Sustainability: Science, Practice, & Policy
http://ejournal.nbii.org

ARTICLE

Growing interest in carbon capture and storage (CCS) for climate change mitigation

Jennie C. Stephens

Environmental Science and Policy, Department of International Development, Community, and Environment, Clark University, 950 Main Street, Worcester, MA 01610 USA (email: jstephens@clarku.edu)

Interest in technologies associated with carbon capture and storage (CCS) has been growing rapidly in both the public and private sectors over the past five to ten years as governments, industry, and individuals grapple with how to reconcile increased energy demand with the need to reduce atmospheric carbon dioxide (CO_2) concentrations to mitigate the risks of climate change. CCS technology involves capturing the CO_2 produced during fossil-fuel combustion and storing it in underground geologic reservoirs instead of emitting it into the atmosphere. The idea of engineering the storage of carbon has developed from relative obscurity to an increasingly recognized approach to stabilizing atmospheric CO_2 concentrations. This paper (1) identifies several influential nongovernmental stakeholders and discusses their contributions to CCS and (2) describes how governmental influence through political positions, government-supported research and development, and economic policy tools and international treaties have influenced CCS initiatives. While the relative strength of nongovernmental and governmental influences is not quantified, this treatment of the various factors contributing to the advancement of CCS technology highlights the complexity associated with integrating developments in science and engineering into sustainable practices.

KEYWORDS*:* Climatic change, carbon cycle, energy consumption, socioeconomic aspects, fuel technology, Kyoto Protocol, political attitudes, policy reform

Introduction

As the current impacts and future risks of climate change become more apparent, and the atmospheric concentration of carbon dioxide (CO_2) continues to increase, carbon capture and storage (CCS) technologies provide a potentially valuable set of tools for achieving the magnitude of emissions reductions required for CO_2 stabilization as society gradually transitions to a non-fossil fuel energy system. Interest in CCS technologies has been growing rapidly in both the public and private sectors over the past five to ten years as governments, industry, and individuals grapple with reconciling increased energy demand with the need to reduce atmospheric CO_2 concentrations to mitigate climate change.

The concept of engineering systems to deliberately capture CO_2 to store the associated carbon in a reservoir other than the atmosphere has evolved from relative obscurity two decades ago to an increasingly recognized set of potential climate change mitigation options. This paper identifies several influential nongovernmental stakeholders and governmental influences that have advanced CCS. I begin by briefly reviewing the technologies associated with CCS that involve geologic CO_2 storage and provide background on other carbon-storage options, including terrestrial carbon sequestration and oceanic carbon storage. I then describe the influence of several specific nongovernmental stakeholders involved with advancing CCS and highlight governmental influence through political positions, government-supported research and development (R&D), and economic policy tools and international treaties. Finally, I discuss the complexity of the nongovernmental and governmental influences on CCS development and relate these to the social challenges of integrating science and engineering developments into sustainable practices.

Carbon Capture and Storage in Context

While this paper focuses on CCS to capture the CO_2 produced during fossil-fuel combustion and to store it in underground geologic reservoirs, the advancement of the relevant technologies is intricately linked to the development of other carbon-storage options, including terrestrial carbon sequestration and oceanic carbon storage. Terrestrial carbon sequestration refers to the storage of carbon in the biosphere relying on the photosynthetic process of capturing and converting atmospheric CO_2 into organic carbon. The notion of ocean storage generally applies to the direct injection of captured CO_2 into the oceans, but also can include other mechanisms for enhancing oceanic uptake of carbon. Another potential carbon-storage approach, often referred to as mineral carbonation, involves chemical reactions that transform the carbon in gas-phase CO_2 into solid-phase carbonate minerals.

As the value of storing carbon in a reservoir other than the atmosphere has become more widely recognized, interest in all of these options has been increasing. Among these approaches, terrestrial carbon sequestration involves the least engineering and the co-benefits of enhancing biomass growth are attractive. Although enhanced biological storage of carbon has the potential to reduce atmospheric CO_2 considerably (Winjum et al. 1992; Mutuo et al. 2005), recent research suggests the biosphere may soon become a net source rather than a net sink of atmospheric carbon due to changes in climate (Lenton & Huntingford, 2003). In addition, ecologically precarious monoculture plantations and the replacement of native forests with faster growing species could negate improvements from large-scale biological storage (Kueppers et al. 2004). This general approach also has the potential to decrease stream flow and to increase soil salinization and acidification resulting from afforestation (Jackson et al. 2005). Terrestrial carbon sequestration is the carbon-storage approach that appears to be the most acceptable option to the general public, as the idea of planting trees as a way to mitigate climate change has been proposed by many prominent commentators, including Al Gore (1992) and Paul Ehrlich (Ehrlich & Ehrlich, 1991).

The notion of injecting captured CO_2 into the deep ocean is another carbon-storage approach with promise, in part because the oceans have the capacity to store a large share of the CO_2 currently being emitted into the atmosphere. However, strong public opposition to engineered ocean storage has prevented R&D projects that involve direct injection and dispersal of CO_2 into the deep oceans (de Figueiredo et al. 2003). Nevertheless, research efforts and interest in the potential for ocean storage continues, particularly in countries like Japan where geologic reservoirs do not exist.

The carbon-storage option that has received the most attention recently is geologic storage, the approach incorporated into CCS. Geologic storage involves the use of depleted oil and gas reservoirs, unminable coal seams, and deep saline aquifers (Holloway, 1997; Holloway, 2001; Bruant et al. 2002; Anderson & Newell, 2004; Metz et al. 2005). Several actual projects (Sleipner in the North Sea, Weyburn in Saskatchewan, and In Salah in Algeria) have begun to demonstrate the safe and secure underground storage of CO_2 (Metz et al. 2005). While unresolved concerns remain related to mobility of the injected gas, potential risks associated with CO_2 leakage into the active biosphere, public acceptance, siting challenges, and uneven geographic distribution of appropriate storage reservoirs, the underground injection of CO_2 has become the storage approach with the greatest large-scale potential for reducing atmospheric CO_2 concentrations (Benson et al. 2002; Chow et al. 2003; Benson, 2003). Current global estimates for geologic storage range from 1,000 to 10,000 $GtCO_2$, which when compared to current emissions is considered sufficient capacity for global CO_2 storage needs for at least the next century (Metz et al. 2005). However, appropriate carbon-storage reservoirs have highly variable regional distribution, so location in proximity to major CO_2 emissions sources is likely to be more limiting than total storage capacity.

Although geologic and oceanic carbon storage are not widely understood or accepted by the general public, exploration of these ideas within the scientific community has been ongoing since the late 1970s. The idea of capturing CO_2 from power plants and disposing of it somewhere other than the atmosphere first appeared in the scientific literature thirty years ago (Marchetti, 1977). In this early proposal, both injecting CO_2 into underground reservoirs and into the deep oceans to bypass the slow kinetics of ocean-atmosphere equilibration were suggested. It was not until over a decade later that the first storage idea relying on a chemical conversion of the CO_2 gas into a carbonate solid was proposed (Seifritz, 1990).

Each of these carbon-storage approaches has different technical challenges, is associated with different levels of implementation readiness, has different constituents working on advancing the concepts, and, therefore, has different factors influencing development. While this paper focuses on geologic CCS, several of the factors discussed below have influenced each of the various carbon-storage approaches.

An engineered geologic CCS system includes four basic steps with different technologies required for each: (1) capture the CO_2 from a power plant or other concentrated stream through chemical or physical absorption, (2) transport the CO_2 gas from the capture location to an appropriate storage location, (3) inject the CO_2 gas into an underground reservoir, and (4) monitor the injected CO_2 to verify its storage (Socolow, 2005). Each storage approach involves different technological components for capturing, transporting, and storing CO_2 and the various methods are at differing levels of technical readiness (Figure 1). Several configurations of a complete CCS system rely only on the integration and scaling-up of existing commercial technologies. For instance, CO_2 capture technology is already widely used in several industrial-manufacturing processes as well as in oil refining and gas processing. Moreover, transportation of CO_2 through pipelines and injection of it underground has been occurring for decades in the United States where the gas is used to enhance oil production of declining wells. In addition, new and emerging technologies associated with CCS are currently in development. Socolow (2005), Anderson & Newell (2004), and IEA (2004) provide detailed analysis of some of these strategies.

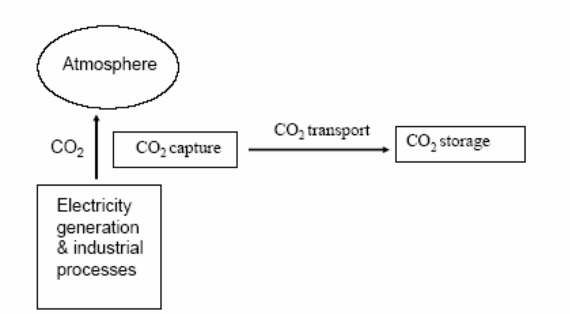

Figure 1 Technology to capture, transport, and store CO_2 is available and being currently used in other industrial applications.

Influential Nongovernmental Stakeholders

Broadly speaking, the expansion in interest over the last twenty years in CCS has occurred in response to strengthening scientific evidence implicating rising atmospheric CO_2 concentrations as the dominant contributor to climate change. These findings, coupled with an associated increase in awareness of the climate-change problem, have forced thorough examination of how to stabilize CO_2 concentrations in the atmosphere while satisfying increased energy demand. In addition to expanding energy production from renewable sources and low-carbon fuels and improving energy efficiency and conservation measures, many analysts are recognizing that CCS has potential for cost-competitive large-scale reductions of atmospheric CO_2 (Parson & Keith, 1998; Herzog, 2001; Metz et al. 2005). While the general public remains largely unaware of CCS options (Palmgren et al. 2004; Shackley et al. 2004), interest from the fossil-fuel industries and some sections of the scientific community has been influential in the recent advancement of these technologies. The following section reviews these factors and explores the small, but not inconsequential, role that environmental advocacy groups have played.

Increased Interest in the Fossil-Fuel Industry

Interest and investment in CCS has been growing in the fossil-fuel industry, particularly oil and gas companies. During the 1980s and much of the 1990s, many corporate managers, frightened by what climate change could mean to the future of their companies, publicly denied the problem and actively supported research and public campaigns that highlighted uncertainties and weaknesses in the theory of anthropogenic climate change (Levy & Rothenberg, 1999; Kolk & Levy, 2001; Gelbspan, 2004). As the scientific case strengthened during the mid to late 1990s, some firms shifted their strategy away from denial (Kolk & Levy, 2001). This shift was stronger and occurred earlier in European-based multinational companies than it did in United States-based firms (Levy & Newell, 2000; Rowlands, 2000). With this change in corporate strategy, an expansion of interest and investment in R&D of carbon-storage options has occurred. Many companies realized that the possibility of CCS weakened the link between fossil fuels and CO_2 driven climate change. The prospect of CCS reduced the threat of climate change mitigation efforts to fossil-fuel industries and made it possible to consider a fossil-based global economy throughout the next century even if controls on CO_2 emissions were instituted (Keith & Parson, 2000). The concept of CCS has, therefore, helped the fossil-fuel industries, as well as nations rich in coal, oil, and natural gas, to accept and agree to confront climate change because it allows them to perceive a future that reconciles continued use of fossil fuels in a carbon-constrained world.

Oil and gas companies, in particular, have become very interested in geologic carbon storage because they are familiar with the technologies for dealing with underground reservoirs and CO_2 injection, a well-established industry technique for enhanced oil recovery (EOR) (Hill, 2005). In mature wells with declining oil production CO_2 injection loosens up residual oil for extraction (van Bergen et al. 2003). Oil companies are therefore already knowledgeable about many critical technologies associated with underground carbon storage. Combining EOR with geologic carbon storage provides low-cost early deployment opportunities for gaining experience with CCS (Holtz et al. 2001; Stevens et al. 2001; van Bergen et al. 2003; Metz et al. 2005).

The Norwegian national oil company Statoil was the first petroleum producer to inject CO_2 underground for storage. The firm has been injecting CO_2 into a geologic formation under the North Sea since 1996. Managers were motivated to store rather than emit the CO_2 extracted from a natural gas stream by a Norwegian tax on the release of CO_2 into the atmosphere (Torp & Brown, 2002). The other currently operating large-scale geologic storage projects are at Weyburn in the Canadian province of Saskatchewan, where CO_2 has been injected underground since 2000 for the dual purpose of enhancing oil recovery and storage, and In Salah (Algeria) where the first large-scale injection of CO_2 into a gas reservoir began in 2004 (Metz et al. 2005). The In Salah project is a joint venture involving Sonatrach (the national oil company of Algeria), BP, and Statoil.

In addition to the In Salah initiative, BP is currently planning, and has begun investing in, at least two other CO_2 storage projects—one off the coast of Scotland and another in California. BP stands out among oil companies through investing heavily in the development and demonstration of geologic CO_2 storage. Interestingly, these BP carbon-storage projects are not economically justifiable in the short term. The company has chosen to fund these initiatives to advance the technology without any direct and immediate economic benefits, but clearly it is aiming to position itself as an industry leader in this area.

Frustration within the Scientific Community on Climate Action

Scientists and engineers who feel a growing sense of urgency about climate change form another influential group of stakeholders that has advanced CCS technology. An expanding segment of this community believes reducing atmospheric CO_2 concentrations to limit climate change is desperately needed. This strong concern is coupled with associated frustration at the lack of effective policy. Although empirical evidence is mounting, world leaders have been slow to take action to stabilize atmospheric CO_2 concentrations, leaving scientists increasingly frustrated and motivated to consider technical rather than political solutions. When faced with the social, economic, and political barriers preventing the implementation of national and international policies to reduce greenhouse-gas emissions, scientists and engineers have looked to deliberate carbon storage as another pathway to action—a pathway that is more open to their involvement. This influence from the frustrated scientific community can be identified in a plethora of articles in high-profile scientific journals, only a sampling of which are referenced here (Abelson, 2000; Hoffert et al. 2002; Caldeira et al. 2003; Pacala & Socolow, 2004; Spotts, 2004; Holdren, 2006).

Minimal Public Awareness and the Role of Environmental Advocacy Groups

Throughout the recent period of rapidly growing interest in CCS, it has been acknowledged that public acceptance will influence ultimate advancement and deployment. Nevertheless, public perception of these technologies remains limited. Studies at the Tyndall Centre in the United Kingdom using focus groups and surveys indicate that with adequate information about the climate-change context, the public may look favorably on CCS (Gough et al. 2002; Shackley et al. 2004). A study conducted in the United States, however, using personal interviews and a survey, suggests that Americans may be more skeptical and less accepting than the British public (Palmgren et al. 2004). The study urges careful consideration in devising strategies to inform people about the technology and suggests that how the public debate gets framed will be critical in determining popular perceptions (Palmgren et al. 2004).

Environmental advocacy groups play a critical role in shaping public debate about how best to address environmental problems, so how these organizations portray CCS is likely to influence public reactions. To date, their role regarding carbon storage has been mixed (Stephens & Verma, 2006). While one leading American environmental group, the Natural Resources Defense Council (NRDC), has taken a strong position supporting the development and demonstration of CCS technologies (Hawkins, 2003; 2005), many other organizations, both national and international, have had reservations about the environmental as well as political implications of CCS (Hawkins, 2001; Union of Concerned Scientists, 2001; Greenpeace, 2005; World Wildlife Fund, 2005).

Although public opposition to CCS has been anticipated, little actual resistance has emerged and environmental advocacy groups have been relatively quiet on the issue.[1] Despite the rapid advancement of demonstration projects, the environmental community has not voiced a strong position for or against the geologic storage of CO_2. Organized environmentalism seems to be trying to balance cautious hesitancy of this "end-of-pipe" "geoengineering" approach with practical acceptance that such carbon-management technologies may be needed to supplement other stabilization measures. Moreover, pervasive resistance to novel technologies within the environmental movement is recognized, and recent work has identified the challenges of overcoming this opposition (Cohen, 2006). Public opposition to the idea of underground storage may be presently minimized due to some awareness (in parts of the world at least) of the successful history of injecting CO_2 underground to enhance oil recovery.

Despite the potential that environmental advocacy groups have to influence the public perception of CCS, in the past 15 years these organizations have facilitated minimal public engagement on the subject

[1] CCS poses some of the same challenges to organized environmentalism as the debate over nuclear power in the balance between the necessity of climate-change action and a fear of technology and its unintended consequences.

and they have not developed a strong and consistent public message. This lack of a position regarding geologic storage has likely contributed to the limited public awareness (Verma & Stephens, 2006).

Division regarding CCS technology can be viewed as representative of the larger challenges facing environmental advocacy groups as they struggle to adjust to the unique and daunting challenges of climate change. There has been a great deal of discussion about the capacity of mainstream environmental organizations in the United States to engage meaningfully on the climate-change issue in the past few years as weaknesses in their response have been identified (McCright & Dunlap, 2000; 2003).

While some division has emerged surrounding the advancement of CCS technology, environmental advocacy groups have been generally supportive of terrestrial carbon sequestration, in part due to other indirect associated environmental benefits of managing land use to maximize carbon uptake (Manion, 2004). Nevertheless, the international environmental community has been strongly opposed to the inclusion of terrestrial carbon sequestration in the Kyoto Protocol due to large uncertainties regarding the continued existence of carbon sinks associated with forests and land-use changes.

In contrast, the idea of ocean storage has not been received well by environmental organizations or the general public. Strong public opposition prevented a collaborative research project involving direct injection of CO_2 into the deep ocean off the coast of Hawaii (de Figueiredo et al. 2003). Despite the development of a public-outreach plan, this case exemplifies a complex mix of emotions contributing to the pattern of opposition, including fear, isolation from the decision-making process, and passion to protect the sanctity of the oceans. Although most of the CO_2 emitted from human activity will eventually end up in the oceans, based on the strength of opposition in this case and a few others, it seems unlikely that the idea of deliberate oceanic injection of CO_2 will become socially acceptable.

Governmental Influence

Governmental influence on this pattern of increased activity regarding CCS technology can be divided into three categories: (1) political positions and strategy, (2) governmental support of R&D, and (3) economic policy tools and international treaties. This section explores each of these groupings with an eye to identifying examples of influence.

Political Positions and Strategy

A political position that supports the advancement of CCS technology as an alternative to regulations to limit CO_2 emissions has clearly influenced CCS development. Nevertheless, proposed CCS approaches were not developed with the intent of eliminating the need for emissions regulations, but, given the magnitude of the CO_2 problem, are largely viewed as a supplement (Pacala & Socolow, 2004). Within the political arena, however, support for CCS is often perceived as an alternative to regulating CO_2 releases. The current United States administration has opposed any national regulation to reduce CO_2 emissions (see e.g., Abraham, 2004), but growing public concern about climate change has forced it to confront the issue and to define actions to mitigate the problem. Supporting CCS as part of the President's Advanced Energy Initiative appears to be a politically convenient way to demonstrate action on climate change without making policy decisions to ensure actual CO_2 emissions reduction (NEC, 2006).

The leadership of UK Prime Minister Tony Blair is another important factor contributing to interest in CCS technologies. In addition to being the world leader pushing hardest to reduce greenhouse-gas emissions, in his role as G8 chairman in 2005, Blair advocated for increased governmental support for carbon abatement as a critical part of addressing climate change (Blair, 2003). Recognizing the importance of American involvement in any strategy to tackle the global problem of climate change, Blair has persistently tried to change the Bush administration's position. This focus on advancing technology rather than pushing for emission-reduction policies can be interpreted as an attempt to find common ground with the United States.

Governmental Support of Research and Development

Governmental efforts to advance the development of CCS technologies through R&D support vary considerably among countries. The potential impact of the successful deployment of CCS systems is related to a region's endemic fossil-fuel resources and level of fossil-fuel energy reliance. As a result, different national priorities are apparent when looking at government-supported CCS research programs.

In the coal-rich, energy-hungry United States, CCS provides the only way to reconcile increased use of domestic coal with climate-change mitigation, so the American government increasingly touts CCS as part of the future energy infrastructure. The federal government currently supports a suite of CCS R&D programs and has also initiated a large-scale demonstration project named FutureGen. The primary goal of the core CCS R&D program in the United States is to support technological developments that will reduce costs; the Regional Sequestration Partnership Program supports region-specific studies to determine the most suitable CCS technologies, regulations, and infrastructure. The FutureGen initiative is a US$1 billion project planned as the first demonstration of a commercial scale coal-fired power plant that captures and stores CO_2. The goal is to establish technical feasibility and economic viability for integrating coal gasification technology (IGCC) with CCS. Although the FutureGen project began in 2003, selection of the location for this power plant is not due to occur until late 2007.

European governments have also supported CCS technology advancement in several ways. The European Community (EC) contributed funds to several CCS projects through its Sixth Framework Programme (FP6, totaling an EC contribution of €35 million during the first proposal round) building on the research done under FP4 and FP5 during the early 1990s that initiated European R&D into CCS. This support includes contributions to the Sleipner project as well as to some other R&D and small-scale demonstration projects. Independently of Brussels, EC member states are also providing modest support for CCS R&D. For instance, the British government recently announced a €40 million fund to support CO_2 storage in depleted North Sea oil and gas fields. Japan is another country that has been actively encouraging CCS. Interestingly, lacking suitable land-based geologic reservoirs, Japan has focused most of its investment on the potential and limitations of oceanic CO_2 storage. Most developing countries have not begun to seriously consider the potential of CCS technologies as a climate change mitigation strategy, so government support for advancing this set of technologies has been minimal or nonexistent.[2]

Recognizing the varied efforts in advancing CCS technology around the world, the United States initiated an international body, the Carbon Sequestration Leadership Forum (CSLF), in 2003. The CSLF provides a forum for collaboration by facilitating joint projects, as well as providing a mechanism for multilateral communication regarding the latest CCS developments and a venue for formulating strategies to transfer technology to developing countries.

In addition to the direct impact that government-supported R&D has on the advancement of CCS, public sponsorship motivates involvement of individuals and companies (Stephens & Zwaan, 2005).

Economic Policy Tools and International Treaties

Governmental activity including the use of economic policy tools and involvement in international treaties has also influenced CCS development by altering perceptions of the relative costs associated with reducing CO_2 emissions versus the costs of storing CO_2. This section explains how the imposition of a carbon tax in Norway directly motivated the first large-scale geologic carbon-storage project beneath the North Sea and how the creation of the Kyoto Protocol's framework for national accounting of carbon sources and sinks influenced the advancement of CCS by highlighting the economic value of carbon storage.

In 1996, the Norwegian government instituted a levy on CO_2 emissions equivalent to approximately US$40/t$CO_2$ that motivated Statoil, the national oil company, to capture the CO_2 emitted from their Sleipner oil and gas field and inject it into an underground formation rather than continue to emit it to the atmosphere (Torp & Brown, 2002). The Sleipner project has had a dramatic impact on the understanding of geologic carbon storage and CCS because researchers from around the world have been monitoring and learning from this pioneering initiative that has successfully been injecting and storing about one million tons of CO_2 per year for the past nine years (Gale et al. 2001). Other governmental economic policy tools, including the European Union emissions trading scheme, have also provided investment incentives for CCS projects (Hasselknippe & Roine, 2006).

A more indirect example of governmental activity influencing CCS development relates to the Kyoto Protocol negotiations. Although the accord in its current form does not include any credit provisions for carbon stored through CCS projects, ongoing discussions have raised awareness of the value of carbon storage. Interest in regional potentials, particularly for terrestrial storage, increased dramatically during the development of the climate-change agreement and associated negotiations about its framework for national accounting of carbon sources and sinks. Initial adoption of the Kyoto Protocol in 1997 committed industrialized nations to legally binding greenhouse-gas reductions. However, contentious negotiations on whether carbon sinks, including forests, should be counted toward reduction targets ensued for several years (IGBP, 1998). On one hand, the United States, Japan, Canada, New Zealand, and Australia supported counting carbon storage associated with forest growth toward meeting their emission-reduction goals. On the other hand, European countries, which have fewer forested tracts, felt that the Kyoto commitments should be met only with direct emission reductions, not through the identification of offsetting carbon sinks. Although the debate focused on terrestrial sequestration, the process increased awareness about the value of carbon storage more generally. Also during this period, research

[2] India has agreed to contribute US$10 million to the United States Department of Energy's FutureGen project.

designed to improve understanding and to quantify the potential of all storage methods increased.

Although the United States did not ratify the Kyoto Protocol, the accounting for terrestrial carbon sinks to offset emission reductions (that the country's delegates ironically championed in negotiations) is included in the agreement now in force (Victor, 2004). Within the agreement, each Annex I nation is responsible for verifying its own carbon-emission reductions and accounting for terrestrial carbon storage within its boundaries. While terrestrial sequestration is currently included in the Kyoto Protocol's Clean Development Mechanism (CDM) (which provides for transferable credit to industrialized countries that invest in projects to avoid emissions in developing countries lacking targets) current negotiations are defining how geologic and oceanic storage projects might be included (Haines et al. 2004; Hohne, 2006).

Conclusion

The rapidly growing interest in and development of CCS technologies has evolved in tandem with ongoing discussions about how society should respond to the risks of climate change. Attempting to compare the various governmental and nongovernmental influences on CCS advancement is beyond the scope of this paper, but is an important area for future research. The various interconnected social factors influencing the advancement of these technologies highlight the complexity of integrating developments in science and engineering into sustainable practices.

A valuable complement to the work presented here would be to identify how the prospect of deploying CCS technologies on a larger scale has influenced the positions, strategies, priorities, and actions of key stakeholders and institutions involved in the debate about how best to mitigate climate-change risks. Figure 2 is a schematic illustration depicting various influences contributing to increased interest in and development of CCS technologies. This figure also demonstrates reciprocal relationships in which growing CCS interest and development has in turn shaped the perceptions, strategies, and actions of various stakeholders. More detailed research would be valuable to identify how expanded attention to CCS has influenced actors with a strong voice on climate change. Methods that could be useful in exploring these reciprocal relationships include interviews with various stakeholders and media analysis.

Despite widespread recognition of the need for a shift in our energy infrastructure to no- or low-carbon technologies to stabilize atmospheric CO_2 concentrations (Hoffert et al, 2002; Pacala & Socolow, 2004; Holdren, 2006), movement in this direction has been

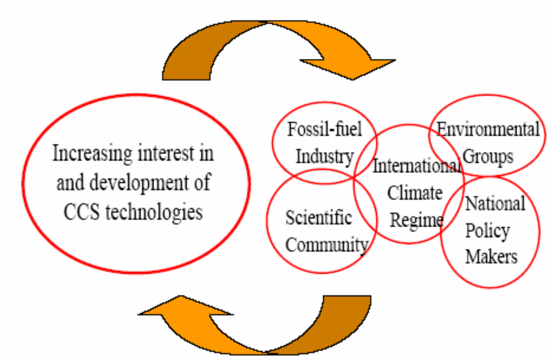

Figure 2 Schematic illustration depicting an influence from various factors supporting increased interest in and develop-ment of CCS technologies. This figure also demonstrates reciprocal relationships in which the increased interest and development of CCS has influenced the actions, percep-tions, and strategies of various critical stakeholders in the societal debate on how to confront climate change.

slow and uncertain (Sagar & Gallagher, 2004; Neuhoff, 2005; Stephens & Zwaan, 2005). While research exploring the challenges of energy-technology diffusion has focused on economic and technical aspects (Isoard & Soria, 2001; Grubler et al. 2002; Nakicenovic, 2002), and generally concentrates on the national scale (NCEP, 2004; Nemet & Kammen, 2007), often overlooked is the complex socio-political context within which new technologies must be integrated. One approach to future research could involve incorporating analysis of the context of CCS development with the emerging literature on transition management. This perspective recognizes the complexity of transitions, including the interactions, interdependencies, and feedbacks among different actors, technologies, infrastructures, and institutions (Kemp et al. 1998; Rotmans et al. 2001; Kemp & Loorbach, 2003; Loorbach & Rotmans, 2006).

Several recent studies have enhanced this body of literature by suggesting different approaches to induce learning for a societal shift in sustainable-energy technologies, including visioning and scenario building (Berkhout et al. 2002), national-dialogue promotion (Vergragt, 2006), and small-scale, bounded experimentation with emerging technologies (Brown et al. 2003; Brown & Vergragt, 2006). Applying these approaches to CCS technologies could contribute a valuable new dimension to both the theory and practice of transition management with energy technologies.

Understanding the evolution of interest in this specific set of highly novel and uncertain technologies has broader implications for how social influences steer technological innovation and shifts in technological norms. Despite the somewhat controversial nature of CCS technologies and their associated imponderables, interest in these approaches has grown as the challenge of reconciling energy demand and climate-change mitigation becomes evermore daunting. The attention focused on CCS is likely to expand in coming years because the value associated with the potential reduction in the atmospheric concentration of CO_2 will increase as human society continues to postpone action to mitigate climate change.

Acknowledgment

Thanks to three anonymous reviewers who provided very useful feedback on this article. Thanks also to those who I have recently worked with on various aspects related to this topic including, Bob van der Zwaan, Preeti Verma, Bill Rosenberg, Kelly Sims Gallagher, John Holdren, David Keith, Elizabeth Wilson, Rob Goble, Halina Brown, and Philip Vergragt. Support from the Energy Technology Innovation Project at Harvard University's Kennedy School of Government and the Department of International Development, Community, and Environment at Clark University is also gratefully acknowledged.

References

Abelson, P. 2000. Limiting atmospheric CO_2. *Science* 289 (5483):1293.

Abraham, S. 2004 The Bush administration's approach to climate change. *Science* 305(5684):616–617.

Anderson, S. & Newell, R. 2004. Prospects for carbon capture and storage technologies. *Annual Review of Environment and Resources* 29:109–42.

Benson, S., Hepple, R., Apps, J., Tsang, C., & Lippman, M. 2002. *Comparative Evaluation of Risk Assessment, Management, and Mitigation Approaches for Deep Geologic Storage of CO_2*. Lab Report LBNL-51170. Berkeley: Earth Sciences Division, Lawrence Berkeley National Laboratory.

Benson, S. 2003. *Carbon Sequestration: Potential and Risks*. Workshop on Novel Approaches to Carbon Management. February 12, Irvine, CA: National Research Council.

Berkhout, F., Hertin, J., & Jordan, A. 2002. Socio-economical futures in climate change impact assessment: using scenarios as "learning machines." *Global Environmental Change A* 12(2):83–95.

Blair, T. 2003. Meeting the sustainable development challenge. *Environment* 45(4):20–26.

Brown, H., Vergragt, P., Green, K., & Berchicci, L. 2003. Learning for sustainability transition through bounded socio-technical experiments in personal mobility. *Technology Analysis and Strategic Management* 13(3):298–315.

Brown, H. & Vergragt, P. 2006. Bounded socio-technical experiments as agents of systemic change: the case of a zero-energy residential building. *Technological Forecasting and Social Change* Published Online: July 3.

Bruant, R., Celia, M., Guswa, A., & Peters, C. 2002. Safe storage of CO_2 in deep saline aquifers. *Environmental Science and Technology* 36(11):240A–245A.

Caldeira, K., Jain, A., & Hoffert, M. 2003. Climate sensitivity uncertainty and the need for energy without CO_2 emissions. *Science* 299(5653):2052–2054.

Chow, J., Watson, J., Herzog, A., Benson, S., Hidy, G., Gunter, W., Penkala, S., & White, C. 2003. Separation and capture of CO_2 from large stationary sources and sequestration in geological formations. *Journal of Air and Waste Management Association* 53(10):1172–1182.

Cohen, M. 2006. Ecological modernization and its discontents: can the American environmental movement overcome its resistance to technology? *Futures* 38(6):528–547.

de Figueiredo, M., Reiner, D., & Herzog, H. 2003. Ocean carbon sequestration: a case study in public and institutional perceptions. In J. Gale & Y. Kaya (Eds.), *Greenhouse Gas Control Technologies* (GHGT-6). pp. 799–804. Oxford: Permagon.

Ehrlich, P. & Ehrlich, A. 1991. *Healing the Planet, Strategies for Resolving the Environmental Crisis*. Reading, MA: Addison-Wesley.

Gale, J., Christensen, N., Cutler, A., & Torp, T. 2001. Demonstrating the potential for geological storage of CO_2: the Sleipner and GESTCO projects. *Environmental Geosciences* 8(3):160–165.

Gelbspan, R. 2004. *Boiling Point: How Politicians, Big Oil and Coal, Journalists, and Activists Are Fueling the Climate Crisis–and What We Can Do to Avert Disaster*. New York: Basic Books.

Gore, A. 1992. *Earth in the Balance: Ecology and the Human Spirit*. Boston: Houghton Mifflin.

Gough, C., Taylor, I., & Shackley, S. 2002. Burying carbon under the sea: an initial exploration of public opinion. *Energy and Environment* 13(6):883–900.

Greenpeace. 2005. Limits of Carbon Capture and Storage in Combating Climate Change. http://www.greenpeace.org/international/press/releases/carboncaptureandstoragereport April 20, 2006.

Grubler, A., N. Nakicenovic, & W. Nordhaus (Eds.). 2002. *Technological Change and the Environment*. Washington, DC: Resources for the Future Press.

Haines, M., Reeve, D., Russell, D., Ribas, A., & Varilek, M. 2004. *Use of the Clean Development Mechanism for CO_2 Capture and Storage*. Seventh International Greenhouse Gas Control Technology Conference. September 5–9. Vancouver.

Hasselknippe, H. & Roine, K. 2006. *Carbon 2006 Report*. Oslo: Point Carbon.

Hawkins, D. 2001. *Stick it Where??—Public Attitudes toward Carbon Storage*. First National Conference on Carbon Sequestration. National Energy Technology Laboratory, Washington, DC. http://www.netl.doe.gov/publications proceedings/01/carbon_seq/1c2.pdf.

Hawkins, D. 2003. Passing gas: policy implications for geologic carbon storage sites. In J. Gale & Y. Kaya (Eds.), *Greenhouse Gas Control Technologies* (GHGT-6). pp. 249–254. Oxford: Permagon.

Hawkins, D. 2005. CO_2 Capture and Storage: Just Do It. http://www.usea.org/Ericeprogram/Presentations-Remarks/Hawkins%201100.pdf. March 15, 2006.

Herzog, H. 2001. What future for carbon capture and sequestration? *Environmental Science & Technology* 35(7):148A–153A.

Hill, G. 2005. *Moving to Utilize Carbon Capture/Sequestration Technologies–A Path Forward to Reduce CO_2 Emissions*. Fourth Annual Conference on Carbon Capture and Sequestration. May 2–5, U. S. Department of Energy, Alexandria, VA.

Hoffert, M., Caldeira, K., Benford, G., Criswell, D., Green, C., Herzog, H., Jain, A., Kheshgi, H., Lackner, L., Lewis, J., Lightfoot, H., Manheimer, W., Mankins, J., Mauel, M., Perkins, L., Schlesinger, M., Volk, T., & Wigley, T. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298(5595):981–987.

Hohne, N. 2006. *What is Next After the Kyoto Protocol: Assessment of Options for International Climate Policy, Post 2012.* Amsterdam: Techne Press.

Holdren, J. 2006. The energy innovation imperative, addressing oil dependence, climate change, and other 21st century energy challenges. *Innovations, Technology, Governance & Globalization* 1(2):3–23.

Holloway, S. 1997. An overview of the underground disposal of carbon dioxide. *Energy Conversion and Management* 38(Supp):S193–S198.

Holloway, S. 2001. Storage of fossil fuel-derived carbon dioxide beneath the surface of the earth. *Annual Review of Energy and the Environment* 26:145–166.

Holtz, M., Nance, P., & Finley, R. 2001. Reduction of greenhouse gas emissions through CO_2 EOR in Texas. *Environmental Geosciences* 8(3):187–199.

International Energy Agency (IEA). 2004. *Prospects for CO_2 Capture and Storage*. Paris: Organization for Economic Cooperation and Development and IEA.

International Geosphere–Biosphere Programme (IGBP). 1998. The terrestrial carbon cycle: implications for the Kyoto Protocol. *Science* 280(5368):1393–1394.

Isoard, S. & Soria, A. 2001. Technical change dynamics: evidence from the emerging renewable energy technologies. *Energy Economics* 23(6):619–636.

Jackson, R., Jobbagy, E., Avissar, R., Roy, S., Barrett, D., Cook, C., Farley, K., le Maitre, D., McCarl, B., & Murray, B. 2005. Trading water for carbon with biological carbon sequestration. *Science* 310(5756):1944.

Keith, D. & Parson, E. 2000. A breakthrough in climate change policy? *Scientific American* 282(2):78–79.

Kemp, R., Schot, J., & Hoogma, R. 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology Analysis and Strategic Management* 10(2):175–195.

Kemp, R. & Loorbach, D. 2003. *Governance for Sustainability Through Transition Management.* Open Meeting of the Human Dimensions of Global Environmental Change Research Community. October 16–19, Montreal.

Kolk, A. & Levy, D. 2001. Winds of change: corporate strategy, climate change and oil multinationals. *European Management Journal* 19(5):501–509.

Kueppers, L., Baer, P., Harte, J., Haya, B., Koteen, L., & Smith, M. 2004. A decision matrix approach to evaluating the impacts of land-use activities undertaken to mitigate climate change. *Climatic Change* 63(3):247–257.

Lenton, T. & Huntingford, C. 2003. Global terrestrial carbon storage and uncertainties in its temperature sensitivity examined with a simple model. *Global Change Biology* 9(10):1333–1352.

Levy, D. & Rothenberg, S. 1999. *Corporate Strategy and Climate Change: Heterogeneity and Change in the Global Automobile Industry.* BCSIA Discussion Paper E-99-13. Cambridge: Environment and Natural Resources Program, Harvard University. http://www.ksg.harvard.edu/gea/pubs/e-99-13.htm.

Levy, D. & Newell, P. 2000. Oceans apart? Business responses to the environment in Europe and North America. *Environment* 42(9):8–20.

Loorbach, D. & Rotmans, J. 2006. Managing transitions for sustainable development. In A. Wieczorek & X. Olsthoorn (Eds.), *Understanding Industrial Transformation.* pp. 75–98. New York: Springer.

Manion, M. 2004. How it works: forest carbon sequestration. *Catalyst* 3(2). http://www.ucsusa.org/publications/catalyst/fa04-catalyst-forest-carbon-sequestration.html.

Marchetti, C. 1977. On geoengineering and the CO_2 problem. *Climatic Change* 1(1):59–68.

McCright, A. & Dunlap, R. 2000. Challenging global warming as a social problem: an analysis of the conservative movement's counter-claims. *Social Problems* 47(4):499–522.

McCright, A. & Dunlap, R. 2003. Defeating Kyoto: the conservative movement's impact on the U.S. climate change policy. *Social Problems* 50(3):348–373.

Metz, B., O. Davidson, H. de Coninck, M. Loos, & L. Meyer (Eds.). 2005. *Carbon Dioxide Capture and Storage.* IPCC Special Report. Intergovernmental Panel on Climate Change Working Group III. http://www.ipcc.ch/activity/srccs/index.htm

Mutuo, P., Cadisch, G., Albrecht, A., Palm, C. & Verchot, L. 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. *Nutrient Cycling in Agroecosystems* 71(1):43–54.

Nakicenovic, N. 2002. Technological change and diffusion as a learning process. In A. Grubler, N. Nakicenovic, & W. Nordhaus (Eds.), *Technological Change and the Environment.* pp. 160–181. Washington, DC: Resources for the Future Press.

National Commission on Energy Policy (NCEP). 2004. *Ending the Energy Stalemate: a Bipartisan Strategy to Meet America's Energy Challenges*. Washington, DC: NCEP. http://www.energycommission.org/files/contentFiles/report_noninteractive_44566feaabc5d.pdf.

National Economic Council (NEC). 2006. *Advanced Energy Initiative.* Washington, DC: The White House NEC. http://www.whitehouse.gov/stateoftheunion/2006/energy/energy_booklet.pdf.

Nemet, G. & Kammen, D. 2007. U.S. energy research and development: declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35(1):746–755.

Neuhoff, K. 2005. Large-scale deployment of renewables for electricity generation. *Oxford Review of Economic Policy* 21(1):88–110.

Pacala, S. & Socolow, R. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* 305(5686):968–972.

Palmgren, C., Morgan, C., de Bruin, W., & Keith, D. 2004. Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. *Environmental Science and Technology* 38 (24):6441–6450.

Parson, E. & Keith, D. 1998. Climate change: fossil fuels without CO_2 emissions. *Science* 282(6):1053–1054.

Rotmans, J., Kemp, R., & van Asselt, M. 2001. More evolution than revolution: transition management in public policy. *Foresight* 3(1):15–31.

Rowlands, I. 2000. Beauty and the beast? BP's and Exxon's positions on global climate change. *Environment and Planning C* 18(3):339–354.

Sagar, A. & Gallagher, K. 2004. Energy technology demonstration and deployment. In *Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges*. p. 117. Washington, DC: National Commission on Energy Policy.

Seifritz, W. 1990. CO_2 disposal by means of silicates. *Nature* 345(6275):486.

Shackley, S., McLachlan, C., & Gough, C. 2004. *The Public Perceptions of Carbon Capture and Storage.* Tyndall Centre Working Paper 44. Manchester: Tyndall Centre for Climate Change Research. http://www.tyndall.ac.uk/publications/working_papers/wp44.pdf.

Socolow, R. 2005. Can we bury global warming? *Scientific American* 293(1):49–55.

Spotts, P. 2004. Stabilizing the global 'greenhouse' may not be so hard. *The Christian Science Monitor.* August 13.

Stevens, S., Kuuskraa, V., Gale, J., & Beecy, D. 2001. CO_2 injection and sequestration in depleted oil and gas fields and deep coal seams: worldwide potential and costs. *Environmental Geosciences* 8(3):200–209.

Stephens, J. & van der Zwaan, B. 2005. The case for carbon capture and storage. *Issues in Science and Technology* 22(1):69–76.

Stephens, J. & Verma, P. 2006. *The Role of Environmental Advocacy Groups in the Advancement of Carbon Capture and Storage (CCS).* Fifth Annual Conference on Carbon Capture & Sequestration. May 8–11, U.S. Department of Energy, Alexandria, VA.

Torp, T. & Brown, K. 2002. *CO_2 Underground Storage Costs as Experienced at Sleipner and Weyburn*. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. September 5–9, Vancouver.

Union of Concerned Scientists. 2001. Policy Context of Geologic Carbon Sequestration. http://www.ucsusa.org/assets/documents/global_warming/GEO_CARBON_SEQ_for_web.pdf. March 15, 2006.

van Bergen, F., Wildenborg, A., Gale, J., & Damen, K. 2003. Worldwide selection of early opportunities for CO_2-EOR and CO_2-ECBM. In J. Gale & Y. Kaya (Eds.), *Greenhouse Gas Control Technologies* (GHGT-6). pp. 639–644. Oxford: Permagon.

Vergragt, P. 2006. *Towards a National Policy Dialogue on Hydrogen in the USA*. Ninth International Conference on Technology Policy and Innovation: Science, Society, and Sustainability. June 18–21, Santorini, Greece.

Verma, P. & Stephens, J. 2006. *Environmental Advocacy Groups' Perspectives on Carbon Capture and Storage.* Climate Change Technology Conference: Engineering Challenges and Solutions in the 21st Century. May 10–12, Engineering Institute of Canada, Ottawa.

Victor, D. 2004. *The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming.* Princeton: Princeton University Press.

Winjum, J., Dixon, R., & Schroeder, P. 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. *Water, Air, and Soil Pollution* 64(1–2):213–227.

World Wildlife Fund. 2005. More Questions than Answers on Carbon Capture and Storage. http://www.wwf.ca/AboutWWF/WhatWeDo/ConservationPrograms/RESOURCES/PDF/css_statement.pdf. March 16, 2006.