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Last chance for Carbon Capture and Storage

Vivian Scott*, Stuart Gilfillan, Nils Markusson, Hannah Chalmers and R. Stuart Haszeldine

Scottish Carbon Capture and Storage, School of GeoSciences, University of Edinburgh, Edinburgh, UK

* Corresponding author: vivian.scott@ed.ac.uk

ABSTRACT:

Anthropogenic energy-related CO_2 emissions are higher than ever. With new fossil fuel power plants, growing energy-intensive industries and new sources of fossil fuels in development further emissions increase seems inevitable. The rapid application of carbon capture and storage (CCS) is a much heralded means to tackle emissions from both existing and future sources. However, despite extensive and successful research and development, progress in deploying CCS has stalled. No fossil fuel burning power plants, the greatest source of CO_2 emissions, are currently using CCS, and publicly supported CCS demonstration programmes are struggling to deliver actual projects. Yet, CCS remains a core component of national and global emissions reduction scenarios. Governments have to either increase commitment to CCS through much more active market support and emissions regulation, or accept its failure and recognise that continued expansion of fossil fuel burning energy capacity is a severe threat to attaining climate change mitigation objectives.

Introduction:

Burning fossil fuels is expected to remain the dominant source of energy for decades to come[1] (Fig. 1). Capturing and isolating the CO_2 from fossil fuel combustion could help prevent the rise of atmospheric CO_2 concentrations. As a result, carbon capture and storage (CCS), the selective capture and long-term geological storage of CO_2 from fossil fuelled power plants and large industrial sources is a much heralded and major component of many national and global emission reduction scenarios. For example, the International Energy Agency (IEA) Blue Map scenario[2] envisages a 19% CO_2 reductions contribution from CCS by 2050. This suggests a need for the construction of hundreds of CCS operations worldwide in the 2020s, rising to thousands in the 2030s and beyond, capturing, transporting and storing over 8Gt of CO_2 per year by 2050 – double the mass of current global annual oil consumption[3]. To date, the viability of CCS to deliver on anything approaching this scale remains unproven – confirmation or otherwise is essential to inform climate mitigation strategy and to have any hope of limiting atmospheric CO_2 levels to 450ppm[4].

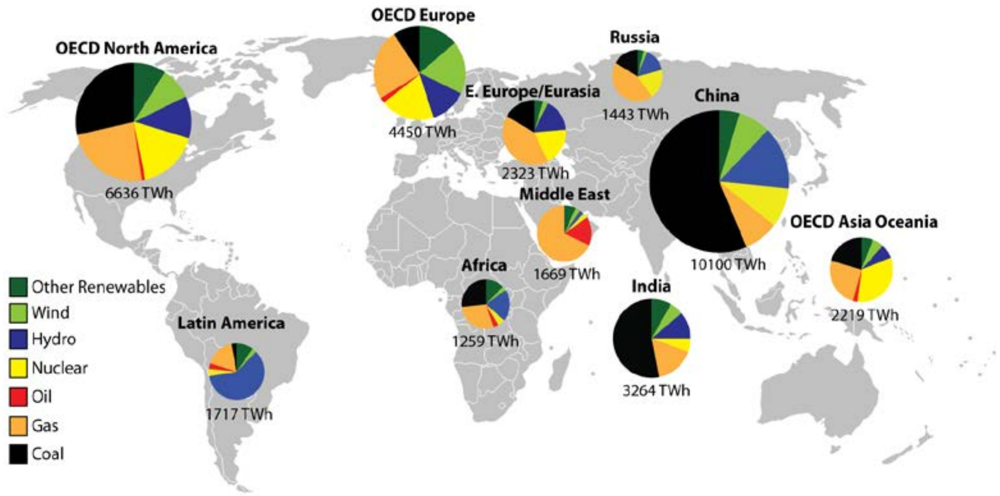

Fig. 1: Projected global electricity sources in 2035. Fossil fuels continue to dominate in many developed and developing economies. CCS is the only technology currently proposed that could enable emissions mitigation with continued fossil fuel use. Data from IEA World Energy Outlook 2011 New Policies Scenario[1].

The IEA World Energy Outlook 2011[1] forecasts that existing energy facilities will account for four-fifths of the available energy-related emissions budget to 2035 without exceeding 450 ppm atmospheric CO_2 concentration. Without further action the remaining fifth will be built by 2017 (Fig. 1). This predicament presents clear challenges for CCS. Is it technically feasible? If so, how can it be made to deliver? To answer these, we examine the status, prospects and challenges facing CO_2 capture, transport and storage processes, assess current CCS activity and explore necessary actions to enable its effective deployment.

CCS is not perfect but is technically feasible with existing technologies. Current capture processes can remove 85-95% of the CO_2 contained in the waste gases produced by a power plant or industrial process. The capture, transport and storage processes all require energy, so additional fuel needs to be extracted, transported and burnt to produce the same saleable output of electricity or product[5]. However, no alternative yet exists for mitigating emissions from the continued use of fossil fuels for electricity generation, or from high CO_2 emitting industry e.g. steel, cement and fertiliser production.

Capturing CO_2

Industrial scale capture of CO_2 from power plant and other large sources presents a complex technical challenge but is achievable now. Pilot (up to 1/10th scale) testing and development integrated with commercial sources has proven successful, and major industrial technology vendors are confident in their ability to deliver commercial scale CO_2 capture facilities on power plant, generating low-carbon electricity at a levelised cost comparable to that from renewables and nuclear[6]. CO_2 capture typically takes one of three different approaches: post-combustion - CO_2 removal following normal combustion; pre-combustion – CO_2 removal prior to combustion (e.g. following gasification of solid fuel); and oxyfuel – altering the combustion constituents to produce a highly concentrated CO_2 waste gas. As the single largest source of anthropogenic CO_2, the deployment of CCS on coal power plants is an immediate priority. For coal, there is as yet no clear winner among the close-to-commercial CO_2 capture approaches. Large scale coal power CCS demonstration experience is critical to comparing the merits of the different methods for new coal-burning plant, whereas post-combustion is the simplest approach for retrofitting existing plants.

Continued construction of new fossil generation capacity worldwide requires the development and delivery of retrofit CO_2 capture options. Retrofitting CCS to existing plant presents considerable, though by no means insurmountable, technical challenges. A recent study commissioned for IEAGHG[7] explored potential approaches to allowing at least some beneficial integration between power plants and retrofitted capture facilities. Measures to encourage easier (and cheaper) subsequent CO_2 capture integration in newly built unabated power plants at relatively marginal upfront cost (typically expected to be no more than around 1% of total capital cost of the plant) – 'capture readiness' – are now included in some jurisdictions (e.g. the EU). The effectiveness of these requirements will depend on how stringently they are implemented and enforced[8,9].

Increasing natural gas availability and affordability resulting from the development of unconventional gas extraction (shale gas) has strengthened the need to demonstrate and deliver CO_2 capture on gas. Fuel switching from coal to gas generation can deliver significant and rapid emissions reductions, but gas is still a high CO_2 emitting fuel and the longer-run aim for energy de-carbonisation requires CCS application to both coal and gas. A growing body of work indicates gas with CCS may prove both economically comparable and technically (the impact on overall generation efficiency) advantageous over coal with CCS especially if assessed by cost per unit low carbon electricity (instead of the common but arguably less relevant metric of cost per unit CO_2 abated)[10-12]. Post-combustion capture is currently favoured for CCS on gas power plants. The lower flue gas CO_2 concentration makes separation more challenging, but once captured the CO_2 volumes needing transportation and storage per unit electricity produced are around half those of coal. Oxy-combustion options for gas are under development but require significantly more effort to reach commercial viability. Pre-combustion of natural gas is technically feasible but is considered unattractive as there are few advantages in transforming one gaseous fuel to another. With hindsight, CCS demonstration programmes and associated research underway in the developed world are perhaps overly targeted on coal power. The research (and related industry) community needs to also consider how CO_2 capture experience gained on coal could be best adapted to gas.

As a relatively immature technology, considerable opportunity exists to increase capture efficiency and reduce costs[13]**.** One key challenge is to balance exploration of relatively high risk options that might offer step-change advances, with the development of incremental improvements to established technologies that can more rapidly be applied. For technologies available or close to commercial deployment, details associated with realistic operating environments need to be addressed. In electricity networks with significant renewable generation capacity, flexibility from any fossil-fired power plant with CO_2 capture will be crucial to achieving a reliable low-carbon electricity supply[14]. While well acknowledged, capture flexibility has received inadequate attention until recently and is a priority both in terms of delivering low-carbon energy, and in providing investor confidence in the long term viability of CCS in markets where future base-load requirement is uncertain. Lastly, given the increasing likelihood of CO_2 emissions reduction targets being breached, the CO_2 capture community should also look to developing scientifically robust 'carbon negative' (see Box 1) solutions that might be required to stabilise or reduce atmospheric levels of CO_2.

CO_2 transport

Onshore, CO_2 pipeline technology is well established with thousands of miles of pipeline supplying enhanced oil recovery (EOR) operations in the southern US. Offshore, a small amount of CO_2 pipeline is also in operation. Further research is underway into many aspects including corrosive process prevention – establishing standards for water and other trace chemical content that might result from different source and capture varieties, mechanisms to prevent catastrophic pipeline failure resulting from Joule-Thompson cooling, and understanding CO_2 dispersion in the event of leakage. But knowledge is sufficient to proceed with projects, which will in turn provide invaluable operational experience.

CO_2 shipping, building on experience with Liquefied Natural Gas (LNG), can be used to fill specific niches. Small CO_2 volumes can be shipped at relatively low cost which could prove valuable in early offshore storage development, enabling flexibility and cost-efficient testing of offshore storage sites. Longer term, shipping may remain cost-effective for very long distance transport especially from isolated sources.

The main challenge for CCS transport infrastructure is planning and coordination. Geographical locations of CO_2 sources and possible storage sites rarely match. Any significant degree of CCS deployment will likely require considerable transport infrastructure with large scale shared networks, e.g. across Western Europe to storage in the North Sea, offering considerable cost-savings over individual developments[15]. While logical, developing large CO_2 transport networks presents a classic chicken and egg problem. An existing transport infrastructure, adapted for the connection of new sources and sinks, through for example the over-sizing of pipes, would make deployment of CCS easier, cheaper and thus potentially faster. But, the rewards for investing in such infrastructure can only be reaped in the future after substantial CCS deployment has taken place.

Long-term storage of CO_2

Ultimately, the success of CCS depends on the safe and secure long-term storage of CO_2. Geological storage, where CO_2 is injected into a deep subsurface storage site has emerged as the preferred option. CO_2 has been injected into the subsurface since the 1970s to increase oil production via CO_2-enhanced oil recovery (EOR). While EOR operations currently inject millions of tonnes of CO_2/yr, for CCS to seriously impact on CO_2 emissions the amount injected must increase by orders of magnitude. This requires a fundamental problem to be overcome – the subsurface does not contain any empty space. Injection of CO_2 into either depleted hydrocarbon fields or saline formations will raise the formation pressure causing either displacement or compression of the existing formation fluids.

In a depleted oil or gas field the pressure can be raised to be close to the initial discovery pressure of the field without any detrimental effects on cap rock integrity[16]. However, if a depleted oil field has undergone water injection for secondary oil recovery, water will now partially fill the spaces that previously contained oil, maintaining a high reservoir pressure and limiting injection capacity[17], although producing extra oil via EOR can partially overcome this issue.

Saline formations (also known as saline aquifers) offer much larger CO_2 storage potential. Early research suggested that these had the capacity to store hundreds of years of CO_2 emissions[5]. These original estimates have now been downgraded, as they did not accurately take into account the fluid pressure increase which would result from the injected CO_2[18,19]. For storage security it is essential that the fluid pressure in a saline formation is not significantly raised to ensure that faults and fractures are not created or reactivated. The increase in fluid pressure is due to two issues. Firstly, a local overpressure effect around the CO_2 injection wells, as a result of high CO_2 velocities created by injection. Increasing the number of injection wells and spacing them appropriately can control this albeit at additional expense[18]. Secondly, regional pressure build up from the inefficient displacement of water by the injected CO_2, meaning that the volume of water being displaced is not enough to compensate for the volume of CO_2 injected[16]. This cannot be reduced by increasing the number of injection wells and is the key limiting factor in the storage capacity of a given saline formation.

Pressure dissipation in saline formations has recently been hotly debated[20-22]. The debate focuses on whether the pressure induced by CO_2 injection can dissipate laterally, termed an 'open formation', or cannot, a 'closed formation'. As a closed formation will not permit pressure dissipation, CO_2 injection will cause pressure build up, low injectivity, brine displacement and possible CO_2 leakage. In reality natural saline formations are somewhere in the middle of these two scenarios and are 'semi-closed' with respect to single phase flow[23,24]. This is due to the inherent flow characteristics of the sealing rocks surrounding the formation. For pressure dissipation this includes not just the top seal as conventionally considered, but also side seals and base seal. Rigorous modelling work has shown that there is a range of seal permeabilities which can retain CO_2 and yet transmit pressure to relieve injectivity[19]. In the event that pressure build up becomes an issue, it is possible to produce (extract) water from the formation, alleviating pressure build up and creating additional volume into which CO_2 can be injected. Water production is routine in the hydrocarbon industry, with an average of three times more water than oil being produced on a daily basis[25].

There are currently three projects injecting in the region of 1Mt CO_2/year apiece into saline formations. Snøhvit (Norway) experienced a significant pressure build up early in the injection phase, but this was remediated by re-perforating the well at a slightly shallower depth, allowing access to a portion of the saline formation with better injectivity[26]. No such pressure build up problems have been experienced in the In Salah (Algeria) and Utsira (Norway) saline formations, despite a four order of magnitude difference in the injectivity between the formations[27]. Future injection rates will have to be an order of magnitude larger again and the response of a saline formation to such a large quantity of CO_2 is difficult to simulate. As indicated by the initial injection issues experienced at Snøhvit, the only certain means to identify how a particular formation will respond to dynamic injection of CO_2 is to actually inject CO_2 into it. Evaluation of the response of a formation could be achieved through the test injection of a small amount of CO_2 allowing injectivity issues to be identified before large scale injection begins.

In order to get the greatest learning benefit from early projects, captured CO_2 should both be stored in the best available sites to establish confidence, and also (in smaller quantities) be strategically used to test potential future storage reservoirs. Adopting a phased approach, using a secure closed structure such as a depleted gas field within a saline aquifer for initial storage, would allow CO_2 to be easily injected into the aquifer adjacent to the gas field enabling accurate pressure responses and injectivity to be determined to inform about suitability for further CO_2 storage[28]. All potential storage sites are to some extent unique. While it is possible to transfer experience from one site to another, there will always be uncertainty that can only be addressed by actually injecting CO_2. Specific injection and monitoring strategies have to be devised for each site but this should not prevent CO_2 storage taking place. At present there are some 30 different CO_2 storage pilot projects operating globally, all of which are successfully injecting CO_2 and demonstrating that it can be traced and accurately monitored. Without doubt, secure storage verification and monitoring remain an area of development and we do not yet have all of the answers, but we do know enough to get started.

Integrating CCS

Integrating CCS components is a challenge in terms of both technical design, and managing the diverse expertise and expectations from the wide range of disciplines and industries involved[29]. Technical issues include agreeing standards for the CO_2 – pressure, temperature, impurities – as it passes between different components, and managing flexible operation and intermittent flow across the system. System integration has been achieved at pilot scale, but commercial-scale CCS demonstration is crucial to understanding and developing effective large-scale system integration.

Delivering CCS

Four large scale CCS projects are currently in operation – three on facilities scrubbing CO_2 from extracted natural gas, and one storing CO_2 produced from coal gasification. Additionally, a number of natural gas processing operations in the US sell CO_2 for EOR use. In all these cases, the technical novelty and additional expense lies principally in the compression, transport, injection and monitoring of the CO_2 in place of venting it into the atmosphere. In contrast to power plant or energy-intensive industry, the CO_2 capture and its energy requirement and costs are essentially integral to the overall production process, making such projects relatively low hanging fruit in terms of complexity and cost.

However, while these projects capture and store significant volumes of CO_2, they are far from carbon neutral. The products remain high carbon fuels that are subsequently burnt without abatement. We recommend the division of CCS projects into three classes in terms of their overall CO_2 emissions reduction[30] – carbon positive (7 projects existing – including EOR storing projects, 5 in construction, 29 in planning – delivery uncertain), near carbon neutral (26 projects in planning – delivery uncertain), and carbon negative (largely speculative)[31] – see Box 1. This is not to say that carbon positive projects should not be encouraged. They remain beneficial as compared to no abatement, and offer the opportunity to establish CO_2 transport and storage infrastructure relatively cheaply and with relatively minimal policy support.

Box 1: Classes of CCS project

Class 1: 'carbon positive' projects where a significant proportion of the carbon in the fuel will still be released to the atmosphere as CO_2. This is because the commercial product still contains significant amounts of carbon which is released when the products are combusted (e.g. natural gas processing, refineries, coal-to-liquids). Projects storing CO_2 as part of enhanced oil recovery (EOR) operations resulting in increased oil production may (or may not) be carbon positive depending on project specifics.

Class 2: 'near carbon neutral' projects where the vast majority of the carbon in the fuel is converted to CO_2 that is captured and stored, producing a commercial product which contains no combustible carbon (e.g electricity, hydrogen, heat).

Class 3: 'carbon negative' projects where there is a net reduction of cumulative CO_2 in the atmosphere. This could be achieved by direct removal of CO_2 from the air or by applying CCS to the combustion of biomass to produce electricity (using similar technology to that used for CO_2 capture from coal and gas combustion), so that CO_2 removed from the atmosphere by the biomass growth is not released when it is combusted and more CO_2 is fixed as replacement biomass is grown.

All currently operating large scale CCS projects are class 1, proposed CCS demonstration projects (see main text) are predominantly class 2, and class 3 remains largely speculative at this stage.

Efforts to establish CCS on fossil power plant and industry (Class 2 candidates) are focussed around publicly supported CCS demonstration programmes. Intended to accelerate development by making up the capital funding difference between actual project cost and commercially viable cost, a global total of between US $ 14 and 20 billion is currently (2012) available to support first generation large scale CCS demonstration projects[32]. Funding CCS demonstration programmes has inevitably resulted in debate over the relative merits or otherwise of CCS in climate mitigation. Their primary role is to inform this debate by establishing evidence in three key areas. First, cost-discovery for fully integrated CCS technology at commercial scale and operation; second, by enabling wider exploration of storage viability and availability; third, by testing the stakeholder (government, industry and publics) acceptability of CCS at scale.

At first glance, CCS demonstration programmes and associated research and development activities seem encouraging. In addition to operating commercial projects, sixty-five large scale projects (the vast majority on coal fired power plants) are in some stage of development[31]. Numerous smaller scale pilot projects have successfully tested capture technologies. Storage assessments and some limited testing have identified appropriate storage locations, and regulatory frameworks to permit CO_2 storage are being enacted. However, despite half of the total available funding for CCS demonstration being at least provisionally allocated to projects, actual delivery is, at best, worryingly slow and is falling far short of that required to significantly cut CO_2 emissions in the near future (Fig 2).

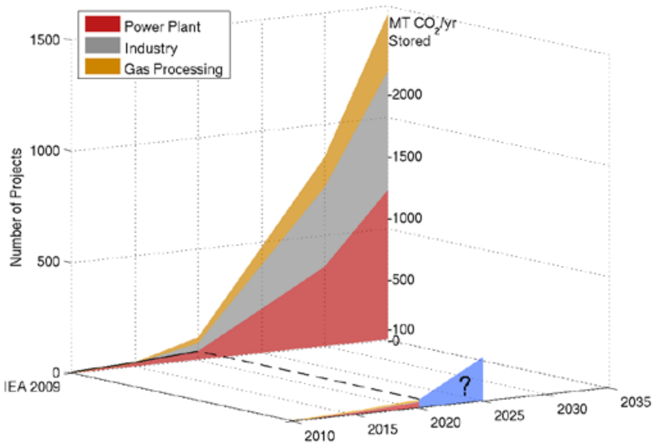

Fig. 2: The IEA 2009 BLUE Map scenario (back) presented an ambitious pathway for CCS deployment contributing to stabilising atmospheric CO_2 concentration at 450ppm[2]. CCS demonstration programmes are suffering delays and setbacks reducing project numbers and pushing delivery for many projects back to 2016-17 and beyond, suggesting that at best by 2020 only half the number of projects envisaged in the BLUE Map might happen (front). Subsequent deployment remains highly uncertain. Data compiled from SCCS global CCS project map[31].

Only two of forty-one currently proposed power plant (class 2) CCS demonstration projects – Kemper County (Mississippi, USA) and Boundary Dam (Saskatchewan, Canada) – are commencing construction. Both have received considerable public capital expenditure funding and tax breaks (around $700 million apiece), and both will sell captured CO_2 for use in EOR. Worse, well funded and technically advanced flagship projects, e.g. AEP's Mountaineer (West Virginia, USA), ZeroGen (Queensland, Australia) and Scottish Power's Longannet (Fife, UK) have been cancelled, and with considerable delays the future of many others is in serious doubt. A degree of attrition is inevitable for any innovative technology, but progress is both much slower than international ambition: 'to launch 20 CCS projects on power and industry by 2010' (G8 2008)[33], and inadequate to properly and timely inform policy options.

Making CCS happen

Ultimately progress with CCS hinges on the political will to make it happen, and CCS is facing the challenge of going from talk to action. The on-going global financial crisis is severely constraining both public and private appetite for major investment at a critical moment. Further, with influential countries and industries (motivated by perceptions of the cost and complexity of climate mitigation) working against progress with climate policy, the will to act on CCS is faltering. It may even be that such actors are keen to talk about CCS to avoid acting on climate policy – the governments expressing the most enthusiasm for CCS are not necessarily the same actors that have the highest ambitions regarding carbon mitigation[34-36]. Assuming there will be a political will to act, there are key policy measures that need to be adopted.

(i) Real incentives required

In the absence of stringent CO_2 emissions regulation (via a high carbon price or otherwise), CCS for electricity generation (class 2) is a costly process with little revenue benefit. This is preventing early deployment and in turn precluding learning and possible cost reductions. Producers of CO_2 perceive little advantage in being first movers in CCS. Public funding to cover the additional capital expenditure of construction is available, but without additional revenue return for CCS-abated low-carbon electricity (or other products), the business case is weak. Technology development involves considerable commercial risk, and only where CCS offers a possible asset-management benefit (e.g. as a long term future for fossil fuel owned by a utility), or reliable revenue through the sale of the CO_2 (e.g. for EOR) can this risk perhaps be justified to, and by, investors. To date, the frameworks created by policy makers have encouraged utilities and industry to examine CCS, but not to seriously commit to investment[37]. Alternative generation methods, or inactivity, currently have a more credible return.

This problem is well-acknowledged, but efforts to address it are limited. As part of wider electricity market reform, UK Government is including CCS as a low-carbon generation method available to receive an incentive price, but critical specifics are yet (July 2012) to be clarified. In the EU, carbon prices remain far too low and uncertain to act as an incentive, while in the US, although preferential pricing (rate-recovery) for CCS electricity remains in consideration in some states and enabled in Mississippi[38], others have rejected it leading to project cancellations.

Carbon pricing offers simplicity, but also uncertainty and vulnerability to external shocks – the EU Emissions Trading Scheme price has plummeted to un-envisioned levels courtesy of over-supply resulting from global recession, increased gas availability and other factors. Either carbon pricing needs significant reform to deliver a high price with long term certainty, or (and) demonstrating CCS, like early wind energy, needs to be made temptingly profitable by attractive tariffs, in the form of a price bonus or a price guarantee[39]. All low-carbon technologies are required in order to deliver substantive climate mitigation. Ascribing to the principal of 'let the market decide', developed governments are reluctant to pick winners among low-carbon technologies. Properly supporting CCS demonstration is about establishing a possibility, not picking a winner.

Almost all the CO_2 that could potentially be captured and stored is currently 'leaking' into the atmosphere. Long-term national and regional emissions reduction targets are in place, but there is little clarity as to how they are to be achieved. Exercises to explore potential decarbonisation pathways (e.g. the EU 2050 Energy Roadmap[40]) envision a significant role for CCS, but most (if not all) jurisdictions are yet to develop coherent strategies for its deployment. Yet, we continue to allow construction and operation of fossil power plant and energy intensive industry.

Assuming CCS demonstrations happen and are successful, the question then becomes what do we do next? An approach using mandated emissions reduction timetables (with or without incentives for CCS) would give utilities and industry the choice between investment in CCS or replacing their CO_2 producing capacity with other low-carbon alternatives. Alternatively, the focus could be on the carbon containing fuel. In a carbon constrained world, CCS is the long term future for the fossil fuels industry. Instead of CO_2 storage being a separate (and minor) possible part of the hydrocarbon industries' activities it could become an integral part of the overall fossil fuel extraction business model. The price for continuing to extract and sell fossil fuels is the proper disposal of the consequences. Such transformatory changes cannot be introduced at full force overnight, but phasing them in can begin now.

(ii) Ensure regulation does not inhibit CCS development

CO_2 storage must be appropriately regulated to protect the public, but excessive concern, given the minimal health risks[41], has perhaps had a detrimental influence on some early CO_2 storage legislation. The current EU legislation places difficult technical and financial restrictions on potential storage site developers. First, 'permanent' CO_2 storage is required – a scientifically naïve requirement. Second, the potentially very onerous liability arrangements attached to stored CO_2 are inconducive to encouraging investment in early projects.

With respect to 'permanence', a rigorously scientific approach is required. Given that the purpose of CO_2 storage is to mitigate climate, arguably a 1% eventual leakage from a deep geological store is less problematic than 100% immediate leakage from the power station flue stack. Early modelling work shows that even relatively insecure CO_2 storage where a significant proportion (up to 1% per year) of the CO_2 migrates back to the atmosphere could be beneficial to at least medium-term climate mitigation efforts[42,43]. Further determination of the relationship between long-term leakage and climate would assist in properly informing storage regulation.

Regarding liability, it remains unclear how unplanned CO_2 migration would be penalised, and what long-term arrangements would be made for the period following closure of a storage site. Storage from demonstrations must be recognised as experimental, and so if government wishes to explore CCS as an option and make investment forthcoming, it is likely to need to take a large share in the risks. Post-demonstration, the state could take over liability within 20-30 years of successful injection completion. Another approach would be to copy the US Price-Anderson Act arrangement for civil nuclear accident liability which blends mutual company-contributed insurance with commercial insurance and final state liability.

(iii) Encourage CCS in the developing world

Low-carbon technology options need to be rapidly deployed worldwide to mitigate climate change. Considerable CCS research and development activity is already underway in China – as of 2006 the largest emitter of energy-related CO_2. Impressively low capture costs ($30-35 per tonne CO_2) have been achieved at pilot post-combustion CO_2 capture facilities[44], and numerous power plant and industry large-scale demonstration facilities exploring all the available technologies are in development, both domestically and in partnership with western technology vendors (see Fig **3**). However, CCS research and development activity does not necessarily result in deployment - serious international political action on climate remains critical.

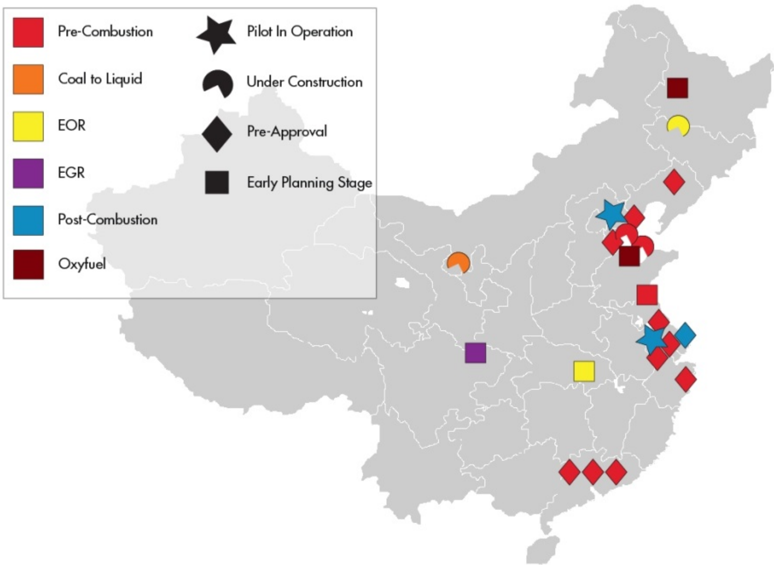

Fig. 3. CCS activity in China. Post combustion pilot capture facilities are in operation on conventional coal power plants. Some IGCC (pre-combustion capture) coal power plants are under construction and others are in the final stages of planning. Oxyfuel coal power plant, capture from industrial facilities and CO_2 EOR and saline formation storage are also in development (Source WRI[45] and SCCS CCS projects map[31]).

Enabling deployment in developing economies raises two major issues – financing and technology development support. Following many years of negotiation, CCS was formally included in the Clean Development Mechanism (CDM) at the Durban 2011 UNFCCC[46]. However, the key issue of long-term liability agreement was avoided by placing it at the discretion of host countries to negotiate with investors. At present, it remains unlikely that the CDM, dependent on the activity of other carbon markets, can realistically supply the finance required. Technology support raises issues around IPR[47] protection. While a balance that gives some benefit from research investment must be found, it is important to recognise that the market in CCS technology is currently essentially speculative. The overarching priority should be to coordinate and share efforts to help create and establish worldwide deployment of the technology.

<u>Outlook</u>

CCS currently sits at a critical point[48]. The next few years will determine whether the present aspirations attached to it as a technology option for climate mitigation are achievable. The outcome of CCS demonstration remains unclear. Should they prove, in some combination, technically, financially or politically overly challenging, CCS as planned will be shown inadequate and the development of further fossil fuel derived energy capacity <u>must</u> be recognised as making current climate change mitigation objectives unattainable. Alternatively, CCS could prove technically possible, but on balance more costly than alternative (non-fossil fuel) technologies. Limited deployment might take place where CCS is of benefit to managing existing assets, and on industrial emissions where no alternatives exist, but its overall role would be much reduced. Lastly, CCS demonstration could prove successful both technically, in achieving reasonable cost and cost-reduction potential, and in attracting renewed political interest. Significant reductions in CO_2 emissions could then be achieved through rapid worldwide deployment, both as a retrofit to existing facilities and on new power and industrial plants.

Lessons should be learned from history. Governments have to intervene, either by providing money and direct command, or by making the rules of tax, planning, extraction, operation and emission such that de-carbonisation is guaranteed. Development and deployment of early nuclear power technology resulted from direct management by national governments through programmes lasting multiple decades. By contrast, as a result of the introduction of stringent, ambitious regulation forcing the market to innovate and adapt, flue gas desulphurisation on coal power plant has been largely successfully implemented in participating countries[29,49] Renewables technologies have also benefited from both legislative and public support. The current stagnation of CCS activity shows that government activity to date has been inadequate. If governments want CCS available, they have to make and sustain a major commitment that makes the market deliver.

CCS has much to offer. While eventual aspirations for a low-carbon future should rightly focus on demand reduction, renewable energy technologies and energy efficiency, it seems highly unlikely that these options can be scaled quickly enough to meet our seemingly ever-growing demand for energy. Considerable research effort and progress on all the constituent processes strongly indicates that CCS can provide an effective and rapidly deployable technology playing a major role in preventing disastrous climate change. A number of scientific challenges undoubtedly remain, and linking the research agenda with priorities in the real world is crucial, but we know enough to get started. For CCS to realise its potential in reducing CO_2 emissions it is imperative that fully integrated large scale CCS projects are delivered as soon as possible. This is essential to allow learning by doing, facilitating the possibility of rapid, widespread and effective global roll-out. To this end, the key decisions remain in the hands of government. CCS is technically deliverable, but will it be delivered before it is too late?

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Author contributions:
All authors contributed extensively to the work and text presented in this paper, with V. Scott being the lead author.

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