INVITED PAPER

Carbon Dioxide Capture and Storage: An Overview With Emphasis on Capture and Storage in Deep Geological Formations

Deep burial of CO_2 is seen to be feasible, and will be needed to reduce carbon dioxide emissions from coal-fired power plants.

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ABSTRACT | A transition to a low-carbon economy can be facilitated by CO_2 capture and storage. This paper begins with an overview of CO_2 capture and storage in the terrestrial biosphere, oceans, and deep geologic systems. The remainder focuses on what now appears to be the most promising option for large-scale deployment—capture and storage in deep geologic formations. A detailed description of the technology is provided, including the potential scale of application, cost, risk assessment, and emerging research issues.

KEYWORDS | Carbon capture and storage (CCS); carbon sequestration; geological storage; greenhouse gas; hydrogen; mitigation

I. INTRODUCTION

Today, 22 billion tonnes of CO_2 are emitted into the atmosphere from man-made sources. Worldwide, approximately one-third of emissions are from electricity production, one-third from transportation, and the rest primarily from heating buildings and industrial processes. Oil, coal, and natural gas are the source of these emissions, and these fossil fuels provide for over 85% of the world's energy needs. Over the next hundred years, demand for energy is expected to more than double. Growth will be particularly critical in developing nations where industrialization and improved quality of life will increase demand. Representative scenarios designed to predict future emissions estimate that by 2100, annual emissions of CO_2 from fossil fuels will range from 16 billion to 110 billion tonnes per year, with many scenarios indicating a doubling of CO_2 emissions by 2050 [1].

Emission of CO_2 into the atmosphere from the use of fossil fuels is the primary reason that CO_2 concentrations have increased from preindustrial levels of 270 parts per million (ppm) to 380 ppm today. Ice-core records from Greenland and Antarctica indicate that CO_2 concentrations this high have not been observed for over 400 000 years. It is not yet possible to predict the consequences of this unprecedented rise in CO_2 concentrations. However, consequences include ocean acidification, sea level rise, climate perturbations, and ecosystem disruption [2]–[4]. Today, CO_2 concentrations continue to rise at about 2 ppm per year. Unchecked, within the next several decades CO_2 concentrations will exceed levels believed to cause dangerous interference with the climate system [4]. Energy technologies with low or no CO_2 emissions will be needed to slow the growth of emissions and eventually stabilize atmospheric concentrations of CO_2 [5].

Given our heavy dependence on fossil fuels and the fact that plentiful reserves of fossil fuels still exist [6], perhaps for a hundred years or more, the question becomes: Can

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fossil fuels provide low or no CO_2 emission sources of energy? Today, all of the CO_2 produced from combustion of fossil fuels is emitted to the atmosphere. We do this because it has no immediate cost, and until about 50 years ago, we also believed it would not be harmful [7], [8]. By analogy to other industrial by-products and municipal waste that are no longer discharged into lakes, streams, and the atmosphere, can CO_2 emissions from fossil fuels be put somewhere besides the atmosphere or treated to reduce or eliminate emissions? For example, sulfur dioxide and nitrous oxide emissions from power plants were found to cause air pollution, so technologies were developed to remove them from the smoke stacks of power plants. Biological pathogens from sewage were damaging the water quality of lakes and rivers, so sewage treatment plants that remove the pathogens were developed. Many more examples such as these demonstrate that management of these by-products can be improved to reduce or eliminate their environmental impacts. In each case, initially it was believed to be too costly. However, once requirements to reduce discharges were put in place, technological innovations spurred through competition for new markets resulting in effective new technologies at acceptable costs. So today, this is the challenge facing continued use of fossil fuels. Can new technologies that reduce or eliminate CO_2 emissions from fossil fuels be developed and implemented at an acceptable cost? And can value-added uses of CO_2 help to build infrastructure and offset the costs of early deployment?

II. OVERVIEW OF CO_2 CAPTURE AND STORAGE TECHNOLOGY

Reducing or offsetting CO_2 emissions from fossil fuel use is the primary purpose of the new suite of technologies called carbon capture and storage or carbon sequestration. Two basic approaches are available. For the first approach, CO_2 is captured directly from the industrial source, then concentrated into a nearly pure form and then pumped into geological formations far below the ground surface. This approach is commonly referred to as carbon dioxide capture and storage (CCS) [9]. CCS is expected to be most useful for large, stationary sources of CO_2 such as from power plants, petroleum refineries, gas processing facilities, and cement factories. It has also been suggested that the deep ocean could also be used for storage. The second approach to CCS enhances natural biological processes that take CO_2 out of the atmosphere and sequester it in plants, soils, and marine sediments. While this approach captures CO_2 from all emission sources, it is particularly useful for offsetting emissions from distributed small sources or mobile sources of CO_2 such as automobiles that would be difficult to capture directly at the source.

A. Carbon Dioxide Capture and Storage

Carbon dioxide capture and storage is a four step process. First, the CO_2 is separated from emissions and concentrated into a nearly pure form. For today's natural gas and coal-fired power plants, from 4% to 14% of the flue gas is CO_2; the rest is primarily nitrogen and oxygen. After the CO_2 is separated from the flue gas, it is compressed to about 100 bars, where it is in a liquid phase. Next, it is put into a pipeline and transported to the location where it is to be stored. Pipelines transporting CO_2 for hundreds of kilometers exist today. The last step is to pump it into the medium in which it will be stored. There are two options for storage.

1) *Deep Underground Geological Storage:* As shown in Fig. 1, CO_2 can be injected into deep underground formations such as depleted oil and gas reservoirs, brine-filled formations, or deep unmineable coal beds [9], [10]. This option is in practice today at three industrial-scale projects and many smaller pilot tests. At appropriately selected storage sites, retention rates are expected to be very high—with CO_2 remaining securely stored for geologic periods of millions of years. The potential storage capacity in geological formations is uncertain, but estimates of storage capacity in oil and gas fields range from 900 billion to 1200 billion tonnes of CO_2 [9]–[11] and the estimated capacity in brine-filled formations is expected to be at least 1000 billion tonnes, and probably is much greater. Significant investment in research and technology development is underway in many countries. This option will be discussed in greater detail in the remainder of the paper.

2) *Ocean Storage:* CO_2 can be injected into the middepth ocean (1000–3000 m deep) which will enable it to be stored for hundreds to thousands of years before returning to the atmosphere via ocean circulation. The injected CO_2 would dissolve and be transported with ocean currents. Alternatively, it could be injected near the ocean bottom, to create stationary "pools" of CO_2. The potential capacity for ocean storage is large—on the order of a thousand billion tonnes of CO_2 [9]. Ocean storage research is being actively pursued by some countries. Concerns about unknown biological impacts, high costs, impermanence of ocean storage, and concerns regarding public acceptance have decreased interest and investment in this technology over the past five years.

Three industrial-scale CCS projects are operating today and more are on the way. Two of them are associated with natural gas production. Natural gas containing greater than several percent CO_2 must be "cleaned up" to pipeline and purchase agreement specifications. The first of these projects, the Sleipner Saline Aquifer Storage Project, began nearly ten years ago. Annually, 1 million tonnes of CO_2 are separated from natural gas and stored in a deep subsea brine-filleds and stone formation [12]. The In Salah Gas Project in Algeria began in 2004 and is storing 1 million tonnes of CO_2 annually in the flanks of a depleting gas field [13]. The third industrial-scale CCS

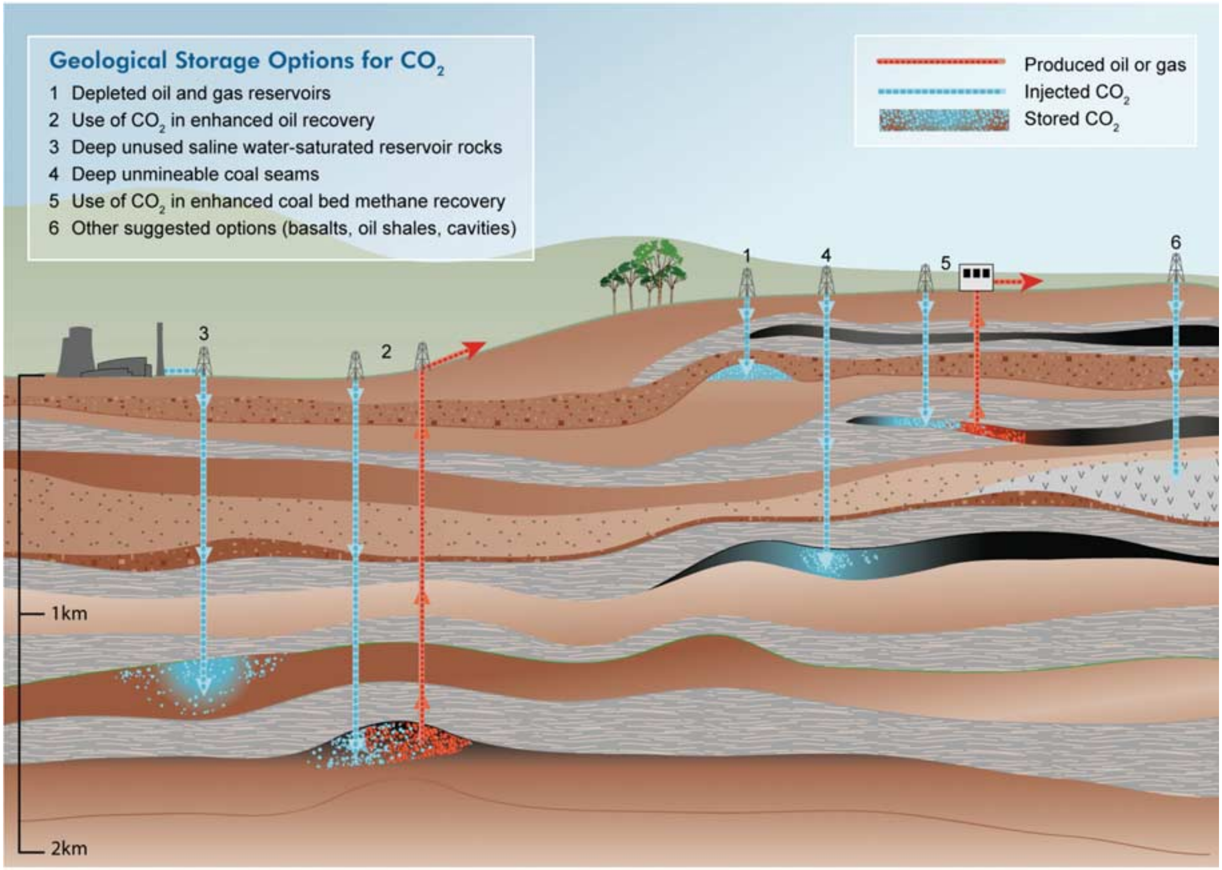


Fig. 1. ***Options for geological storage of CO_2 (courtesy of Peter Cook, CO2CRC).***

project, located in Saskatchewan, Canada, uses CO_2 from the Dakota Gasification Plant in North Dakota to simultaneously enhance oil production and store CO_2 in the Weyburn Oil Field [14]. While CCS is not the primary purpose for injecting CO_2 underground at Weyburn, a significant research and monitoring program was implemented to evaluate the efficacy of CO_2 storage and now the operators intend to continue storing CO_2 in the reservoir after oil recovery operations cease.

Electric power stations that use fossil fuels are large point-source emitters of CO_2 that are amenable to CCS. At issue is the ability to economically capture and separate CO_2 from the processes that produce electricity. Pre- and post combustion approaches to economically capturing CO_2 from power plants are being developed [15]. Integrated gasification combined cycle (IGCC) technology holds particular promise for an efficient means of capturing CO_2. Coal gasification, followed by a water–gas shift reaction (a chemical reaction to convert CO and H_2O to CO_2 and H_2) could produce hydrogen for running a gas turbine and CO_2 for storage [16]. Hydrogen could also be available for other purposes. Similar approaches have been proposed for natural gas power stations [17]. Emission reductions of about 85%–90% are possible using CCS with fossil-fuel powered electric generating stations [9].

Future approaches to the minimization of CO_2 in the atmosphere must also include the transportation sector. As CCS is deployed for electricity production, cogeneration of electricity and H_2 could be used to develop alternative approaches to reduce CO_2 emissions from the transportation sector. For example, H_2 could be used in fuel cell vehicles or directly in combustion engines. For now, low-CO_2 production of H_2 could be obtained by reforming natural gas, or from coal and biomass gasification with CO_2 capture and storage. But in the future, hydrogen could also be obtained from the electrolysis of water using electricity from carbon-free sources. Building the distribution and storage infrastructure for fossil fuel based H_2 could help to accelerate deployment of H_2 produced from carbon-free sources. Alternatively, as battery technology improves, electric vehicles charged from low-carbon electricity could help to reduce CO_2 emissions from the transportation sector. Many options are being explored to reduce CO_2 emissions from vehicles, including highly efficient hybrid vehicles, and it is still too early to tell which technologies will penetrate the market.

If CO_2 capture and storage is combined with biomass-based energy production (e.g., energy from agricultural wastes, energy crops such as switch grass and trees), even deeper reductions in emissions are possible [9]. Not only is biomass displacing CO_2 emissions from fossil fuels, but storing the CO_2 generated by combusting biomass will result in negative overall emissions. This strategy may be useful to compensate or offset emissions from the transportation sector or other sectors where traditional CCS is too costly.

B. Carbon Sequestration in Terrestrial and Marine Ecosystems

Carbon sequestration in terrestrial and marine ecosystems relies on natural or accelerated photosynthesis to extract CO_2 from air and then sequester it in living and decaying biomass. Terrestrial sequestration aims to increase the uptake of carbon by forests or increase the amount of carbon stored in agricultural soils and range land. Carbon sequestration in trees and soils can also provide the cobenefits of ecosystem restoration, soil quality improvement, and fire suppression.

Over the years, many forests have been cut down for lumber and conversion to other land uses. Reforesting these lands and managing forest lands to conserve carbon stocks could potentially sequester 220 billion to 320 billion tonnes of CO_2 by the year 2050 [18]. Soils are another important option for storing carbon. Plant roots, decaying biomass, and a variety of complex organic molecules compose what is commonly referred to as soil carbon. Forests and agricultural soils are large natural reservoirs of carbon. As a result of common agricultural practices such as tilling, fallowing, and drainage, soil carbon stocks have been depleted. Changing agricultural practices can reverse this trend, help to rebuild soil carbon stocks and sequester an estimated 80–160 billion tonnes of CO_2 over the next 50 years [18]. Terrestrial sequestration is underway today. Many electrical utilities have very active programs in tree planting and reforestation. In addition, research is underway to examine methods for changing farming and ranch land management practices to enhance CO_2 uptake and long-term sequestration.

Another form of biological sequestration is possible in marine environments—the so-called practice of ocean fertilization. Scientific experiments have been conducted to evaluate whether adding iron to the ocean could increase biological productivity, thus increasing the rate of ocean uptake CO_2. In 2001, the Southern Ocean Iron Experiment (SOFEX) was conducted in the southern Pacific [19]. Results from this and similar experiments showed rapid increases in biological productivity, but many questions remain regarding long-term ecosystem impacts and the effectiveness of this technique for lowering atmospheric CO_2 concentrations. Consequently, at present, ocean fertilization is not under serious consideration for large-scale carbon capture and storage.

Having provided a broad overview of carbon capture and storage, the remainder of this paper will focus on CO_2 Capture and Storage in deep geological formations. This, together with terrestrial sequestration have significant potential to reduce or offset CO_2 emissions and are likely to be important elements of the port folio of technology options used to stabilize atmospheric CO_2 concentrations. In the short term, applications of CCS are likely to focus on the electricity sector; however, over the long run, application to the transportation sector are also promising. Finally, the possibility to combine biomass-based energy production with CCS holds promise for even greater emission reductions. Early progress in this regard could be achieved by cofiring fossil fuels and biomass [9].

III. TECHNOLOGICAL STATUS OF CO_2 CAPTURE AND GEOLOGIC STORAGE TECHNOLOGY

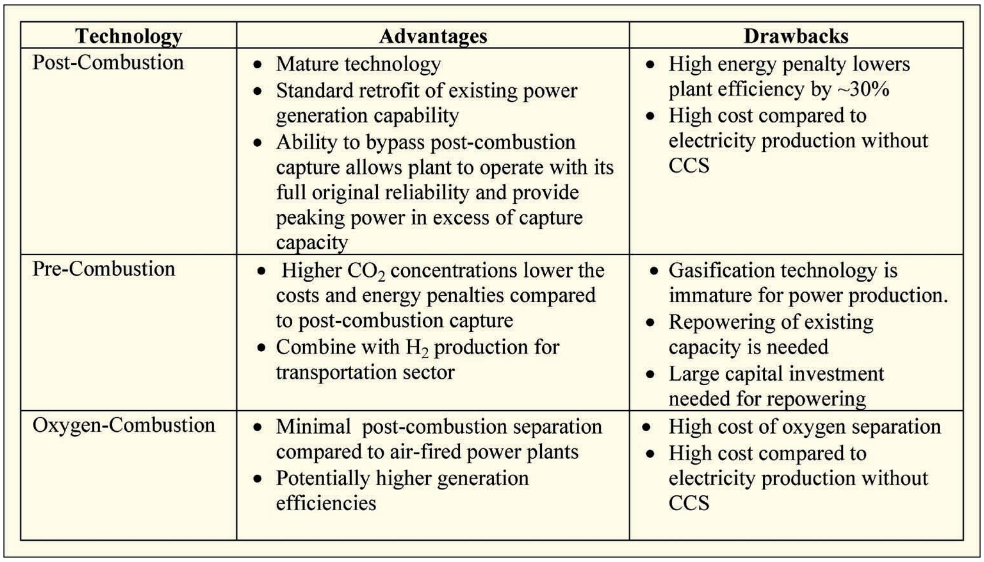
Carbon dioxide capture with storage in deep geological formations is currently the most advanced—and the most likely CCS approach to be deployed on a large scale in the coming decades. Almost every element of this technology is employed on an industrial scale today, for a variety of purposes, from fertilizer manufacturing to enhanced oil recovery. Lacking is the integrated experience applied to electricity generation and cost-effective approaches to CO_2 capture. Large-scale CO_2 storage in geologic systems will also require practical experience in selecting appropriate storage sites, monitoring, risk management, and regulatory oversight.

A. Capture Technology

There are three general means for capturing CO_2 from fossil-fired power plants: postcombustion capture, precombustion capture, and use of oxygen for combustion. Worldwide, significant scientific research and engineering development has been invested in all of the approaches over the past decade. Each has its advantages and disadvantages as described below (see Table 1).

Postcombustion capture removes CO_2 from the flue gas of a power plant using chemical solvents, primarily regenerable amines [20]. The flue gas is run through a low pressure gas/liquid contactor, CO_2 partitions into the amine solvent and then, the amine is heated to release nearly pure CO_2. The advantage of postcombustion capture is that existing electric generation plants could be retrofitted with a postcombustion capture unit and the technology is well established. Disadvantages include the large energy requirements to regenerate the amine and compress the CO_2 from near-atmospheric pressure to pipeline pressures in excess of 100 bars. For newly constructed plants with postcombustion capture, it may be possible to reduce costs and energy requirements significantly by more efficient energy integration and preconcentrating the CO_2 before separation [20].

Table 1 Comparative Benefits of Postcombustion, Precombustion, and Oxygen Combustion



Technology	Advantages	Drawbacks
Post-Combustion	• Mature technology • Standard retrofit of existing power generation capability • Ability to bypass post-combustion capture allows plant to operate with its full original reliability and provide peaking power in excess of capture capacity	• High energy penalty lowers plant efficiency by ~30% • High cost compared to electricity production without CCS
Pre-Combustion	• Higher CO_2 concentrations lower the costs and energy penalties compared to post-combustion capture • Combine with H_2 production for transportation sector	• Gasification technology is immature for power production. • Repowering of existing capacity is needed • Large capital investment needed for repowering
Oxygen-Combustion	• Minimal post-combustion separation compared to air-fired power plants • Potentially higher generation efficiencies	• High cost of oxygen separation • High cost compared to electricity production without CCS

Of potentially greater promise is the capture of CO_2 in a precombustion process. The most promising electricity generation technology currently under evaluation which would lend itself to precombustion is IGCC technology [16]. Precombustion capture separates the CO_2 by reacting fossil fuel with steam and air or oxygen before it is combusted. The reaction creates "synthesis gas," a mixture primarily of CO and H_2. The CO is then reacted with water to produce CO_2 and more H_2. The mixture is then separated to produce H_2, which can be used for electricity generation or other purposes, and CO_2 for storage. Advantages include the ability to produce hydrogen, lower compression requirements, and lower energy use for the separation process. Disadvantages include the lack of experience of the electrical utility industry with advanced chemical processing facilities such as IGCC and lack of widespread application for the purpose of power production. Gasification is used today to produce ammonia for fertilizers and H_2 for petroleum processing. Currently, there are four IGCC units, two in Europe and two in the United States. Two additional commercial units are being planned in the United States.

There are a number of promising technologies that utilize oxygen, rather than air, for combusting fossil fuels, so-called oxygen combustion [21]. The advantage is that the only gaseous emissions are water vapor, CO_2, and between 5% and 10% O_2 and N_2 with small amounts of SO_2 and NO_x. These are easily separated and CO_2 can then be readily captured. The disadvantage is that there are energy and economic penalties in the production of oxygen as part of the process.

Large-scale demonstration projects of electric generation with CCS are planned in the United States, the United Kingdom, and Sweden. In the United States, the government sponsored FutureGen project will demonstrate IGCC with CCS in a deep geologic formation over the next decade. In the United Kingdom, a natural gas fired power plant will be converted to a hydrogen-fired power plant and captured CO_2 will be pumped into a depleting oil field under the North Sea for the combined purpose of enhanced oil recovery and CO_2 storage. A third project is now planned in the United States, where petcoke will be gasified to produce electricity and H_2. Captured CO_2 will be pumped into an on-shore oilfield for enhanced oil recovery and CO_2 storage. In Sweden, the Vatten fall project will test electricity production from oxygen combustion of lignite coal. Additional commercial and government sponsored demonstration projects are likely to be announced worldwide over the next few years. Within less than a decade, significant experience operating IGCC power plants with CO_2 storage will be available.

B. Carbon Dioxide Storage in Deep Geological Formations

Everywhere under a thin veneer of soils or sediments, the earth's surface is made up primarily of two types of rocks: those formed by cooling magma, either from volcanic eruptions or from magmatic intrusions far beneath the land surface, and those formed as thick accumulations of sand, clay, salts, and carbonates over millions of years. The latter types occur primarily in what are termed sedimentary basins. Geographic locations overlying sedimentary basins are best suited for geological storage of CO_2 and, fortuitously, the majority of CO_2 sources are located in or near to sedimentary basins.

Sedimentary basins often contain many thousands of meters of sediments where the tiny pore spaces in the rocks are filled with salt water (saline formations) are where oil and gas reservoirs are found. Sedimentary basins consist of many layers of sand, silt, clay, carbonate, and evaporite (rock formations composed of salt deposited from evaporating water). The sand layers provide storage space for oil, water, and natural gas. The silt, clay, and evaporite layers provide the seal that can trap these fluids underground for periods of millions of years and longer. Geologic storage of CO_2 would take place deep in sedimentary basins trapped below silt and clay layers, much in the same way that oil and natural gas are trapped today [22], [23]. Possible storage formations include oil reservoirs, gas reservoirs, saline formations, and even coal beds (see Fig. 1).

The presence of an overlying, thick, and continuous layer of silt, clay, or evaporite is the single most important feature of a geologic formation that is suitable for geological storage of CO_2. These fine-textured rocks physically prevent the upward migration of CO_2 by a combination of viscous and capillary forces. Oil and gas reservoirs are found under such fine-textured rocks and mere presence of the oil and gas demonstrates the presence of a suitable reservoir seal. In saline formations, where the pore space is initially filled with water, after the CO_2 has been underground for hundred to thousands of years, chemical reactions will dissolve some or all of the CO_2 in the salt water, and eventually some fraction of the CO_2 will be converted to carbonate minerals, thus becoming a part of the rock itself [23].

One of the key questions for geologic storage is, how long will the CO_2 remain trapped underground? This question is best addressed from the perspective of how long must it remain trapped to be an effective method for avoiding CO_2 emissions to the atmosphere. While there is not a generally accepted answer to the latter question, most studies agree that if greater than 90% of the CO_2 remains underground over a thousand-year period, CCS will be a very effective method for avoiding CO_2 emissions [24]. The question then becomes, will geologic formations retain CO_2 over such periods?

There are a number of lines of evidence which suggest that for well-selected and managed storage formations, retention rates will remain very high and more than sufficient for the purpose of avoiding CO_2 emissions into the atmosphere [9], specifically the following.

- Natural oil, gas, and CO_2 reservoirs demonstrate that buoyant fluids such as CO_2 can be trapped underground for millions of years.
- Industrial analogues such as natural gas storage, CO_2-EOR, acid gas injection, and liquid-waste-disposal operations have developed methods for injecting and storing fluids without compromising the integrity of the caprock or the storage formation.
- Multiple processes contribute to long-term retention of CO_2, including physical trapping beneath low permeability rocks; dissolution of CO_2 in brine; capillary trapping of CO_2; adsorption on coal; and mineral trapping—together, these trapping mechanisms increase the security of storage over time, thus further diminishing the possibility of potential leakage and surface release.
- Early experiences at the Sleipner Project in the North Sea, the Weyburn Project in Saskatchewan, and the In Salah Project in Algeria have been successful, with no evidence of leakage or safety problems.

The technology for storing CO_2 in deep underground formations is adapted from oil and gas exploration and production technology. For example, technologies to drill and monitor wells that can safely inject CO_2 into the storage formation are available. Methods to characterize a site are fairly well developed. Models are available to predict where the CO_2 moves when it is pumped underground, although more work is needed to further develop and test these models, particularly over the long time frames and large spatial scales envisioned for CO_2 storage. Monitoring of the subsurface movement of CO_2 is currently being successfully conducted at several sites, although, again, more work is needed to refine and test monitoring methods.

IV. EXISTING AND PLANNED CO_2 CAPTURE AND STORAGE PROJECTS

A. Existing CO_2 Storage and Injection Projects

Today 3–4 million tonnes per year of CO_2 are captured and stored in deep geological formations at Sleipner, Weyburn, and In Salah [12]–[14]. The Sleipner and In Salah Projects where designed with CCS as their primary purpose. The Weyburn Project was designed initially as an enhanced oil recovery project, but has evolved to a project that combines enhanced oil recovery with CO_2 storage. Today, over 16 years of cumulative experience has been gained from these projects.

Vast experience pumping CO_2 into oil reservoirs also comes from nearly 30 years of CO_2-enhanced oil recovery (CO_2-EOR), where today, nearly 30 million tonnes are injected every year. About 70 projects are underway worldwide, with the vast majority in west Texas. When CO_2 is pumped into an oil reservoir, it mixes with the oil, lowering the viscosity and density the oil. Under optimal conditions, oil and CO_2 are miscible, which results in efficient displacement of oil from the pore spaces in the rock. An estimated increase in oil recovery of 10%–15% of the initial volume of oil-in-place is expected for successful CO_2-EOR projects. Not all of the injected CO_2 stays underground as 30%–60% is typically produced back with the oil. On the surface, the produced CO_2 is separated from the oil and reinjected back into the reservoir. If CO_2 is left in the reservoir after oil production stops, most of the CO_2 injected over the project lifetime remains stored underground.

The majority of CO_2-EOR projects today use CO_2 from naturally occurring CO_2 reservoirs. The high cost and limited availability of CO_2 has restricted deployment of CO_2-EOR to those areas with favorable geological conditions and a readily available source of CO_2. A few projects use CO_2 captured from industrial sources, notably the Weyburn Project discussed above and the Salt Creek Project in Wyoming, which is injecting several million tonnes per year.

The recent high oil prices have spurred interest in expanding application of CO_2-EOR. This together with prospects for obtaining tradable credits for storing CO_2 has attracted considerable interest by the oil and gas industry.

B. Planned Industrial and Pilot-Scale Projects

A number of industrial-scale projects are under development and expected to be operational within the next five years. Plans for new CCS projects are now being announced at a rate of several each year.

In Norway, the Snohvit Project, will produce liquefied natural gas (LNG), and nearly 1 million tonnes per year of CO_2 emissions will be captured and stored in an offshore saline formation. This project should be operational by 2007. In early 2006, plans were also announced for an 860-MW gas-fired power plant with postcombustion capture. Captured CO_2 will be injected into depleting oil fields for enhanced oil recovery.

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In the United States, the FutureGen Project, a Department of Energy cofunded project, will produce electricity and H_2 from coal while capturing and storing CO_2. An industrial consortium will lead the ten-year effort to create the "world's cleanest fossil fuel power plant." Plans include a 275-MW coal-fired power plant that will store 1 million tonnes of CO_2 per year. The location of the facility will be decided in 2006.

In Australia, the Gorgon Project has proposed to produce LNG and store nearly 5 million tonnes per year in a deep saline formation [25].

In early 2006, a joint venture to produce electricity and H_2 from petroleum-coke in Long Beach, CA, was announced. The plant will provide 500 MW of electricity, and the captured CO_2 will be injected into an oil reservoir for CO_2-EOR and storage.

In the United Kingdom, a 350-MW natural gas-fired power plant will be converted to use H_2, and the captured CO_2 will be stored offshore in the Miller Field, with enhanced oil recovery in a depleting oil field.

In addition to these industrial-scale projects, there are dozens of small-scale geological storage pilot projects underway worldwide and more are expected. For example, in the United States, the Department of Energy has sponsored seven regional sequestration partnerships. Over the next four years, these partnerships will conduct 25 pilot tests of storage in geological formations. These pilot and demonstration projects will help to assess the geographical extent and capacity of geological formations. Similar pilot tests are being carried out in Australia, Canada, Germany, Japan, the Netherlands, and Poland, and many more countries are expected to announce plans for pilot tests soon.

V. HEALTH, SAFETY, AND ENVIRONMENTAL RISKS OF CO_2 CAPTURE AND STORAGE

Carbon dioxide is used in a wide variety of industries, from chemical manufacture to beverage carbonation and brewing, from enhanced oil recovery to refrigeration, and from fire suppression to inert atmosphere food preservation. Because of its extensive use and production, the hazards of CO_2 are well known and routinely managed. Engineering and procedural controls are well established for dealing with the hazards of compressed and cryogenic CO_2. Carbon dioxide capture and transportation pose no unique risks that are not managed routinely in comparable operations.

While CO_2 is generally regarded as a safe and nontoxic inert gas, exposure to elevated concentrations of CO_2 can lead to adverse consequences. In particular, since CO_2 is denser than air, hazardous situations arise when large amounts of CO_2 accumulate in low-lying, confined, or poorly ventilated spaces. While the chances of this occurring are very low, if a large amount of injected CO_2 were to escape from a storage site, it could present risks to health and the local environment. Such releases could be associated with surface facilities, injection wells, or leakage from the storage formation itself. They may be small-scale diffuse leaks or leaks concentrated near the injection facilities. Leakage, if unchecked, could harm groundwater and ecosystems. Persistent leaks could suppress respiration in the root zone or result in soil acidification and eventually lead to tree-kills such as those associated with soil gas concentrations in the range of 20%–30% CO_2 which have been observed at Mammoth Mountain, CA, where volcanic out gassing of CO_2 has been occurring for several decades [26].

Analogous experience with gas and liquid injection derived from seasonal storage of natural gas [27], disposal of liquid wastes [28], acid gas injection [29], and oil field operations shows that underground injection activities can be carried out safely. In the unusual circumstances where leakage or surface releases occur, they are mostly caused by leakage from the injection well, or leakage from wells that were drilled long ago and not properly sealed (so-called abandoned wells) [30]. Leaking wells can be resealed by pumping cement into them. One of the biggest challenges to CCS in the United States and Canada, where many millions of wells have been drilled, is to locate, evaluate, and seal them before beginning underground injection operations [31].

Extensive industrial experience with injection of CO_2 and gases in general indicates that risks from geologic storage facilities are manageable using standard engineering controls and procedures. Regulatory oversight and institutional controls further enhance the safety of these operations, and ensure that the site selection and monitoring strategy are robust. Employed on a scale comparable to existing industrial analogues, the risks associated with CCS are comparable to those of today's oil and gas operations. Eventually, if CCS were to be deployed on the grand scale needed to significantly reduce CO_2 emissions (billions of tonnes annually), the scale of operations would increase to become as large as or larger than existing oil and gas operations [32]. In this eventuality, experience gained in the early years of CCS would be critical for assessing and managing the risks of the very large scale geological storage projects.

VI. MONITORING AND VERIFICATION OF CO_2 STORAGE IN DEEP GEOLOCIAL FORMATIONS

While retention rates for well selected and managed sites are expected to be high, verifying that the CO_2 remains in the storage reservoir is important for assuring effective containment. A number of monitoring approaches are available, many of which were developed for applications in the oil and gas industry. Monitoring methods such as seismic imaging, the observation of sound waves propagating through the earth, have been used successfully to locate CO_2 injected at Sleipner, Weyburn, and several pilot projects [33]–[35]. Methods are also available to monitor the injection wells to ensure that injection rates and pressures stay within defined operating parameters [9]. Periodic inspection of the injection wells using "well logs," information collected by lowering electronic instruments into a well, can be used to check that the construction and condition of the well is satisfactory [9].

It is also possible to directly monitor the ground surface to detect if CO_2 is seeping back into the atmosphere. Eddy covariance and flux accumulation chamber methods developed to study cycling of CO_2 between the atmosphere and the biosphere are expected to have the sensitivity needed to detect even small amounts of see page [36].

Certainly more work is needed to test, enhance, and validate the performance of monitoring technologies available today. In addition, research and development is likely to discover more efficient and cost-effective approaches for monitoring and verifying the performance of geological storage projects. Nevertheless, even with today's technologies, prospects for reliable monitoring are good. Over time, as experience with CO_2 storage projects grows, standard protocols for monitoring and verification should be developed.

VII. COST OF CO_2 CAPTURE AND STORAGE

With today's technology, estimated additional costs for generating electricity from a coal-fired power plant with CCS range from \$20/tonne to \$70/tonne of CO_2 avoided [9], [37], [38]. These costs are mainly dependent on the capture technology and concentration of CO_2 in the stream from which it is captured [37]. This metric is useful for comparing the cost of CCS with other methods of reducing CO_2 emissions. Another metric is the increase in costs of electricity generation. Costs would increase by from \$0.01/kWh to \$0.05/kWh [9], with a typical cost of \$0.025/kWh, depending on the design of the power plant and a number of site specific factors, or the equivalent of about a 50% increase in the costs of base-load power generation from a newly constructed power plant.

Since consumers pay for generation plus other costs associated with the delivery and management of the electrical system, percentage increases to consumers associated with CCS would be somewhat less than this and would differ based on the cost of delivered electricity. (In 2004, the average consumer cost of electricity was \$0.0762/kWh, ranging from over \$0.10 in the northeastern United States and the West Coast to about \$0.06/kWh in the midcontinent. Over time, the cost of electricity production with CCS is expected to decrease due to a combination of improved capture technology, the experience gained from "learning by doing," and market forces.

Capture and compression typically account for over 75% of the costs of CCS, with the remaining costs attributed to transportation and underground storage. Pipeline transportation costs are highly site-specific, depending strongly on economy of scale and pipeline length.

In addition to the cost of CCS, the "energy penalty" for capture and compression must be considered. Postcombustion capture technologies use up to 30% of the total energy produced, thus significantly decreasing the overall efficiency of the power plant. Tight integration between the power generation and separation plant could lower these energy requirements, as could improvements in the performance of solvents [15]. Oxy-combustion has a similarly high energy penalty, although eventually new materials may lower the energy penalty by allowing for higher temperature and consequently more efficient combustion [9]. Precombustion technologies have the potential to lower energy penalties to 10%–15%, leading to higher overall efficiency and lower capture costs.

Public and privately sponsored research and development programs are aggressively trying to lower the costs of CO_2 capture. One industrial consortium, the CO_2 Capture Project, established a goal of reducing capture costs by 50% over today's baseline for retrofits and 75% for new-builds and several technologies show promise to meet that goal [15]. The U.S. Department of Energy has a cost goal of \$10/tonne CO_2. These extremely challenging targets are likely to be hard to meet without significant advances in separations technology, including membrane separators and new absorbents. Recent outreach efforts by the Department of Energy and the National Academy of Sciences are trying to engage academic researchers with new ideas in these areas. Clearly achieving these cost reduction goals would significantly increase the probability of CCS deployment.

The fact that electricity generation with CCS is more costly than without it suggests that sustained policy initiatives will be needed to stimulate deployment. For example, one of the roles of many public utility commissions is to support construction of new generating capacity that provides reliable services at the lowest possible cost. This objective is not consistent with deployment of CCS or construction of IGCC plants. To encourage deployment of IGCC, the federal government has developed a number of incentives to reduce the financial risk to developers, including loan guarantees, investment tax credits, and cost-shared research and development. In addition, some states are developing incentives for providing electricity with low-carbon generating facilities. At present, however, it is not clear whether these will applicable to fossil fuel fired power plants with CCS. Measures implemented to date are not expected to be sufficiently attractive for widespread deployment of IGCC and CCS. To accomplish this, the cost and risk gaps between modern pulverized coal plants and IGCC must be closed. One example would be to encourage building IGCC plants with subsidies that are similar to wind power (currently a production tax credit of \$0.019/kWh). Using the same level of incentives would put IGCC on equal footing with a conventional pulverized coal plant. For example, if a plant operated at a capacity factor (percentage of the year the facility is operating) of about 80% it would be competitive with a conventional plant and it would become the favored choice at a normal capacity factor of 88%. Additional measures would be needed to stimulate deployment of IGCC with CCS. Developing effective policy instruments now will avoid continued capital investment in fossil fuel fired power plants that cannot easily be adapted for use in a carbon-constrained world.

It is too early to pick technology winners in CCS. Investment in research and development is needed for postcombustion, precombustion, and oxy-combustion to drive technology improvements across the board. Each is likely to have a role to play if CCS is deployed on a large scale.

VIII. CONCLUSION

Over the past decade, carbon sequestration in the terrestrial biosphere and carbon dioxide capture and storage have emerged as important and necessary elements in the portfolio of energy technologies for a carbon-constrained world. Today, planting trees, managing forests to preserve carbon stocks, and changing the way that soils are cultivated can offset carbon emissions from industrial sources. That terrestrial sequestration can also help restore ecosystems, reduce risks from wildfires, and improve soil quality makes it all the more attractive. But it will not be enough. The limited capacity and finite lifetime of terrestrial carbon stocks will not be sufficient to offset enough anthropogenic CO_2 emissions. Options are needed for greater quantities and near-permanent capture and storage.

At first impression, CO_2 capture and storage in geological formations may appear to be a radical idea that would be difficult and perhaps risky to employ. Closer analysis however reveals that many of the component technologies are mature. A great deal of experience with gasification, CO_2 capture, and underground injection of gases and liquids provide the foundation for future CCS operations. No doubt, challenges lie ahead for CCS. The cost of capture, the large scale on which geological storage maybe employed, and adapting our energy infrastructure to accommodate CCS are significant hurdles to overcome. But for now, none of these seem to be insurmountable, and progress marches on through continued deployment of industrial-scale projects,research and development, and growing public awareness of this promising option for lowering CO_2 emissions. ■

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REFERENCES

[1] N. Nakicenovic *et al.*, *Special Report on Emissions Scenarios, Intergovernmental Governmental Panel on Climate Change*, Cambridge, U.K.: Cambridge Univ. Press, 2001.

[2] C. L. Sabine, R. A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. S. Wong, D. W. R. Wallace, B. Tilbrook, F. J. Millero, T.-H. Peng, A. Kozyr, T. Ono, and A. F. Rios, "The oceanic sink for anthropogenic CO_2," *Science*, vol. 305, pp. 367–371, Jul. 2004.

[3] C. D. Thomas, A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. Townsend Peterson, O. L. Phillips, and S. E. Williams, "Extinction risk from climate change," *Nature*, vol. 427, pp. 145–148, 2004.

[4] J. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. (2001). *Climate change 2001:*

The scientific basis. [Online]. Available: http://www.grida.no/climate/ipcc_tar/wg1/pdf/WG1_TAR-FRONT.PDF

[5] T. M. Wrigley, R. Richels, and J. A. Edmonds, "Economic and environmental choices for the stabilization of atmospheric CO_2 concentrations," *Nature*, vol. 379, pp. 240–243, 1996.

[6] *U.S. Geological Survey,* World Petroleum Assessment, 2000.

[7] S. R. Weart, *The History of Global Warming*. Cambridge, MA: Harvard Univ. Press, 2003.

[8] R. Sommerville, *The Forgiving Air*. Berkeley, CA: Univ. of California Press, 1996.

[9] B. Metz, O. Davidson, H. de Coninck, M. Loos, and L. Meyer, Eds., *Special Report on Carbon Dioxide Capture and Storage*, Cambridge, U.K.: Cambridge Univ. Press, 2006.

[10] S. M. Benson, *Carbon Dioxide Capture for Storage in Deep Geological Formations—Results From the CO_2 Capture Project*. Oxford, U.K.: Elsevier, 2005, vol. 2, *Geologic Storage of Carbon Dioxide With Monitoring and Verification*.

[11] IEA GHG, *A Review of Global Capacity Estimates for the Geological Storage of Carbon Dioxide, IEA Greenhouse Gas R&D Programme Technical Review (TR4)*, Mar. 23, 2004.

[12] T. A. Torp and J. Gale, "Demonstrating storage of CO_2 in geological reservoirs: The Sleipner and SACS projects," in *Proc. 6th Int. Conf. Greenhouse Gas Control Technologies (GHGT-6)*, vol. 1, J. Gale and Y. Kaya, Eds., 2002, pp. 311–316.

[13] F. A. Riddiford, A. Tourqui, C. D. Bishop, B. Taylor, and M. Smith, "A cleaner development: The In Salah gas project, Algeria," in *Proc. 6th Int. Conf. Greenhouse Gas Control Technologies (GHGT-6)*, vol. 1, J. Gale and Y. Kaya, Eds., 2002, pp. 601–606.

[14] R. Moberg, D. B. Stewart, and D. Stachniak, "The IEA Weyburn CO_2 monitoring and storage project," in *Proc. 6th Int. Conf. Greenhouse Gas Control Technologies (GHGT-6)*, J. Gale and Y. Kaya, Eds., 2002, pp. 219–224.

[15] D. C. Thomas and H. R. Kerr, "The CO_2 capture project introduction," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, D. C. Thomas, Ed. London, U.K.: Elsevier Science, 2005, vol. 1, *Capture and Separation of Carbon Dioxide From Combustion Sources*, pp. 1–15.

[16] P. Chiesa, S. Consonni, T. Kreutz, and R. Williams, "Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology. Part A: Performance and emissions," *Int. J. Hydrogen Energy*, vol. 30, no. 2005, pp. 747–767, 2005.

[17] G. Wotzak, N. Z. Shilling, G. Simons, and K. Yackly, "An evaluation of conversion of gas turbines to hydrogen fuel," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, D.C. Thomas, Ed. London, U.K.: Elsevier Science, 2005, vol. 1, *Capture and Separation of Carbon Dioxide From Combustion Sources*, pp. 427–440.

[18] P. Kauppi *et al.*, "Technological and economic potential of options to enhance, maintain and manage biological carbon reserves and geo-engineering," in *Climate Change 2001: Mitigation*, B. Metz, O. Davidson, R. Swart, and J. Pan, Eds. Cambridge, U.K.: Cambridge Univ. Press, 2001.

[19] K. O. Buesseler, J. E. Andrews, S. M. Pike, and M. A. Charette, "The effects of iron fertilization on carbon sequestration in the Southern Ocean," *Science*, vol. 304, pp. 414–417, 2004.

[20] G. Choi, R. Chu, B. Degen, H. Wen, P. L. Richen, and D. Chinn, "CO_2 removal from power plant flue gas—cost efficient design and integration study," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, D. C. Thomas, Ed. London, U.K.: Elsevier Science, 2005, vol. 1, *Capture and Separation of Carbon Dioxide From Combustion Sources*, pp. 99–116.

[21] I. Miracca, K. I. Aasen, T. Brownsecombe, K. Gerdes, and M. Simmonds, "Oxygen combustion for CO_2 capture technology," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, D. C. Thomas, Ed. London, U.K.: Elsevier Science, 2005, vol. 1, *Capture and Separation of Carbon Dioxide From Combustion Sources*, pp. 99–116.

[22] S. Holloway, Ed., "The underground disposal of carbon dioxide. Final report of JOULE II Project No. CT92-0031," British Geological Survey, Keyworth, U.K., 1996, p. 355.

[23] W. D. Gunter, S. Bachu, and S. Benson, "The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage for carbon dioxide," in *Geological Storage of Carbon Dioxide: Technology*, S. Baines and R. H. Worden, Eds. London, U.K.: Geological Society, 2004, Special Publication 233.

[24] R. Hepple and S. M. Benson, "Geologic storage of carbon dioxide as a climate change mitigation strategy: Performance requirements for surface see page," *Environ. Geol.*, vol. 47, pp. 576–585, 2005.

[25] P. M. Oen, "The development of the Greater Gorgon gasfields," *APPEA J. 2003*, vol. 43, no. 2, pp. 167–177.

[26] B. Martini and E. Silver, "The evolution and present state of tree-kills on Mammoth Mountain, California: Tracking volcanogenic CO_2 and its lethal effects," in *2002 AVIRIS Airborne Geoscience Workshop*, Pasadena, CA.

[27] K. F. Perry, "Natural gas storage industry experience and technology: Potential application to CO_2 geological storage," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, S. M. Benson, Ed. London, U.K.: Elsevier Science, 2005, vol. 2, *Geologic Storage of Carbon Dioxide With Monitoring and Verification*, pp. 815–826.

[28] J. Apps, "The regulatory climate governing the disposal of liquid wastes in deep geologic formations: A paradigm for regulations for the subsurface disposal of CO_2," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, S. M. Benson, Ed. London, U.K.: Elsevier Science, 2005, vol. 2, *Geologic Storage of Carbon Dioxide With Monitoring and Verification*, pp. 1163–1188.

[29] S. Bachu and K. Haug, "In-situ characteristics of acid-gas injection operations in the Alberta basin, western Canada: Demonstration of CO_2 geological storage," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, S. M. Benson, Ed. London, U.K.: Elsevier, 2005, vol. 2, *Geologic Storage of Carbon Dioxide With Monitoring and Verification*, pp. 867–876.

[30] S. M. Benson, "Lessons learned from industrial and natural analogs for health, safety and environmental risk assessment for geologic storage of carbon dioxide," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, S. M. Benson, Ed. London, U.K.: Elsevier, 2005, vol. 2, *Geologic Storage of Carbon Dioxide With Monitoring and Verification*, pp. 1133–1141.

[31] S. E. Gasda, S. Bachu, and M. A. Celia, "The potential for CO_2 leakage from storage sites in geological media: Analysis of well distribution in mature sedimentary basins," *Environ. Geol.*, vol. 46, no. 6–7, pp. 707–720, 2004.

[32] R. Burruss, "Geologic storage of carbon dioxide in the next 50 years: An energy resource perspective," presented at the Pew Center 10–50 Workshop, Washington, DC, 2004.

[33] R. A. Chadwick, R. Arts, and O. Eiken, "4D seismic quantification of a growing CO_2 plume at Sleipner, North Sea," in *6th Petroleum Geology Conf.—Petroleum Geology: North West Europe and Global Perspectives*, A. G. Dore and B. Vining, Eds., London, U.K. 2005, p. 15.

[34] S. D. Hovorka, S. M. Benson, C. Doughty, B. M. Freifeld, S. Sakuri, T. M. Daley, Y. K. Kharaka, M. H. Holtz, R. C. Trautz, H. S. Nance, L. R. Myer, and K. K. Knauss, "Measuring permanence of CO_2 storage in saline formations—The frio experiment," *Environ. Geosci. (special issue)*, 2005.

[35] D. White, Ed., "Theme 2: Prediction, monitoring and verification of CO_2 movements," in *Proc. 7th Int. Conf. Greenhouse Gas Control Technologies (GHGT-7)*, vol. 3, M. Wilson and M. Monea, Eds., 2005, IEAGHG Weyburn CO_2 Monitoring and Storage Project Summary Report 2000–2004, pp. 73–148.

[36] N. Miles, K. Davis, and J. Wyngaard, "Detecting leaks from CO_2 reservoirs using micrometeorological methods," in *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results From the CO_2 Capture Project*, S. M. Benson, Ed. London, U.K.: Elsevier Science, 2005, vol. 2, *Geologic Storage of Carbon Dioxide With Monitoring and Verification*, pp. 1031–1044.

[37] E. Rubin and A. Rao, "Uncertainties in CO_2 Capture Project, V. Capture and sequestration costs," in *Proc. Greenhouse Gas Control Technologies 6th Int. Conf. (GHGT-6)*, vol. 1, J. Gale and Y. Kaya, Eds., 2004, pp. 1119–1124.

[38] H. Herzog, "The economics of CO_2 capture," in *Proc. 4th Int. Conf. Greenhouse Gas Control Technologies*, B. Eliason, P. Reimer, and A. Wokaun, Eds., 1999, pp. 101–106.

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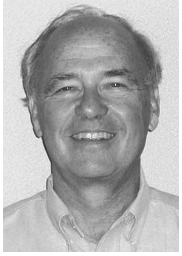

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