Energy Policy 39 (2011) 2256–2264

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Carbon capture and storage as a corporate technology strategy challenge

Frances Bowen [a,b,*]

[a] Haskayne School of Business, University of Calgary, Canada
[b] Smith School of Enterprise and the Environment, University of Oxford, UK

ARTICLE INFO

Article history:
Received 26 April 2010
Accepted 11 January 2011
Available online 3 March 2011

Keywords:
Carbon capture and storage
Corporate strategy
Innovation

ABSTRACT

Latest estimates suggest that widespread deployment of carbon capture and storage (CCS) could account for up to one-fifth of the needed global reduction in CO_2 emissions by 2050. Governments are attempting to stimulate investments in CCS technology both directly through subsidizing demonstration projects, and indirectly through developing price incentives in carbon markets. Yet, corporate decision-makers are finding CCS investments challenging. Common explanations for delay in corporate CCS investments include operational concerns such as the high cost of capture technologies, technological uncertainties in integrated CCS systems and underdeveloped regulatory and liability regimes. In this paper, we place corporate CCS adoption decisions within a technology strategy perspective. We diagnose four underlying characteristics of the strategic CCS technology adoption decision that present unusual challenges for decision-makers: such investments are precautionary, sustaining, cumulative and situated. Understanding CCS as a corporate technology strategy challenge can help us move beyond the usual list of operational barriers to CCS and make public policy recommendations to help overcome them.

1. Introduction

There is now a scientific and policy consensus that stabilizing atmospheric concentrations of greenhouse gas (GHG) emissions will require fundamental technological and associated institutional changes. The pressing technology management question is no longer whether to invest in GHG-reducing technologies, but which technologies to emphasize among the portfolio of promising options. Government policy-makers need to decide how to incent the development of appropriate GHG mitigation technologies; corporate decision-makers face choices on how to develop corporate technology strategies within a carbon-constrained context.

One family of technologies that is almost universally relied upon in future mitigation and stabilization scenarios is carbon capture and storage (CCS). According to the International Energy Agency, widespread deployment of CCS could account for one-fifth of the needed global reduction in emissions by 2050. CCS accounts for one of Socolow's seven "wedges" that each promise reductions of one billion tons of carbon each year by 2050 (Socolow, 2006). Furthermore, CCS is an important technology to reduce the overall cost of stabilization (Akimoto and Tomoda, 2006), with some estimates putting this cost reduction as high as 30% when including CCS in a portfolio of measures (IPCC, 2005).

Developing an integrated system to capture, transport and store CO_2 emissions will rely on technology investments by both firms and governments. The short-term burden of establishing viability will require some public subsidy, but as with most R & D the public funding committed will eventually be dwarfed by corporate investments (de Coninck et al., 2009). The long-term viability of CCS as a solution will depend on the technology being deployed for commercial reasons (Socolow, 2006). Carbon pricing will help: our experience with other emissions abatement technologies shows that market experience leads to cost reductions, and that market expectations frame corporate R & D choices (Grubb, 1997).

The public policy challenge is that waiting for carbon prices to incent market CCS investments is too slow process for the urgent emissions mitigation required (Schrag, 2009). Even with a strong carbon price signal, there are recognized uncertainties about the viability, affordability, effectiveness and public acceptability of CCS (Shackley and Gough, 2006). So far, much corporate activity on CCS, especially among "those whose fortunes are most tightly tied to fossil fuels" (Meadowcroft and Langhelle, 2009a: p. 7) has been focused on basic scientific research and lobbying governments for subsidies and support rather than investments needed to deploy the technology on a commercial scale (Stephens, 2009). Yet CCS remains an attractive option to both governments and incumbent firms since there are lower technical, economic and

* Correspondence address: Haskayne School of Business, University of Calgary, 2500 University Dr. NW, Calgary, AB, Canada T2N 1Z3. Tel.: +1 403 220 6723.
E-mail address: fbowen@ucalgary.ca

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.01.016

social barriers to lowering CO_2 emissions by modifying existing industrial processes and electricity generation than by more radical low carbon solutions (Gibbins et al., 2006).

There has been a recent flurry of research effort – both in this journal and elsewhere – that places CCS technology investments within a broader political (e.g. Meadowcroft and Langhelle, 2009a, 2009b), socio-technical (e.g. Stephens and Jiusto, 2010) or innovation (Praetorius and Schumacher, 2009) system. A parallel literature is being developed on how and why firms differ in their climate change innovation strategies (e.g. Pinkse and Kolk, 2010) or preparations for energy futures (e.g. Chang and Yong, 2007). Some studies have included industry perspectives in panels of experts on CCS (e.g. Hansson and Bryngelsson, 2009; Dapeng and Weiwei, 2009). However, so far the strategic decisions of the primary CCS technology consumers – the industrial users of CCS technologies – on whether and how to invest in CCS technologies have been neglected. While we have a long list of potential operational barriers to CCS adoption, we have not yet placed these in the context of adopting firms' corporate technology strategy.

In this paper, we develop a corporate technology strategy perspective on CCS investments to diagnose the investment challenges of CCS, and potential solutions to those challenges. We begin with a brief introduction to CCS technologies and to corporate technology strategy, before outlining four distinctive challenges of CCS for corporate strategists. CCS investments are precautionary, sustaining, cumulative and situated. We aim to show that adopting a corporate technology strategy perspective provides both corporate decision-makers and public policy-makers with a more nuanced understanding of the barriers to CCS investments and potential ways to overcome them.

2. An introduction to CCS technologies

"CCS technology" can more accurately be thought of as a chain of technologies designed to separate CO_2 from industrial sources, transport it to a storage location and isolate it for the long-term from the atmosphere (IPCC, 2005). CCS technology can reduce CO_2 emissions from large industrial sources and coal-fired power stations by approximately 85% depending on the type of non-capture plant displaced (IPCC, 2005). Each stage of the CCS chain – capture, transport and storage – has different technological options, technology maturity, cost implications and industry players.

The most expensive element of the CCS technology chain is the initial CO_2 capture (McKinsey, 2008; IPCC, 2005). Two types of CO_2 capture systems are well developed: post-combustion and pre-combustion. In post-combustion capture, CO_2 is separated from the flue gas emitted from an industrial process such as a coal-fired power plant. Pre-combustion requires the initial gasification of a fuel source, but yields a purer stream of CO_2 for capture at the end of the process (Hertzog, 2009). Thus "although the initial fuel conversion steps of pre-combustion are more elaborate and costly, the higher concentrations of CO_2 in the gas stream and the higher pressure make the separation easier" (IPCC, 2005: p. 5). These two CO_2 capture technologies use separation processes, based on solvents, membranes, cryogenic technologies or other chemical or physical processes that are already applied in industry, for instance in the petrochemical industry to increase the yield in the lighter fractions in oil distillation, or in the food industry, to produce CO_2 for fizzy drinks (European Commission, 2007: p. 4). Oxyfuel combustion is another promising capture technology that has been built and operated at the scale of a pilot plant, but this is a less mature technology than the pre- and post-combustion technologies. Estimates of the costs of these capture technologies range from \$15 to \$115 (US) per ton of net CO_2 captured, depending on the particular process configuration (McKinsey, 2008; Rubin et al., 2007). The CO_2 capture technology industry is dominated by energy equipment manufacturing firms that have expertise in boilers, plants, turbines, etc. such as Alstom, Siemens, BASF AG, Mitsubishi, Doosan Babcock and GE.

CO_2 transportation is mostly by pipeline, though CO_2 shipping may become economically feasible under specific conditions. There are already over 3400 miles of CO_2 pipelines in the USA, transporting CO_2 from naturally occurring reservoirs to the oil fields of West Texas and the Gulf Coast for enhanced oil recovery (Hertzog, 2009). The cost of CO_2 transportation is an order of magnitude less than for capture (\$1–8 US per ton CO_2 transported), and pipeline technology is established and mature (IPCC, 2005). Thus the key issues in this part of the CCS technology chain are more about the siting and routes of pipelines, the purity of CO_2 transported, and the potential for future pipeline tie-ins, than the intrinsic technologies associated with compression and pipeline integrity. Established players include major oil and natural gas pipeline companies.

There are several CO_2 injection and storage technology options, of which the most mature are geological storage, either in depleted oil and gas reservoirs or in deep saline formations, and enhanced oil recovery (EOR). In the UK, Norway and other North Sea oil-producing countries, the focus of CCS projects is on offshore storage (Shackley and Gough, 2006), though in Canada and the US projects tend to focus on geological storage onshore (Schrag, 2009). The costs of geological storage are roughly equivalent to the costs of transportation, and there are relatively constant costs across a wide range of storage capacity. Currently, no large companies specialize exclusively in CO_2 storage services or long-term stewardship (Hertzog, 2009), though oilfield services companies such as Schlumberger and Halliburton, and firms familiar with the extraction and storage of oil and gas (e.g. E.ON, Statoil) may be well positioned to do so.

In this paper we will adopt the perspective of the primary technology consumers: the users of CCS technologies. CCS is most likely to be deployed initially by large electricity utilities (such as Vattenfall, RWE Power, American Electric Power Corp. or TransAlta), especially those with extensive assets in coal-fired power plants, though several oil and gas firms (such as Shell and BP) and even cement or steel producers (such as Lafarge and Emirates Steel Industries) have publicly considered CCS projects. Managers in these CCS technology consumer firms face a range of strategic options on how to respond to calls to dramatically reduce carbon dioxide emissions. Adopting CCS is one of these options. Common explanations for delay in corporate CCS investments include operational concerns such as the high cost of capture technologies, technological uncertainties in integrated CCS systems and underdeveloped regulatory and liability regimes. In this paper, we move beyond these barriers to address four distinctive challenges of the strategic CCS technology adoption decision: such investments are precautionary, sustaining, cumulative and situated. Developing a corporate technology strategy perspective on CCS investments can help us coherently frame the barriers to CCS, and potential solutions to those challenges.

3. CCS as a corporate technology strategy challenge

Much of the discussion on CCS has so far focused on CCS technology management, that is, the optimal integration of CCS technologies into energy systems (e.g. Akimoto and Tomoda, 2006; Gibbins et al., 2006). This has led CCS advocates to focus on operational issues such as how to reduce the cost of the technology, limit the energy penalty, design liability regimes and gain public acceptance (e.g. Chen and Rubin, 2008; Ashworth et al., 2009). If these problems could be somehow 'solved', the mainstream argument goes, then private investment in CCS would follow. However, this operational focus on CCS technology adoption misses a vital dimension of corporate decision-making: from the adopting firm's point of view, investing in CCS is a strategic activity. CCS adoption choices are made within the firm's overall technology strategy, that is, choices about the acquisition, management and exploitation of a portfolio of technologies (Clarke et al., 1995; Oswald, 2003). Firms' CCS investment decisions are intrinsically linked with broader corporate strategy (Ahmed and Shepherd, 2010), in this case with firms' climate change strategies (Pinkse and Kolk, 2010). Seeing CCS investments as strategic opens up questions of how firms can reconcile trade-offs between exploiting known technologies and exploring new ones (March, 1991; Benner and Tushman, 2003), how to value uncertain technology investments over time (Luehrman, 1998), and when and how to enter (and exit) technology life cycles (Roussel et al., 1991).

Initial evidence on firms CCS technology strategies suggests that firms answer these questions in different ways. For example, corporate CCS strategies reveal different answers to the exploitation versus exploration question. Peabody Energy, the largest coal producer in the US, focuses on exploiting current coal extraction technologies and reserves through retrofitting the world's existing – and future planned – coal fleet with post-combustion CCS technologies (Boyce, 2010). Although Peabody is investing in some exploration of CCS technology options, this is mostly through membership of clubs and industry consortia (Bowen, 2010). Peabody's CCS investment pattern is consistent with its overall position as a "global leader in clean coal solutions, advancing more than a dozen global projects and partnerships that will help fuel the low-carbon, high-growth economies of the future" (Peabody Energy, 2009b).

BP plc, in contrast, focuses on "investments in the areas where we believe we can create the greatest competitive advantage. We have substantial businesses in wind and solar power and are developing advanced biofuels and clean energy technologies such as hydrogen power and carbon capture and storage" (BP.com, 2010). BP's technology strategy shows that the firm prefers to explore a wider range of technology investments, where CCS is just one of the portfolio of investment options. It also reveals a corporate preference for CCS projects that are synergistic with the firm's other technology investments – the firm withdrew from a proposed CCS project in Scotland, but is a lead partner in the Hydrogen Energy California Project that reinforces its investment in hydrogen technologies.

Adopting firms are making different strategic choices on CCS technologies. A corporate technology strategy perspective seeks to position these choices within the broader strategies and technology portfolios of adopting firms. In the next section we go on to show how CCS technologies present four specific strategic challenges for firms, and how each of these challenges can inform policymakers.

3.1. *CCS investment is precautionary*

The first challenge for CCS technology adopters is that CCS is precautionary. The only reason that firms are considering risky investments to develop CCS technology is as a precaution against an even greater long-term future risk: that of dangerous climate change. Since the impacts of climate change are not tangible, immediate or visible, decision-makers invest little to address them, yet waiting for impacts to occur will, by definition, be too late (Giddens, 2009). Similarly, Gallagher (2009) argues that energy investment choices suffer an "Acting in Time" problem where people fail to invest to prevent or lessen an easily predictable crisis, cost or catastrophe, where making investments sooner rather than later would have a relatively high payoff. Firms' CCS decisions are inevitably linked with their broader climate change strategies; and climate strategies are known to vary systematically across firms depending on their stances towards the precautionary risk of climate change (Levy and Kolk, 2002).

Precautionary investments are particularly problematic when, as with climate change, the future potential risk is intangible, temporally distant and with highly distributed impacts. For firms, the strategic conundrum is further compounded when the whole point of investing in the technology is to prevent something from happening at all. To investors only the upfront costs are visible, and individual firms are not rewarded for their proactive CCS strategies and the fact that the subsequent climate crisis did not occur. There is a failure of private incentives for CCS because of the low private demand for future avoidance of climate change.

Firms are familiar with evaluating precautionary investments in other domains by using tools such as options pricing models (Luehrman, 1998) or scenario planning (see Marcus, 2009 for a review). Hedging and managing risks of situations that might never occur is one of the central locations where firms can gain market rewards. Indeed, some business models are premised on the provision of precautionary investments such as insurance, safety equipment or security systems. But corporate decision-makers are less well equipped to deal with investments where the precautionary downside relates to a social, rather than a private risk (Farrow, 2004).

At an operational level, a concrete challenge for firms arising from the precautionary nature of CCS is that CCS project proponents face a two-level public acceptance challenge: acceptance of the potential risks of carbon transport and storage at the local level, and acceptance of the broader precautionary reason why CCS is needed. For example, firms are less likely to undertake CCS investments in local contexts where there is lack of public acceptance or interest in climate change as a problem. Similarly, firms find precautionary investments more challenging where the risks of the CCS technology itself are more proximate as evidenced by the relative ease of promoting offshore carbon sequestration (such as Statoil's Sleipner platform) compared with onshore projects (such as Vattenfall's inability to acquire the permits needed to sequester CO_2 from its CCS pilot plant at the Schwarze Pumpe power station in Germany).

At a more strategic level, the precautionary nature of CCS investments draws corporate managers into a public conversation on energy system alternatives for which they are often ill-prepared. Matching the firm's internal technological profile and options with the external environment is a core issue within technology strategy (Ahmed and Shepherd, 2010). In many cases, corporate enthusiasm for CCS projects is not matched by local publics (Van Noorden, 2010). In order to invest in the technology, firms must address both levels of public risk perception. Analyses of corporate communications on CCS (e.g. Bowen, 2010) and of public perceptions of energy technologies (Ashworth et al., 2009), suggest that corporate communication strategies must address the dangers of broader climate change as well as the perceived risks of CCS technologies. Educating investors and the public about the relative risks of CCS and broader climate change remains a significant challenge.

3.1.1. *Policy implications*

Casting CCS as a precautionary investment suggests at least three policy implications. The first lesson is for public bodies to assist with public awareness and education on both CCS technologies and the broader climate change problem. Corporations are among the least trusted sources of information on CCS (Huijts et al., 2007), yet experiences in early projects suggest that corporate and public perceptions of CCS may be misaligned. Public protests against Shell's proposed Barendrecht project serve as a reminder that support from government and project proponents is not enough: local publics can derail an otherwise supported project (Van Noorden, 2010). Another dimension of this lesson is for policymakers to appreciate the challenges faced by corporations during the CCS project approval process. Precautionary investments have a higher planning acceptability hurdle as both the planned project and the precautionary reasons for the investment come under public scrutiny. This reinforces the need for a policy environment that communicates the pressing nature of the climate problem and CCS as one of the portfolio of solutions to address it. Policymakers play a vital role in developing a supportive institutional context for firms to explore new technologies.

The second implication for policy-makers on precautionary investments is to beware the business of precaution. Entire industries and technologies have been built upon the business opportunities inherent in mitigating precautionary risks. For example, overinvestment in security (compared with the magnitude of the risk faced) since the terrorist attacks of September 11, 2001, has accelerated innovation in body scanners, suspect detection systems and biometric cards. There is a similar danger that the fear of the economic consequences of retooling economies in the face of climate change can lead to an over-reliance on apparently easy technological investments such as CCS.

Of course, the most important lesson on CCS as a precautionary investment is to ensure that investment in CCS technologies does in fact influence the precautionary risk, that is the probabilities of dangerous climate change, by reducing the amount of CO_2 released to the atmosphere. Governments should (1) invest research dollars in monitoring technologies to ensure that the claimed CO_2 sequestered does in fact stay isolated from the atmosphere for an acceptably long time, and (2) ensure that any subsidies given to develop the technologies go to sequestering CO_2 over the long-term, and not to processes such as enhanced oil recovery that may in fact generate more hydrocarbons that are later released into the atmosphere.

The core problem with precautionary investments from the firm perspective is that outputs and impacts of strategic investments are uncertain, difficult to measure and to capture for private benefit. Corporate strategists do have some tools at their disposal for evaluating technology investments under uncertainty, but firms need support in developing an enabling context for optimal carbon-reducing decisions.

3.2. *CCS investment is sustaining*

An important distinction in the corporate technology strategy literature is between sustaining and disruptive innovations (Christensen, 1997). Sustaining innovations maintain or increase the industry's current trajectory in process or product performance, whereas disruptive innovations redefine the performance trajectory (Dosi, 1982). In the case of CCS, post-combustion capture and industrial separation are sustaining innovations: given the new low carbon emission constraint, these capture technologies promise the maintenance of current energy system assets. Innovation in post-combustion capture is aimed at sustaining operations through the steady reduction in the cost of carbon capture as the end-of-pipe technology improves. Post-combustion capture promises incremental performance improvements through cleaning-up flue gases in a way that is compatible with existing industrial assets and technological trajectories (Hertzog, 2009; Praetorius and von Stechow, 2009). Of the 23 large CCS demonstration projects announced in North America, Europe and Australia since 2008, more than half are to develop post-combustion capture or retrofits of existing facilities (Bowen, 2010). Post-combustion capture deals with CO_2 as if it is an industrial waste or air pollution to be dealt with at the end of the industrial process (Purdy, 2006). Investing in post-combustion CCS technology is also compatible with incumbent coal, oil and gas firms' usual operations based on a large-scale and centralized model (Vergragt, 2009).

Sustaining innovations such as post-combustion capture are more popular among established, incumbent firms (Christensen, 1997). Evidence from industries as diverse as disk drives, life insurance or steel production suggests managers in incumbent firms prefer to focus on their existing business and capitalize on investments in their existing assets rather than embrace disruptive alternatives. Such investments might sustain high-emission intensity incumbent firms' license to operate, but the possibility of gaining competitive advantage through CCS as an end-of-pipe technology is limited. Such a "pollution control" strategy, where negative environmental impacts are "trapped, stored, treated and disposed of using pollution-control equipment" (Hart, 1995: p. 992) is end-of-pipe in the sense that it attempts to deal with potential environmental impacts as a "bolt-on" to existing production processes (Aragon-Correa, 1998). Pollution control equipment may be easily acquired or purchased by other firms, so could potentially be imitated and thus cannot be a source of long-term sustained competitive advantage (Klassen and Whybark, 1999). Furthermore, relying on sustaining innovations, rather than relatively more disruptive ones such as renewable or distributed energy systems, can feed rigidity and dangerous over-confidence among incumbents about their business model (Christensen et al., 2004). Sustaining innovations may be adequate in the short run, but in the long run incumbents are vulnerable to disruptive technologies.

While CCS is usually considered a sustaining innovation, one type of CCS – pre-combustion capture technology – may have the potential to be a disruptive innovation, in the sense that it may redefine the industry's performance trajectory. This capture technology is built on fuel gasification capabilities and yields a potentially valuable additional output: a pure hydrogen stream of use in the future hydrogen economy (IPCC, 2005; Hertzog, 2009). In the best case, pre-combustion capture techniques could constitute a disruptive innovation, where initially incumbents consider the process as inferior to existing processes but it is refined and reconfigured over time to surpass the features of the original process (Charitou and Markides, 2003).

RWE Power, for example, was developing its Integrated Gasification Combined Cycle (IGCC) pre-combustion technology in the 1980s and 1990s primarily with a view to efficiency improvements and decreasing the energy penalty. Today RWE is designing an IGCC coal-fired power plant to be built near Cologne in Germany because "unlike other processes, carbon capture is comparatively easy using the IGCC process, so that the effects of CCS on efficiency can be kept relatively low" (RWE, 2009). Current plans include burning the hydrogen output in a gas turbine to produce energy, but possible future uses for the synthesis gas outputs include hydrogen as a transportation fuel or (with some additional conversion steps) methanol, synthetic natural gas, or even diesel or petrol. As RWE states, "this flexibility on the product side for future applications is one more important motivation for the use of (pre-combustion) coal gasification" (RWE, 2009). Incorporating leading-edge oxygen production and gas turbine technologies with IGCC can yield an overall system that is more efficient than a current plant without CCS, and reduce the cost of CCS by 50% (Chen and Rubin, 2009).

Thus while most planned CCS investments are sustaining innovations, some types of CCS technologies may turn out to be disruptive—they redefine the performance trajectory away from ever more expensive and inefficient pollution control equipment (as in the case of post-combustion capture), towards valuing diversity in feedstocks, the ease of separating CO_2 for capture, and flexibility in the end use of hydrogen as an output (as in pre-combustion capture). Generation with pre-combustion CCS is inferior to current technologies in the short-term because it is more expensive. However, over time a rising carbon price, increasing value of the alternative outputs and improved pre-combustion technology efficiency may lead to a tipping point where pre-combustion processes transform the industry standard.

Clearly, the most disruptive innovation in the low-carbon power generation industry may not come from incumbents investing in CCS at all, but rather from developments in renewable energy sources such as wind, solar, biomass, geothermal, tidal, etc. The challenge for corporate decision-makers is that investing in sustaining investments may leave them vulnerable. Broadly, CCS investments are less disruptive than renewable alternatives, and post-combustion CCS is less disruptive than pre-combustion. It is difficult for incumbents to make the leap into new technological trajectories promised by disruptors, whether into renewables or pre-combustion CCS.

3.2.1. Policy implications

First, policy-makers should beware of incumbents' incentives to prefer sustaining investments (Christensen, 1997). Incumbents that perceive climate-related concerns as a threat rather than an opportunity are likely to lobby and discredit potential changes to protect their assets (Dewald and Bowen, 2010). Managers will put off addressing major decisions in favor of less important initiatives until there is an imminent cost to avoidance (Bazerman, 2009): it is easier for incumbents to defer investments when climate regulation and carbon pricing seems remote.

One way to encourage CCS investments even when managers perceive low-carbon requirements as a threat to their business is to increase the level of urgency through concrete policy timelines and targets (Dewald and Bowen, 2010). The US coal industry has been particularly slow in becoming involved in CCS investments (Stephens, 2009). Peabody Energy in the US is a good example of a late-mover into CCS investment due to weak regulatory requirements and hence a lack of urgency to act on carbon emissions. Now that there is more urgency on carbon emissions reduction in the US, Peabody has entered into a number of partnerships to develop CCS technologies, including GreenGen in China, COAL21 Fund in Australia and the Midwest Geological Sequestration Consortium in the US. However, in all of these cases, Peabody is a relatively small, symbolic participant and consistently emphasizes the need for "reasonable timelines" for CCS investments (Peabody Energy, 2009a, 2009b). The coal industry in Germany also has a "rather passive" stance towards CCS and has limited its involvement in CCS to "a few information sheets" (Praetorius and von Stechow, 2009: p. 146). Meadowcroft and Langhelle (2009b: p. 289) summarized the strategic stance of these firms as "CCS when absolutely necessary; but surely it is not necessary quite yet".

An implication for policy-makers is to look away from technologies promoted by the usual suspects, especially incumbent firms, and to seek to support innovation at the industry's periphery. Public funds allocated to CCS demonstration projects heavily favor incumbent coal- and gas-fired power plant CCS projects. All of the six CCS projects currently supported by the European Commission's €1.05bn funding under the European Economic Recovery Plan, for example, involve pilots at power plants planned, built or operated by powerful EU-based power generation incumbents (Bowen, 2010). These incumbent firms have successfully positioned CCS as a bridging or transitional technology that allows postponement of more radical energy system changes (Praetorius and von Stechow, 2009). While understandable, this preference for sustaining investments may lead to crowding out more disruptive alternatives. "Green" stimulus plans may in effect prop up established power generators that may struggle to survive in the new low-carbon economy (Pinkse and Kolk, 2010), wasting public resources. In the long run, breakthrough innovations are more likely to come from business opportunities at the fringe of these industries – industrial chemicals, project management, oilfield services – rather than from incumbent power generation companies.

Second, policy-makers should build alliances with firms that have positive risk experience. Managers that have had favorable experience in making risky decisions are more likely to take the risk of adopting disruptive new technologies (Pablo, 1997). Another explanation for Peabody's deferral or resistance to low-carbon technologies is that the company has operated for most of its 125-year history in the relatively stable, protected and highly regulated coal industries of the USA and Australia (that still account for nearly 90% of its operations). This has not helped it to gain the risk experience of other CCS players such as Shell or Rio Tinto that have more international exposure, risk experience or complementary assets in renewable technologies (Pinkse and Kolk, 2010).

The literature suggests that investments in CCS may be more likely in firms that pursue a broader portfolio of carbon management initiatives. Major energy firms differ in their investments in future energy technologies (Chang and Yong, 2007). Firms implementing a portfolio approach may be able to redeploy capabilities developed in proximate industries and businesses to CCS activities (Fremeth, 2010). Energy utilities that have invested in renewables beyond coal-based power generation will find it easier to develop green reputations, useful to attract CCS funding (Delmas et al., 2007). The oil and gas industry was quicker to pursue CCS than the coal industry in both the US (Stephens, 2009) and Germany (Praetorius and von Stechow, 2009), since firms had useful experiences in technologies and processes dealing with underground reservoirs and CO_2 injection. Thus policy-makers should also look for risk experience in domains closely related to CCS investment.

Finally, policy-makers should be wary of the energy and efficiency penalties associated with sustaining investments, especially in the case of post-combustion CCS. Despite the positive rhetoric about CCS investment as part of short-term economic stimulus plans (e.g. the EU's European Economic Recovery Plan, or the US stimulus package), end-of-pipe investments promise less innovation and competitiveness benefits than truly disruptive investments over the longer term (Hart and Milstein, 2003). More radical low-carbon energy system changes, such as switching to renewables, may promise more synergistic public policy benefits (e.g. reduction of air pollutants such as sulfur dioxide and nitrogen oxides) than CCS can deliver. Technologies exist to "co-capture and co-store" other pollutants, like sulfur, with the CO_2 but these are prohibitively expensive (Socolow, 2006). Policy-makers need to evaluate the extent to which CCS can contribute strongly to other public policy objectives (e.g. employment, increasing capital productivity, etc.) compared to the more disruptive renewable energy investment alternatives.

3.3. CCS investment is cumulative

As with climate change itself, CCS technology investments are inherently cumulative in the long run (Allen et al., 2009). Early successful carbon sequestration promises more climate impact because emissions are avoided not only in the year of investment but also in all future years as long as the CO_2 remains isolated from the atmosphere. The timing of CCS investments is therefore crucial for the likely impact of the CCS solution: earlier investments promise more cumulative emissions reductions (Meadowcroft and Langhelle, 2009a). However, technological learning through CCS implementation is also cumulative: we can expect reductions in mitigation costs over time due to the experiences gained in earlier projects (McKinsey, 2008). Decision-makers are caught in a dilemma: early adoption decisions yield the highest cumulative emissions reduction impact, yet they must be made when costs are highest and policy, technology and climate impacts are most uncertain (Fuss et al., 2009; Nehrt, 1996). Firms face challenging technology strategy choices on when and how to enter into (or exit from) CCS technology investments.

Typically the R & D effort required to achieve performance improvements in new technologies is depicted as an *S*-curve (Foster, 1986): after initial heavy basic research investment, the emphasis moves to development, demonstration and deployment. Firms must decide when to enter a new technology by investing on any given *S*-curve trajectory, and the relative emphasis on basic research, development or deployment. They face a tension between "steady walk" deployment, and the "R & D then sprint" option that focuses on technology development first because the cost of deploying the same technology later may be lower (Grubb, 1997). The challenge is whether to risk the eventual higher cost by investing early and steadily in CCS, or focus on basic research now and deploy later at scale when the costs have been reduced through learning.

These are urgent firm choices because, due to the cumulative nature of CCS and its impacts, earlier adoption has greater potential to mitigate carbon emissions. Decision-makers find it difficult to commit to early project design choices when the dominant design of the CCS technology system has not yet evolved (Abernathy and Utterback, 1978). There are currently a suite of promising CCS technologies and it is unclear which, if any, will be market winners in the long term. This can lead to a waiting game where existing large-scale emitters wait for the pioneering leaders to develop projects and narrow the degrees of freedom in defining successful CCS projects in the future.

A problem for corporate strategists is that committing to any one process or project cannot itself solve the problem of climate change, but can contribute to defining preferred technological trajectories over time. The cumulative nature of CCS leads to strategic questions on when and how to invest.

3.3.1. Policy implications

The primary implication for policy-makers is to remember that climate change innovations such as CCS are not exogenous, but are instead induced by policy and market conditions (Pinkse and Kolk, 2010; Otto and Reilly, 2007). Firms can be encouraged along the CCS technology learning curve through a transparent subsidization process and focusing public research spending on early basic research, as well as providing clear incentives through higher carbon prices. Poorly framed subsidies or processes that select winning technologies could slow down the implementation process. BP reportedly abandoned plans for a zero-emissions power plant in Peterhead, Scotland in mid-2007 partly because, as a pre-combustion capture project based on natural gas, it would not have fitted with the UK government's preference for post-combustion technology based on coal (Nicholls, 2009). Although the UK government has since reversed this preference (Scrase and Watson, 2009), these early experiences suggest that subsidization processes should be stable and transparent in their time-scales, timing, selection processes and technology parameters.

Public research spending should usually be focused on generic CCS-related technologies that could be deployed by a range of point course emitters. Some CCS investors, notably Statoil with its Sleipner and Snovit projects, are willing to publically release their learning on capture technologies and the stability of sequestered carbon in reservoirs (World Energy Council, 2007). For most commercial investors, however, generating proprietary strategically valuable know-how and intellectual property is a primary motivator for early adoption (Pinkse and Kolk, 2010; Nehrt, 1996). It is these resources that might form the basis of future competitive advantage (Sharma and Vredenburg, 1998). Sharing CCS technology knowledge to move more quickly down the learning curve is a major rationale for public subsidization of research projects, yet this could be hampered by nondisclosure agreements signed as part of the inducement for private firms to take on CCS project risks. The message for policy-makers here is to focus public research funding, including to privately-led CCS demonstration projects, on the generation of shared intellectual property rather than highly specific technologies, or those protected by nondisclosure agreements.

An important caveat should be placed on this emphasis on government support for basic research: incumbents face incentives to prolong the basic research phase, and push the demonstration and deployment phases further out to the future. For example, the power generation industry is notorious for low R & D spending (Nemet & Kammen, 2007; Pinkse and Kolk, 2010), but has been quite effective in lobbying for support for basic research activities rather than near-term commercial deployment of CCS (Stephens, 2009). The G8's commitment to announcing 20 large-scale demonstration projects on CCS by 2010 with a view to deployment by 2020 is a good example of a dual commitment to both development and deployment. It is widespread deployment that offers the highest cumulative emissions reduction, not basic research. Policymakers should focus on getting to widespread deployment most efficiently, not just the number of dollars allocated to research or to favored pilot projects.

The final implication for policy-makers on the cumulative dimension of CCS investment is that early, low cost measures may have substantial impact on technological adoption trajectories. The most obvious example is to immediately mandate that all new large point source emitters are "carbon capture ready". Relatively low cost measures, such as ensuring that new facilities have available space for future carbon capture and compression equipment and access to possible carbon transport routes can maintain an option for later CCS adoption (Bohm et al., 2007).

3.4. CCS investment is situated

The potential of CCS technologies to limit carbon dioxide emissions is highly situated not only geographically due to the physical nature of the processes, but also in developing energy systems, industry clusters and national policy contexts. First, the potential for CCS as a solution for climate change is situated within developing energy systems. Even full deployment within the developed countries of Western Europe, North America and Australia will not provide sufficiently deep CO_2 emissions cuts to impact the climate change problem. In most IPCC scenarios, much larger volumes of CO_2 will be captured in China and India by 2050 than in developed countries. The scale and pace of energy system development, and the necessary CCS technology transfers, is daunting. In China one GW of coal powered generation is currently being installed every week (Chen and Xu, 2010;

Hertzog, 2009), equivalent to the entire capacity of the UK electricity network every year.

This presents two strategic challenges to CCS adopters. First, CCS investments in North America or Europe may not make much difference to the overall climate problem, so the incentives to invest are further dampened. Second, transferring mitigation technologies from the contexts where they are invented, demonstrated and developed to where they are most advantageously deployed is a recognized problem (World Energy Council, 2007), even within multinational firms (Kolk and Pinkse, 2008). Optimists about CCS technology transfer to developing countries should remember that even transferring cost-saving technologies such as transgenic seeds has been difficult. Even when operational barriers, such as incenting CCS investments in developing countries or developing robust intellectual property regimes have been overcome adopters face the strategic technology management challenge of moving expertise within their distributed multinational networks.

Second, the potential CCS solution is situated within industry clusters. Some firms will inevitably have better commercial CCS opportunities than others. The competitive advantage of firms in global industries is built within a national competitive advantage context (Porter, 1990). For example, firms from countries with weak manufacturing industries, such as Australia, are poorly positioned to develop lucrative carbon capture technologies. In contrast, Japanese equipment manufacturing firms are well positioned to benefit from the commercial opportunities in CCS technologies. Japan has scarce natural energy resources, a technologically educated workforce, strength in process technologies and an export-oriented industrial focus that helps support energy manufacturing technology development. From the CCS adopting firm's point of view, industry clusters can greatly facilitate or hinder CCS investments, and help determine optimal locations for projects. For example, BP's proposed hydrogen-fueled power plant is planned in California, a strong supporter of renewable energy, while Canadian CCS adopters focus on post-combustion mitigation from oil sands upgraders because of the supporting industry cluster in these technologies.

Finally, the CCS solution is situated within the vested interests of national politics. Canada, the USA and Australia, for example, rely heavily on CCS deployment in their future emissions reduction plans, and yet have been relatively slow in deploying the technology. As Meadowcroft and Langhelle (2009a: p. 13) note, "This suggests a deep paradox that runs throughout the CCS story: its most enthusiastic advocates use the promise of future CCS-secured emission reductions to resist calls for immediate abatement today". As with other large-scale energy investments, adopters need to recognize that their CCS projects are tied to specific national and regional political environments. Not only do adopters face an uphill battle where there is an explicit lack of government support for CCS. They also need to look beyond the rhetoric and symbolism of stated support within their political environment to correctly gauge the realism of actual government commitment to CCS projects (Bowen, 2010). CCS investments – both corporate and government – are highly situated in the vested interests of national political systems.

3.4.1. *Policy implications*

First, policy-makers need to balance their desire to support the development of emerging domestic CCS technologies against potentially better technologies from abroad. For example, in Australia there is not a strong manufacturing industry, and thus no Australian technology manufacturer has specialized in CCS technologies, particularly the lucrative capture technologies (Innovation Norway, 2009). This seriously questions the Australian Chamber of Commerce and Industry's claim that "Australia has the expertise and technical capacity to play a leading role in exporting technology to developing countries" (ACCI 2006 in Sinclair and Gunningham, 2009: p. 64). The Australian government committed $2.4 billion (AUS) to support CCS projects, and to "boost Australian technology", and yet the two selected IGCC CCS projects in Australia's Carbon Capture and Storage Flagships Program rely on technologies from Japan (Mitsubishi in the case of the ZeroGen Project) and the US (GE in the Wandoan Power Project) (The Gov Monitor, 2009). Policy-makers should be aware that naively claiming that subsidies support the development of exportable domestic technologies, while in fact signing joint venture contracts with favorable terms for foreign capture equipment companies could be exposed by advocacy NGOs. The incentives facing government-supported CCS adopters, in this case Australian domestic coal companies, are not the same as for foreign suppliers that are able to develop competitively valuable capture technologies.

Second, incentives must be designed to overcome the institutional uncertainty inhibiting multinational firms that adopt CCS from transferring their operational experience with the technology to developing countries (Ockwell et al., 2008). We may be able to draw lessons from technology transfer in other domains, but multinational firms' experience with transferring technologies such as agricultural biotechnology is mixed at best. One solution that is actively discussed in current international negotiations is to recognize CCS investments as clean development mechanism (CDM) project activities (UNFCC, 2008; de Coninck, 2008; Shackley and Verma, 2008). CCS adopters in developing countries would gain carbon credits for the CO_2 emissions abated through implementing the technology, facilitating CCS technology transfer to developing countries. Industry associations such as the World Coal Institute advocate for this measure and estimate that "including CCS in the CDM could result in 6–9% of total CDM credits being supplied from CCS projects by 2020" (World Coal Institute, 2009). However, this policy option is controversial since the institutional structures required for monitoring, measuring and verification of CO_2 injection are particularly lacking in developing countries and the extent to which CCS facilitates sustainable development is contested (Greenpeace, 2008).

There is also an urgent need for mechanisms for sharing learning from commercial scale demonstration projects across national and industry cluster borders (de Coninck et al., 2009). Potential CCS users need to be able to access learning from other publicly-funded projects both in their own county and beyond. The first wave of demonstration projects should help us identify which, if any, technical dimensions of projects are highly situated and which are not. Investments in physical infrastructure for CCS may be highly situated, but the underlying technologies may not be.

4. Implications and extensions

Since over 80% of current world energy supplies come from fossil fuels, substantial advantages could be gained from emissions abatement methods that are central to the energy supply system (Shackley and Gough, 2006). Yet, the scale and pace of CCS deployment required to impact the climate problem yields both public and private policy challenges. Conceiving CCS investments as precautionary, sustaining, cumulative and situated can help us understand some of the complexities of the corporate technology strategy challenge, and yield powerful implications for policy-makers.

Most discussions of CCS include a long list of CCS implementation barriers (Sathaye et al. 2001; IPCC, 2005; Schrag, 2009; Dapeng and Weiwei, 2009). In this paper, we have argued that each CCS implementation barrier arises because of underlying CCS technology characteristics. Lack of public awareness and acceptance of the effectiveness of new technologies, for example, are recognized problems for precautionary investments. Organizational, managerial and cognitive barriers to change are prominent in explaining incumbents' preference for sustaining investments, as are political vested interests. Enabling investment environments for the development of new technologies are particularly important for cumulative investments over the long term. Clear technology transfer mechanisms are crucial for highly situated investments. Thus the four corporate technology strategy characteristics discussed in this paper both provide shape to the usually long list of CCS implementation barriers, and clues to successful policies to lower them.

Some of these recommendations are the usual suspects in discussions of CCS. It is, of course, important to continue to pay attention to operational concerns discussed in this journal and elsewhere on, for example, effective risk communication and public engagement processes for new, precautionary technologies (e.g. Shackley et al., 2007; Huijts et al., 2007), emissions mitigation and energy penalty data across the entire lifecycle of processes using CCS, especially when used for EOR (e.g. Bergerson and Lave, 2007), and how best to share knowledge derived from publicly-funded CCS demonstration projects, including across national borders (e.g. de Coninck et al., 2008).

Our approach emphasized policy choices based on the more strategic dimensions of CCS technology adoption decisions. For example, it really matters whether policy-makers are trying to encourage CCS as a sustaining or as a disruptive energy technology. The corporate strategy literature suggests that pre- and post-combustion CCS technologies may promise different technological trajectories: post-combustion sustains incremental improvement, whereas pre-combustion is a potentially disruptive innovation. Hansson and Bryngelsson (2009) noticed an "interpretive flexibility" where some experts view CCS as an incremental innovation and others as a way to break current energy lock-in in the long run. What they did not ask is whether these views differed systematically with different types of CCS technology. We need to understand whether government and corporate decision-makers perceive pre-combustion capture processes as truly disruptive to current technological trajectories.

Furthermore, the four strategic characteristics are inter-connected. From a situated, national competitive advantage perspective, for example, policy-makers can help move a country's CCS project portfolio from an end-of-pipe solution to one that could contribute to developing new disruptive capabilities. It may be appropriate to focus public funding for demonstration projects on relatively more disruptive projects, rather than on sustaining investments. Incumbent firms would make sustaining investments on their own in any case with appropriate carbon price incentives. The current policy emphasis on post-combustion CCS feeds inertia in incumbent emitters who have an incentive to promote sustaining investments as a bolt-on technological fix. Policy-makers have the opportunity to shift the balance when offering subsidies to prioritize high-potential disruptive projects. "Picking winners" can be a dangerous policy game, but a transparent subsidization process and a willingness to support promising technologies from wherever they may emerge can go part of the way to mitigate this.

Understanding CCS as one of a portfolio of potential carbon-reducing technologies raises some other policy questions. For example, insufficient attention has so far been paid to the extent to which CCS can provide synergistic public policy benefits (e.g. employment, increasing capital productivity) compared with alternative investments such as renewables. We would also encourage new research on the extent to which CCS public subsidies promote the development of domestic or foreign proprietary intellectual property and corporate capabilities based on the situated nature of CCS.

CCS technology adoption is a rich research site to investigate other issues within corporate technology strategy such as technology lock-in and lock-out (e.g. Unruh, 2000), vested interests (e.g. Meadowcroft and Langhelle, 2009a; 2009b; Bowen, 2010), organizational inertia (Bazerman, 2009), or the development of industry clusters and complementary assets (e.g. Pinkse and Kolk, 2010). Furthermore, due to the public funding of many CCS demonstration projects, project ownership structures are relatively transparent compared with privately funded projects of this scale, providing an opportunity to investigate large-scale research project monitoring, control and incentives.

The widespread deployment of CCS may prove to be one of the key technologies in retooling our energy system to a low-carbon path. While the scale and pace of the required CCS deployment is daunting, in this paper we have argued that the CCS investment challenge has underlying strategic features that are similar to other widely deployed technologies. Conceiving of corporate CCS adoption in this way can help us move beyond the special pleading and lobbying currently rife in the CCS industry. While the CCS deployment challenge is particularly daunting because investments are precautionary, sustaining, cumulative *and* situated, policy-makers can use these characteristics to coherently frame the challenges of CCS, and potential solutions to those challenges. This analysis also suggests fruitful avenues for future applied and theoretical social science research on the compelling applied challenge of investment in new low-carbon technologies.

References

Abernathy, W.J., Utterback, J.M., 1978. Patterns of industrial innovation. Technology Review 80 (7), 40–47.

Ahmed, P.K., Shepherd, C.D., 2010. Innovation Management: Context, Strategies, Systems and Processes. FT/Prentice Hall, Harlow, UK.

Akimoto, K., Tomoda, T., 2006. Costs and technology role for different levels of CO_2 concentration stabilization. In: Schellnhuber, H.J., Cramer, W., Nakicenovic, N., Wigley, T., Yohe, G. (Eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, UK, pp. 355–360.

Allen, M., Frame, D, Mason, C., 2009. The case for mandatory sequestration. Nature Geoscience 2, 813–814.

Aragon-Correa, J.A., 1998. Strategic proactivity and firm approach to the natural environment. Academy of Management Journal 41 (5), 556–567.

Ashworth, P., Boughen, N., Mayhew, M., Millar, F., 2009. An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond. Energy Procedia 1 (1), 4749–4756.

Bazerman, M., 2009. Barriers to acting in time on energy and strategies to overcome them. In: Gallagher, K. (Ed.), Acting in Time on Energy Policy. Brookings, Washington, DC, pp. 162–182.

Benner, M.J., Tushman, M.L., 2003. Exploitation, exploration and process management: the productivity dilemma revisited. Academy of Management Review 28 (2), 238–258.

Bergerson, J., Lave, L., 2007. The long-term life cycle private and external costs of high coal usage in the US. Energy Policy 35, 6225–6234.

Bohm, M.C., Hertzog, H.J., Parsons, J.E., Sekar, RC., 2007. Capture-ready coal plants: options, technologies and economics. International Journal of Greenhouse Gas Control, 113–120.

Boyce, G., 2010. Making black the new green. In: Keynote Speech at 8th Coaltrans China Conference, Beijing, 12 April, 2010.

Bowen, F.E., 2010. The social energy penalty: CCS demonstration projects and the competition for symbolic capital. IRIS Working Paper, Haskayne School of Business, University of Calgary, June 2010.

BP.com. 2010. Our Strategy, 〈www.bp.com〉 accessed 28 August, 2010.

Chang, Y., Yong, J., 2007. Differing perspectives of major oil firms on future energy developments: an illustrative framework. Energy Policy 35, 5466–5480.

Charitou, C., Markides, C., 2003. Responses to disruptive strategic innovation. Sloan Management Review 44 (2), 55–63.

Chen, C., Rubin, E.S., 2008. CO_2 control technology effects on IGCC plant performance and cost. Energy Policy 37, 915–924.

Chen, C., Rubin, E.S., 2009. CO_2 control technology effects on IGCC plant performance and cost. Energy Policy 37, 915–924.

Chen, W., Xu, R., 2010. Clean coal technology development in China. Energy Policy 38, 2123–2130.

Christensen, C., 1997. The Innovator's Dilemma. Harvard Business School Press, Cambridge, MA.

Christensen, C.M., Scott, D.A, Roth, E.A., 2004. Seeing What's Next: Using the Theories of Innovation to Predict Industry Change. Harvard Business School Publishing, Boston, MA.

Clarke, K., Ford, D., Saren, M., Thomas, R., 1995. Technology strategy in UK firms. Technology Analysis & Strategic Management 7 (2), 169–191.

Dapeng, L., Weiwei, W., 2009. Barriers and incentives of CCS deployment in China: results from semi-structured interviews. Energy Policy 37, 2421–2432.

de Coninck, H., 2008. Trojan horse or horn of plenty? Reflections on allowing CCS in the CDM. Energy Policy 36, 929–936.

de Coninck, H., Fischer, C., Newell, R.G., Ueno, T., 2008. International technology-oriented agreements to address climate change. Energy Policy 36, 335–356.

de Coninck, H., Stephens, J, Metz, B., 2009. Global learning on carbon capture and storage: a call for strong international cooperation on CCS demonstration. Energy Policy 37, 2161–2165.

Delmas, M., Russo, M.V., Montes-Sancho, M., 2007. Deregulation and environmental differentiation in the electric utility industry. Strategic Management Journal 28, 189–209.

Dewald, J., Bowen, F.E., 2010. Storm clouds and silver linings: responding to disruptive innovations through cognitive resilience. Entrepreneurship Theory and Practice 34 (1), 197–218.

Dosi, G., 1982. Technological paradigms and technological trajectories. Research Policy 11, 147–162.

European Commission, 2007. CO_2 Capture and Storage Projects. Office for Official Publications of the European Communities, Luxembourg ISSN 1018-5593.

Farrow, S., 2004. Using risk assessment, benefit–cost analysis, and real options to implement a precautionary principle. Risk Analysis 24 (3), 727–735.

Foster, R., 1986. Innovation: The Attacker's Advantage. MacMillan.

Fremeth, A., 2010. Redeployment of compliance-specific capabilities and renewable energy growth in the United States. Working Paper, Richard Ivey School of Business, University of Western Ontario, April 2010.

Fuss, S., Johansson, D.J.A., Szolgayova, J., Obersteiner, M., 2009. Impact of climate policy uncertainty on the adoption of electricity generating technologies. Energy Policy 37, 733–743.

Gallagher, K. (Ed.) 2009 Acting in Time on Energy Policy, Brookings: Washington, DC.

Gibbins, J., Haszeldine, S., Holloway, S., Pearce, J., Oakey, J., Shackley, S., Turley, C., 2006. Scope for future CO_2 emission reductions from electricity generation through the deployment of CCS technologies. In: Schellnhuber, H.J., Cramer, W., Nakicenovic, N., Wigley, T., Yohe, G. (Eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, UK, pp. 379–384.

Giddens, A., 2009. The Politics of Climate Change. Polity Press, Cambridge, UK.

Greenpeace, 2008. Clean Development Mechanism: No place for Carbon Capture and Storage.

Grubb, M., 1997. Technologies, energy systems and the timing of CO_2 emissions adatement. Energy Policy 25, 159–172.

Hansson, A., Bryngelsson, M., 2009. Expert opinions on carbon dioxide capture and storage – a framing of uncertainties and possibilities. Energy Policy 37 (6), 2273–2282.

Hart, S., 1995. A natural-resource-based view of the firm. Academy of Management Review 20 (4), 986–1014.

Hart, S., Milstein, M., 2003. Creating sustainable value. Academy of Management Executive 17 (2), 56–69.

Hertzog, H., 2009. Carbon dioxide capture and storage. In: Helm, D., Hepburn, C. (Eds.), The Economics and Politics of Climate Change. Oxford University Press, pp. 263–283.

Huijts, N., Midden, C., Meijnders, A., 2007. Social acceptance of carbon dioxide storage. Energy Policy 35, 2780–2789.

Innovation Norway, 2009. International Carbon Capture and Storage Technology Survey. Issue 5. July 2009.

IPCC, 2005. Intergovernmental Panel on Climate Change Special Report on Carbon Capture and Storage. Cambridge University Press, Cambridge, UK.

Klassen, R.D., Whybark, D.C., 1999. The impact of environmental technologies on manufacturing performance. Academy of Management Journal 42 (6), 599–615.

Kolk, A., Pinkse, J., 2008. A perspective on multinational enterprises and climate change: learning from 'An Inconvenient Truth'. Journal of International Business Studies 39 (8), 1359–1378.

Levy, D., Kolk, A., 2002. Strategic responses to global climate change: conflicting pressures on multinationals in the oil industry. Business and Politics 4 (3), 275–300.

Luehrman, T.A., 1998. Investment opportunities as real options. Harvard Business Review, July–August, 51–67.

March, J.G., 1991. Exploration and exploitation in organizational learning. Organization Science 2 (1), 71–87.

Marcus, A., 2009. Strategic Foresight: A New Look at Scenarios. Macmillan.

McKinsey & Company, 2008. Carbon Capture & Storage: Assessing the Economics. McKinsey & Company Inc..

Meadowcroft, J., Langhelle, O., 2009a. The politics and policy of carbon capture and storage. In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 1–21.

Meadowcroft, J., Langhelle, O., 2009b. The politics and policy of carbon capture and storage: the uncertain road ahead. In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 267–298.

Nehrt, C., 1996. Timing and intensity of environmental investments. Strategic Management Journal. 17, 535–547.

Nemet, G.F., Kammen, D.M., 2007. US energy R & D: declining investment, increasing need, and the feasibility of expansion. Energy Policy 35 (1), 746–755.

Nicholls, T., 2009. Causes for optimism for nascent CCS. Petroleum Economist. January 2009. Back Page.

Ockwell, D.G., Watson, J., MacKerron, G., Pal, P., Yamin, F., 2008. Key policy considerations for facilitating low carbon technology transfer to developing countries. Energy Policy 36, 4104–4115.

Oswald, D.J.S., 2003. Strategic technology management in a mid-corporate firm: the case of Otter Controls. Journal of Management Studies 34 (4), 511–536.

Otto, V.M., Reilly, J., 2007. Directed technical change and the adoption of CO_2 abatement technology: The case of CCS. Energy Economics 30 (6), 2879–2898.

Pablo, A.L., 1997. Reconciling predictions of decision making under risk: insights from a reconceptualised model of risk behaviour. Journal of Managerial Psychology 12 (1), 4–20.

Peabody Energy, 2009a. Clean Generation. 〈www.peabodyenergy.com〉 accessed November 12, 2009.

Peabody Energy, 2009b. 2009 Corporate and Social Responsibility Report.

Pinkse, J., Kolk, A., 2010. Challenges and trade-offs in corporate innovation for climate change. Business Strategy and the Environment 19, 3.

Porter, M.E., 1990. The Competitive Advantage of Nations. Free Press, New York, NY.

Praetorius, B., Schumacher, K., 2009. Greenhouse gas mitigation in a carbon constrained world: the role of carbon capture and storage. Energy Policy 37, 5081–5093.

Praetorius, B., von Stechow, C., 2009. Electricity gap versus climate change: electricity politics and the potential role of CCS in Germany. In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 125–157.

Purdy, R., 2006. Geological carbon dioxide storage and the law. In: Shackley, S., Gough, C. (Eds.), Carbon Capture and its Storage: An Integrated Assessment. Ashgate, Aldershot, UK, pp. 87–137.

Roussel, P.A., Saad, K.N., Erikson, T.J., 1991. Third Generation R & D: Managing the Link to Corporate Strategy. HBS Press, Cambridge, MA.

Rubin, E.S., Chen, C., Rao, A.B., 2007. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy 35, 4444–4454.

RWE, 2009. IGCC/CCS Power Plant: Combined Cycle with CCS technology viable on an industrial scale. 〈www.rwe.com〉 accessed December 19, 2009.

Sathaye, J., Bouille, D., Biswas, D., Crabbe, P., Geng, L., Hall, D., Imura, H.A.J.L., Peszko, G., Verbruggen, A., Worrell, E., Yamba, F., 2001. Barriers, opportunities and market potential of technologies and practices. In: Metz, B., Davidson, O., Swart, R., Pan, J. (Eds.), Climate Change 2001: Mitigation; Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Schrag, D.P., 2009. Making carbon capture and storage work. In: Gallagher, K. (Ed.), Acting in Time on Energy Policy. Brookings, Washington, DC, pp. 12–38.

Scrase, I., Watson, J., 2009. CCS in the UK: squaring coal use with climate change?. In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 158–185.

Shackley, S., Gough, C., 2006. Carbon Capture and its Storage: An Integrated Assessment. Ashgate, Aldershot, UK.

Shackley, S., Verma, P., 2008. Tackling CO_2 reduction in India through use of CO_2 capture and storage (CCS): prospects and challenges. Energy Policy 36, 3554–3561.

Shackley, S., Waterman, H., Godfroij, P., Reiner, D., Anderson, J., Draxlbauer, K., Flach, T., 2007. Stakeholder perceptions of CO_2 capture and storage in Europe: results from a survey. Energy Policy 35, 5091–5108.

Sharma, S., Vredenburg, H., 1998. Proactive environmental strategy and the development of competitively valuable capabilities. Strategic Management Journal 19 (8), 729–753.

Sinclair, D., Gunningham, N., 2009. CCS in Australia: from political posturing to policy potential. In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 50–74.

Stephens, J.C., 2009. Technology leader, policy laggard: CCS development for climate mitigation in the US political context. In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 22–49.

Stephens, J.C., Jiusto, S., 2010. Assessing innovation in emerging energy technologies: socio-technical dynamics of carbon capture and storage (CCS) and enhanced geothermal systems (EGS) in the USA. Energy Policy 38, 2020–2031.

Socolow, R., 2006. Stabilization wedges: an elaboration of the concept. In: Schellnhuber, H.J., Cramer, W., Nakicenovic, N., Wigley, T., Yohe, G. (Eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, UK, pp. 347–354.

The Gov Monitor, 2009. Australia to Short List $2 Billion Carbon Capture and Storage Projects. 8th December 2009.

UNFCC, 2008. Synthesis of views on technological, methodological, legal, policy and financial issues relevant to the consideration of carbon dioxide capture and storage in geological formations as project activities under the clean development mechanism, FCCC/SBSTA/2008/INF.3, 25 September, 2008.

Unruh, G., 2000. Understanding carbon lock-in. Energy Policy. 28, 817–830.

Van Noorden, R., 2010. Carbon sequestration: buried trouble. Nature 463, 871–873.

Vergragt, P.J., 2009. CCS in the Netherlands: glass half empty or half full? In: Meadowcroft, Langhelle (Eds.), Caching the Carbon: The Politics and Policy of Carbon Capture and Storage. Edward Elgar, Cheltenham, UK, pp. 186–210.

World Coal Institute, 2009. CCS and the CDM. Climate Policy Paper 3. London, UK.

World Energy Council, 2007. Carbon Capture and Storage: A WEC "Interim Balance". London: UK.