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Pipe Dreams? Carbon Capture and Storage as a Corporate Technology Strategy Challenge

Prepared by

Frances Bowen

*IRIS: International Resource Industries and Sustainability Centre
Haskayne School of Business
University of Calgary*

ISEEE Research Paper

February 2009

Title: Pipe Dreams? Carbon Capture and Storage as a Corporate Technology Strategy Challenge

Author: Dr. Frances Bowen

Affiliation: Frances Bowen is an Associate Professor and Director of the International Resource Industries and Sustainability Centre (IRIS) at the Haskayne School of Business, University of Calgary. Contact Dr. Bowen at (frances.bowen@haskayne.ucalgary.ca).

Please cite as: Bowen F 2009 “Pipe Dreams? Carbon Capture and Storage as a Corporate Technology Strategy Challenge” February 2009. ISEEE Research Paper

Paper available at: <http://www.iseee.ca>

**The Institute for Sustainable Energy,
Environment and Economy
Room 1040, Earth Sciences Building
University of Calgary
2500 University Drive NW, Calgary, AB T2N 1N4
T: 403-220-6100; F: 403-220-2400; info@iseee.ca
www.iseee.ca**

ACKNOWLEDGMENTS

Funding for this paper was provided to ISEEE by the Government of Canada, through Natural Resources Canada. ISEEE thanks Natural Resources Canada for their support of this project.

This paper was initiated during my tenure as a Senior Visiting Fellow at the Smith School of Enterprise and the Environment, University of Oxford in early 2009. I am grateful to participants at the IRIS-ISEEE Knowledge Forum on CCS Risk Management held in Calgary in September 2009 and at a research seminar on this topic hosted by the Smith School in November 2009 for their insights, suggestions and improvements to this paper.

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COMMENTS

This paper has been submitted to *Energy Policy*.

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ABSTRACT

Carbon Capture and Storage (CCS) is a key technology to achieve the radical reductions in greenhouse gas emissions needed to avert dangerous climate change. Latest estimates suggest that widespread deployment of CCS could account for up to one-fifth of the needed global reduction in emissions by 2050. Governments are attempting to stimulate investments in CCS technology both directly through subsidizing CCS 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 the high cost of capture technologies, technological uncertainties in integrated CCS systems and underdeveloped regulatory and liability regimes. In this paper, I move beyond this list of barriers to address four underlying characteristics of the CCS technology adoption decision: such investments are precautionary, disruptive, cumulative and situated. Understanding CCS as a corporate technology strategy challenge can help us coherently frame the barriers to CCS, and potential solutions to those barriers.

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 strategy question is no longer whether to invest in GHG-reducing technologies, but which technologies to emphasise 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 in 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). In the UK, CCS could lead to large (approx 45%) reductions in carbon dioxide (CO₂) emissions from electricity generation (Gibbins et al., 2006). Furthermore, CCS is an important technology to reduce the overall cost of stabilization (Akimoto and Tomoda, 2006; Metz & van Vuuren, 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 CO₂ emissions will rely on strategic 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. 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). Just as the cost of offshore oil platforms declined rapidly as companies sought to continue operations in the face of declining oil prices in the 1980s, we can expect the future costs of CCS to decrease with stronger carbon emission prices over time.

The public policy challenge is that waiting for carbon prices to incent market CCS investments is too slow a 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 & Gough, 2006). It is tempting for corporate decision-makers to claim that developing CCS technology is a unique and politically motivated investment that requires significant public subsidy. So far, much corporate activity on CCS, especially among “those whose fortunes are most tightly tied to fossil fuels” (Meadowcroft & Langhelle, 2009a: 7), has been focused on basic scientific research and lobbying governments for subsidies, 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 social barriers to lowering CO₂ emissions by modifying existing industrial processes and electricity generation than by more radical low carbon solutions (Gibbins et al., 2006). We need to move beyond incumbent firm special pleading that CCS technology is somehow “unique”, and systematically think through the distinctive features of the CCS corporate technology strategy decision.

In this paper, I develop a corporate technology strategy perspective on CCS investments to diagnose the investment challenges of CCS, and potential solutions to those challenges. I will begin with a brief introduction to CCS technology before outlining four distinctive characteristics of the strategic technology adoption decision. CCS investments are precautionary, disruptive, cumulative and situated. Diagnosing these characteristics will provide both corporate decision-makers and public policy-makers more nuanced recommendations on how to encourage CCS adoption at the rate required for radical reductions in GHG emissions before 2050.

AN INTRODUCTION TO CCS TECHNOLOGIES

“CCS technology” can more accurately be thought of as a chain of technologies designed to separate CO₂ 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 CO₂ 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. Most processes involved in the CCS system have been used individually for various industrial purposes, but there is very limited experience of full-scale integration in a CCS system (Shackley & Gough, 2006).

The most expensive element of the CCS technology chain is the initial CO₂ capture (McKinsey, 2008; IPCC, 2005). Two types of CO₂ capture systems are well developed: post-combustion and pre-combustion. In post-combustion capture, CO₂ 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 CO₂ 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 CO₂ in the gas stream and the higher pressure make the separation easier” (IPCC, 2005: 5). These two CO₂ 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 CO₂ for fizzy drinks (European Commission, 2008: 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 CO₂ captured, depending on the particular process configuration. The CO₂ 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.

CO₂ transportation is mostly by pipeline, though CO₂ shipping may become economically feasible under specific conditions. There are already over 3,400 miles of CO₂ pipelines in the USA, transporting CO₂ from naturally occurring reservoirs to the oil fields of West Texas and the Gulf Coast for enhanced oil recovery (Hertzog, 2009). The cost of CO₂ transportation is an order of magnitude less than for capture (\$1-8 US per ton CO₂ 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 CO₂ 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 such as Enbridge in Canada or National Grid plc in the UK.

There are several CO₂ 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 & 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. Once the infrastructure for transporting and storing CO₂ has been developed, then there are few if any additional costs per unit of CO₂ stored. As Wildenborg et al. (2005: 603) put it “the cost of CO₂ transport and storage in Europe is likely to have a cap.” Shackley and Gough (2006: 7) argue that this is also likely to be the case in North America.

For the purposes of this paper, I will exclude less mature storage technology options such as direct ocean storage, which is currently deemed environmentally unacceptable in the EU (European Commission, 2007), and sequestration from the combustion of biomass, which can lead to a net reduction of atmospheric CO₂ as trees and soil take up atmospheric CO₂ (see Read, 2006 for a review of biomass capture and biological sequestration). Currently, no large companies specialize exclusively in CO₂ 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 options about the capture, transport and storage options selected. Common explanations for delay in corporate CCS investments include the high cost of capture technologies, technological uncertainties in integrated CCS systems and underdeveloped regulatory and liability regimes. In this paper, I move beyond these barriers to address four distinctive characteristics of the CCS technology adoption decision: such investments are precautionary, disruptive, 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.

WHAT IS DISTINCTIVE ABOUT CCS INVESTMENTS?

1. CCS Investment is Precautionary

The first distinctive characteristic of CCS investment is that it is precautionary. The only reason that governments or firms are considering risky investments to develop CCS technology is as a precaution against an even greater future risk: that of dangerous climate change. Analysts of the politics of climate change have begun to grapple with this problem that is common to many climate-related technologies (Meadowcroft & Langhelle, 2009b). Giddens (2009) analyses the political implications of a paradox where since the impacts of climate change aren't tangible, immediate or visible, decision-makers invest little to address them, yet waiting for impacts to occur will, by definition, be too late. Similarly, Gallagher (2009) argues that energy policy suffers 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.

Less attention has so far been paid to the corporate strategy technology implications of CCS as a precautionary investment. This is an important investment characteristic since 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 situation 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 the fact that the 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 making precautionary investments in other domains by using tools such as real options or scenario analysis. 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). To incent precautionary CCS investments, even understanding that the eventual private costs of adaptation to climate change will be at least an order of magnitude larger than the costs of mitigating climate change (European Commission, 2007) is not enough. Managers must understand which costs will be borne by firms, and which by society more broadly should the precautionary hazard occur.

Given that CCS technology is not risk-free, CCS is harder to promote as a precautionary investment where there is an active public conversation on immediate and more distant risks of CCS as an emissions reduction solution. CCS project proponents face a two-level public acceptance challenge: acceptance of the potential risks of carbon transport and storage technologies, and acceptance of the broader precautionary reason why CCS is needed. For example, firms are less likely to undertake CCS investments in contexts where there is lack of public acceptance of or interest in climate change as a problem since such investments are seen as a “politically correct subsidy to a technology that makes no economic sense” (comment from industry participant). 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 CO₂ from its CCS pilot plant at the Schwarze Pumpe power station in Germany).

In order to implement a precautionary investment such as CCS, firms must address both levels of public risk perception. Corporate communication strategies must address the dangers of broader climate change as well as the perceived risks of CCS (Ashworth et al., 2009; Reiner, 2008), but educating investors and the public about the relative risks of CCS and broader climate change remains a significant challenge. CCS technologies are relatively technical and remote so there are few immediate points of connection in the lay public’s frame of reference to many of the key concepts (Shackley & Gough, 2006:142). Evidence suggests that the more that people know about uncertainties surrounding CCS, the less they like the technology (Ha-Duong et al. 2009). Evidence is also mixed on the usefulness of analogies such as nuclear power in public conversations about CCS (Reiner & Nuttall, 2009).

In promoting precautionary investments, firms are increasingly able to draw on a growing body of successes and failures of CCS risk acceptance. The Ocean Field Experiment in Hawaii is an iconic example of how a few dedicated activists and slow recognition of the need for public outreach derailed the project (de Figueiredo et al., 2003). Similarly, Shell is still recovering from the damage to its stakeholder relations incurred during the approval process to store CO₂ below the Dutch town of Barendrecht. Approved by the Dutch government in November 2009, Shell's Barendrecht project had previously been opposed by more than 1,000 people at a Shell-hosted town hall meeting, street protests, and by the city council that is still threatening legal action to stop the project (Pals, 2009; Financial Post, 2009). Essent has cancelled CCS investment plans at least partly due to public opposition, led by Greenpeace (Vergragt, 2009).

Lessons are beginning to be drawn from successful public acceptance processes. Notable successes include Epcor's use of mental model mapping and Community Advisory Task Groups to shape repeated community dialogues over many years (Carpenter, 2009). These demonstrable public acceptance capabilities were valuable in positioning Epcor's Genesee project as one of three selected in the province of Alberta's competition to allocate of \$2bn to CCS projects. Similarly, Total's Lacq project in France has received broad public acceptance despite being implemented during a polarizing municipal election (McDaniels & Bowen, 2010).

Casting CCS as a precautionary investment suggests at least four lessons for government policy-makers. The first is to provide climate policy certainty. Even if corporate decision-makers are not persuaded by the science of potential climate catastrophe, strong public policy signals can frame the larger precautionary risk to assist appropriate risk models and corporate decision-making. The more that corporate decision-makers are aware of the private downside policy risks

of insufficient climate-related actions, the more they can use established risk mitigation models such as real options or scenario planning.

The second lesson is for public bodies to assist with public awareness and education on both CCS technologies and the broader climate change problem (ICO2N, 2009). Corporations are among the least trusted sources of information on CCS (Huijts et al. 2007), yet experiences in early projects suggest that corporate precautionary investments require two-level buy-in from both investors and local publics. The third lesson is to be aware of 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. Even low-risk CCS projects may not be implemented if planning processes are too cumbersome. The formation of arm's-length planning authorities to speed up decisions on CCS project approvals (such as the newly created Infrastructure Planning Commission in the UK for power plant approvals) may be a useful model for CCS siting decisions.

The fourth lesson to policy-makers on precautionary investments is to beware the business of precaution. As noted above, entire industries have been built upon the business opportunities inherent in mitigating precautionary risks. Just as overinvestment in security (compared with the magnitude of the risk faced) has continued since the terrorist attacks of September 11th 2001, there is a 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 precautionary investments.

Perhaps 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 CO₂ released to the atmosphere. Governments should (1) invest research dollars in monitoring technologies to ensure that the claimed CO₂ 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 CO₂ 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.

2. CCS Investment is Disruptive

Investments in CCS technology are disruptive in the sense that production with CCS is less energy and cost efficient than production without. Each of the CCS capture technologies requires significant energy inputs, and if this energy comes from fossil fuel-based sources, the capture process incurs an energy penalty (Shackley & Gough, 2006; European Commission, 2008). Additional energy costs in the capture process are the main component of increased operational expenditure of processes with CCS. Around 80% of the additional operational costs from CCS technology are incurred in the capture stage of the processes (IPCC, 2005:11), and it is the capture stage that suffers the largest cost efficiency penalty.

An important distinction in the corporate technology strategy literature is between sustaining and disruptive innovations. Sustaining innovations maintain or increase the industry's rate of improvement 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 a 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 & von Stechow, 2009).

Sustaining innovations such as post-combustion capture are more popular among established, incumbent firms (Christensen, 1992). 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 (Charitou & Markides, 2003). Post-combustion capture deals with CO₂ 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).

Such investments might sustain high-emission intensity incumbent firms' license to operate, but the corporate environmental strategy literature suggests that 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: 992) is reactive 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 sustained competitive advantage (Klassen & Whybark, 1999). Thus if CCS technology is seen as a sustaining innovation, the energy and efficiency penalties incurred in capture processes lead to the failure of private incentives for CCS because of operational inefficiency and the lack of potential for gaining competitive advantage.

Pre-combustion capture technology, on the other hand, may have the potential to be a disruptive innovation. 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 truly 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 & Markides, 2003). Just as Kodak, with its business model based on producing, selling and processing film, was slow to react to the rapid improvements in the quality of digital photography (Dewald & Bowen, 2010), incumbent firms that select post-combustion capture technologies may face the threat of CCS technologies that reconfigure the desired characteristics in the industry.

RWE Power, for example, was developing its IGCC (Integrated Gasification Combined Cycle) 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). The energy penalty is likely to be lower for pre-combustion processes with natural gas as a feedstock, compared with RWE’s coal. Natural gas is likely to

offer relatively low-cost CO₂ capture so long as gas prices remain low, particularly for new natural gas combined cycle plants designed for capture from the outset (Gibbins et al., 2006: 381).

Thus in the best case, some types of CCS technologies may turn out to be disruptive in the sense that 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 CO₂ for capture, and flexibility in the end use of hydrogen as an output (as in pre-combustion capture). BP is experimenting with some of the more radical technologies based on its interest in hydrogen-related capabilities, and so is focusing its efforts on pre-combustion IGCC.

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. However, conceptualizing CCS as a disruptive investment – either in the weak sense of incurring an energy and efficiency penalty, or in the strong sense of altering the industry’s performance trajectory – allows policy-makers to learn from the corporate technology strategy literature.

First, policy-makers should beware of incumbents’ incentives to resist low-carbon requirements through lobbying and efforts to amend legislation to protect incumbent assets. This is likely to be strongest in incumbents that perceive climate-related concerns as a threat rather than an opportunity (Dewald & Bowen, 2010). Managers will put off addressing major decisions in favour of less important initiatives until there is an imminent cost to avoidance (Ainslie & Haslam, 1992): 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 & 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, 2009). 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 & von Stechow, 2009: 146). Meadowcroft and Langhelle (2009b: 289) summarise the strategic stance of these firms as “CCS when absolutely necessary; but surely it’s not necessary quite yet”.

An implication for policy-makers is to look away from the usual suspects, especially incumbent lobbyists, and to seek to support innovation at the industry’s periphery. Public funds allocated to CCS demonstration projects heavily favour 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. These incumbent firms have successfully positioned CCS as a bridging or transitional technology that allows postponement of more radical energy system changes

(Praetorius & von Stechow, 2009). Policymakers should remember that CCS will be required not only in power generation, but also in other industrial processes. They should also be aware that successful CCS implementation requires innovation and advanced process technology deployment by firms in adjacent industries – industrial chemicals, project management, oilfield services – as well as by the power utilities. In the long run, breakthrough innovations are more likely to come from business opportunities at the fringe of these industries, rather than from incumbent power generation companies. “Green” stimulus plans may in effect prop up established power generators that may struggle to survive in the new low-carbon economy (Pinske & Kolk, 2010).

Second, policy-makers should build alliances with firms that have positive risk experience. Managers that have had favourable experience in making risky decisions are more likely to take the risk of adopting 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 (Pinske & Kolk, 2010).

The corporate environmental strategy literature suggests that innovation in CCS may be more likely in firms that pursue a broader portfolio of carbon management initiatives. Firms implementing a portfolio approach may be able to redeploy capabilities developed in proximate industries and businesses to CCS activities (Van der Byl, 2010). For example, TransAlta may be able to redeploy acquired stakeholder integration capabilities (Sharma & Vredenburg, 1998)

from its Canadian Hydro Developers merger to the CCS Pioneer Project stakeholder engagement process. 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 & von Stechow, 2009), since firms had useful experiences in technologies and processes dealing with underground reservoirs and CO₂ injection. Another example is Epcor's valuable experience with risk mitigation through community consultation mentioned above. Thus policy-makers should 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 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. 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 sulphur dioxide and nitrogen oxides) that CCS does not deliver (Metz & Van Vuuren, 2006). Technologies exist to "co-capture and co-store" other pollutants, like sulphur, with the CO₂ 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 renewable energy investment alternatives.

3. CCS Investment is Cumulative

The sheer scale of the emissions reduction challenge means that a large number of commercial scale CCS projects must be operational before having any appreciable impact on atmospheric concentrations of CO₂. As Socolow (2006: 351) puts it, to achieve the CCS emission reduction “wedge” by 2050, we need to capture and store CO₂ equivalent to 3,500 Sleipners. Since 23% of global CO₂ emissions arise from the production of cement, iron, glass, chemicals and pulp (Shackley & Gough, 2006:44), CCS would need to be deployed not only on power plants, but also across a wide range of industrial processes. Of the almost 8,000 global stationary point sources emitting over 0.1 tonnes of CO₂ per year, more than 3,000 are outside the power sector (IPCC, 2005). In order to be part of the climate solution, CCS must be deployed on a massive scale.

Furthermore, as with climate change itself, CCS technology investments are inherently cumulative in the long run (Allen, Frame & Mason, 2009). Early successful carbon sequestration promises more climate impact because emissions are avoided not only in the year of investment but in all future years as long as the CO₂ remains isolated from the atmosphere. The timing of CCS investments is crucial for the likely impact of the CCS solution (Meadowcroft & Langhelle, 2009a). 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 (Schellnhuber et al., 2006; McKinsey, 2008). The IPCC (2005: 11) estimates that the cost of capture could be reduced by 20-30% before 2015, and that even bigger cost reductions should be achievable by new technologies that are in the research or demonstration phase.

Framing CCS investments and learning as a cumulative problem reveals a tension between “steady walk” deployment to achieve the largest cumulative emission reductions, 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). Both governments and firms need to decide whether to risk the eventual higher cost by investing early and steadily in CCS, or focus on research now and deploying later at scale when the costs have been reduced. The power generation industry is notorious for low R & D spending (Pinske & 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). In either case, as Kallbekken & Rive (2006) point out, the “R & D then sprint” option cannot be an excuse for inaction: if we start deployment late, then we will need to deploy at a faster rate for the same cumulative emissions reduction.

For corporate decision-makers, the CCS cumulative investment problem has two dimensions: scale and rate of deployment. The required scale of investment poses questions for firms on the availability of resources, skills and capabilities to implement CCS. The most basic resource required is capital finance. Demonstration scale CCS projects require a significant financial capital investment of \$1-2bn. During the recent financial crisis, proponents of large-scale energy projects have experienced difficulties in raising the necessary finance even for projects based on proven technologies. For example, Santos’ Moomba storage project in South Australia was shelved in the wake of the financial crisis and lower oil and gas prices (Wallace, 2009). While the financial resources required are likely to become more available as credit markets recover, CCS projects may face shortages of other resources. Evidence from Australia indicates that there may be insufficient skilled engineers to be able to build and operate CCS projects at the required scale.

The scale of investment and range of capabilities required for any one individual CCS project means that, as is the case with many climate change innovations (Unruh, 2000), most projects are delivered by consortia or joint venture arrangements. As Gardiner Hill, director of CCS technology at BP points out “There need to be partnerships along the value chain in which companies can play to their strengths” (Nicholls, 2009). E.ON’s Kingsnorth supercritical coal-fired power station proposal, for example, involves partners with expertise in project management (Arup), international technology dissemination (Electric Power Research Institute), capture plant engineering (Foster Wheeler), capture technology (Mitsubishi Heavy Industries) and pipeline transportation (Penspen) as well as their own E.ON gas storage group. While collaboration with firms that are not direct competitors can help protect valuable firm capabilities, collaborative projects generate additional transaction costs and strategic exposure (Pinske & Kolk, 2010).

The rate of deployment dimension of the cumulative investment challenge may prove to be even more significant for corporate decision-makers than scale. Early adoption decisions yield the highest cumulative emissions reduction impact, yet they must be made in the most uncertain policy, technology and climate impact contexts (Nehrt, 1996). Early project design choices are particularly crucial as capture methods or pipeline routes selected in the first wave of investment can have a substantial impact on CCS technological trajectories over time. Such path dependency in the CCS investment decision is complemented by significant inertia as owners of existing plants may fear that early, mandatory CCS could force the premature retirement or under utilization of their current assets. Evidence on first mover advantages in new technology adoption is mixed. Many incumbent firms considering CCS adoption possess the process engineering capabilities or formalized structures better suited to a fast follower or fast second

strategy (Markides & Geroski, 2004). 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.

Policy-makers should also remember that climate change innovations such as CCS are not exogenous, but are instead induced by policy and market conditions (Pinske & Kolk, 2010; Otto & Reilly, 2007). Firms can be encouraged along the CCS technology learning curve through a transparent subsidization process and focusing public research spending on generic technologies, as well as providing clear incentives through higher carbon prices. It is possible that poorly framed subsidies could slow down the implementation process. As one industry participant put it: “the first builds get subsidies, and the next ones don’t build as they sit around waiting for their share”. Subsidization processes that select winning technologies can also lead to slower implementation. 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 & 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 be focused on generic CCS-related technologies that could be deployed by a range of point source emitters. Some CCS investors, notably Statoil with its Sleipner and Snøvit 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 (Pinske & Kolk, 2010; Nehrt, 1996). It is these resources that might form the basis of future competitive advantage (Sharma & Vredenburg, 1998). Sharing CCS technology knowledge 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 that could yield competitive advantage to particular firms.

The final implication for policy-makers on the cumulative dimension of CCS investments 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 the future installation of carbon capture and compression equipment, and access to possible carbon transport routes can maintain an option for later CCS adoption (Environment Agency, 2008; Bohm et al. 2007).

4. CCS Investment is Situated

CCS technology decisions are highly situated: not only geographically due to the physical nature of the processes, but also in national policy contexts, energy systems and industry clusters. The transfer of mitigation technologies from the contexts where they are invented, demonstrated and developed to where they are most advantageously deployed is a recognized problem (Metz & Van Wuuren, 2006; World Energy Council, 2007). Large multinational companies must actively manage the situated nature of CCS investments as climate change

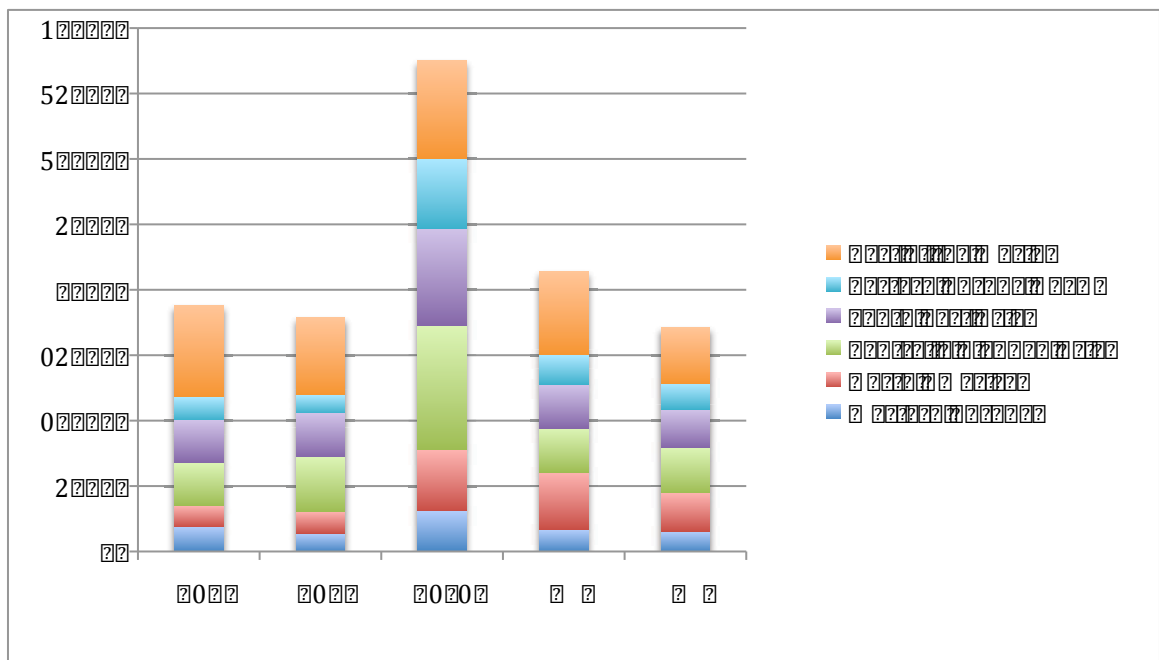
policy can present opportunities in one geographic location, but threats in another (Kolk & Pinsky, 2008).

The CCS investment challenge is that even full deployment in the developed countries of Western Europe, North America and Australia will not have the necessary impact on emissions reduction. The main focus in policy discussions is on the importance of deploying CCS in China and India (Stern, 2006). These rapidly growing economies with large populations are also heavy in available domestic coal resources (Schrag, 2009). The sheer scale of energy development and concomitant technology transfers needed is daunting: in China one GW of coal powered generation is currently being installed every week (Hertzog, 2009), equivalent to the entire capacity of the UK electricity network every year. Senior (2005) estimates that by 2030, China is expected to have nine times the installed coal power plant capacity of the EU, and to be using five times as much coal. The *additional* CO₂ emissions from coal-fired power in China and India by 2030 will be 3 Gt CO₂, equivalent to 13 times the UK's current power-sector CO₂ emissions (House of Commons, 2006).

Figure 1 shows estimates of the amount of CO₂ captured in different regions in 2050 based on a variety of IPCC scenarios. In most of the 2050 scenarios, much larger volumes of CO₂ are captured in Centrally Planned Asia (mostly China) and South East Asia (mostly India) than in Western Europe or North America. Most IPCC scenarios rely on massive deployment of CCS in the developing and industrializing countries of today. This is the case for all but the lower-growth, more environmentally focused scenarios (B1 and B2), in which case CCS is deployed more in the industrialized world (Shackley & Gough, 2006:7) due to the relative costs of energy efficiency technologies (Akimoto & Tomada, 2006).

Fortunately, the carbon storage stage of the CCS value chain appears to be less of a problem than the capture stage outlined above. Geological formations with storage potential “are – like coal reserves – quite evenly spread across the world” (European Commission, 2008: 5). There appears to be plenty of potential storage relative to demand in high deployment regions such as the USA, Australia, Canada, China and India where there are large numbers of point source emitters within ~500km of sedimentary basins (Shackley & Gough, 2006; Gibbins et al. 2006). However, while potential storage reservoirs exist around the world, some countries will inevitably have better CCS opportunities than others (Hertzog, 2009).

Figure 1: Potential CO₂ Capture under different IPCC Scenarios in MtCO₂, 2050



Source: IPCC CCS Report (2005), adapted from Table 2.6

The situated nature of CCS investments is at the core of the growth and equity issues in global climate change policy (Giddens, 2009). Intergovernmental negotiations focus on the

extent to which developing and industrializing countries can now have equal access to the opportunity to use their own energy resources as industrialized countries had before the carbon constraint. Since CCS investments are expensive, precautionary and disruptive, policy-makers must design mechanisms to overcome market failures for CCS investments due to the lack of effective demand in developing countries for a more expensive growth path (Meadowcroft & Langhelle, 2009a).

Incentives must be designed to overcome the institutional uncertainty surrounding CCS investments in developing countries, especially with regard to intellectual property and capture technologies. We may be able to draw lessons from technology transfer in other domains, but experience with transfer technologies such as agricultural biotechnology is at best, mixed. One solution that is actively discussed in current international negotiations is to recognise CCS investments as clean development mechanism (CDM) project activities (UNFCCC, 2008). Proponents of CCS investments in developing countries would gain carbon credits for the CO₂ 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 CO₂ injection are particularly lacking in developing countries and the extent to which CCS facilitates sustainable development is contested (Greenpeace, 2008).

Whether CCS in developing countries is incentivised by the clean development mechanism or by other means, several policy challenges remain due to the situated nature of CCS. 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 on 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 & Cunningham, 2009: 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 Programme 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).

This is a common problem for countries that are early supporters of CCS such as Norway. As Tjernshaugen & Langhelle (2009: 120) put it: "a world record in early CCS enthusiasm by no means automatically translates into a leading position as a technology supplier". 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 favourable terms for foreign capture equipment companies, could be exposed by advocacy NGOs. If the development of exportable technologies is an important policy objective, then policy-makers should ensure that agreements on intellectual property developed through subsidized demonstration projects allow knowledge to be shared with domestic supporting industries.

Second, policy-makers should ensure that appropriate and enforceable IP regimes for new capture technologies are developed – both at home and abroad. Enforceable and predictable IP

regimes help to limit the uncertainty associated with protecting private investments, especially in developing countries. Third, an emerging issue may be the race for securing access to preferred storage sites. In most jurisdictions, pore space for storage is owned by the state. However, in the US this is not the case and the right to use the subsurface would need to be acquired from every owner where the CO₂ plume might migrate (Hertzog, 2009). While there appears to be adequate storage sites for the quantities of CO₂ to be injected and stored on a global basis, policy-makers should actively devise a framework for the allocation of such sites before negotiated *ad hoc* solutions become impractical.

Much of the emissions reduction potential of CCS is from deployment in developing countries, hence the focus in this and other papers on technology transfer and diffusion. The situated nature of CCS investments is also important in understanding intriguing trends in CCS policy across developed countries. 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 & Langhelle (2009a: 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”. CCS investments – both corporate and government – are highly situated in the vested interests of national political systems.

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 & 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, disruptive, cumulative and situated can help us understand some of the complexities of the corporate technology adoption 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). In this paper, I 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 recognised problems for precautionary investments. Organisational, managerial and cognitive barriers to change are prominent in discussions of disruptive investments, as are political vested interests. Enabling investment environments for the development of new technologies are particularly important for cumulative investments. Clear legal liability and intellectual property frameworks 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.

Analysing CCS as a technology adoption decision also reveals at least eight areas where future applied research is needed on the impacts and viability of CCS. Policy-makers need better data on decision-crucial issues such as (1) the extent to which CCS can provide synergistic public policy benefits (e.g. employment, increasing capital productivity) compared with alternative investments such as renewables; (2) effective risk communication and public engagement processes for new, precautionary technologies; (3) emissions mitigation and energy penalty data across the entire lifecycle of processes using CCS, especially when used for EOR; (4) how best to share knowledge derived from publicly-funded CCS demonstration projects, including across national borders; (5) corporate decision-makers' perceptions of whether pre-

combustion capture processes are truly disruptive to current technological trajectories; (6) the extent to which CCS public subsidies promote the development of domestic or foreign proprietary intellectual property and corporate capabilities; (7) the availability of skilled workers and engineers within national borders to be able to deploy CCS at the necessary scale and/or the training or immigration policies needed to develop such a skilled pool; and, most crucially, (8) optimal monitoring technologies to ensure that the claimed CO₂ sequestered does in fact stay isolated from the atmosphere for an acceptably long time.

So far social scientists examining CCS have focused on the politics, public risk perception, communications and acceptability dimensions of CCS as a new precautionary technology. Seeing CCS as a corporate technology adoption decision opens up several new theoretical avenues in technology management research. CCS technology adoption is a rich research site to explore theoretical issues in the literature such as technology lock-in and lock-out (e.g. Unruh, 2000), vested interests (e.g. Meadowcroft & Langhelle, 2009), organizational inertia (Bazerman, 2009), or the development of industry clusters and complementary assets (e.g. Pinske & 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 I have argued that the CCS investment challenge has underlying 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, disruptive, 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.

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