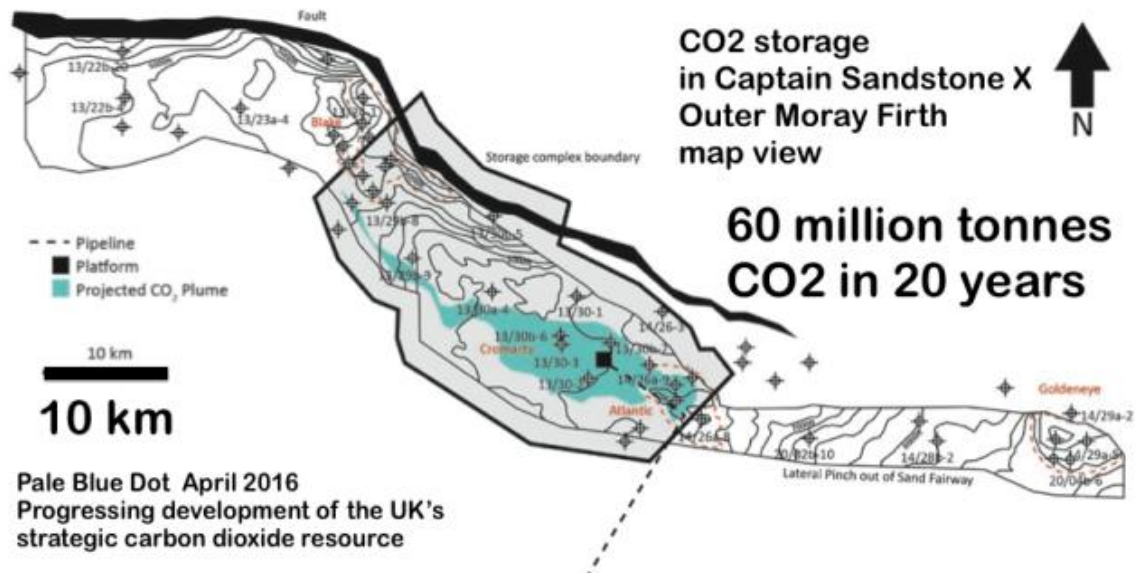


Fig 2 Captain X sandstone storage map offshore Central North Sea. This shows the footprint of the injected CO<sub>2</sub> plume spreading laterally along the top of the sandstone reservoir after a 30 year period of injection. The plume is approximately 30 x 8 km

- In 2011, the ETI completed a 2 year £4m project on a more detailed UK Storage Assessment of the whole UK offshore, publishing in 2013, and being publicly available from ETI and The Crown Estate as [www.CO2stored.co.uk](http://www.CO2stored.co.uk). Initial analysis showed that “Infrastructure incorporating six shoreline hubs, less than 20 stores and having a net present cost of c. £5bn should accommodate the UK’s CO<sub>2</sub> storage requirements to meet its 2050 climate change targets.”
- In April 2016, a 1 year investigation was made by Pale Blue Dot, of 5 typical stores around the UK offshore, funded by DECC at £2.5m, and managed by ETI. This compiled legacy information from offshore hydrocarbons to show that 1,500mt CO<sub>2</sub> storage could be provided by 2030. It is claimed that no additional boreholes are needed to make additional evaluations of storage capacity – the legacy information from offshore oil and gas is adequate. If storage sites move to development, then 2 to 7 new boreholes will be needed at each site (example in figure 2).
- UK CO<sub>2</sub> storage can now be rolled out rapidly for the first 1,500Mt of CO<sub>2</sub> stored.

**Costs and prices: the impossibility of innovation by procurement**

19. Cost estimates for development of storage made during the Pale Blue Dot (2016) study included new subsea pipelines and new injection boreholes, and new offshore engineering facilities.
20. These were made by experienced offshore North Sea organisations and staff, using well-known equipment and processes. No significant innovation is needed to develop these offshore sites for CO<sub>2</sub> storage. The calculated costs, on a levelised basis the same as CCS FEED studies, arrived at all five sites at a range of £12-18 per tonne CO<sub>2</sub>.
21. The quality of these geological assessments is not as advanced as CO<sub>2</sub>MultiStore, but does include commercial-quality costs estimates of new pipelines and associated equipment, new offshore boreholes, CO<sub>2</sub> handling and injection equipment. The Peterhead-to-Goldeneye and White Rose-to-Endeavour FEED studies are closely similar to these, and so can be compared. Although the costs of transport and storage are not published in detail for the FEED, it is clear that the costs charged within the FEED projects have been multiplied by a factor of about four. Thus £15 cost spent for transport and storage became £60 price charged. An identical inflation of prices occurred in the Longannet CCS competition (Fig 3). The problem is identical in both cases.

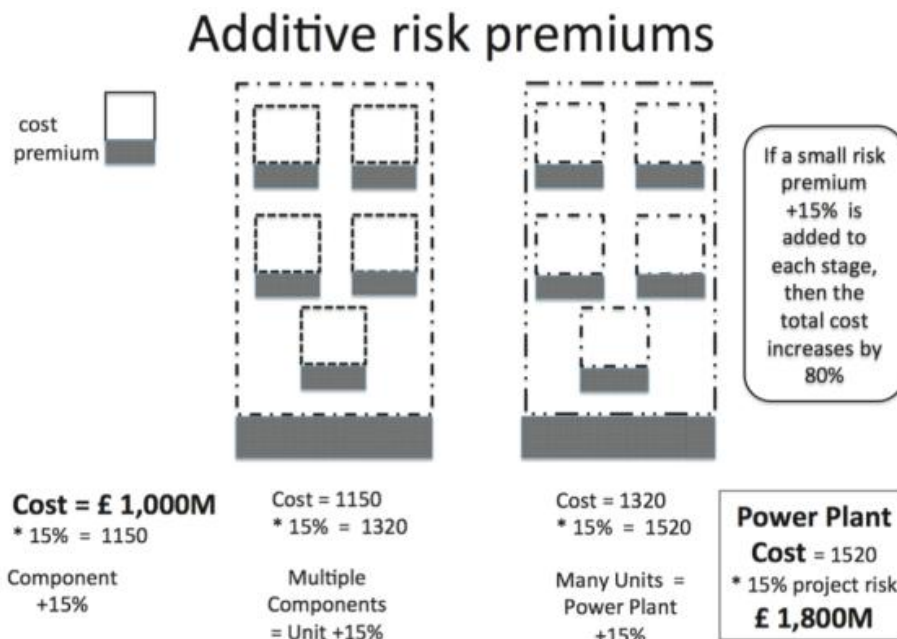


Figure 3. Illustration of cost inflation, when 15% risk premium is added to each stage of the powerplant plus capture design. This moves from Components, to Units comprising multiple components, to power Plant comprising multiple units, with a final premium added to the whole Project. The un-risked cost is £1Bn, the risk-protected cost is £1.8Bn. There can be a role for Governments to underwrite early projects and reduce costs, but active management or smart contracts are clearly needed.

Haszeldine 2012 Energy and Environment v23, pp 437 - 450

22. Because UK Government refuses to accept any significant risk in underwriting these CCS projects, and because UK Government specifications require extremely high certainty that the project will operate and will not fail, then at each stage overdesign occurs, and at each stage a risk premium is also added to finance borrowing, or insurance, or self-insurance by explicit internal provisions. The calculation in Fig 3 illustrates that the overall project cost can then inflate by 80% or more. The examples of storage costs published by Pale Blue Dot show this even more clearly, and it seems probable that during the latest CCS competition in the UK, cost to price of storage increased by about 400%.
23. Is this an endemic and inevitable problem? Contrast the cost of operational CCS in the North Sea at £35/ton CO<sub>2</sub> for capture and storage in the Sleipner setting, with the projected cost component of £80-100 per tonne just for transport and storage in the CCS FEED studies. The first has risk retention by the designers and operators, with no clear certainty of when CO<sub>2</sub> is handed over to the State; the second has risk managed by the project operator in a way in which they have experience, understand, and can manage. The similar effects from previous CCS projects make it clear that a government wish to create innovation of CCS by procurement and no risk, is a very expensive solution and is impossible to achieve by this “competition and procurement” method.
24. Important general points from this series of storage assessments are that
  - Geology beneath the seas surrounding the UK is exceptionally suitable for CO<sub>2</sub> storage. A huge amount of storage exists, about 30% of EU capacity;
  - The reliable appraisal of large quantities of storage can be undertaken quickly using hydrocarbon industry skills, public data, and loaned commercial data;
  - Six types of storage site exist offshore, but each site is individual, and needs appraisal as an individual site (figure 4);
  - Good quality existing pipelines are very useful to re-use and reduce costs. All pipes, boreholes and equipment can be renewed for >30years life, included in the cited costs (excluding risk and profit);
  - The lifetime levelised cost of storage is small, about £12-18 per tonne CO<sub>2</sub> (i.e. adding £3-10 cost per barrel of oil at \$50 (£35)).



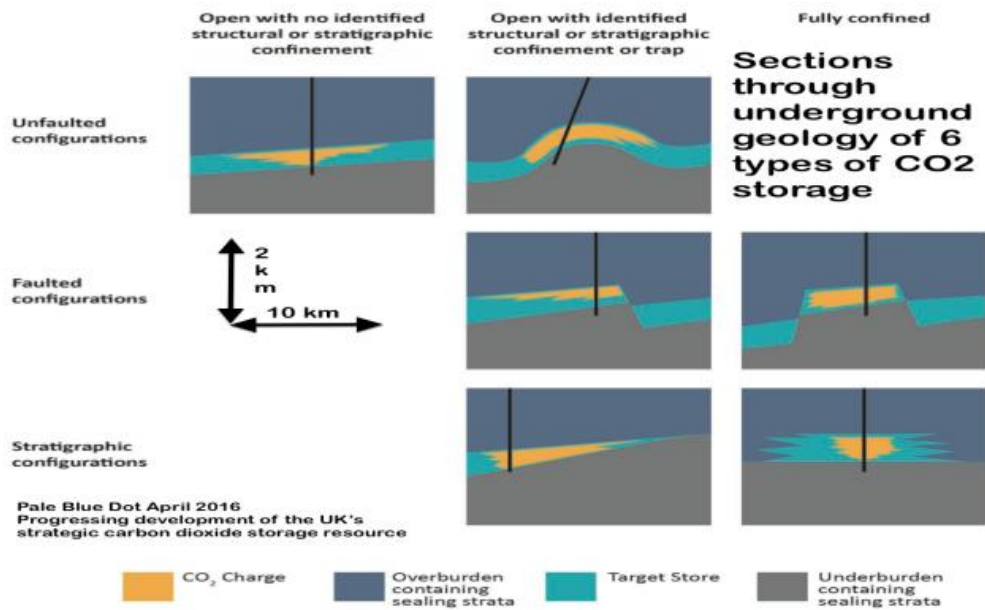


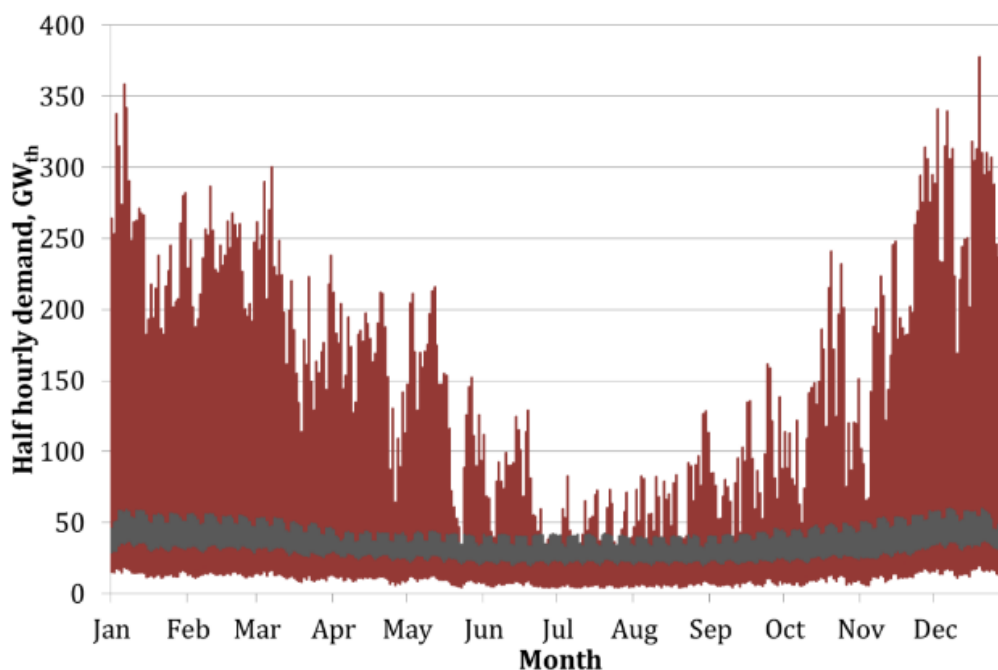
Fig 4 Cartoon representation of different types of CO<sub>2</sub> storage site, showing diversity of shapes and sizes. Structures are types 2, 3,4 ; stratigraphic are 1, 5, 6.

### Collaboration on storage development

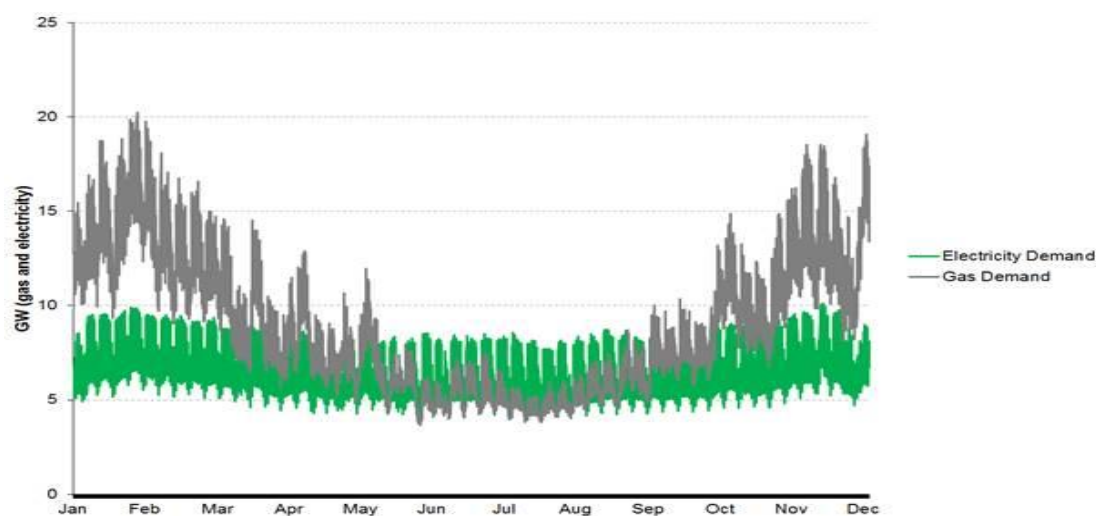
25. The costs of a CCS project are large, and the offshore transport and storage of CO<sub>2</sub> could be priced at up to 50% of a total project cost. Is there a gain in sharing that cost, by partnership between several oil company subsurface developers or even two countries?
26. Clearly the costs could be shared between multiple partners, and that could make participation more viable. But the questions for a commercial actor would include “what do my shareholders gain from this partnership?” It is not immediately clear that there is a gain.
27. The generic knowledge to transport and inject CO<sub>2</sub> is widely available within oil companies, so no technical learning is achieved. Several oil companies : BP, Statoil, Shell, Total, Petrobras have already undertaken CO<sub>2</sub> injection projects offshore and onshore. So, would the particular knowledge of an injection site be useful to a joint partnership? Again it is not clear that is useful. There is no competitive CO<sub>2</sub> storage market, to gain commercial insight on particular geologies or geographies and as can be seen from the diagrams above, there are a number of types of site, and each site is an individual.
28. The main beneficiary is the site operator, for that particular knowledge, but the generic learning is small. The biggest benefit would in all probability be the actual realization of an operating project of CO<sub>2</sub> injection offshore. Even that, though will not create an offshore storage industry on its own, as the confidence for reliable and profitable income still needs to be credible to investors over 30 years.

## Appendix 5: Decarbonising heat

1. The challenge of keeping the UK warm is illustrated by the diagram below which is the work of Robert Sansom of Imperial College. It shows synthesised national half hourly heat demand (red) for 2010 and actual half hourly national electricity demand (grey).



2. The well-known and pronounced seasonal and daily variation in electricity demand is dwarfed by the much larger and more variable demand for heat in the UK. The pattern is comparable to that of Austria (which has a much higher dependence on electric heating) but more pronounced (see diagram below from Pöyry). This is likely to be the result of better insulation of the Austrian residential buildings and suggests the size of dividends that might be derived from improved insulation here.



3. This suggests that if in the UK electrification of the heating demand is coupled with effective building insulation the maximum winter heating demand could perhaps drop to around 200 GW around four times larger than the present maximum winter demand for electricity. If heat pumps were widely adopted the maximum demand could be further reduced. However, heat pumps are really effective only in new developments and it would need to be a planning requirement that they were incorporated from the beginning. They would not have great application in the existing housing stock that turns over rather slowly.
4. It is hard to avoid the conclusion that electrification of heat in the UK would require the electricity supply grid to be strengthened to carry a maximum load of perhaps four times the present maximum. This estimate takes no account of the additional load from the charging of electric vehicles which would be no problem in much of the year but could be difficult on cold days in winter. There is also a possible technical issue with the inductive nature of the load requirement of heat pumps and the impact that has, at scale, on grid stability.
5. Electricity for the additional winter heating requirements would need to come from an increased contribution from wind (in winter there is little sun) coupled with on-grid storage. There would need to be a significant amount of despatchable generation from either CCGTs and/or small nuclear reactors or cheap storage of renewable power in whatever form that came.
6. There is currently no known cost-effective form of inter-month storage available at the scale required to meet these demands.
7. If electrification is the chosen way forward important decisions need to be made now. Perhaps most importantly the development of the technologies that are either not yet available or available affordably. Regardless of the progress of renewables and SMRs (small modular nuclear reactors) and the effectiveness of demand side management, it is hard to envisage a future that does not involve at least some new thermal power stations that would need CCS if decarbonisation targets are to be reached.
8. A completely different approach would be to use hydrogen as the main vector of energy for heating. It has the great advantage that burning it for any purpose yields only water vapour. Because over the last twenty years much of the gas grid has been replaced with welded polyethylene piping it would be suitable to carry hydrogen. In some areas further replacement of cast iron by polyethylene would be needed along with some wider strengthening of the grid.

9. Furthermore the burners in every gas fired appliance would need to be replaced as the switchover from natural gas to hydrogen took place. This what happened forty years ago when the country switched from 'Town Gas' to natural gas. Town gas was around 50% hydrogen, 35% methane, 10% carbon monoxide and 5% ethylene. The switch over today would be a much bigger operation than the previous change and would be more akin to the implementation of the smart meter programme.
10. Hydrogen could be produced in a number of different ways. One way is by electrolysis – passing an electrical current through water to cause dissociation of the hydrogen and oxygen. This can be done more efficiently at high temperature and could use heat and power from a thermal or nuclear power station. Even so, this method is cost prohibitive.
11. However, producing hydrogen in the quantities needed to heat the country would almost certainly mean producing it by the catalytic steam reforming of natural gas. This is a well-established industrial process which along with the hydrogen generates pure CO<sub>2</sub>.
12. Steam reformers would need to be located at the import hubs for natural gas. Hydrogen could be fed into the gas grid and the CO<sub>2</sub> could be used for any desired purpose but the default position would be that it would be piped to a sequestration reservoir in coastal waters. In essence decarbonisation of natural gas would take place as it entered the country.
13. If there was a general move towards hydrogen there is no reason why its application should be restricted to heating. CCGTs for generating electricity could be run on hydrogen – again a known technology. This would obviate the need for local CCS at the power station. A detailed analysis is needed of the system costs and efficiencies of a CCGT with local CCS and a CCGT running on hydrogen from a reformer. It is interesting that the US DoE is supporting a project in industry to run a CCGT on hydrogen produced from coal.
14. At present investors see significant risk in building CCGTs fuelled by natural gas. They are aware of the general threat of progressively tightening restrictions on emissions and worry that they may become obliged to retrofit CCS to continue generating. If they were able to build a hydrogen fuelled plant next to a reformer they could be confident of emission free generation for the life of the plant.

15. The wide availability of hydrogen would have other interesting implications for decarbonisation. The main limitation on the success of California's 'hydrogen highway' is the relatively small number of filling stations. The general availability of hydrogen in the UK would transform the opportunity for low emission vehicles and EVs running on fuel cells or even burning hydrogen inefficiently in internal combustion engines; it would also introduce more competition into the EV market.
16. We have not discussed the use of hydrogen in aviation or shipping. It has potential application in both areas. Both aviation and marine traffic are essentially international and the UK influence is limited. High energy-density liquids will continue to be needed for aircraft for the foreseeable future. Whatever fuel future aircraft use it will need to be universally available.
17. It is clear that an economy that used both electricity and hydrogen as energy vectors would have greater resilience than one based on electricity alone. More broadly, a hydrogen based economy appears to offer an easier transition to a future without fossil fuels as new ways of generating hydrogen gradually displace the steam reforming of natural gas.
18. We note that the hydrogen alternative does not depend on any new technology. It could turn out to be the least expensive route to decarbonising the economy but at present there is no way of being sure.
19. In the comparison between national pervasive electrification (and the displacement of natural gas) and the replacement of natural gas by hydrogen, there is one very important difference. Given the size of the UK winter peak, electrification means a significant increase in generating capacity will be needed but fully used for at a maximum a third of the time because there is no means of inter-seasonal electricity storage. Inter-seasonal storage of hydrogen however could be achieved in much the same way as natural gas is stored today. The capital investment in plant would be much less and hydrogen generation could operate at more or less the same level throughout the year.

Oxburgh (2016): LOWEST COST DECARBONISATION FOR THE UK: THE CRITICAL ROLE OF CCS.  
Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary  
Advisory Group on Carbon Capture and Storage (CCS)

Committee members and report authors are listed on pages 47 - 49