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Abstract: Carbon capture and storage (CCS) could play a significant role in reducing global CO_2 emissions. It has the unique characteristic of keeping fossil carbon in the ground by allowing fossil fuels to be used, but with the CO_2 produced being safely stored in a geological formation. Initial versions of the key component technologies are at a sufficient level of maturity to build integrated commercial-scale demonstration plants. If CCS is to reach its full potential to contribute to global efforts to mitigate the risk of dangerous climate change, it is urgent that a number of actions begin now in order to be ready for CCS deployment from around 2020 using proven designs that can be built in large numbers. This article discusses some key challenges for CCS, with a focus on development in the next decade, highlighting the potential benefits of a two tranche programme for integrated commercial-scale demonstration to develop proven reference plant designs and reviewing the importance of distinguishing between different classes of CCS according to their ability to significantly reduce CO_2 emissions associated with fossil fuel use. It also identifies some ongoing CCS projects and initiatives and examines some possible implications of current policy discussions for technology development.

Keywords: carbon capture and storage, carbon dioxide capture, technology innovation, energy policy

1 INTRODUCTION AND BACKGROUND

Carbon capture and storage (CCS) has been proposed as a way to prevent carbon dioxide (CO_2) from fossil fuels entering the atmosphere. A useful introduction to the key technology options is provided in a special report of the Intergovernmental Panel on Climate Change published in 2005 [**1**]. In most current fossil fuel combustion (or other energy uses, e.g. gasification) CO_2 is emitted to the atmosphere. If CCS is used then CO_2 would be separated from the other combustion products and then compressed to a dense liquid which can be transported to a secure geological storage site, probably by pipeline or ship. At a typical geological storage site, the CO_2 is injected a kilometre or more underground into porous rock layers overlain by impermeable layers to act as a seal. The importance of CCS for climate change mitigation is summed up in the Stern review on the economics of climate change, commissioned by the UK Government:

> Even with very strong expansion of the use of renewable energy and other low carbon energy sources, hydrocarbons may still make over half of global energy supply in 2050. Extensive CCS would allow this continued use of fossil fuels without damage to the atmosphere. . . [**2**].

CCS requires energy and additional equipment so inevitably adds to the cost of using fossil fuels, but a range of electricity generation cost studies have concluded that levelized costs for CCS electricity could be no higher (and possibly lower) than renewable energy technologies currently receiving support in many jurisdictions (e.g. offshore wind) [**3**, **4**]. Some studies have suggested that in future energy systems CO_2 reduction measures that cost more than \$100/tCO_2 would be implemented [**2**, **3**, **5**]. If this marginal cost of CO_2 abatement was seen as a CO_2 tax or emissions permit price (and possibly also at lower CO_2 price levels), using fossil fuels with CCS is expected to be cheaper than using fossil fuels unabated and purchasing CO_2 emission allowances at suggested future prices.

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Versions of technologies to capture, transport, and store CO_2 have all been demonstrated to some extent and it is expected that they can be successfully developed to the point where they become suitable for routine use [**2**]. Although a significant engineering and scientific effort is needed, no major scientific breakthroughs appear to be required in order to achieve commercial scale development and deployment of CCS [**6**]. A range of studies suggest that knowing that CCS technologies could be developed is, however, not the same as having them commercially available, since a significant amount of CCS deployment at scale is needed for 'learning by doing' and to give buyers confidence before making multi-billion dollar investments [**6**, **7**].

The most significant barrier to successful implementation of initial commercial-scale CCS projects could, therefore, be obtaining adequate financial support commensurate with both the stage of development for CCS technologies and their potential to make a significant contribution to mitigating the risk of dangerous climate change. General schemes to require payment from power plant operators for CO_2 emissions, such as the EU Emissions Trading Scheme, could provide an incentive for CCS in the long run. It is unlikely, however, that this approach will be adequate for the initial stages in the deployment of any new technology since relatively high costs are expected for early projects [**8**], which eventually fall with time, while the expected trend for carbon prices is to rise over time . While renewables (and previously nuclear) have received additional support in some countries for many years, CCS has only really attracted significant attention since about 2005, with the G8 Gleneagles Statement [**9**] being a major milestone in CCS recognition.

The International Energy Agency (IEA) Energy Technology Perspectives report published in 2008 [**3**] suggested that CCS could play a significant role in both power generation and industrial applications such as steel and cement manufacture. In the BLUE Map scenarios considered in this report, various options for reducing global CO_2 emissions by 50 per cent by 2050 are explored and CCS commercialization begins around 2020 with an annual global build rate of up to 17.5 GW coal-fired power plants plus 10 GW gas-fired plants, all with CCS installed. It can, therefore, be argued that CCS technology faces to a '10 year challenge' to be ready to able to be deployed to meet these ambitious targets.

In this context, a range of commentators have suggested that a high priority objective for CCS development should be to have some proven technologies and a nucleus of experience available as soon as possible [**6**, **7**]. This objective must be met before successful, widespread rollout of CCS. For example, it seems likely that the political process required to establish some of the conditions to support global rollout of CCS will be difficult to complete without experience from initial commercial-scale projects and also that nations that are heavily reliant on fossil fuels are more likely to enter binding agreements to make large emission reductions if CCS is available as a back-stop technology [**2**, **3**].

This article will first review the role of CCS in global climate change mitigation policy and introduce a selection of current CCS initiatives and projects. A range of technologies that are closest to commercial deployment will then be discussed. The remainder of the article will then focus on the '10 year challenge' outlined above. A summary of a two tranche model to prepare for global rollout of CCS proposed in previous work [**10**] will be presented and the importance of differentiating between CCS applications, based on their varying climate benefits, will be highlighted. Finally, some implications of ongoing policy developments for CCS deployment and engineering requirements will be identified.

CCS is currently associated mainly with the use of coal, although if emission reduction targets of 80 per cent and more are to be achieved, as suggested in the first report of the UK Committee on Climate Change report [**5**], then clearly CCS must be applied to all fossil fuel use, with primary energy being converted to a carbon-free energy vector such as electricity, heat or hydrogen. This article will focus on immediate challenges for engineers in the field of CCS and will therefore concentrate principally on coal and its main use, electrical power generation.

2 CCS AND GLOBAL CLIMATE CHANGE MITIGATION POLICY

Some studies [**5**] have suggested that global greenhouse gas emission reductions of 50 per cent or more by 2050, followed by further cuts in the latter half of the century, to limit cumulative greenhouse gas emissions to acceptable levels, will be required to reduce the risk of dangerous climate change to an acceptable level. If these aspirations are to be achieved, it is very likely that the only way to use fossil fuels will be with extensive CCS. It, therefore, seems unlikely that major coal-based economies (e.g. USA, China, and India) would be able to commit to achieving these reductions unless and until CCS is available as a proven option. CCS is not expected to be able to make a major contribution to achieving a possible global target of emission stabilization by 2020 since only a relatively small number of commercial-scale projects are likely to be deployed within the next decade (although even initial CCS projects are large enough to appear significant in comparison with renewables. For example, the single CCS project proposed by BP at Peterhead (near Aberdeen, Scotland) in 2005 would have produced approximately as much low-carbon electricity per year as all of the

wind turbines then installed in the UK). As already noted, this development period is, however, needed as a precursor to any, potentially very rapid, reduction in CO_2 emissions that could be assisted by CCS deployment in the 2030s, 2040s, and 2050s and beyond. This section outlines some important differences between CCS and other approaches proposed for long-term climate mitigation and introduces a selection of initial commercial-scale CCS projects that are in progress at the time of writing.

2.1 Long-term climate change mitigation benefits for CCS projects

While being able to implement large cuts in global emissions may depend on the availability of CCS, widespread deployment of CCS probably also depends on there being a serious global programme of action to mitigate the risk of dangerous climate change. In some cases, additional costs for nuclear and renewable energy can be justified on energy security grounds. In contrast, implementing CCS requires more fossil fuel per unit useful energy output and thus it can be argued that it reduces energy security, except inasmuch as changes in fuel supply diversity by allowing continued use of fossil fuels with CCS may provide security of supply benefits in some jurisdictions. The main benefit to trade off against the costs of CCS is, however, only CO_2 emission reductions. But it is likely that such emission reductions can only translate into actual climate change mitigation, and thus justify the costs involved, if they are part of an effective global strategic programme that can achieve the necessary long-term limits on cumulative emissions [**5**, **11**].

CCS does, however, have the unique characteristic of providing a technological means for addressing a critical issue for effective climate change mitigation, the long-term fate of the fossil carbon that is not emitted to atmosphere when a low-carbon energy source is used. That stored CO_2 will be retained for millennia is, quite reasonably, a matter of concern for CCS projects. It is addressed by a suitable choice of storage location, an effective design for the CO_2 injection system and its eventual closure, and monitoring of the injection site during and after injection, with appropriate action if significant deviations from expected behaviour are observed [**12**]. Somewhat surprisingly, the fact that the fossil fuel that is not used if other energy sources are employed could generally stay underground indefinitely appears to obscure a more realistic discussion of whether or not it actually will, against the same criterion of millennia of storage being required for the fossil carbon not to contribute to dangerous climate change.

As outlined in Table 1, either long-term political restraints or a shift in the relative costs of fossil and non-fossil energy appear to be the only mechanisms to ensure that any unused fossil fuel (which by definition must be potentially extractable) is not used. It should be noted that the fossil fuel price that renewable energy has to beat to avoid there being an incentive to use the former is the fundamental cost of production, without much of the additional, often large, profit that has been part of recent fossil fuel prices. This is the general price level that fossil fuels can be expected to fall to if non-fossil energy sources ever start to compete successfully without financial and/or regulatory support. Figure 1 (based on data from reference [**13**]

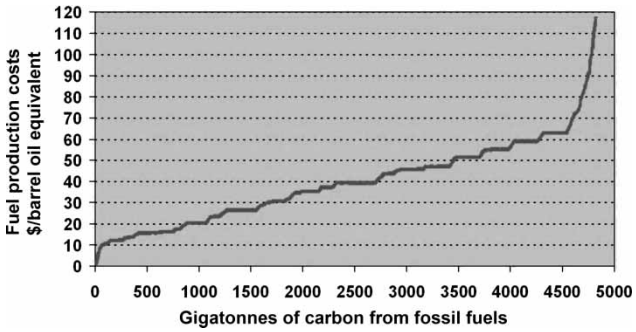

Fig. 1 Fossil fuel production costs as a function of carbon content (Data from Rogner, 1997, adjusted from 1990 to 2006 oil costs. Discussed in Gibbins and Barnett, 2008) [**14**]

Table 1 Comparison of long-term climate change characteristics of fossil with CCS and non-fossil energy sources for electricity generation

	Fossil with CCS	Non-fossil energy source
Low-emission electricity generation technology	Fossil with CCS	Nuclear and/or renewables
Output	Low-emission electricity	Low-emission electricity
End result	Fossil C in the ground, not in the atmosphere	Fossil C in the ground, not in the atmosphere
Form of the fossil C underground	CO_2 dispersed in pores in a geological formation, eventually dissolved in formation water and reacted with rocks	Unused fossil fuel
Requirement for retention of fossil C underground	Want <1% leakage of stored CO_2 per century over millennia	Want <1% use of unused fossil fuel per century over millennia
How retention is to be achieved	Suitable selection of storage location, injection system design, and monitoring during and after injection process	Either: long-term binding ban on fossil fuel use (emission cap, but cap tending towards zero over time), or: expectation that non-fossil energy will become cheaper and better than fossil energy for all applications for millennia

and discussed in reference [**14**]) suggests that this estimates for this fundamental price are likely to be very low and to rise only slowly. Production cost assessments from Rogner [**13**] based on 1990 oil prices ($22/bbl [**15**]) have been adjusted to 2006 oil prices of $35/bbl [**15**]. These estimates are relevant to understanding the general level to which fossil fuel prices could fall if it is assumed that action to mitigate the risk of dangerous climate change will lead to reduced fossil fuel demand and, hence, fewer occasions when sufficient supply is not available.

2.2 Examples of current CCS initiatives and projects

Although there have been relatively large-scale demonstrations of CO_2 storage operating successfully for over 10 years [**16**, **17**] there are, at the time of writing, no commercial-scale integrated CCS projects involving CO_2 capture at power plants. As the potential for CCS to make a significant contribution to mitigating the risk of dangerous climate has been recognized and accepted, a number of initiatives and projects to encourage initial commercial deployment of CCS in integrated commercial scale projects have, however, been announced.

In 2008 two significant events were the decision by G8 leaders to encourage the deployment of 20 large-scale integrated CCS projects [**18**] that could form a first tranche of plants, as discussed below, and a European agreement to provide financial support for up to 10–12 projects using an incentive mechanism funded by allowances from the EU Emissions Trading Scheme [**19**]. If successful, these multi-national agreements and funding arrangements could allow significantly faster development of commercial-scale CCS than would be possible with individual countries acting in isolation. The potential for significant benefits to accrue from international cooperation and coordination on early projects has also led to the Australian Government establishing a Global CCS Institute [**20**].

Although coordinating action in an international context is clearly important, contributions by national and local Governments (or other non-industry funders) also seem to be essential in getting ready for CCS rollout and supporting initial deployment. Some Governments have already made commitments to fund projects including a demonstration project being developed by SaskPower for the Boundary Dam power plant in Saskatchewan, Canada [**21**]. The Greengen project in China [**22**] also has the potential to be among the first commercial-scale power plants constructed with CCS.

In the USA it is possible that federal support for the FutureGen project [**23**] will be restarted and also that fast track CCS projects based on near commercial technologies will receive the necessary supplementary funding to go ahead. Although it is not certain if and when project finance will be obtained, it is possible that some of the $3.4 billion set aside for CCS in the US economic stimulus package in response to the 2008/2009 global economic turndown [**24**] could provide sufficient support for some projects. Such projects might include a Basin Electric power plant close to the North Dakota Gasification site that provides CO_2 for the well-known Weyburn storage project [**25**], an integrated gasification combined cycle plant built in Indiana by Duke Energy [**26**] and two projects proposed in Kern County, California (a BP petcoke gasification project [**27**], and a natural gas fired oxyfuel project proposed by Clean Energy Systems [**28**]).

Within Europe, a number of CCS projects are at different stages of development including a broad range identified by the European Zero Emissions Technology Platform in their proposal for a flagship fast track deployment programme [**29**]. The European Economic Recovery Package, also developed in response to global economic problems, included €1.05 billion which must be spent on a range of projects on a shortlist agreed at European level [**30**]. Individual European member state action is expected to be necessary to supplement joint European activities. For example, the UK Government launched a competition in 2007 for funding for a post-combustion capture (or oxyfuel) plant in the UK that can capture the CO_2 generated by 300 MW of electricity generation [**31**] and three projects are in the second phase of bidding for support at the time of writing (June 2009). A number of pre-combustion projects have also been proposed in the UK including by Progressive Energy [**32**] and Powerfuel [**33**]. Although these projects are not eligible for support from the UK Government competition, they are likely to be eligible for further UK Government funding announced in April 2009 [**34**] and could also be eligible for support within the European 'flagship programme' noted above.

3 CARBON CAPTURE TECHNOLOGIES FOR ELECTRICITY PRODUCTION FROM COAL, CO_2 TRANSPORT, AND GEOLOGICAL STORAGE TECHNOLOGY

A comprehensive review of a wide range of CCS technologies is available in a special report on CCS produced by the Intergovernmental Panel on Climate Change [**1**] and a more recent summary of CCS component technologies, including some potential technology developments to 2050, was produced by the authors for a UK Foresight Programme review of the state of science in energy [**35**]. Only a brief summary is therefore given here. The focus of this article is on the immediate challenge of developing effective CO_2 capture technologies for coal-fired power

generation. It should also be noted, however, that CCS should also be applied to power generation from all carbon-containing fuels and other large point sources of CO_2 (e.g. cement works, steel and aluminium production etc) if the greenhouse gas emissions reduction aspirations noted in the previous section are to be met.

Although the focus here is on describing basic technology characteristics, a number of other factors must also be considered and successfully implemented in real CCS projects. For example, project developers will be required to identify and adhere to all relevant regulatory requirements. A wide range of other stakeholder perspectives could also have a significant influence on how CCS projects develop. Johnsson *et al.* [**36**] report results from a survey of a range of stakeholders in the USA, Japan and Europe and the Dutch national programme on CCS, CATO, has explored how the general public in the Netherlands view CCS [**37**]. Many of the conclusions from these studies agree with the earlier ACCSEPT study carried out under the sixth research framework programme of the European Commission which concluded that, although CCS appears to be 'acceptable' to most European stakeholders, there is limited understanding of general public perception [**38**, **39**].

3.1 CO_2 capture

Three different approaches for CO_2 capture at power plants are generally considered to be closest to commercial-scale deployment and are illustrated in Fig. 2. Processes to remove conventional pollutants including particulates and oxides of nitrogen and sulphur are not included in these schematic diagrams. They are, however, discussed in the technology descriptions below.

In the post-combustion capture options closest to commercial deployment, CO_2 is removed from flue gas after a normal combustion process using slightly alkaline chemicals such as ammonia or amines

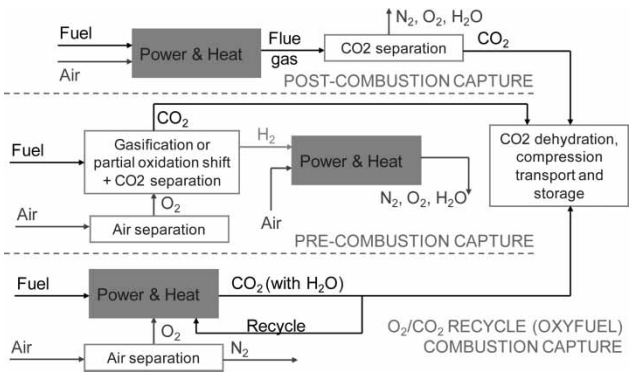

Fig. 2 Schematic overview of CO_2 capture approaches closest to commercial deployment after Jordal *et al.*, 2004

[**40**]. Since minimal modifications are required to an industry standard pulverized coal plant (or natural gas combined cycle) it is relatively easy to retrofit post-combustion capture options to existing plants provided that certain basic requirements such as sufficient space (and, of course, access to suitable geological storage) is available at existing sites [**41**]. Most existing control measures for conventional pollutants will not be significantly changed by the addition of post-combustion capture. For many solvents, one exception is likely to be that improved flue gas desulphurization (FGD) will be required to avoid the formation of heat stable salts in the alkaline chemicals used for CO_2 capture.

In pre-combustion capture, coal is gasified to produce a synthesis gas consisting mainly of carbon monoxide (CO) and hydrogen (H_2). Following a shift reaction to convert the CO plus added water, often as steam, to CO_2 and additional H_2, the CO_2 is separated from the H_2 stream, typically using a physical solvent such as Selexol [**42**] or Rectisol [**43**]. CO_2 capture is generally more difficult to retrofit to integrated gasification combined cycle (IGCC) plants due to the relatively high levels of integration that are typically required by plant designers. Retrofitting a gasifier to a natural gas combined cycle plant has, however, been suggested as a potentially attractive option in some locations [**44**] and avoids the problem of sizing a gasifier to be a suitable size both with and without CO_2 capture. IGCC plants typically also have very low levels of conventional pollutant emissions [**45**].

In oxyfuel combustion, oxygen (O_2) is separated from air and the fuel is then combusted in an O_2/CO_2 atmosphere. Although energy is required for separation of O_2 from air, the subsequent use of oxygen in the combustion process significantly increases the CO_2 concentration in the flue gas. This allows the chemical CO_2 separation process required for post-combustion capture to be avoided, although some CO_2 clean-up, including drying, will still be required during the CO_2 compression process. Retrofit of air-like oxyfuel systems to existing plants may be possible, but could be challenging if near-zero levels of air in-leakage are to be achieved so that minimal volumes of nitrogen (and other inert gases in air) are to be delivered to the CO_2 clean-up and compression system. A number of options for conventional pollutant removal in oxyfuel processes are under discussion and, in some cases, fundamental work is required to understand potentially significant differences between conventional and oxyfuel combustion processes. For example, Santos [**46**] reviews the current understanding of the fate of sulphur in oxyfuel combustion, focusing on the capture of sulphur by the ash in an oxyfuel furnace.

For coal-fired electricity generation there is currently no clear winner between these three options for CO_2 capture when public domain information on

long-run levelized costs of different alternatives are compared [**47**]. It is quite likely, though, that different approaches will be best suited to different sites and jurisdictions. Also the technologies are not static; even with the present limited market for CCS technologies there is extensive activity directed towards improving the performance and/or reducing the costs of CO_2 capture. This includes continuing incremental improvements that can build up to significant developments, as well as more radical possible step changes [**48**].

3.2 CO_2 transport and storage

Once CO_2 has been captured and compressed it must be transported to a site where it can be safely stored (or used). A useful introduction to key CO_2 transport technologies and factors to consider in determining which transport options are likely to be best for any particular project is included in the 2005 Intergovernmental Panel on Climate Change special report on CCS [**1**]. For the volumes involved for commercial-scale CCS projects, it is expected that pipelines will often be the best option, although a ship may be more cost-effective in some niche applications. Onshore CO_2 pipeline transport is generally considered proven due to a large, existing network for enhanced oil recovery (EOR) operations in the USA, particularly in the Permian Basin in Texas. It will be necessary, however, to ensure that engineers and operators gain a good understanding of any significant differences between existing networks, developed to service EOR, and the more heterogeneous networks that will be required to connect plants and geological facilities intended purely for CO_2 storage. Significant factors could include, but are not limited to, non-steady production of CO_2 and the potential introduction of more significant levels of impurities in transported CO_2 than are typically observed in CO_2 from natural sources. In addition, at the time of writing there is very limited experience of transporting CO_2 offshore [**49**].

Given current levels of experience and capacity in CO_2 transport infrastructure, getting ready for commercial deployment should include preparations for a CO_2 pipeline infrastructure and 'learning by doing' with initial projects, as well as development of other aspects of the CCS chain. Infrastructure development should include careful consideration of appropriate specifications for CO_2 produced by power generation and other large sources entering a pipeline network (or ship) from a CO_2 capture scheme. It is also important to consider whether the transport infrastructure should be deliberately oversized for initial projects due to potential longer term benefits associated with establishing a network that is able to accommodate CO_2 produced at later projects [**50**, **51**]. Although this point may seem trivial at first glance, the policy environment in which CCS projects are developed and the business models used can lead to some complications that may not be obvious at first sight. For example, operators of initial demonstration projects are likely to aim for full cost recovery to be provided by any Government (or other) support that the project is able to attract. Especially if funding is obtained in competition with other projects, there may be a strong incentive to minimize capital costs for initial demonstration projects, e.g. by sizing transport infrastructure to be of sufficient capacity for only the CO_2 to be transported from the funded demonstration project, even if this leads to higher costs in the longer term as a larger transport network develops.

Long-term storage of CO_2 in geological formations involves a number of different phases, including site selection, CO_2 injection and site closure, with appropriate monitoring required at all stages [**12**, **52**]. Many of the technologies required can be adapted from existing oil and gas activities, although some adaptation or learning may be necessary for CCS applications. For example, a number of monitoring techniques developed for hydrocarbon extraction could be appropriate for CCS, but it is necessary to test which options will be most appropriate for particular storage sites [**53**]. Techniques for remediating any leaks from CO_2 storage sites are under development and new, long-term low-cost monitoring techniques are also being explored [**54**] Another ongoing activity is the development of detailed estimates of CO_2 storage capacity. Although a number of basin-wide screening studies have already been carried out in many areas [**55–57**], further work is now required to confirm whether promising storage sites will have the capacity that has been estimated in these initial studies. This requires thorough investigation of selected sites [**58**], probably including some test injections of CO_2.

4 THE '10 YEAR CHALLENGE' FOR COMMERCIAL-SCALE CCS DEVELOPMENT

Previous sections of this article have outlined the role that some studies [**3**] propose for CCS within a portfolio of technologies to be deployed with the intention of mitigating the risk of dangerous climate change. There has also been increasing recognition that for CCS to make such a significant contribution from 2020, there is a '10 year challenge' to successfully deploy initial commercial-scale projects so that real project costs can be discovered and 'learning by doing' to reduce these costs can begin [**6**, **7**]. This section, therefore, focuses on a discussion of key actions that could be undertaken to facilitate successful deployment of the initial plants that are also required to provide a basis for commercial guarantees to support widespread rollout.

4.1 A two tranche model for preparing for global rollout

If CCS is to fulfil its potential role in mitigating the risk of global climate change then successful, global rollout will be required. Given the current scale and experience with CCS component technologies, it is necessary to identify an appropriate development strategy, using commercial-scale projects covering the full CCS chain, before commencing a wider commercial rollout [**6**, **7**]. Given the time taken to build CCS projects and the target for rapid rollout of CCS from around 2020 already discussed, there are limited options available for this strategy.

Figure 3 (based on reference [**10**]) shows how two learning cycles for CCS technologies might be obtained globally before a 2020 rollout, with two tranches of plants. Since one key outcome of initial commercial scale deployment of CCS is expected to be building up capacity and experience it seems likely that two tranches of plants with some additional support measures provide a much better basis for developing the supply chains, people and stakeholder confidence (policy-makers, regulators, industry and others) that is expected to be required for the very large infrastructure investment that fully commercial CCS deployment represents, rather than just one tranche.

A critical factor in being able to achieve two learning cycles by 2020 is the speed with which work on the first tranche of plants is started. It is reasonable to argue that speed is much more important than the precise number of plants built for this first tranche, since no large scale power plants have commercial-scale CCS installed at the time of writing. Even a handful of projects would, therefore, represent a huge advance on current knowledge. In this context, if undertaken rapidly and at reasonable scale, the proposal by the G8

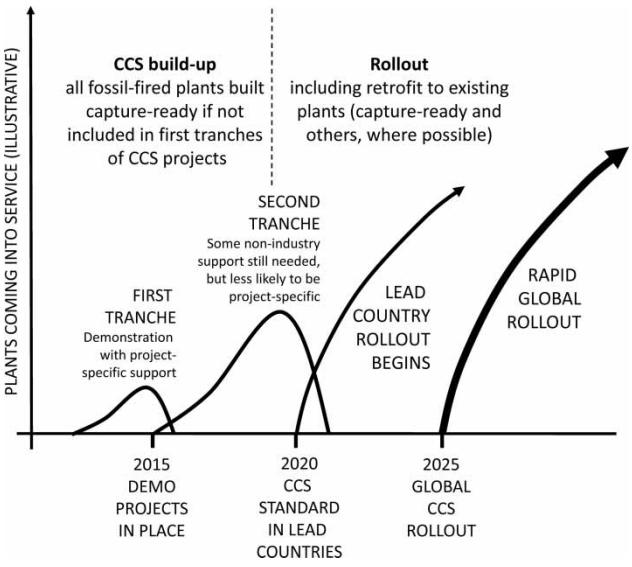

Fig. 3 A two tranche model for CCS development (based on Gibbins and Chalmers, 2008) [**10**]

countries in June 2008 [**18**] that 20 CCS demonstration projects should be 'launched' by 2010 might lead to an adequate first tranche. As noted above (section 2.2), at the time of writing, although some finance for these projects is becoming available it is not yet certain that financial commitments will be possible before the end of 2010.

As already noted, these initial projects should be followed by a second tranche of plants to apply and test the lessons learned in the first tranche, to expand the experience base for CCS and to provide a number of reference projects for further plants that will be built under commercial conditions as part of rollout. In this case, perhaps of the order of 40–80 additional CCS projects might be required globally in the second tranche.

4.2 Identifying projects for first and second tranche projects

Particularly given the importance of speed in getting ready for commercial deployment of CCS, one consideration in identifying projects for additional support as part of the first or second tranche of plants is whether retrofit opportunities can be identified to facilitate fast-track CCS development. Chalmers *et al.* [**41**] provide an introduction to the role that retrofits could play in both tranches of demonstration. It seems likely that retrofit options will be more attractive for some CO_2 capture approaches than others. In particular, it is likely that post-combustion capture will provide the best opportunity for fast-track demonstration with retrofit since it requires relatively minimal alterations to existing base power plant design. In this case, construction times could be significantly reduced since only the CCS-specific aspects of the project (i.e. not a new base power plant) are needed. It is also possible that permits will be obtained more quickly for existing sites since there may be fewer objections from local residents who are already familiar with the existing plant.

For other technologies it is expected that the time saving for retrofits would be less significant than with post-combustion capture, but there may still be some benefits associated with repowering at an existing site. Although some significant construction work for a new base power plant would be expected for a repowering project, existing coal import facilities, some power generation facilities (possibly including gas turbines for an integrated gasification combined cycle project) and connections to the electricity network are likely to be useful in many cases. It should be noted, however, that repowering typically requires a significant increase in capital expenditure when compared to retrofit projects so may have more difficulty in providing a business case for investors, at least in some jurisdictions [**59**].

It is also important that the right classes of CCS technology are developed in tranches 1 and 2 to support the rollout requirements, as illustrated in Table 2. In this context the effectiveness of a CCS project for climate mitigation is particularly relevant. Projects producing synthetic gasoline, diesel or natural gas from coal or other 'unconventional' hydrocarbon sources may have low CO_2 emissions at the plant itself with CCS, but a very significant part of the fossil carbon will still end up as CO_2 emitted to the atmosphere (order 50 per cent for liquid fuel production from the coal, a little less for synthetic natural gas (SNG) production). Although these projects could play a role in reducing global CO_2 emissions, it is likely to be necessary for the products from class 1 projects to be used with CCS in the longer term to meet the climate requirements outlined in earlier sections. The lessons that can be learned from deploying CCS at coal-to-liquids and similar plants are also typically of limited value for application to most class 2 and class 3 plants producing carbon-free energy vectors such as electricity, hydrogen, and heat.

Although Table 2 focuses on CO_2 capture aspects of a CCS project, it is also necessary to consider whether captured CO_2 is transported or used in determining whether it will have an overall climate benefit. Although this is normally clear if CO_2 is stored in a saline aquifer, more careful consideration is required if CO_2 is injected into a hydrocarbon reservoir. One classic example is the injection of CO_2 into oilfields to 'wash out' addition oil as part of EOR operations. The implications of the produced oil on the net CO_2 emissions from the whole CCS project depend on whether it is expected that the oil would have been produced anyway, even if the EOR scheme had not been implemented. Some studies have also explored how CO_2 injection strategies might change at EOR projects if CO_2 storage, rather than additional oil produced, is to be maximized [**60**, **61**]. It should also be noted that it is unlikely that using CO_2 from class 1 projects for EOR projects will provide significant learning to facilitate class 2 and 3 projects. CO_2 storage from class 1 projects in other geological formations could, however, be useful to allow sites to be proved for use for class 2 or 3 CCS projects and to gain some experience in other critical activities, including permitting and monitoring.

4.3 Carbon capture readiness

Another important result of using some retrofit plants within the two tranches of initial commercial scale deployment of CCS is that it should ensure that technologies are developed that are suitable for retrofit to the existing global power plant fleet once CCS is rolled out. This is crucial since overall emissions from the global fleet can only be reduced either if emissions from existing plants are reduced by retrofitting or if existing plants are shut down (probably prematurely from a technical and economic perspective in many cases) and replaced with new plants with lower CO_2 emissions. Plants suitable for retrofit could include some plants built before CCS was being considered and also plants built to be 'capture ready' during a preparatory period when only limited numbers of new build plants have CCS installed from the outset.

An IEA Greenhouse Gas R&D Programme study on capture readiness provides a comprehensive review of both essential requirements and optional pre-investments for power plant plants designed to be capture ready [**67**]. It is expected that implementing the essential requirements for capture readiness when building new pulverized coal power plants would add less than 1 per cent to the total capital requirements [**68**] and that some of the approaches suitable for coal plants could also be used at reasonable cost for natural gas combined cycle plants [**69**].

Table 2 Classes of CCS (after Gibbins and Chalmers [**62**])

Class	Maximum CO_2 emissions reduction possible	Typical examples
Class 1 carbon positive CCS	Typically a maximum of around 50% of CO_2 produced by fuel carbon can be captured, but depends on how products are used.	CCS for hydrocarbon production could be widely deployed in the immediate future including for SNG production, oil sands development, and coal-to-liquids projects [**63**, **64**]
Class 2 (near) carbon neutral CCS	Can capture close to 100% of CO_2 produced by use of fuel, although levels achieved in reality will partly depend on economic drivers.	Much higher capture levels are possible since carbon free energy vectors (e.g. electricity, hydrogen, heat) are produced. Many class 2 technologies can also be used for class 3B CCS
Class 3 carbon negative CCS	Net removal of CO_2 from the air leads to 'negative' emissions	Class 3B: in addition to producing carbon-free energy vectors, biomass is used as a primary fuel (can be co-combusted or co-gasified with fossil fuels to offset residual emissions at an individual site) Class 3A: direct capture from the air which is likely to be more expensive than class 3B CCS but could be necessary if stocks of CO_2 in the atmosphere become too high [**65**, **66**]

Although very few or no new unabated coal-fired power plants may now be built in some developed countries, developing countries are typically continuing to include new coal-fired power plants in the rapid build programmes that are required to support industrial expansion and improve the quality of life for their citizens [**70**]. These new coal-fired plants that will be built anyway are prime candidates to be made capture ready in order to minimize the overall fleet costs for retrofit and hence the risks of widespread 'carbon lock-in' [**71**]. There can also be some value in making natural gas combined cycle plants capture ready, although they typically have shorter operating lives and lower capital costs than coal-fired power plants so are likely to be easier to close and replace if sufficiently stringent CO_2 emissions reductions requirements are introduced. It is also generally expected that CO_2 capture will be applied at coal-fired power plants first since the greater concentration of CO_2 in their flue gases typically leads to a lower $\$/tCO_2$ cost for CO_2 capture [**47**]. In the UK, though, government permits for new natural gas combined cycle plants have included a requirement to be suitable for the retrofit of CO_2 capture since 2007 and guidelines to be applied by the environmental regulator were published for consultation in 2009 [**72**].

5 IMPLICATIONS OF POLICY FOR TECHNOLOGY DEVELOPMENT

As with many other energy technologies, successful development commercial-scale CCS will rely on relatively complex processes requiring successful cooperation between a number of stakeholders [**73**]. Some of these factors, including public perception, were identified and discussed above. Although a full treatment of all of the factors affecting CCS technology development is beyond the scope of this article, an introduction to some policy developments that could affect if, when and where initial CCS projects are deployed is included here. As noted in previous sections, policies affecting whether the initial tranches of CCS projects proposed above can be built expeditiously could be particularly significant in determining if and when commercial-scale projects can be successfully financed (based on the existence of satisfactory reference plants) and hence the long-term shape of CCS technology development.

There will always need to be a driver for CCS, either a 'carrot' in the form of a value or avoided cost for CO_2 emissions reduction (or payment for use of captured CO_2), or a 'stick' in the form of regulatory requirements that CCS takes place. Although a number of CCS projects are under development, it is clear that incentive and regulatory decisions by policy-makers will have a significant impact on CCS technology development. As already discussed, successful demonstration and deployment of initial commercial scale integrated CCS projects is very likely to require intervention from Governments, except in limited cases where another driver for CCS deployment exists or a non-industry stakeholder is willing to pay the costs for the CCS component of a project. It is, therefore, important to understand how decisions by policy-makers (and other key stakeholders) could affect construction and operation of CCS projects.

A number of policy mechanisms to provide incentives for initial commercial scale demonstration and deployment of integrated CCS could be used to support successful implementation of two tranches of projects by 2020 and potentially also the subsequent CCS rollout. Although a detailed review of these options is beyond the scope of this article, it is likely that support mechanisms designed specifically for CCS will be most successful, at least during the first two tranches of deployment, since market failures for innovation in this new family of technologies are difficult to overcome with less targeted approaches [**62**, **74**].

An immediate concern for many project developers, particularly in the USA and western Europe, is that many environmental groups (and other key stakeholders) are campaigning, often successfully, to stop new coal-fired power plants being built unless CCS technology is deployed to capture the majority of emissions from a whole power plant site from the beginning of its operating life [**75**], even where it can be argued that such CCS technology is not currently available and new plants would contribute to its development. In April 2009, UK Government proposed a compromise that would require any new coal-fired power plants to have a commercial scale demonstration unit, but not full CO_2 capture from the outset [**34**]. At the time of writing, a detailed consultation on how this proposal should be implemented is yet to be published. If this approach could be successfully introduced then it should encourage prudent technology development, allowing new build plants to progress CCS development at a smaller scale (e.g. one capture train out of the four that might eventually be fitted) with the expectation that full CCS would be used eventually, but not immediately. In jurisdictions where overall CO_2 emissions are already restricted (e.g. sectors covered by the EU Emissions Trading Scheme, including power generation in Europe) this phased deployment of CCS should not increase near-term cumulative CO_2 emissions since any additional emissions at one CO_2 source must be offset by buying emissions allowances which effectively ensure that CO_2 emissions are reduced elsewhere, so that the overall cap is maintained.

One important technical aspect that can be affected by policy decisions is the scope for flexible operation of power plants fitted with CCS. Since CO_2 is a long-lived, global pollutant [**76**], it is reasonable to

suggest that targets for total cumulative emissions over an extended period are more appropriate than plant level performance standards, analogous to those for oxides of sulphur and nitrogen, with specified limits that have to be met on an hourly or daily basis in some jurisdictions. For example, at least annual averaging of CO_2 emissions is allowed in existing 'cap and trade' schemes such as the EU Emissions Trading Scheme (and effectively much longer when emission allowances can be banked for future compliance periods). It is not guaranteed, however, that future legislation for CCS will also take this approach. For example, in September 2008 the environment committee of the European Parliament discussed the use of emissions performance standards that may have required plants to limit their CO_2 emissions, possibly to as low as 350 gCO_2/kWh electricity produced, whenever they were operating [**77**]. Although this proposal was not retained in the final European energy and climate change package passed by the European Council in December 2008 [**78**], it is likely that it will be considered again for future legislation, probably including the Industrial Emissions Directive that is under development at the time of writing [**79**].

If a restrictive emissions limit was introduced then it could significantly increase the cost of incentives required to facilitate a given level of CCS demonstration and deployment without decreasing cumulative CO_2 emissions to atmosphere (or would reduce the amount of emission reduction for a given level of incentives). Using competitive electricity markets as an example, it can be seen that the opportunity cost of CO_2 capture is higher when electricity prices increase (e.g. during peaks in electricity demand), since the plant capacity that is not available for dispatch because it is providing energy for the capture plant would then be worth more if it could be sold into the wholesale electricity market. It may be technically feasible for some power plants to bypass capture units during these peak periods and hence reduce the incentive required to make a CCS project economically viable [**80**]. This option could, however, be constrained by regulators even though cumulative emissions of CO_2 would not be expected to increase in jurisdictions with an overall limit to CO_2 emissions, as discussed above (or even if they were offset by additional CO_2 capture at the same, or another, plant). It should also be possible for operators to use biomass co-firing or other approaches such as solvent storage to offset or avoid additional emissions associated with avoiding the energy penalty associated with CO_2 capture during peak periods [**81**, **82**]. Flexible operation of power plants with CO_2 capture could also be important for network operators to be able to provide likely requirements for back-up services in future scenarios with high penetrations of intermittent renewable generation and, in some cases, relatively inflexible nuclear power plants [**83**].

It is also crucial that any incentive mechanisms and regulatory frameworks implemented to encourage or require CCS give continuity to a developing industry. As previously discussed, although some component parts of CCS have been demonstrated, significant technical work is required to grow this initial experience into a commercially viable and globally available contributor to mitigating the risk of dangerous climate change. If CCS is to fulfil its potential, a sustained effort will be required over the next 10 years to develop initial capacity for global rollout and then for build-up over at least several decades afterwards, until full fossil decarbonization has been achieved. It is likely that this technical development will require a clear and stable regulatory regime that allows CCS project developers and financers to assess the risks and opportunities associated with potential projects with reasonable certainty.

6 CONCLUSIONS

CCS is potentially an important option for achieving significant reductions in global CO_2 emissions. A range of different technology options are available to capture CO_2 at large point sources, such as coal-fired power plants, and then transport it to safe storage in a geological formation. One unique characteristic of CCS projects is that they provide an option for significantly reducing CO_2 emissions at the same time as using up fossil fuel reserves. They, therefore, have the potential to provide a technical solution to the problem of ensuring that potential CO_2 emissions from available fossil fuels do not reach the atmosphere. This contrasts with other low-carbon energy sources, such as renewable and nuclear power, that leave fossil fuel reserves, and their associated potential CO_2 emissions, accessible to future generations. The alternatives to successful deployment of CCS projects, including long-term CO_2 storage, are equally long-term prohibitions on fossil fuel use or achieving large enough reductions in the costs of non-fossil energy to make it cheaper than unabated fossil energy so that fossil fuel extraction and use becomes unattractive.

Given the currently proposed scale of action to reduce the risk of dangerous climate change, it is likely that significant cuts in global CO_2 emissions will be required throughout this century. Studies such as the 2008 IEA Energy Technology Perspectives report [**3**] have suggested that significant, rapid rollout of CCS from around 2020 could play an important role in mitigating the risk of dangerous climate change. Due to the time required to develop and construct CCS projects, and accrue the associated benefits of 'learning by doing', there is a strong case for taking action now to get ready for global rollout of CCS. One approach to responding to this '10 year challenge' would be to deploy two tranches of commercial-scale integrated

projects to develop reference designs and hence commercial confidence in CCS. Complementary work to establish CO_2 transport networks by 2020 can be also be envisaged. For the first tranche of plants, speed of deployment is likely to be more important than the precise number of plants delivered. A global fleet of 20 commercial-scale integrated CCS projects operating by no later than 2015 could, therefore, be sufficient. A second tranche of projects might then contain around 40–80 projects.

It is also critical that policy-makers and other key stakeholders appreciate that different classes of CCS can have different climate mitigation benefits. Although class 1 (carbon-positive) projects could have some useful outcomes, they are likely to make a limited contribution to long-term global mitigation efforts since a significant proportion of the CO_2 produced by the fossil fuel is still released to the atmosphere. The critical path for significant reductions in global CO_2 emissions requires, therefore, that class 2 (approximately carbon-neutral) and class 3 (carbon negative) CCS options are successfully demonstrated and made available for global commercial deployment.

A number of CCS initiatives and projects are now under development around the world but will require financial support if they are to be completed successfully. Although some funding mechanisms have been established recently, future policy decisions on if and how CCS projects are to be incentivized are likely to have a significant impact on technology development. In addition, regulatory stability could be important to facilitate growth of a skilled workforce and the way regulations affect the scope for plant operating flexibility could determine which roles CCS plant are able to fulfil within future electricity networks.

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