

**CO₂ CAPTURE AND STORAGE (CCS):
EXPLORING THE RESEARCH,
DEVELOPMENT, DEMONSTRATION,
AND DEPLOYMENT CONTINUUM**

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CO₂ Capture and Storage (CCS): Exploring the Research, Development, Demonstration, and Deployment Continuum

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Abstract

The adoption of carbon dioxide capture and storage (CCS) technologies is increasingly considered a potentially significant contributor to the energy infrastructure changes required to stabilize atmospheric carbon dioxide (CO₂) concentrations for the mitigation of climate change. Investing in new energy technologies is a well-recognized critical component of confronting the climate change problem. Prioritizing limited resources, however, for investments in the research and development (R&D), demonstration, and deployment continuum of emerging technologies is a difficult challenge. This paper explores the current balance and needs in R&D, demonstration, and deployment for technologies associated with CCS. Regional differences in public support for advancing CCS technologies are linked with political, economic, and geological heterogeneities. Interest and investment in CCS technologies from the private sector are growing rapidly, demonstrating the increasing likelihood that CCS technology may play an important role in future energy production. At this stage, the greatest need is government policies and strategies that provide incentives for the early deployment of CCS technology.

1. Introduction

Carbon dioxide (CO₂) emissions continue to rise due to growing worldwide demand for and use of fossil-fuel-derived energy, despite the growing recognition of the need to reduce CO₂ emissions to mitigate the risks associated with climate change. The magnitude of emissions reductions required to stabilize atmospheric CO₂ concentrations at a level that reduces dangerous human interference with the earth's climate system is such that all plausible ideas and potential energy technologies that may contribute to reducing the emission of CO₂ into the atmosphere deserve careful consideration. Government support of research, development, demonstration, and deployment of new energy technologies is a well-recognized central component of confronting the problem of climate change, yet dividing up limited resources to each of these different components of technology innovation to realize the required technological transition is a formidable challenge.

To achieve stabilization of atmospheric CO₂ concentrations at an approximate doubling of pre-industrial levels, current carbon emissions of about 7 gigatons per year (GtC/year) will need to be reduced by about two thirds by the end of the century, followed by continued reductions in the following centuries. Technologies associated with CO₂ capture and storage (CCS) are increasingly considered to be likely contributors to achieving these CO₂ emission reductions. The term CCS incorporates many technologies associated with capturing CO₂ and storing the associated carbon in a reservoir other than the atmosphere, that is, in underground geologic formations, in the ocean, or at the earth's surface (in biomass or solids).

The purpose of this paper is to investigate the research and development (R&D), demonstration, and deployment continuum (Figure 1) for the case of CO₂ capture and storage technologies by reviewing the current technological status of CCS technologies and outlining current government efforts to advance CCS technology. The idea of capturing and storing CO₂ has evolved in the past decade from an obscure idea to an increasingly recognized important climate change mitigation option.

Despite the promising potential associated with CCS today, this discussion recognizes that currently promising energy technologies may unexpectedly end up having a limited scope. Nuclear energy, for example, was predicted in the 1960s to become 'too cheap to meter' yet, as a result of issues that were difficult to foresee at the inception of the civil use of fission technology, nuclear energy's potential was drastically reduced during the 1980s and 1990s. Given society's experience with the unfulfilled perceptions of nuclear power, we may now be able to better anticipate both the potential and limitations of emerging energy technologies including CCS. Consideration of effective balancing of government support in R&D, demonstration projects, and deployment strategies could maximize opportunities for successful advancement of CCS technologies.

This paper first provides background on the energy resources context within which CCS is currently being considered as a potential set of technologies to contribute to climate change mitigation (section 2). A review of the current status of technologies for CO₂ capture, transportation, and storage (in section 3) is followed by a discussion on regional differences in public support for advancing CCS technologies and how these differences are linked to political, economic, and geological heterogeneities (section 4). In the concluding discussion (section 5) recommendations of the major R&D,

demonstration, and deployment needs to advance CCS technology are presented.

2. Energy Technologies for Climate Change Mitigation: CCS in Context

CCS is only one set of technologies with potential to contribute to the changes in our energy infrastructure that are required to establish a path toward CO₂ stabilization. In considering energy technologies more generally, two ends of a technology readiness spectrum are often poised against each other (Figure 2). On one side, a persuasive argument has been made that humanity already possesses the technical know-how to begin solving the carbon/climate problem, so attention should be focused on implementation and deployment strategies (Pacala and Socolow, 2004). Improving efficiency and reducing the use of existing technologies, as well as increasing energy production from renewable sources and low-carbon-intensity fuels, are all changes that can be made with existing technology. On the other end of this spectrum is the longer-term view that we have not yet developed sufficient non-CO₂-emitting energy technologies, and revolutionary changes in energy production technologies are required to effectively address the carbon/climate problem (Caldeira et al., 2003; Hoffert et al., 2002). Debate among the energy technology and environment community on these seemingly opposing views on technological readiness has developed in large part due to concerns about potential policy implications of these different views. These two perspectives, however, should not be viewed as inconsistent with each other, or as competitors, because the different perspectives are primarily associated with the time scale under consideration and the characteristics of a stabilization path.

A stabilization target for atmospheric CO₂ concentrations of 500-550 parts per million (ppm), a target roughly double that of pre-industrial levels, is often considered to be a possible societal goal. During the initial 50 years of this stabilization path, emissions only have to be maintained at the current level (Wigley et al., 1996), so the point of the Pacala and Socolow position is that existing technologies can be implemented to achieve the initial part of a CO₂ concentration stabilization path. After this initial 50-year period, however, atmospheric CO₂ concentration stabilization requires steep CO₂ emission reductions, and Hoffert *et al.*, (2002) point out that we do not yet have the technologies to achieve these reductions. The view that we have a portfolio of existing technologies that allow us to commence today on the path toward stabilization is thus not inconsistent, but instead complimentary, with the view that to maintain a stabilization path beyond fifty years, new technologies will definitely be required.

Feedback and interactions among R&D efforts, demonstration projects, and experience through deployment creates synergism throughout the innovation process (Sagar and Gallagher, 2004). Nevertheless, a misleading dichotomy with respect to these two positions has developed largely because the different timescales have not been appropriately reconciled. Within the policy arena, the different timescales defining appropriate action also must be carefully considered and reconciled. Within a long-term strategy to reduce CO₂ emissions, R&D must play a major role as radical changes to the energy system are required, while as part of a near-term strategy, deployment of current and existing clean energy technologies must be the focus. In considering investment prioritization between R&D projects and deployment strategies, the time frame considered is only one of the elements to take into account. Generally, irrespective of the time frame viewed, there is complementarity and interdependence among R&D efforts,

demonstration projects, and deployment strategies. The critical question is not whether to combine R&D, demonstration, and deployment efforts, but rather how to balance limited resources among these stages of innovation (Sagar and van der Zwaan, forthcoming).

Both R&D and learning-by-doing play important roles in the process of technological change. Major changes in existing technologies are unlikely without explicit support for R&D, but any new technological concept will not advance without learning-by-doing in demonstration projects and early deployment opportunities. It is often through accumulated experience and the learning-by-doing associated with demonstrating or deploying a technology that substantial cost reductions are realized.

Interestingly, technologies associated with CCS are included in discussions of energy technologies at both ends of the spectrum portrayed in Figure 2 and actually span the spectrum. Three of the fifteen potential changes involving existing technology proposed by Pacala and Socolow (2004) involve capturing CO₂ and storing it underground in geologic formations, while sequestering carbon released from energy production from fossil fuels is one of the potential carbon-emission-free primary energy sources identified by Hoffert et al (2002) as needing intensive research and development to overcome limiting deficiencies in existing technology. CCS, therefore, must be recognized as a set of technologies and concepts at varying stages of readiness, with varying needs associated with R&D, demonstration, and deployment. Research, development, and demonstration of CCS associated technologies have been increasingly supported by both governments and private companies in the past decade. As the technological feasibility of some CCS configurations is strengthened, the need for the next step in the innovation continuum, deployment strategies, is growing.

3. Status of CCS Technologies

Various different sets of technological components associated with capturing, transporting, and storing CO₂ are at different levels of technical readiness (Figure 3). Several configurations of a complete CCS system rely only on the integration and scaling-up of existing, commercially-used technology. CO₂ capture technology is already widely used in several industrial manufacturing processes as well as oil refining and gas processing. And the transportation of CO₂ gas through pipelines and the injection of CO₂ underground have been occurring for decades in the United States where CO₂ is used to enhance oil production of declining-production wells. In addition, new and emerging technologies associated with CCS are currently in development -- one million tons of CO₂ have been successfully stored underground at Sleipner since 1996 (details in 3.3). This section provides a broad overview of actual and potential technologies and projects associated with CO₂ capture, transport, and storage. More detailed discussion and analysis of specific technologies can be found elsewhere (Anderson and Newell, 2004; IEA, 2004; Socolow, 2005)

3.1 CO₂ Capture

CO₂ can be captured from large point sources including power plants and large industrial facilities before it is released to the atmosphere, or, alternatively, CO₂ can be captured directly from the atmosphere. Most discussions of CO₂ capture are referring to technologies designed to capture CO₂ from large, point-source emitters, particularly power plants. CO₂ capture technologies associated with power plants can be divided into

three categories: (i) post-combustion or “end-of-pipe” CO₂ capture, (ii) pre-combustion CO₂ capture, and (iii) oxyfuel combustion.

Existing post-combustion capture methods rely primarily on the chemical absorption of the CO₂ in a solvent (amines are most commonly used). Although amine scrubbing for separating CO₂ from dilute gas streams is a widely used process in several industrial applications, amine capture of CO₂ from power plant emissions has not yet been demonstrated on a full-scale commercial power-plant, so demonstration projects integrating CO₂ capture technology at operating power plants are needed. Post-combustion capture using chemical absorption is expensive and is estimated to account for 80% of the overall predicted costs of a CCS system. The development of advanced methods of post-combustion capture that could reduce costs (including membranes and adsorption onto solids) is, therefore, one of the critical goals of CO₂ capture R&D efforts. CO₂ capture demonstration projects would also bring down costs through “learning-by-doing”

Pre-combustion CO₂ capture refers to technologies that can separate CO₂ from gaseous fuel before the fuel is burned. The primary currently-available pre-combustion capture technology relies on physical absorption of the CO₂ gas onto a solvent. Pre-combustion capture is more efficient and less expensive than post-combustion capture because of the higher percentage of carbon in gaseous fuels before they are burned compared to post-combustion emissions. Pre-combustion CO₂ capture is only relevant for gaseous fuel, so for this technology to be used with coal-fired power plants the coal must be gasified first. With current capture technology, therefore, the coal power plant technology called integrated gasification combined cycle (IGCC) allows CO₂ to be captured at a lower cost than in conventional pulverized coal plants. R&D in pre-combustion capture is currently focusing on developing novel reactor concepts and new adsorption and absorption processes. Although the technology is used in other smaller-scale applications, demonstration of pre-combustion capture on a commercial-scale power plant has not yet been achieved.

Oxyfuel combustion, introducing oxygen instead of air during combustion, is another approach to capturing CO₂ in coal-fired power plants, because this produces a relatively pure stream of CO₂ in the emissions. This approach is considered by some to be the best option for retrofitting existing pulverized coal power plants. The costs of separating oxygen from air to be added to the combustion chamber are high, however. Oxyfuel combustion on a large-scale power plant has not yet been demonstrated.

While most discussions of CO₂ capture refer to capturing CO₂ from large point-sources, direct-air-capture of CO₂ or “air extraction” also has potential and would be extremely valuable if it could be achieved because it provides the only way to consider storage of CO₂ that has already been released to the atmosphere from small, non-point sources including vehicles. Current research is focused on designing a device that would rely on chemical reactions to capture CO₂ directly from the atmosphere (Lackner, 2002; Lackner et al., 1999; Zeman and Lackner, 2004), but this is a technical challenge due to the low concentrations of CO₂ in the ambient atmosphere (380ppm = 0.038 percent).

Once the CO₂ is separated and captured, the CO₂ needs to be compressed to reduce the volume of the gas to allow for transportation to a storage location. Compressing gas is energy intensive, so this part of the CO₂ capture system adds significantly to the overall operating costs and is also a contributor to the overall energy

penalty associated with CCS.

3.2 CO₂ Transportation

After capture and compression, CO₂ needs to be transported to an appropriate storage location. CO₂ can be transported by pipeline, by truck, by rail, or by ship, but the large volume of CO₂ in a CCS system rules out transportation by truck or rail. A network of CO₂ pipelines is already in existence in several regions in the United States where CO₂ is used to enhance oil production, so building CO₂ pipelines does not pose technical or safety challenges although regional siting limitations are possible. Given the similarity of CO₂ pipeline technology to that used to transport other gases for which vast networks have been built throughout the world, substantial cost reductions are unlikely from learning-by-doing with CO₂ pipelines. CO₂ transportation by ship is also an established technology that could become important if CO₂ sources and storage locations are far apart; based on estimated costs ship transportation is thought to be favored over pipelines only if CO₂ transportation greater than ~1000 kilometers is needed.

3.3 CO₂ Storage

Several approaches to storing the carbon released from the burning of fossil fuels in a reservoir other than the atmosphere have been proposed. These approaches involve three alternative locations for the carbon: (i) geological storage in underground reservoirs, (ii) ocean storage in marine ecosystems, and (iii) land storage in biomass or carbonate minerals (Figure 4). Geologic storage is the most promising approach, however ocean and land storage also have potential.

In addition to considering CO₂ storage in terms of location, storage options can also be categorized by process, i.e. whether biological, chemical or physical processes are the primary mechanism for storage (Figure 4). Within this categorization, biological approaches rely on photosynthesis to capture and convert atmospheric CO₂ into organic carbon, chemical approaches rely on a chemical reaction to transform the carbon in gas-phase CO₂ into dissolved or solid-phase carbon, and physical approaches rely on barriers that confine gas-phase CO₂ in a location other than the atmosphere.

Within this categorization scheme, physical approaches have received the most attention. The most promising of the physical processes is direct injection of CO₂ gas into geologic formations including depleted oil and gas reservoirs, unminable coal seams, and deep saline aquifers. Commercial experience injecting CO₂ underground has been established in the oil industry where CO₂ injection is used to enhance oil recovery (EOR), that is to loosen up residual oil in a well with declining production. This established commercial application of CO₂ injection provides experience as well as early opportunities for deploying CO₂ injection for storage. The physical injection of CO₂ into the deep ocean is another approach with promise, because the oceans have the capacity to store much of the CO₂ that is currently being emitted into the atmosphere, however strong public opposition to this idea has prevented R&D projects that involve direct injection of CO₂ into the oceans. Research efforts and interest in further understanding the potential of direct injection into the oceans have been intense, particularly in countries like Japan where geologic reservoirs do not exist.

Chemical approaches include engineering geochemical processes to accelerate the formation of the solid carbon form known as carbonate minerals and to increase the

ocean's carbon storage capacity by altering the chemistry of the oceans. Chemical approaches also include using CO₂ in the production of chemical products. Accelerating the slow rates of chemical reactions required for these approaches without inputting excessive amounts of energy is the current critical limitation with these strategies.

To enhance biological carbon storage, changes in forest management practices have been proposed to increase aboveground biomass, living biomass in soils, and the storage of recalcitrant organic and inorganic carbon in soils (DOE, 2004), while fertilization of nutrient-depleted areas of the ocean have been proposed to increase biological storage in the oceans (Buesseler and Boyd, 2003). While biologic storage is the approach that involves the least engineering, the short (decade-scale) storage time-frame limits the long-term storage capacity of biological storage as does recent research suggesting the biosphere may soon become a net source rather than a net sink of atmospheric carbon due to changes in climate (Lenton and Huntingford, 2003). In addition, the negative environmental impacts of large-scale biological storage associated with ecologically precarious monoculture plantations and the replacement of native forests with faster growing species could be devastating (Kueppers et al., 2004).

These limitations with both biological and chemical approaches have reduced the potential of these options. Additional limitations include the impermanence and short, decade-long time scale of terrestrial storage, risks to marine ecosystems, and the public aversion to the idea of ocean dumping associated with oceanic storage. Despite these obstacles, R&D in both land and ocean storage remains strong. The potential for the physical storage of CO₂ in geologic formations has not been limited by these same concerns.

In contrast, recent interest in physical, underground carbon storage has been growing as both the private and public sectors have supported a handful of underground CO₂ storage projects. At Sleipner in the North Sea off the coast of Norway Statoil has been injecting CO₂ into a saline aquifer since 1996, and at Weyburn in Saskatchewan, Canada, CO₂ has been injected underground since 2000 for the dual purpose of enhancing oil recovery and storing the CO₂. More recently, at In Salah in Algeria, BP began injecting CO₂ underground in the fall of 2004. In total, these projects and two smaller projects (the Frio project in Texas and an enhanced gas recovery project in the Netherlands) account for the successful underground storage of about 3-4 million tons of CO₂ per year, and several other projects of even greater scale than the existing projects are planned in Australia, Germany, and the United States. Given the high degree of heterogeneity among different geologic formations, these first few projects do not yet provide sufficient experience representative of many other potential storage locations. Although some preliminary work has been done to understand the global distribution of appropriate underground storage reservoirs (Bradshaw and Dance, 2004) the regional availability of storage locations has not yet been well characterized, yet this will be critical in determining the extent of CCS deployment throughout the world.

Although the physical process of trapping CO₂ in geologic formations is currently the most promising storage approach, underground carbon storage is not free of risks and uncertainties. Continued research on the mobility of the injected gas and the risks associated with leakage of the CO₂ is necessary. Risks associated with leakage in geologic reservoirs located below the ocean floor (like Sleipner) are less than risks of leakage from reservoirs on land, because escaping gas will diffuse in the ocean rather

than re-enter the atmosphere.

In addition to undermining the purpose of the storage project, CO₂ leakage from an underground reservoir into the atmosphere could also have local impacts including ground and water displacement, groundwater contamination, and biological impacts. In Mammoth Mountain, California, for example, leaking CO₂ from a naturally occurring underground reservoir caused vegetation mortality (Biondi and Fessenden, 1999; Stephens and Hering, 2002), acidification that lead to enhanced soil mineral weathering (Stephens, 2002), increased mobility of heavy metals, and at least one human fatality. The development of effective measurement, monitoring, and verification tools and procedures will play a critical role in managing these risks.

3.4 Economics of CCS Technologies

The costs of implementing CCS technology will determine the extent to which CCS technologies can compete with carbon-mitigating energy alternatives. Despite the extensive commercial experience with the use of each of the three technological components in other applications, the minimal experience obtained so far in integrating capture, transport, and storage into one system means that current cost projections are quite uncertain.

For power plants using modern coal-gasification combined-cycle technology or a natural gas combined cycle, the costs of capturing, transporting, and storing carbon dioxide are estimated to be about \$20-25 per metric ton of CO₂ (20-25 \$/tCO₂). For plants using traditional pulverized coal steam technology, costs are estimated to be as much as double this level. CO₂ capture technology is itself energy-intensive and requires a substantial share of the electricity generated. Accounting for the corresponding power plant efficiency reduction (up to 30%) by expressing costs in '\$/tCO₂ avoided', the costs of CCS application in power plants range from \$25-70 per tCO₂ avoided. Expressed in more meaningful terms for plant operators, these figures imply an additional 1-2 cents per kilowatt-hour kWh for new coal gasification power plants with a baseline cost of about 4 cents per kWh.

These cost estimates are currently dominated by the cost of capture (including compression). If transport distances are assumed to be less than a few hundred miles the costs of capture constitute about 80% of the total cost. The broad range of current cost estimates for CCS systems results from a high degree of variability in site-specific considerations such as the particular power plant technology, the required transportation distance, and the specific characteristics of the storage site. For all power plant alternatives and cost components, the costs are expected to decline as new technologies are developed and also as experience is obtained through 'learning-by-doing' in demonstration projects and early-deployment efforts.

4. Regional Differences in CCS R&D, Demonstration, and Deployment

Government efforts to advance CCS technologies vary regionally. The potential impact of successful deployment of CCS systems is related to a region's endemic fossil fuel resources and the region's level of fossil fuel energy reliance, so different priorities are apparent when looking at government supported CCS 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 U.S.

government increasingly touts CCS as part of the future energy infrastructure. The United States currently supports a suite of CCS R&D programs, with an annual budget in 2004 of about \$75 million, and has also initiated a large-scale demonstration project named FutureGen. The primary goal of the core U.S. CCS R&D program is to support technological developments that will reduce costs, and a Regional Sequestration Partnership program supports the development for region-specific research for determining the most suitable CCS technologies, regulations, and infrastructure in different parts of the U.S. The U.S. Department of Energy is providing \$100 million for the next four years to advance the research within the Regional Sequestration Partnership Program from the laboratory stage to the field testing and validation stage. The data generated by these partnerships has been integrated into a database called NATCARB to consolidate geologic and terrestrial data on potential storage sites. This effort will also include public outreach and efforts to identify best-management practices for future deployment in each of the regions.

The U.S. FutureGen Initiative is a \$1 billion project that is planned to be the first demonstration of a commercial scale coal-fired power plant that captures and stores CO₂; the goal of this project is to establish technical feasibility and economic viability for integrating coal gasification technology (IGCC) with CCS. Although the FutureGen project was initiated in 2003, a site has not yet been selected and funding for the construction phase of the project has not yet been allocated, so the future of the project is uncertain.

Although the U.S. government is supporting CCS R&D and has begun funding for a large-scale CCS demonstration project, the U.S. government has not yet provided any regulatory incentives to encourage CCS deployment. Many new power plants are soon to be built in the United States, but no government policy yet provides encouragement for these power plants to include CCS systems. Coordinating demonstration or early-deployment projects with commercially motivated enhanced oil recovery activities in the United States provides a cost-effective early opportunity for advancing CCS.

In Europe, although coal reserves are small compared to those of the United States and there are fewer depleted oil and gas fields that could be appropriate storage reservoirs, European governments have supported advancement of CCS technology in several ways. In 1996 the Norwegian government instituted a tax on CO₂ emissions equivalent to ~\$50/tCO₂ that motivated Statoil, the national oil company, to capture the CO₂ emitted from their Sleipner oil and gas field and inject in an underground aquifer starting in 1996. In addition, the European Community is contributing funds to several CCS projects through its 6th Framework Programme (FP6, totalling an EC contribution of 35 million euro during the first proposal-round) building on the earlier research done under FP4 and FP5 that initiated European R&D into CCS in the early 1990s (EC, 2004). This support includes contributions to the Sleipner project as well as some other R&D and small scale demonstration projects. Independently of Brussels, EC member states also provide small amounts of support for CCS R&D. Integration of these national efforts with the EC and European industries would be beneficial; this could be done through the European Research Area (ERA), an established mechanism to integrate European R&D.

A timely opportunity exists in Europe for early deployment of CCS with the

declining oil and gas production in the reservoirs beneath the North Sea. Injecting CO₂ to enhance oil and gas recovery in these wells is not currently commercially viable. Given the high costs of decommissioning these production wells and the economic benefits associated with retaining jobs and extracting more oil and gas, however, it might be in the governments' best interest to support CCS for enhanced oil and gas recovery to extend the production in the North Sea for several more decades. In addition to the potential of offsetting several decades of European CO₂ emissions, supporting CO₂ injection to postpone the expensive and imminent decommissioning of the North Sea oil and gas fields is financially attractive for both governments and industry who jointly bear the costs of decommissioning. Within the context of managing risks associated with CO₂ leakage, the North Sea provides a relatively safe opportunity for initial large-scale deployment because the ocean provides a buffer; escaping gas would diffuse into the ocean rather than back to the atmosphere.

The British government has already recognized this opportunity as they recently announced a 40 million Euro fund to support CO₂ storage in depleted North sea oil and gas fields. This support was justified not only as a way to reduce CO₂ emissions, but also as an investment in a valuable new export opportunity. This effort was initiated a month before the G8 summit, where Prime Minister Tony Blair, this year's G8 chairman, advocated for increased governmental support for developing carbon abatement technology as a critical part of addressing climate change. The British offshore oil and gas fields are already in decline, and the Norwegian, Danish, and Dutch fields are not far behind, so it is likely that these other European governments will initiate similar programs soon.

Another country that has been actively supporting advancement of CCS is Japan. Interestingly, Japan has focused most of its R&D support on understanding the potential and limitations of oceanic storage of CO₂ because Japan does not have suitable land-based geologic reservoirs to use for 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 is minimal or non-existent. The rapid expansion of the energy infrastructure in many developing countries, particularly China and India, however, has created an immediate and urgent need to begin understanding potential CO₂ storage opportunities in developing countries. Whether or not coal-rich countries like China and India have domestic geologic reservoirs to store CO₂ is a critical unanswered question. As international pressure to address climate change grows, the answer to that question could have an impact on energy technology choices in these countries.

Recognizing the varied efforts in advancing CCS technology around the world, an international body, the Carbon Sequestration Leadership Forum (CSLF), was initiated by the United States in 2003. The CSLF provides a forum for international collaboration (currently 17 nations are members) by facilitating joint projects, as well as providing a mechanism for communication in the latest developments in CCS technology and a venue for developing strategies to transfer CCS technology to developing countries.

5. Discussion

Given the technological status of CCS and current government interest world-wide in stimulating CCS innovation, three primary recommendations for advancing CCS

emerge: (i) increase support for R&D, in particular for improving capture technology and determining the geographic opportunities and limitations of CCS application, (ii) increase investments in multiple large-scale capture and storage demonstration projects in a diverse set of geological locations, and (iii) design policies that provide economic incentives for actual early deployment of CCS. As the technical feasibility of CCS as a viable clean energy option is progressively more accepted, and the urgency of addressing the climate change problem is increasingly recognized, these recommendations should be implemented concurrently. Meanwhile, all CCS stimulation efforts should also include public outreach and education programs as the public's perception of this set of technologies is an important element affecting their development.

Increased R&D support should be focused on improving CO₂ capture technology to reduce its costs, because the capture component of CCS technology has the greatest potential for contributing to overall CCS cost reductions. R&D investment is also needed to create detailed, regional maps of storage opportunities throughout the world. Particularly, geologic assessments are needed in China, India, and other rapidly-growing developing countries. Increased support for improving our understanding and the management of the potential risks and environmental impacts associated with storing CO₂ underground is also needed.

Demonstration is a critical component of technological innovation, so increased funding for demonstration projects is essential to the advancement of CCS technology. The integration of the various components of a CCS system has not yet been demonstrated on a large scale, nor has capture technology yet been demonstrated on an operating commercial-scale power plant. While the U.S. FutureGen project was designed to be the first fully integrated demonstration effort, the slow progress and uncertain future of this project has been frustrating for those involved and has cast doubt on whether the use of such a large proportion of the total U.S. funds earmarked to advance CCS in one ambitious commercial-scale power plant is an efficient use of limited financial resources. The demonstration of capture technology on existing power plants or the integration of capture technology in the design of several of the new power plants that are inevitably going to be built in the next few years could be a more cost-effective way to achieving operational proficiency and realizing overall CCS cost reductions through learning-by-doing.

In addition to the need for demonstration of CO₂ capture technology in commercial-scale power plants, more large-scale CO₂ storage demonstration projects are needed in a diverse set of locations. Geologic formations appropriate for CO₂ storage are heterogeneous, so the handful of current CO₂ storage projects, including Sleipner and Weyburn, do not provide sufficient storage experience in different geologic settings. To advance our understanding of issues such as CO₂ storage integrity, the number of underground CO₂ storage sites should be increased from the current 5 projects (representing 3-4 MtCO₂/yr stored), beyond the additional 5 sites being planned (within two years close to 10 MtCO₂/yr), to many more sites in different continents and geologic formations. An additional 5-10 storage demonstration projects in each continent with a minimal size of 1 MtCO₂/yr (within the decade increasing total storage activity by an order of magnitude) would provide necessary experience in a sufficiently large variety of geologic formations and political and economic environments. Containment and risk management experience derived from these additional projects could strengthen the case

for geologic storage by providing additional information that would assuage safety and environmental concerns.

The future trajectory of CCS technologies will be influenced by government supported R&D and demonstration projects, but the most critical need at this point is government policies to create incentives for companies to begin early-deployment of CCS technologies. Many companies in the oil and gas industry show interest and preparedness to develop and deploy CCS technologies. Most recently, in June 2005, BP and several industry partners announced plans to build the world's first integrated commercial-scale power-plant with CO₂ capture and storage. The project will involve a new 350 megawatt power plant from which CO₂ is captured and transported to the North Sea to be injected and stored in underground reservoirs for enhanced oil recovery. For the moment, however, this plan involves only one power plant: without a regulatory framework to provide rewards for reducing CO₂ emissions, private firms will remain hesitant and are limited in how much they can actually do. The high cost of CCS deployment and the complex integration of CCS technologies with existing energy infrastructures, as well as their large physical scale, restrict the private sector from acting without clear governmental rules and support.

The timely opportunity for early deployment of CCS technologies with the declining oil and gas fields in the North Sea has been recognized by several stakeholders, including the British government and the aforementioned oil company, BP. Additional governmental support to deploy CCS could further postpone the expensive and imminent decommissioning of the North Sea oil and gas fields while advancing learning-by-doing for CCS technologies. Many early deployment opportunities in the United States are also associated with enhanced oil and gas recovery projects.

In terms of its capital intensity and the required financial incentives, as well as the public stimuli and regulatory framework needed, advancing CCS technology can be likened more to the development of a resource such as nuclear energy than that of small-scale modular photovoltaic technology. As with both of these other energy production alternatives, government-provided incentives and support are indispensable. Another consideration for deployment strategies that is intricately linked to the frameworks designed by national governments and their international coordination is the nature of the mechanisms to be created (e.g. CDM-like) to generate incentives for CCS deployment in the developing world, notably China and India.

Unlike other emerging energy technologies that may be viewed by some as involving competition with existing fossil fuel infrastructures, the potential for CCS to provide a way for fossil fuel industries to reconcile their continued burning of fossil fuels with inevitably required climate change mitigation measures is unique. This potential has already resulted in substantial interest in CCS technologies from the private sector. The current challenge is for governments to harness the private sector's interest by developing policies that reward investments in early-deployment of CCS systems.

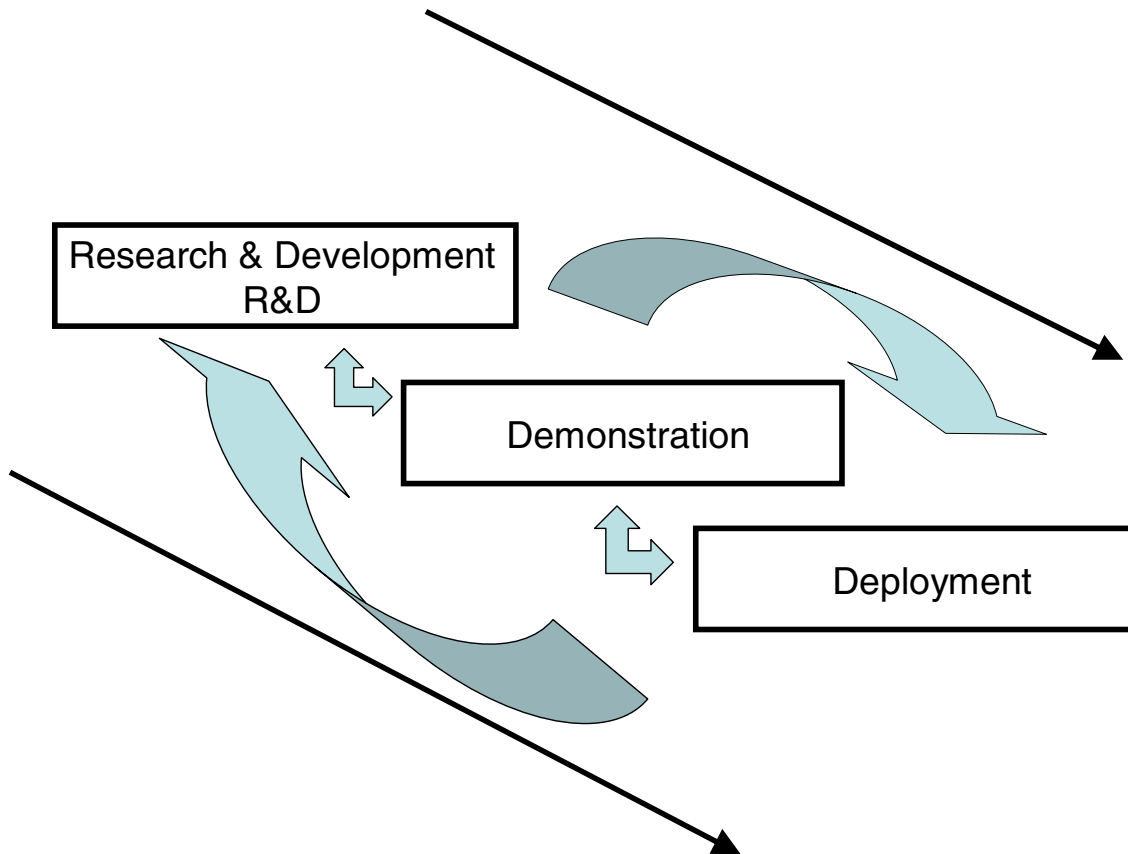


Figure 1 – The technology innovation continuum.

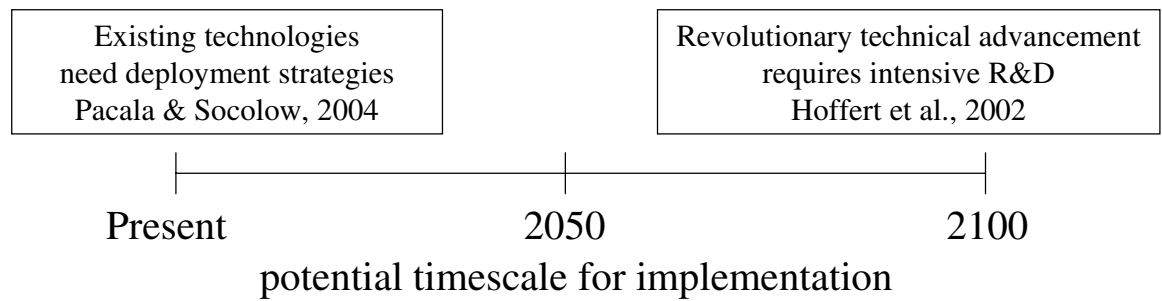


Figure 2. Spectrum of maturity of technological solutions to mitigate against global climate change. Technologies associated with capturing and storing CO₂ span this spectrum.

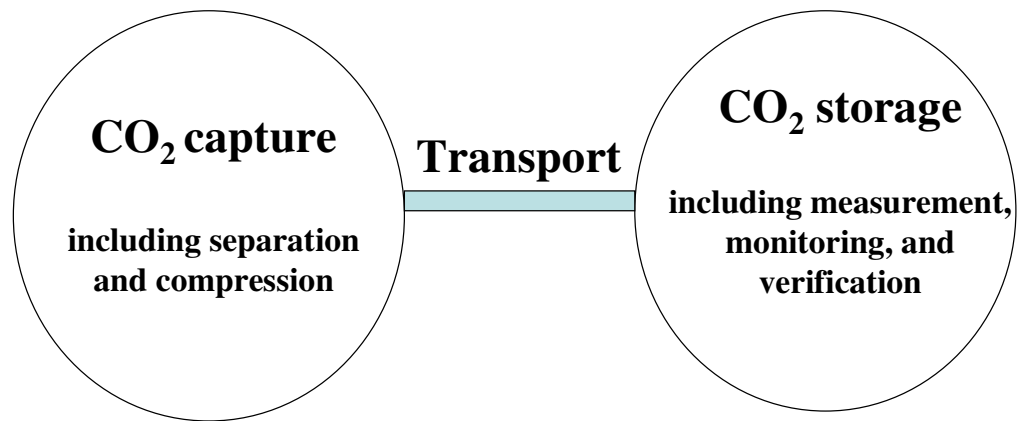


Figure 3 – A complete CCS system involves three components: CO₂ capture, transport, and CO₂ storage. Commercially established technologies associated with each are currently available, but have not yet been integrated or demonstrated at the appropriate scale.

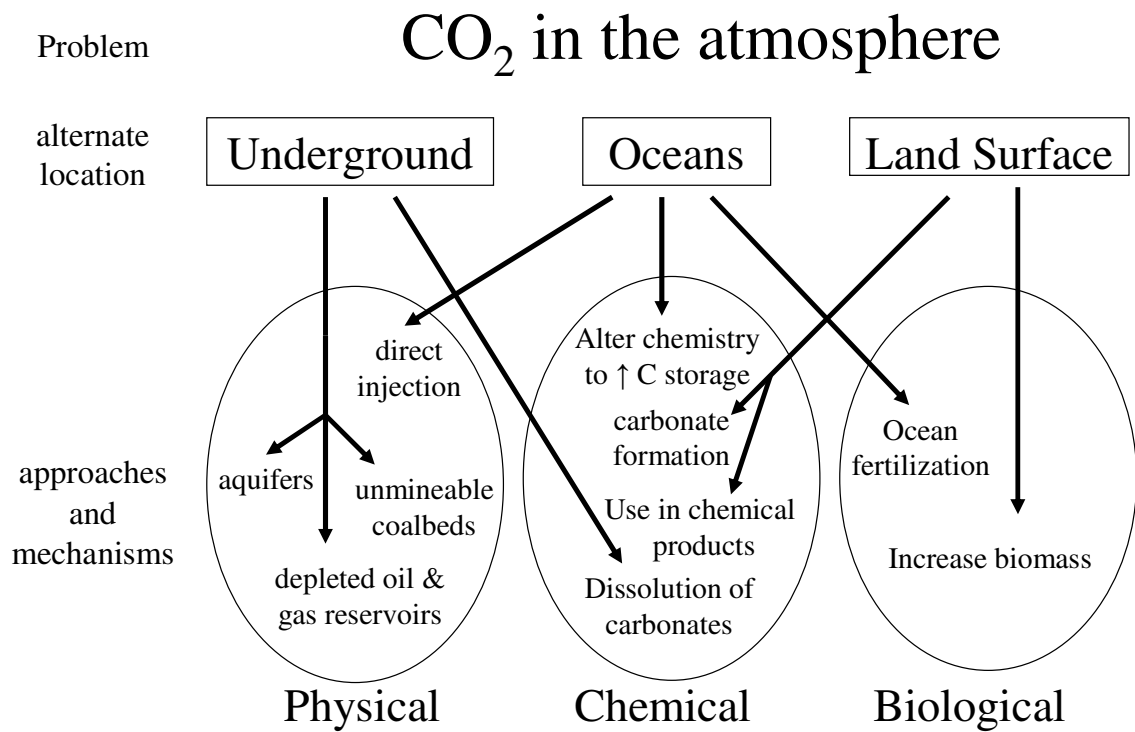


Figure 4 - Schematic illustration of potential carbon dioxide storage locations with specific approaches categorized by the mechanism required.

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