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Learning through a portfolio of carbon capture and storage demonstration projects

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Carbon dioxide capture and storage (CCS) technology is considered by many to be an essential route to meet climate mitigation targets in the power and industrial sectors. Deploying CCS technologies globally will first require a portfolio of large-scale demonstration projects. These first projects should assist learning by diversity, learning by replication, de-risking the technologies and developing viable business models. From 2005 to 2009, optimism about the pace of CCS rollout led to mutually independent efforts in the European Union, North America and Australia to assemble portfolios of projects. Since 2009, only a few of these many project proposals remain viable, but the initial rationales for demonstration have not been revisited in the face of changing circumstances. Here I argue that learning is now both more difficult and more important given the slow pace of deployment. Developing a more coordinated global portfolio will facilitate learning across projects and may determine whether CCS ever emerges from the demonstration phase.

Economic models deem rapid wide-scale deployment of CCS in the next few years to be essential in restraining the costs of meeting the 2 °C target for global temperature[1,2], but CCS technologies are still at the pilot and demonstration phase. Paradoxically, it is primarily the costs of the early demonstration projects that have hampered further deployment. As each CCS 'demonstration' plant costs on the order of US$1 billion, during a time of fiscal austerity it has proved difficult to justify public support. Near-term pressure to develop CCS has also eased as most countries found it easier to meet their Kyoto targets because of the economic crisis (and other factors such as the US shale gas revolution). Meanwhile, unlocking private financing remains elusive and depends on developing necessary legal, institutional and commercial frameworks, as well as significant cost reductions and de-risking that can only come from operating multiple plants[3].

Difficulties in justifying pilot and demonstration plants or deployment policy are hardly restricted to CCS, and can be found for nuclear power, renewables and indeed virtually any novel technology[4,5], but the emphasis on demonstration is most common in the process industries[6]. At its broadest, CCS 'demonstration' has been identified as having a dozen or more manifestations, ranging from discourse creation to coalition formation[7]. I acknowledge the many important dimensions of demonstration, indeed, different disciplines have radically different conceptions of the nature of demonstration[6]. Given the overwhelming government and industry focus on cost reduction[8,9], however, I use this as a test of how learning is operationalized. Governments should at least be able to construct a portfolio of projects along the dimension that they deem as central to the enterprise of demonstration.

The technical rationales for demonstrations being large-scale include understanding power system reliability and performance[10] and adequately characterizing each geological formation[11]. As large-scale projects must store roughly 1 million tCO_2 per year[10,11], this scale requirement poses a number of challenges when seeking to learn from multiple projects.

In this Perspective, I explore the history of CCS demonstration in an effort to understand how the initial optimism about large-scale rollout led to multiple, uncoordinated efforts to learn from diversity. In the absence of widespread deployment of CCS, the projects that have endured do not form a coherent programme aimed at learning. Going forward, therefore, any effort to successfully relaunch CCS at scale will need to revisit the fundamental case for demonstration, including how best to derive the most learning from the billions of dollars already invested and that will need to be invested in the next wave of projects. There is a need for greater clarity over what time frame, at what scale, at what cost and to what end CCS demonstration is being pursued[12].

Great expectations for CCS

CCS technologies have long faced the challenge of wanting to be seen, on the one hand, as novel technologies that warrant public support and, on the other, as a well-established set of technologies that should reassure investors (including governments) that the first plants can be viable at commercial scale (~300 MW capacity)[13]. In some respects, CCS as a suite of component technologies is indeed hardly novel. Each element in the chain has a long history — Statoil's Sleipner project has been storing a million tonnes of CO_2 a year in the Utsira field under the North Sea since 1996[14]; CO_2 has been shipped hundreds of kilometres from natural sources in Colorado for use in enhanced oil recovery operations in west Texas for over thirty years[15]; and CO_2 has been separated from natural gas and hydrogen since 1930 and hundreds of plants worldwide currently remove CO_2 at a range of scales up to 40 MW (ref. 16).

The first large-scale CCS power project was proposed by BP at Peterhead in 2002[17]. Yet, only in late 2014 did Boundary Dam in Saskatchewan become the first fully integrated CCS power project that incorporates capture, transport and storage. The owner of the 120 MW unit, SaskPower, has claimed that it would be able to reduce costs by 20–30% for the next unit at the same plant[18].

CCS first emerged on the international agenda at the Gleneagles G8 summit in Scotland in 2005, leading to a programme of work for the International Energy Agency (IEA) and to several countries seeking to roll out CCS technologies. In that same year, the Intergovernmental Panel on Climate Change (IPCC) produced a Special Report on CCS to review the state of knowledge[10]. During this period of optimism through to 2009, the European Union,

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Box 1 | National ambitions for CCS.

Driven by aspiration for rapid wide-scale deployment, there was a competition in rhetorical ambition. In March 2007, European leaders issued a declaration calling for up to 12 CCS demonstration power projects to be in operation by 2015 and launched the EU Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP). This aim was amended to 10–12 projects by 2020 and envisaged 80–120 commercial CCS projects by 2030 in the EU alone[54].

In parallel, Norway also committed to taking the lead on CCS technology, and in 2006, Prime Minister Stoltenberg described CCS as their "moon landing" with a pledge to capture 100,000 tonnes a year at the Mongstad refinery on a pilot basis and then scale that up to 2 million tonnes a year after five years[55].

Other countries also signalled their ambitions. The United States proposed the US$1 billion Futuregen project in 2003, which would have been a 275 MW integrated gasification combined cycle plant in Illinois, followed in 2009 by stimulus spending pledges of over US$3 billion on a range of projects. The Canadian government offered C$650 million for large-scale CCS projects, supplemented by C$1.3 billion from the Government of Alberta. Apart from project support, Australian Prime Minister Rudd pledged A$100 million per annum over four years for a Global CCS Institute. In 2007, the British government offered £1 billion in capital support (and the promise to cover higher operating expenditures) as part of a competition for a coal-fired post-combustion project, which was to be followed by three further CCS plants. Other major countries actively investigating large-scale CCS projects (with differing degrees of state and private interest) included the Netherlands, Germany, France, Poland, Spain, Italy and Romania as well as developing countries including China, Brazil, Saudi Arabia and UAE.

Canada (or rather, Alberta), Australia and the United States each developed their own sets of criteria that would guide the deployment of a portfolio of projects. The different nations' proposals are summarized in Box 1.

Although countries pledged significant sums at the time, there was an obvious disconnect between the envisaged role that CCS could play in keeping global temperature rise below 2 °C and the reality of government budgets and the legal, regulatory, commercial and technical challenges of deploying dozens or even hundreds of new billion-dollar power plants within a decade or two. The ambitious IEA 2009 technology roadmap imagined 100 plants by 2020 and 3,000 by 2050 with required investments of US$5–6 billion per year between 2010 and 2020, with roughly two-thirds of the investment coming in developed countries[19]. Even in 2009, given the slow pace of developing large infrastructure in most advanced economies, the proximity of 2020 did not offer much opportunity for a rollout where there would be much learning from one project to the next.

The key question is how best to learn. Research and development on CCS is seen as having one of the highest median returns[20], which begs the question of why and when to demonstrate CCS options relative to continued R&D. CCS faces unproven business models and sceptical investors, novel technology integration challenges and the need to deliver at a commercial scale while still at the demonstration phase[21].

Principles of demonstration

To establish a set of criteria, it is necessary to ask basic questions about the nature of any demonstration program. Some of the many possible objectives cited include: speed of deployment[22], value for money, industrial policy and learning potential. As we shall see, each of the first three objectives can ultimately be understood in terms of learning potential (or uncertainty reduction)[6].

Ultimately, given its higher costs, CCS will need a sustained high carbon price and/or a binding technology mandate, but first an effective demonstration is needed to convince investors (including governments) to support CCS in the near term and ahead of other competing technologies such as nuclear power or renewables with storage, Thus, the eventual speed of deployment will not depend on sheer number of projects but the success of learning at the demonstration phase.

Providing cost competition will help improve the value proposition, but 'value for money' is meaningless without a clear understanding of 'value'. Individual demonstration plants can be assessed in terms of carbon abated (or avoided) per unit cost, but if that was truly the objective, then many other technologies would offer both better value and greater certainty. At the demonstration stage at least, the chief value is in either revealing technology performance relative to expectations or other technologies (learning from diversity)[23] or demonstrating potential cost reductions at later stages (learning from replication)[24]. Thus, a technology shown to be capable of saving 30% for the next unit will be of superior value to one leading to minimal saving potential or significant cost overruns[25].

Much like basic R&D, demonstration requires tolerance of failure[26]. At the scales discussed (~300 MW or 1 million tCO_2 stored), the stakes are high and costly early failures may reduce support for the technology. Governments or regulators will want to impose budgetary constraints or otherwise protect consumers from cost overruns, but the nature of demonstration implies the need to assume some risk by identifying innovative technologies that might have a higher potential for learning[27].

Finally, national priorities such as industrial policy or energy security are put forward as justifications for CCS[28,29]. Similar to both previous propositions though, CCS will only deliver large-scale industrial redevelopment or a significant share in the energy mix if it can demonstrate that costs are reasonable and can be driven down further. Lowering CCS costs is essential in trade-exposed sectors such as steel, chemicals or cement where producers have a credible threat of shifting production abroad, unlike fixed assets such as power plants[30].

Given the focus on cost considerations, I largely neglect the important subject of social learning[12] and restrict the discussion of learning potential to learning from diversity, which seeks validation of the main available technological options, and learning from replication or learning-by-doing. There are important trade-offs and complementarities between the two. Replication assumes a degree of clarity regarding where to place resources in the hope of driving down costs, whereas investments in diversity implies a spreading of bets in the hopes of resolving uncertainties[31].

Replication has been (and is) particularly important for technologies such as solar photovoltaics or wind, which has seen costs fall dramatically as millions of kW-scale units have been produced[32,33]. In contrast, CCS projects are 'lumpy', insofar as each project is on the 100 MW scale and up and there is still the danger of technology lock-out or lock-in[34–36]. Learning may not be stable and may vary over time[37,38]. In the near-term therefore, priority should be on learning from diversity. But soon there will be a need to balance replication in the form of second- or third-of-a-kind demonstration, which will provide better assessment of cost reduction potential, against the benefits from investing in new technologies that may offer longer-term breakthroughs or benefits that may be cut off by a too-early focus on replication.

Recognizing the cost of even single plants, there have been calls for greater international coordination. Principles have been outlined[39] for a world-wide demonstration program including laudable goals such as global coordination to enable a variety of CCS

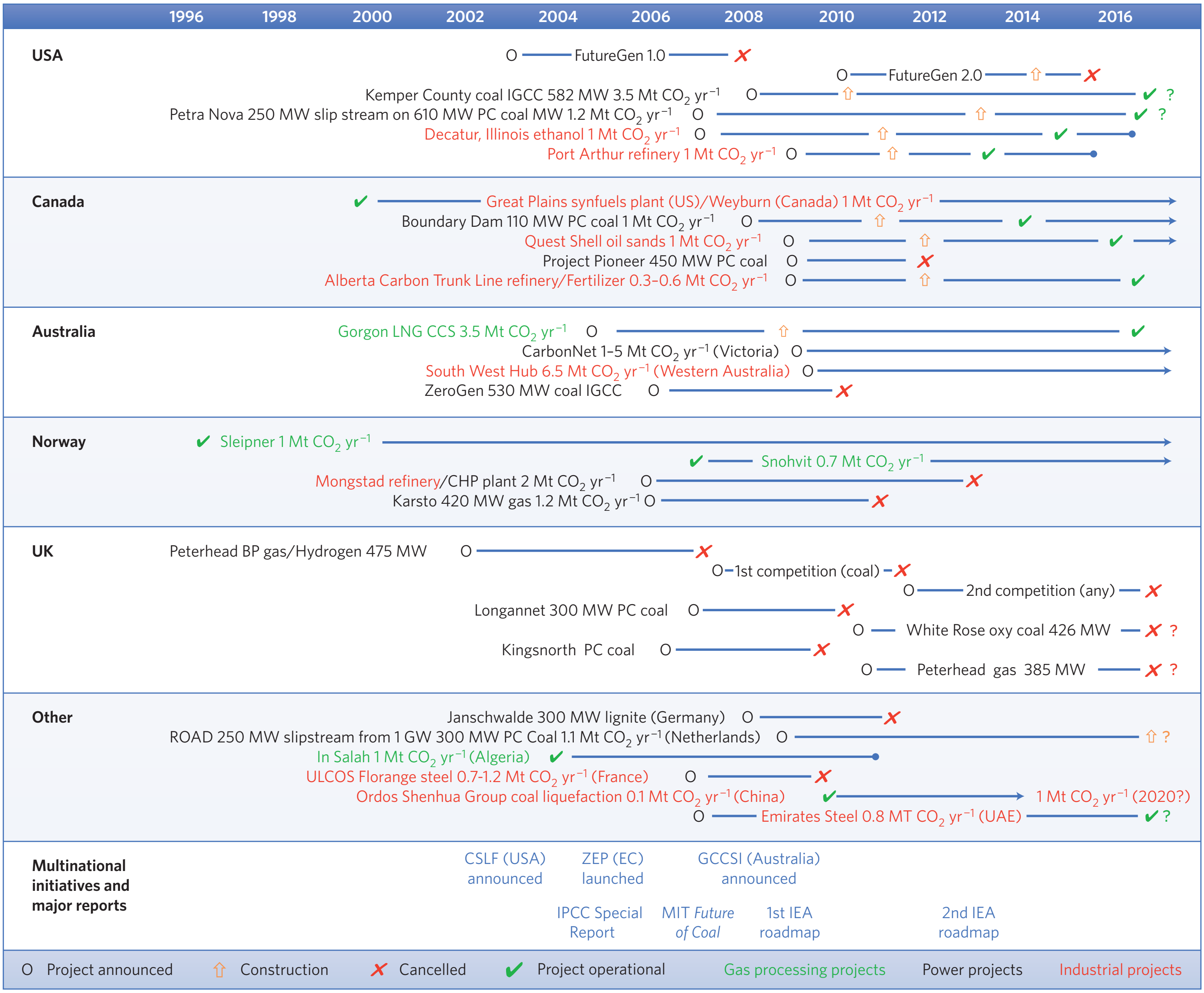

Figure 1 | Timeline of major CCS demonstration projects. There have been projects that have captured, transported and/or stored CO_2 for many decades, but I include here only integrated capture, transport and storage projects that were conceived as CCS projects. I do not include the many projects that have been announced but which never received significant government and/or industry support. Gas processing projects have largely been driven by regulatory requirements such as the carbon tax in Norway or being associated with profitable liquefied natural gas (LNG) enterprises as in Australia. Industrial projects refer to projects in energy-intensive industrial sectors including steel, cement, fertilizer and refineries. For reference, I also include major reports and cross-national initiatives. Project data is largely drawn from the MIT CCS Project Database (https://sequestration.mit.edu/tools/projects), supplemented by individual project websites and media reports.

technologies to be demonstrated in various contexts and countries, greater exchange of information and more effective communication. But most challenging is the aim of cost-sharing to pool global demonstration funds. Independent national approaches inevitably produce inefficiency and barriers to learning, but the potential for a global cost-sharing mechanism is easier to imagine for 'big science' projects such as ITER (International Thermonuclear Experimental Reactor) or LHC (Large Hadron Collider), rather than projects primarily developed by industry and aiming to be commercial within a decade[40]. Instead, a focus on fewer countries, nonbinding mechanisms, and greater use of review procedures can help facilitate more effective agreements[41].

Past efforts to develop portfolios of CCS projects

Although learning about costs was incorporated into the portfolios of CCS projects, they also added other, less clearly defined objectives or priorities, in many cases seeming to create more of a wish list that balanced out different constituencies rather than a clearly crafted set of principles that would produce a CCS rollout at least cost. Figure 1 presents a timeline of the most advanced demonstration projects and Box 2 summarizes the different national efforts.

What is striking about each set of criteria is, on the one hand, their ambition and comprehensiveness, and on the other, their independent formulation and seeming lack of coordination in development. Even if all projects had been successful, more coordination would have been warranted to improve the likelihood of genuine learning from diversity and to help reassure investors regarding technology cost.

Reflecting the ambition of the time, Fig. 2 illustrates a scenario[22] in which where there would be a 'first tranche' of demonstrations through 2015, a 'second tranche' driven by commercial and regulatory drivers from 2015 to the early-2020s and a global CCS rollout

Box 2 | National CCS programmes.

USA. US\$3.4 billion has been designated for CCS largely via economic stimulus spending: US\$1.5 billion for industrial CCS projects on a competitive basis, US\$800 million for the Clean Coal Power Initiative (CCPI), and US\$1 billion for FutureGen. In 2009 the US Government Accountability Office compared the original and restructured FutureGen projects in the US and suggested more attention instead be paid to the competitive process adopted by CCPI to demonstrate advanced coal-based power generation technology in multiple projects at commercial scale[56]. CCPI selection criteria included: a minimum scale (0.3 Mt per year) and capture efficiency, demonstrating significant progress with "less than 10% increase in electricity costs", using domestic coal, and the private sector providing at least half the funding.

Australia. The government pledged A\$2 billion (US\$1.65 billion) for demonstration projects. The Low Emissions Technology Demonstration Fund (LETDF) was a A\$500 million support scheme that sought to fund CCS demonstrations plus other novel forms of low-carbon energy. In its first round, LETDF sought to support four fossil-fuel projects (three coal and one natural gas) as well as a large-scale solar concentrator. LETDF applied five 'merit' criteria: potential to reduce emissions over the longer term, support government's policy and program initiatives, leverage greater non-Australian-government investment, demonstrate value for money, and address any significant barriers or risks for the project.

Alberta. In 2008, Alberta undertook a similar exercise and initially sought 3–5 operating projects at a cost of C\$2 billion. The government of Alberta wanted a total portfolio that added up to 5 $\mathrm{MtCO_2\ yr^{-1}}$ by 2015, including a minimum project threshold of 500,000 $\mathrm{tCO_2\ yr^{-1}}$. Each project was to be fully integrated and at least one would store more than 1 $\mathrm{MtCO_2\ yr^{-1}}$. In terms of capture and storage options, at least one would provide direct storage (for example, in a deep saline formation) rather than enhanced oil recovery, at least one retrofit and one new build, at least one electric power application, at least one oil-sand application and at least one 'other' application.

European Union. In October 2007, the EU ZEP technology platform described the manifold goals of the EU flagship program including over-optimistic objectives such as "demonstrate Europe's leading-edge technology and spur action by other countries" (notably India, China and the US), as well as objectives that relate back to the principles of demonstration listed in the main text, such as ensuring "a diverse geographical and technological spread of projects" (learning from diversity) and accelerating cost discovery (learning from replication)[54]. Fourteen portfolio criteria were presented, which can be grouped by diversity: (i) storage option: depleted oil and gas fields, deep saline aquifers, onshore and offshore; (ii) capture technology: pre-combustion, post-combustion and oxy-fuel; (iii) fuel: hard coal, lignite, gas, co-fired biomass; (iv) transportation mode: ship, cross-border pipeline; and (v) new build and retrofit.

The portfolio was also meant to include a project in an emerging economy and at least one non-power project, all of which would test efficiency, geography and commercial structures. Some of these criteria, notably learning from diversity in capture technology, are critical to the fate of CCS, but others simply reflect a subset of the many possible permutations in developing CCS projects and would not, in themselves, significantly contribute to cost reductions or de-risking.

Following initial support of €1.05 billion for six projects via stimulus spending in 2009, support was to be operationalized through the NER300 program, which would auction 300 million emissions allowances (EUAs) set aside as part of the New Entrant Reserve (NER). At the time of its launch, EUA prices hovered around €15 per tonne of $\mathrm{CO_2}$, which would have yielded almost €5 billion in available funds, primarily for CCS. Launched in November 2010, the European program was expected to co-fund eight CCS projects: one to three for each capture technology, at least three in depleted oil and gas reservoirs, and at least three in saline formations.

beginning in 2025. Updating this vision, I have added a rough schematic of what the actual deployment of CCS projects has looked like. The past decade has delivered a 'first tranche' much smaller in scale and lasting much longer than originally anticipated. Given a roughly ten-year lead time for any projects not currently in the pipeline, the real question post-2025 is how much the next generation of projects will benefit from learning and whether there is any realistic possibility of radical innovation and rapid diffusion[43,44].

The need for learning from diversity is acute. A comprehensive study[45] of the current status of CCS costs concludes that although there have been some relative shifts between technologies, the "range of mitigation costs […] show considerable overlap", leading to the same conclusion as a decade earlier in the IPCC report[10] over the inability to pick winners.

Post-2009 progress and roadmaps

The 2009 IEA CCS roadmap[19] had highlighted the need to develop 100 CCS projects over 2010–2020, storing around 300 $\mathrm{MtCO_2\ yr^{-1}}$ based on a global spend of US\$5–6 billion per year, whereas by 2013, four operational projects and nine projects under construction were expected to store some 13 $\mathrm{MtCO_2\ yr^{-1}}$ by 2016, with a spend of some US\$10 billion between 2007 and 2012. Instead of 100 plants, the 2013 IEA roadmap called for "upwards of 30 operating CCS plants", with a greater emphasis on the importance of developing countries and of industrial applications[42]. Still, given the proximity to 2020 and the current status of project funding around the world, this is an ambitious target.

Many of the proposals shown in Fig. 1 failed because of tepid or shifting government (and industry) support or because of genuine technical challenges and escalating costs encountered along the way, whereas other projects have soldiered on. In Norway, the costs of Technology Centre Mongstad spiralled almost fourfold above initial estimates leading to an investigation by the Auditor General and the Norwegian government shutting down the project and withdrawing from plans to move beyond the pilot phase.

In Alberta, Shell proceeded with a final investment decision on the Quest project in the oil sands on a zero net-present-value basis (a decision few other companies could or would be willing to carry on their balance sheet), and began operations in late 2015. The Alberta Carbon Trunk Line project is to begin in 2016, operating at a small fraction of the pipeline's capacity[46]. Other projects, such as the Pioneer power project, proved too costly to proceed.

In Australia, the ZeroGen project was cancelled by the Queensland government owing to cost concerns and a lack of viable $\mathrm{CO_2}$ storage options, but the Gorgon project will capture 3.5–4 million $\mathrm{tCO_2}$ beginning in 2017 (largely because CCS was included as part of the package to allow the lucrative liquefied natural gas facility to be sited on Barrow Island rather than onshore). Moreover, the

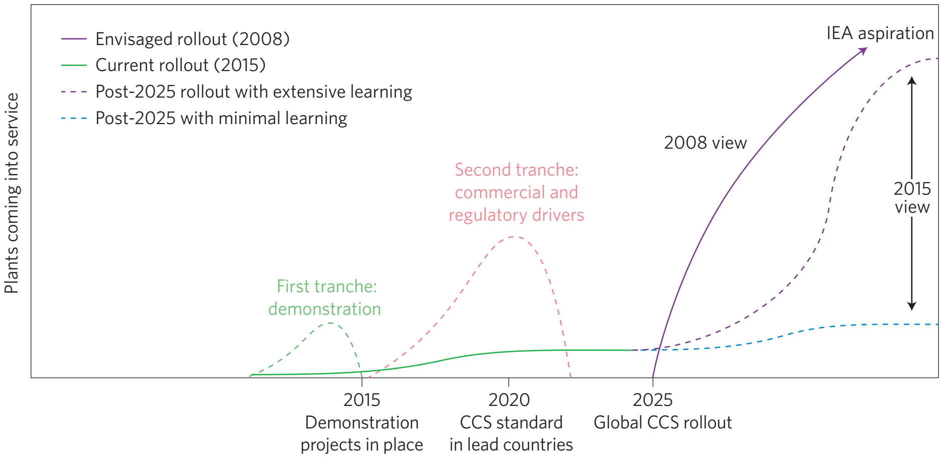

Figure 2 | An updated model for CCS demonstration and deployment. The current rollout has fallen far short of aspirations. The dashed green and red curves show two anticipated tranches of projects, leading to a rapid global rollout (solid purple line). Instead, the solid green curve shows the very few plants that have come into service to date or that are in the pipeline. If costs remain high then several other demonstration plants will be built, but there will be no large-scale rollout (dashed blue line). If learning of 20–30%, such as that claimed for Boundary Dam, can be extended, then there is a chance that, with a lag, there will be a global rollout as envisaged in the 2013 IEA roadmap[42] but following a more traditional logistic technology deployment curve (dashed purple line). Figure adapted from ref. 22, Elsevier.

South West Hub project in Western Australia and the CarbonNet network project in Victoria (both of which are ambitious pipeline projects) survived the climate-sceptical Abbott government, which was vocally hostile to CCS, because they were able to sustain moderate levels of funding, but have not yet proceeded to final investment decision.

In the United States, FutureGen 2.0, beset by delays and an impending deadline to spend its stimulus funding, was cancelled in early 2015. The 582 MW integrated gasification combined cycle (IGCC) plant at Kemper County in Mississippi is due to begin operations in 2016 after delays of several years and costs spiralling to US\$5.6 billion, above the US\$2.4 billion cap imposed by the state utilities commission. Once operational, it will be the largest power CCS project and the first to use IGCC. Other successful projects include two large industrial CCS projects at the ADM Decatur, Illinois ethanol facility and the Port Arthur refinery.

The worst record is perhaps in the European Union. Apart from the global financial crisis of 2009 reducing EU emissions, making it easier to meet emissions targets and sapping government ambitions and finances, it was also directly tied to the EU's main funding mechanism. Rather than raising the anticipated €5 billion to support CCS, the EU Allowance price halved and the NER300 yielded only €2.15 billion in funding. Moreover, the scope was expanded to include innovative renewable technologies (IRTs) and €1 billion was raised in the first round in late 2012 for 24 IRTs in 16 member states, but not a single CCS project[47]. This CCS–renewable split reflects the breadth of support for renewables compared with CCS, which is only being pursued seriously in a small number of EU member states.

Part of the reason for the lack of CCS projects was that the European Commission based its rank ordering of projects on volume of CO_2 avoided, thereby favouring large coal projects[48]. The Don Valley Power Project, a proposed 920 MW (gross) IGCC project, was ranked first overall by the European Commission but did not even make the top four projects in the UK's own competition. In the second round, €300 million was ultimately allocated to the White Rose coal oxy-fuel project in the UK (along with an additional €1 billion for 19 IRTs in 12 member states).

Until recently, the most advanced European projects were the two finalists in the UK Commercialisation Competition, but that competition was unexpectedly cancelled in late 2015. One residual learning benefit from these projects (as well as the two projects in the previous failed competition) is that the British government paid £100 million for detailed front-end engineering design (FEED) studies, so these studies are now available to future developers. Apart from the more basic problem of the credibility of government commitment, the UK Commercialisation Competition had limited the potential for learning by mandating that plants operate in base load, thereby preventing learning about flexibility, which is one of the key rationales for considering CCS relative to other low-carbon technologies.

As European countries retrenched, there have been signs of a willingness to fund across borders. For example, following German and Norwegian failures, both countries seem willing to fund the Dutch ROAD project, which now remains the most advanced CCS project in Europe, but which had been stalled because of a funding shortfall[49]. Although hardly a model for international cost-sharing, it is a first recognition of a need to move away from purely national approaches.

Conclusions

The exuberance of 2005–2009 has been replaced with obituaries of the technology[50,51], but neither extreme reflects the more nuanced current state of affairs[52]. Inevitably, CCS has been subject to a technology hype-cycle[26,53]. The expectations of the earlier period in part reflected a conflation of positive and normative assessments of technology rollouts, that is, how many large-scale CCS plants it would be technically, politically and commercially feasible to build versus how many plants would be needed if the world is to have a hope of remaining on a trajectory that would keep warming below 2 °C. Informed by the IEA and other analyses of the urgency of large-scale CCS deployment, many believed that single jurisdictions such as the EU or even Alberta could develop a sufficiently large portfolio of projects such that concerns over wider coordination or deep consideration of project timing, ordering and selection could be largely disregarded.

As the pipeline of projects rapidly dissipated after 2009, it is perhaps understandable that there has been an overwhelming focus on delivering what was left rather than worrying about coordination and learning as some projects were inevitably better than no projects. Still, for CCS to begin to play a larger role in reality rather than simply in the models of future deployment, it is imperative to finally begin to differentiate more and less costly technologies. There are, of course, many competing principles behind demonstration and cost differentiation is not in itself sufficient, but given the scarcity of projects and the overwhelming emphasis on costs by governments and industry, it is undoubtedly critical to whether CCS is to emerge from its own 'valley of death'.

The lack of CCS projects that have emerged may say more about the seriousness with which nations have addressed climate change than about CCS technologies per se. Concerns about cost reduction dominate the industry and government views on how to proceed[9], but there has been precious little effort to revisit what constitutes an effective global portfolio in the face of greatly diminished individual national efforts. Rather than imagining some centrally conceived portfolio, there is a need for more negotiation across jurisdictions and accounting for what is going on elsewhere and learning from every stage of these other projects, both foreign and domestic.

Having arrived at the current hodge-podge of projects by virtue of decisions made in 2005–2009 in a completely different political and economic context, there is now little guidance on what the next tranche of projects should seek to accomplish. If China were to aim to build a large-scale CCS project, should it choose a post-combustion coal project similar to Boundary Dam (learning by replication) or a gas-fired post-combustion or oxy-fuel coal plant (learning from diversity, assuming the UK is not going ahead with its projects)? How might China best reflect on what is needed globally and explicitly take into account projects in Canada, USA, Australia, Saudi Arabia and elsewhere (thereby strengthening international coordination)? Should greater emphasis be placed on learning about plant flexibility to improve understanding about operations and help de-risk the technology? Should it seek to demonstrate bioenergy plus CCS or an industrial CCS hub (further broadening learning by diversity)?

Striking the balance between learning from diversity and learning from replication will depend on finding ways to develop effective international coordination mechanisms and account for timing (and the inevitable delays and cancellations). There are no easy answers and the costs of each 'bet' are high, but there is an urgent need for opening a debate on the subject.

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References

1. IPCC *Climate Change 2014 Synthesis Report.* (eds Core Writing Team, Pachauri, R. K. & Meyer, L.) (Cambridge Univ. Press, 2014); http://www.ipcc.ch/report/ar5/syr/
2. Riahi, K. *et al.* Technological learning for carbon capture and sequestration technologies. *Energy Econ.* **26,** 539–564 (2004).
3. *Carbon Capture and Storage: Mobilising Private Sector Finance for CCS in the UK* (Energy Technologies Institute and Ecofin Research Foundation, 2014); http://go.nature.com/DUo6fn
4. Aldy, J. E. *et al.* Designing climate mitigation policy. *J. Econ. Lit.* **48,** 903–934 (2010).
5. Jacobsson, S. & Bergek, A. Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Ind. Corp. Change* **13,** 815–849 (2004).
6. Frishammar, J., Söderholm, P., Bäckström, K., Hellsmark, H. & Ylinenpää, H. The role of pilot and demonstration plants in technological development: synthesis and directions for future research. *Technol. Anal. Strategic Manage.* **27,** 1–18 (2015).
7. Russell, S., Markusson, N. & Scott, V. What will CCS demonstrations demonstrate? *Mitig. Adapt. Strategic Glob. Change* **3,** 105–111 (2012).
8. *The Global Status of CCS: 2014* (Global CCS Institute, 2014).
9. *The Potential for Reducing the Costs of CCS in the UK* (UK CCS Cost Reduction Task Force, 2013); http://go.nature.com/I4ppJQ
10. IPCC *IPCC Special Report on Carbon Capture and Storage* (eds Metz, B., Davidson, O., de Coninck, H., Loos, M. & Meyer, L.) (Cambridge Univ. Press, 2005); http://go.nature.com/WBun8Q
11. Katzer, J. *et al. The Future of Coal: Options for a Carbon-Constrained World* (MIT, 2007).
12. Markusson, N., Ishii, A. & Stephens, J. C. The social and political complexities of learning in carbon capture and storage demonstration projects. *Glob. Environ. Change* **21,** 293–302 (2011).
13. Herzog, H. J. Scaling up carbon dioxide capture and storage: From megatons to gigatons. *Energy Econ.* **33,** 597–604 (2011).
14. Torp, T. A. & Gale, J. Demonstrating storage of CO_2 in geological reservoirs: the Sleipner and SACS projects. *Energy* **29,** 1361–1369 (2004).
15. Orr, F. M. & Taber, J. J. Use of carbon dioxide in enhanced oil recovery. *Science* **224,** 563–569 (1984).
16. Rochelle, G. T. Amine scrubbing for CO_2 capture. *Science* **325,** 1652–1654 (2009).
17. Scrase, I. & Watson, J. in *Caching the Carbon* (eds Meadowcroft, J. R. & Langhelle, O.) Ch. 7 (Edward Elgar, 2009).
18. Monea, M. SaskPower's case for carbon capture and storage. *Cornerstone* **3,** 17–19 (2015).
19. *Technology Roadmap: Carbon Capture and Storage* (International Energy Agency, 2009); http://go.nature.com/ypCuIa
20. Baker, E., Bosetti, V. Anadon, L. D., Henrion, M. & Aleluia Reis, L. Future costs of key low-carbon energy technologies: harmonization and aggregation of energy technology expert elicitation data. *Energy Policy* **80,** 219–232 (2015).
21. Kramer, G. J. & Haigh, M. No quick switch to low-carbon energy. *Nature* **462,** 568–569 (2009).
22. Gibbins, J. & Chalmers, H. Preparing for global rollout: a 'developed country first' demonstration programme for rapid CCS deployment. *Energy Policy* **36,** 501–507 (2008).
23. Torvanger, A. & Meadowcroft, J. The political economy of technology support: Making decisions about carbon capture and storage and low carbon energy technologies. *Glob. Environ. Change* **21,** 303–312 (2011).
24. Gallagher, K. S., Anadon, L. D., Kempener, R. & Wilson, C. Trends in investments in global energy research, development, and demonstration. *WIREs Clim. Change* **2,** 373–396 (2011).
25. Jamasb, T., Nuttall, W. J., Pollitt, M. & Maratou, A. in *Delivering a Low-Carbon Electricity System: Technologies, Economics, and Policy* (eds Grubb, M., Jamasb, T. & Pollitt, M. G.) Ch. 3 (Cambridge Univ. Press, 2008).
26. Verbong, G., Geels, F. W. & Raven, R. Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970–2006): hype-cycles, closed networks and technology-focused learning. *Technol. Anal. Strategic Manage.* **20,** 555–573 (2008).
27. Menanteau, P. Learning from variety and competition between technological options for generating photovoltaic electricity. *Technol. Forecast. Soc. Change* **63,** 63–80 (2000).
28. Reiner, D. M. & Liang, X. Stakeholder views on financing carbon capture and storage demonstration projects in China. *Environ. Sci. Technol.* **46,** 643–651 (2012).
29. Wilson, E., Zhang, D. & Zheng, L. The socio-political context for deploying CCS in China and the U.S. *Glob. Environ. Change* **21,** 324–335 (2011).
30. Babiker, M. H. Climate change policy, market structure, and carbon leakage. *J. Int. Econ.* **65,** 421–445 (2005).
31. Markusson, N. *et al.* A socio-technical framework for assessing the viability of carbon capture and storage technology. *Technol. Forecast. Soc. Change.* **79,** 903–918 (2012).
32. Brown, J. & Hendry, C. Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology in solar photovoltaics. *Energy Policy* **37,** 2560–2573 (2009).
33. Harborne, P. & Hendry, C. Pathways to commercial wind power in the US, Europe and Japan: The role of demonstration projects and field trials in the innovation process. *Energy Policy* **37,** 3580–3595 (2009).
34. Markusson, N. & Chalmers, H. Characterising CCS learning: The role of quantitative methods and alternative approaches. *Technol. Forecast. Soc. Change* **80,** 1409–1417 (2013).
35. Cowan, R. Nuclear power reactors: a study in technological lock-in. *J. Econ. Hist.* **50,** 541–567 (1990).
36. Shackley, S. & Thompson, M. Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? *Climatic Change* **110,** 101–121 (2012).
37. Sagar, A. D. & van der Zwaan, B. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. *Energy Policy* **34,** 2601–2608 (2006).
38. Rubin, E. S., Azevedo, I. M., Jaramillo, P. & Yeh, S. A review of learning rates for electricity supply technologies. *Energy Policy* **86,** 198–218 (2015).
39. de Coninck, H., Stephens, J. C. & Metz, B. Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration. *Energy Policy* **37,** 2161–2165 (2009).
40. Georghiou, L. Global cooperation in research. *Res. Pol.* **27,** 611–626 (1998).
41. Victor, D. G. Toward effective international cooperation on climate change: Numbers, interests and institutions. *Glob. Environ. Politics* **6,** 90–103 (2006).

42. *Technology Roadmap: Carbon Capture and Storage* (International Energy Agency, 2013); http://go.nature.com/k7Box3
43. Harborne, P., Hendry, C. & Brown, J. The development and diffusion of radical technological innovation: The role of bus demonstration projects in commercializing fuel cell technology. *Technol. Anal. Strategic Manage.* **19,** 167–188 (2007).
44. Winskel, M. *et al.* Learning pathways for energy supply technologies: Bridging between innovation studies and learning rates. *Technol. Forecast. Soc. Change* **81,** 96–114 (2014).
45. Rubin, E. S., Davison, J. E. & Herzog, H. J. The cost of CO_2 capture and storage. *Int. J. Greenhouse Gas Control* **40,** 378–400 (2015).
46. Kern, F., Gaede, J., Meadowcroft, J. & Watson, J. The political economy of carbon capture and storage: An analysis of two demonstration projects. *Technol. Forecast. Soc. Change* http://doi.org/9k7 (in the press).
47. Lupion, M. & Herzog, H. J. NER300: Lessons learnt in attempting to secure CCS projects in Europe. *Int. J. Greenhouse Gas Control* **19,** 19–25 (2013).
48. Arranz, A. M. Carbon capture and storage: Frames and blind spots. *Energy Policy* **82,** 249–259 (2015).
49. Year in review – CCS on the move. (Bellona Europa, 10 December 2014); http://go.nature.com/jBRt13
50. Stephens, J. C. Time to stop CCS investments and end government subsidies of fossil fuels. *WIREs Clim. Change* **5,** 169–173 (2014).
51. Maddali, V., Tularam, G. A., Glynn, P. Economic and time-sensitive issues surrounding CCS: A policy analysis. *Environ. Sci. Technol.* **49,** 8959–8968 (2015).
52. Scott, V., Gilfillan, S., Markusson, N., Chalmers, H. & Haszeldine, R. S. Last chance for carbon capture and storage. *Nature Clim. Change* **3,** 105–111 (2013).
53. Borup, M., Brown, N., Konrad, K. & van Lente, H. The sociology of expectations in science and technology. *Technol. Anal. Strategic Manage.* **18,** 285–298 (2006).
54. *EU Demonstration Programme for CO_2 Capture and Storage (CCS): ZEP's Proposal* (European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2009); http://go.nature.com/wU3wQp
55. van Alphen, K., van Ruijven, J., Kasa, S., Hekkert, M. & Turkenburg, W. The performance of the Norwegian carbon dioxide, capture and storage innovation system. *Energy Policy* **37,** 43–55 (2009).
56. *Clean Coal: DOE's Decision to Restructure FutureGen Should Be Based on a Comprehensive Analysis of Costs, Benefits, and Risks* (General Accounting Office, 2009); http://go.nature.com/kH6Mx4

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Competing interests

The author declares no competing financial interests.