Learning through a Portfolio of Carbon Capture and Storage Demonstration Projects

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Abstract

Carbon dioxide capture and storage (CCS) technology is considered by many an essential route to meet our 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 help in learning by diversity, learning by replication, de-risking the technologies, and developing viable business models. From 2005 to 2009, optimism over 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, yet the initial rationales for demonstration have not been revisited in the face of changing circumstances. Here we 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 decide whether CCS ever emerges from the demonstration phase.

Introduction

Carbon dioxide capture and storage (CCS) technologies are still at the pilot and demonstration phase, even though 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 temperatures. [1,2] Paradoxically, it is primarily the costs of the early demonstration projects that have hampered further deployment. Since each CCS ‘demonstration’ plant costs on the order of $1 billion, at a time of fiscal austerity it has proven difficult to justify public support. Near-term pressure to develop CCS has also eased since most countries found it easier to meet their Kyoto targets because of the economic crisis (and other factors such as the U.S. 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 derisking 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] We 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, we use this as a test of how learning is operationalised. 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 [16] and adequately characterising each geological formation. [17] Since large-scale projects must store roughly 1 million tons of CO_2 per year, [16-17] this scale requirement poses a number of challenges when seeking to learn from multiple projects

In this Perspective, we explore the history of CCS demonstration in an effort to understand how the initial optimism about large-scale rollout led to multiple, uncoordinated efforts at learning from diversity. In the absence of widespread deployment of CCS, the projects which have endured do not form a coherent program aimed at learning. Going forward, therefore, any effort to successfully re-launch 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. [18]

Great Expectations for CCS

CCS technologies have long faced the challenge of wanting to be seen, on the one hand, as a novel technology that warrants 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).[10] 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 tons of CO_2 a year in the Utsira field under the North Sea since 1996 [11]; 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 [12]; 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. [13]

The first large-scale CCS power project was proposed by BP at Peterhead in 2002. [14] 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. [15]

CCS first emerged on the international agenda at the Gleneagles G8 summit in Scotland in 2005, leading to a program of work for the International Energy

Agency (IEA) and to several countries seeking to rollout CCS technologies. In that same year, the Intergovernmental Panel on Climate Change produced a Special Report on CCS to review the state of knowledge. [16] During this period of optimism through to 2009, the European Union, Canada (or rather, Alberta), Australia and the United States each developed their own sets of criteria, which would guide the deployment of a portfolio of projects. The different nations' proposals are summarised in Box 1.

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 envisioned 80-120 commercial CCS projects by 2030 in the EU alone. [19]

In parallel, Norway also committed to taking the lead on CCS technology, and in 2006, Prime Minister Stoltenberg described CCS as their "moon landing" [20] with a pledge to capture 100,000 tons a year at the Mongstad refinery on a pilot basis and then scale that up to 2 million tons a year after five years.

Other countries also signaled their ambitions. The United States proposed the $1 billion Futuregen project in 2003, which would have been a 275 MW integrated gasification combined cycle (IGCC) plant in Illinois, followed in 2009 by stimulus spending pledges of over $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 Premier 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.

Although countries pledged significant sums at the time, there was an obvious disconnect between the envisioned 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 3000 by 2050 with required investments of $5 to $6 billion per year between 2010 and 2020, with roughly two-thirds of the investment coming in developed countries. [21] 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. R&D on CCS is seen as having one of the highest median returns [22], which begs the question of why and when to demonstrate CCS options relative to continued R&D. CCS faced unproven business models and skeptical investors, novel technology integration challenges and the need to deliver at a commercial scale while still at the demonstration phase. [23]

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 [24], 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 lies in either revealing technology performance relative to expectations or other technologies (learning from diversity) [25] or demonstrating potential cost reductions at later stages (learning from replication). [26] 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. [27]

Much like basic R&D, demonstration requires tolerance of failure. [28] At the scales discussed (~300 MW or 1 million tons of CO_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. [29]

Finally, national priorities such as industrial policy or energy security are put forward as justifications for CCS. [30-31] 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 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. [32]

Given the focus on cost considerations, we largely neglect the important subject of social learning [18] and restrict our 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 tradeoffs 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 [33]

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. [34-35] By contrast, CCS projects are 'lumpy', insofar as each project is 100 MW scale and up and there is still the danger of technology lock-out or lock-in. [36-38] Learning may not be stable and may vary over time. [39-40] 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.

Recognising the cost of even single plants, there have been calls for greater international coordination. de Coninck, Stephens and Metz [41] outline principles for a world-wide demonstration program including laudable goals such as global coordination to "enable a variety of CCS 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 or LHC, rather than projects primarily developed by industry and aiming to be commercial within a decade. [42] Instead, a focus on fewer countries, nonbinding mechanisms, and greater use of review procedures can help facilitate more effective agreements. [43]

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 wishlist 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, while Box 2 summarises the different national efforts.

[Insert Figure 1 around here]

Box 2. National CCS Programmes

USA

The U.S. designated $3.4 billion for CCS largely via economic stimulus spending: $1.5 billion for industrial CCS projects on a competitive basis, $800 million for the Clean Coal Power Initiative (CCPI), and $1 billion for FutureGen. US GAO (2009) 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. [44] 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 that the private sector provide at least half the funding.

Australia

In Australia, the government pledged A$2 bn (US$1.65 bn) 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 (3 coal and 1 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 $MtCO_2$ per year by 2015, including a minimum project threshold of 500,000 tCO_2 per year. Each project was to be fully integrated and at least one would store >1 $MTCO_2$/year. In terms of capture and storage options, at least one would provide direct storage (e.g., in a deep saline formation) rather than enhanced oil recovery (EOR), at least one retrofit and one new build, at least one electric power application, at least one oilsand 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 overoptimistic objectives such as "demonstrate Europe's leading edge technology and spur action by other countries" [19] (notably India, China and the U.S.), as well as objectives that relate back to our principles of demonstration listed ~~above~~in the main text, such as ensuring "a diverse geographical and technological spread of projects" [19] (learning from diversity) and accelerating cost discovery (learning from replication). Fourteen portfolio criteria were presented, which can be grouped by diversity in: (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 derisking.

Following initial support of €1.05 bn for six projects via stimulus spending in 2009, support was to be operationalised 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 ton of CO_2, which would have implied almost €5 billion in funds available, primarily for CCS. Launched in November 2010, the European program was expected to co-fund eight CCS projects: 1-3 for each capture technology, at least 3 in depleted oil and gas reservoirs, and at least 3 in saline formations.

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.

[Insert Figure 2 around here]

Reflecting the ambition of the time, in Figure 2, Gibbins and Chalmers (2008) [24] describe a vision 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 beginning in 2025. Updating this vision, we 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. [46-47]

The need for learning from diversity is acute. As Rubin, Davison and Herzog (2015) conclude in a comprehensive study of the current status of CCS costs, 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 over the inability to pick winners. [48]

Post 2009 Progress and Roadmaps

The 2009 IEA CCS roadmap [21] had highlighted the need to develop 100 CCS projects over 2010-2020, storing around 300 $MtCO_2$/year based on a global spend of $5-6billion/year, whereas by 2013, four operational projects and nine projects under construction were expected to store some 13 $MtCO_2$/year by 2016, with a spend of some $10billion 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. [45] Still, given the proximity to 2020 and the current status of project funding around the world, that is an ambitious target.

Many of the proposals shown in Figure 1 failed because of tepid or shifting government (and industry) support or because of genuine technical challenges and escalating costs encountered along the way, while other projects have soldiered on. In Norway, the costs of Technology Centre Mongstad spiralled almost four-fold 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 oilsands on a zero net present value basis (a decision few other companies could or would be willing to carry on their balance sheet), and just 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. [49] 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 lack of viable CO_2 storage options, but the Gorgon project will capture 3.5-4 million tCO_2 beginning in 2017 (largely because CCS was included as part of the package to allow the lucrative LNG facility to be sited on Barrow Island rather than onshore). Moreover, the South West Hub project in Western Australia and 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 which 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 IGCC plant at Kemper County in Mississippi is due to begin operations in 2016 after delays of several years and costs spiralling to $5.6 billion, above the $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 most dire 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 EUA 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. [50] This CCS-renewable split reflects the breadth of support for renewables compared to 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 favoring large coal projects. [51] 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, €300m was ultimately allocated to the White Rose coal oxy-fuel project in the UK (along with an additional €1 bn for 19 IRTs in 12 member states).

The most advanced European projects are those participating in the UK Commercialisation Competition, which is still progressing with two plants, White Rose and a gas-fired post-combustion project at Peterhead. An important 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. A downside is that the UK Commercialisation Competition mandates that both plants operate in baseload, preventing learning about flexibility, which is one of the key rationales for considering CCS relative to other low-carbon technologies.

As some 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 remains the most advanced CCS project in continental Europe, but which had been stalled because of a funding shortfall. [52] 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 [53-54], but neither extreme reflects the more nuanced current state of affairs. [55] Inevitably, CCS has been subject to a technology hype cycle. [28, 56] The expectations of the earlier period in part reflected a conflation of positive and normative assessments of technology rollouts, i.e., 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 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 that concerns over wider coordination or thinking deeply over project timing, ordering and selection could be largely disregarded.

As the pipeline of projects rapidly dissipated post-2009, it is perhaps understandable that there has been an overwhelming focus on delivering what was left rather than worry about coordination and learning since 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 has emerged may say more about the seriousness with which nations have addressed climate change than about CCS technologies *per se*. Concerns over 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. For example, if the UK supports oxy-fired coal and post-combustion projects, what rationale underlies the next UK investment? Is it simply to proceed with the next two plants on its 2010 shortlist or should the

UK consider a second oxyfuel project or post-combustion gas plant (learning by replication) and/or 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 our 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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Figure 1. Timeline of Major CCS Demonstration Projects. There have been projects which have captured, transported and/or stored CO_2 for many decades, but we include here only integrated capture, transport and storage projects that were conceived as CCS projects. We generally 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 LNG enterprises as in Australia. Industrial projects refer to projects in energy-intensive industrial sectors including steel, cement, fertiliser, and refineries. For reference, we 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.

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 anticipated two 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 envisioned in IEA (2013) [45] but following a more traditional logistic technology deployment curve (dashed purple line). Adapted ~~with permission~~ from ~~Gibbins and Chalmers (2008)~~ref. [24], Copyright (2008), with permission from Elsevier.