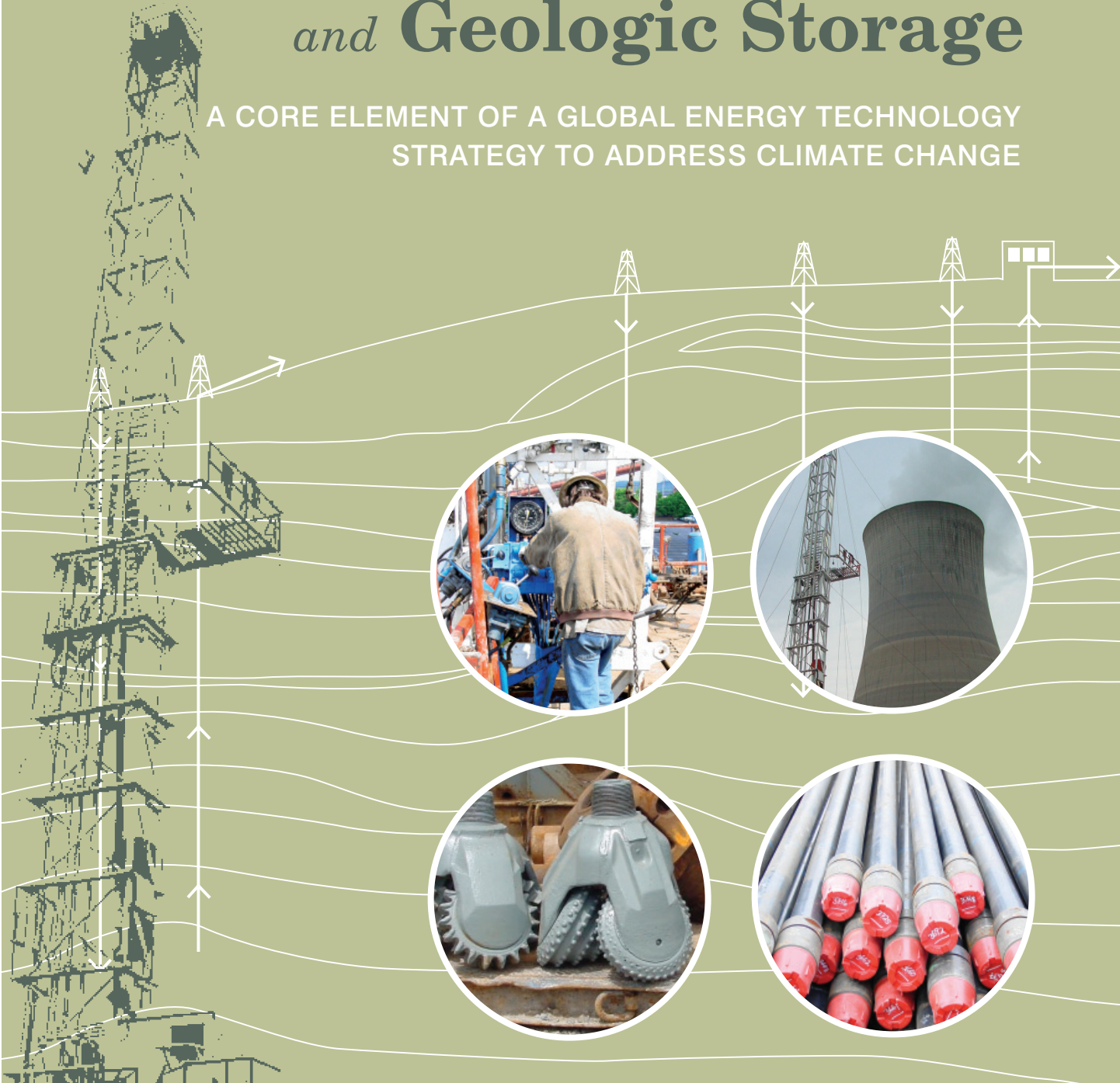


# Carbon Dioxide Capture *and* Geologic Storage

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY  
STRATEGY TO ADDRESS CLIMATE CHANGE



A TECHNOLOGY REPORT FROM THE SECOND PHASE OF  
THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM



Global Energy Technology  
Strategy Program

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THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

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## THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is a unique, global, public and private sector research collaboration, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Addressing Climate Change: Initial Findings from an International Public-Private Collaboration*, demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change.

A central conclusion was that a robust “technology strategy” required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to “solve” the climate

problem. That is, *a priori*, there is no technological “silver bullet.” Rather, the GTSP concluded that a variety of technologies and technology systems show promise for making substantially expanded contributions to the global energy system in a climate-constrained world. These include biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage.

The first phase of the GTSP produced ground-breaking research, including many results that have made their way into the frequently cited literature. The first phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology.

But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 is pushing the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy. GTSP Phase 2 is in the process of distilling important lessons gleaned from research on the potential roles of six carbon management technology systems in the context of a competitive future global energy system. These summaries of key research insights will take the form of “capstone reports” for each of the six technology areas. This is the first capstone report—on Carbon Dioxide Capture and Geologic Storage. In addition, a set of overall conclusions will be drawn from the complete body of the GTSP work and will be published in 2006.

For more information about the GTSP, please contact

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## TO THE READER

The findings presented in this report stem from more than ten years of research at Battelle’s Joint Global Change Research Institute (JGCRI) to better understand the significant potential of carbon dioxide capture and storage (CCS) technologies in addressing climate change. A central focus of this report is on actions that will allow CCS technologies to transition from their current status as *potential solutions* to climate change to the point where these systems are deployed widely and have become *safe, effective, and trusted cornerstones of the global energy system*.

CCS technologies are increasingly seen as critically important elements of a global portfolio of advanced energy technologies needed to address climate change. One sign of the significant interest in CCS technologies is the recent publication of the Intergovernmental Panel on Climate Change’s *Special Report on Carbon Dioxide Capture and Storage* (2005). While acknowledging the significant contributions being made by many other research groups, national governments, state agencies, and private firms who are pushing forward the development and early commercial deployment of CCS technologies, this document is meant to summarize research performed under the Global Energy Technology Strategy Program (GTSP), and therefore principally focuses on CCS research carried out at Battelle and JGCRI during the first and second phases of the GTSP.

Overall, this document fulfills the GTSP objective of articulating the cost and environmental performance targets for CCS, as well as the institutional means that will enable its commercial deployment in a greenhouse-gas-constrained world. The report establishes that CCS technologies can make a significant contribution to reducing greenhouse gas emissions. The report also describes the cost, performance and other key characteristics of the component technologies comprising a complete CCS system. Included in this is an examination of deep underground geologic sites and the permanence

**A Note on Terms:** CCS technologies, as used here, do not include planting trees, increasing soil carbon, or other bio-based activities. These activities are more commonly referred to as “carbon sequestration.” This report will not use the term “sequestration” in order to avoid any possible confusion.

## GTSP Phase II— Program Objective

**To articulate the cost and environmental performance targets for technologies and technology systems in a greenhouse-gas-constrained world, and the institutional means of implementation.**

of injected carbon dioxide storage. Market and economic cost analyses are presented to elucidate the potential deployment of CCS technologies. Finally, the report explores how the world—especially industries, such as electricity generators—would make decisions about using CCS under a policy that places a value on carbon dioxide emissions.

Our CCS research has been supported by numerous firms, nongovernmental organizations, and government agencies. We are grateful for their support, which has enabled us to pursue this important work. However, JGCRI, GTSP and James J. Dooley, who leads JGCRI and GTSP’s research related to CCS technologies, along with the other authors are solely responsible for the content of this report. Also, we would like to acknowledge and thank the many peer reviewers who freely gave their time to comment on earlier drafts of this document. Their thoughtful review helped to significantly improve this document.

For more information about the GTSP’s program on CCS, please contact

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# EXECUTIVE SUMMARY The Role of Carbon Dioxide Capture and Storage Technologies in Mitigating Climate Change

## THE CHALLENGE OF CLIMATE CHANGE AND THE TECHNOLOGY PORTFOLIO RESPONSE

Addressing climate change is a large-scale, global challenge to reduce and avoid the release of enormous amounts of greenhouse gases (GHGs) over the course of this century. Currently, the world's economies annually emit approximately 26 gigatons of carbon dioxide (GtCO<sub>2</sub>) to the atmosphere from the combustion of fossil fuels. In the absence of explicit efforts to address climate change, rising global populations, higher standards of living, and increased demand for energy could result in as much as 9,000 gigatons of cumulative CO<sub>2</sub> being emitted to the atmosphere from fossil fuel combustion over this coming century.

However, to stabilize CO<sub>2</sub> concentrations in the atmosphere “at a level that would prevent dangerous anthropogenic interference with the climate system” as called for in the United Nations Framework Convention on Climate Change, the cumulative amount of CO<sub>2</sub> released to the atmosphere over this century would need to be held to no more than 2,600 to 4,600 GtCO<sub>2</sub>—a substantial reduction and formidable challenge.

The Global Energy Technology Strategy Program (GTSP) has shown conclusively the value of developing an enhanced portfolio of energy technologies in meeting this challenge. Some aspects of this portfolio will involve continued energy efficiency improvements in homes, offices, and automobiles, as these technologies not only reduce CO<sub>2</sub> emissions but also help to improve economic efficiency, competitiveness, and local environmental quality. Renewable energy, advanced bioenergy and biotechnologies, advanced transportation including hydrogen production and fuel cell technologies, and nuclear power have also been shown to be key aspects of the broad portfolio of energy technologies needed to address climate change. GTSP research has demonstrated that all aspects of this portfolio need to be capable of delivering significant and sustained reductions in CO<sub>2</sub> emissions over the course of this century.

Carbon dioxide capture and storage (CCS) technologies, which are the focus of this report, have the potential to be central elements of this advanced energy technology portfolio. CCS technologies are capable of deploying widely across the globe in many different economic sectors and in many different locales. These technologies are capable of delivering deep, cost-effective, and sustained emissions reductions. This report seeks to conclusively demonstrate the technical feasibility and potential economic value of CCS in this broader portfolio of advanced energy and carbon management technologies.

## POTENTIAL TO DELIVER BENEFITS TODAY, TOMORROW, AND WELL INTO THE FUTURE

CCS systems offer several unique benefits as part of a climate change mitigation portfolio:

- In the near term, CCS systems help the owners, operators and beneficiaries of established, economic production methods—which lie at the heart of the modern industrial economy—to find a financially viable pathway forward into a world in which there are significant constraints on CO<sub>2</sub> emissions. CCS may be pivotal in helping reduce the emissions from fossil fuel-fired electricity generation, steel and cement manufacturing, refining, and chemicals production. Without CCS technologies, many of these firms may see efforts to address climate change as threats to their businesses. The potential cost savings from using CCS systems opens the dialog with these industries about how best to address climate change in the future.
- In the medium term, the implementation of CCS technologies allows for a smoother transition of the global economy to a low-GHG emissions future. Established production methods and existing infrastructure can continue to be utilized, and the costs of transitioning to a lower-emitting energy system can be minimized.

- In the long term, CCS will help make valuable commodities like electricity and hydrogen cheaper than they would otherwise be. This is the key merit; CCS technologies are not ends in themselves but a means—a means of realizing abundant energy and industrial production, without CO<sub>2</sub> emissions.

## CURRENT MARKET DEPLOYMENT

Many component technologies for CCS systems already exist, including CO<sub>2</sub> capture, transportation via pipeline, and injection into geologic formations deep underground. However, both the scale of existing CCS systems and the number of CCS commercial and field demonstration projects are very small compared to the scale necessary for significant and sustained CO<sub>2</sub> emissions reductions. The very newness of CCS systems and a lack of real-world operational experience in essential markets such as electric power generation are current impediments to the expanded adoption of CCS technologies.

Globally, there are currently more than 8,100 large CO<sub>2</sub> point sources (accounting for more than 60% of all anthropogenic CO<sub>2</sub> emissions) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO<sub>2</sub> emissions reductions. These 8,100 large CO<sub>2</sub> point sources are predominantly fossil-fueled electric power plants, but there are also hundreds of steel mills, cement kilns, chemical plants, and oil and gas production and refining facilities. A very small number of these facilities are already capturing and selling CO<sub>2</sub>, suggesting that in certain niche applications it is already profitable to deploy some CCS component technologies. However, the vast majority of these existing facilities have not adopted CCS systems. Moreover, the vast majority of the new power plants and other large industrial CO<sub>2</sub> point sources that are now being built or that are in various stages of early development are also not planning to adopt CCS systems. This reveals an important point; the deployment of CCS technologies is almost exclusively motivated by the need to significantly reduce greenhouse gas emissions, and, therefore, their large-scale adoption depends upon explicit efforts to control such emissions.

## CO<sub>2</sub> STORAGE CAPACITY

Our research and that of many other research groups demonstrate that potential deep geologic CO<sub>2</sub> storage sites exist around the world, although the distribution of these candidate storage sites is quite uneven (as is true for many other types of natural resources). Our preliminary estimate of the potential global deep geologic CO<sub>2</sub> storage capacity is nearly 11,000 GtCO<sub>2</sub>. Assuming that other advanced energy technologies are developed and deployed along with CCS systems, this potential capacity should be more than enough to address global CO<sub>2</sub> storage needs for at least this century. In many places, candidate CO<sub>2</sub> storage formations are near large groupings of power plants and other industrial facilities, which should lower the cost of deploying CCS systems.

## COST AND ECONOMIC VALUE

For most applications, assuming the adoption of currently available CCS component technologies, the cost of employing CCS systems most likely lies below \$50/tCO<sub>2</sub> including capture, transport, injection, storage and monitoring. At this cost level, CCS systems are capable of reducing the costs of climate stabilization by trillions of dollars because these technologies allow for the continued use of fossil fuels and enable the deployment of other key mitigation technologies such as large-scale, low-emissions hydrogen and synfuels production. GTSP research also confirms that the costs of CCS systems should be competitive with—and in some cases significantly less costly than—other potential large-scale CO<sub>2</sub> emissions reduction and abatement technologies.

## SAFETY AND ENVIRONMENTAL EFFICACY

At a properly designed and well-managed CCS facility, the chance of appreciable CO<sub>2</sub> leakage from the deep geologic storage formation is very small. The principal task for the measurement, monitoring, and verification of stored CO<sub>2</sub> centers on how to demonstrate the long-term retention of stored CO<sub>2</sub> to regulators and the public. New and improved measurement and monitoring techniques and standards for their use need to be developed to provide proof of public and environmental safety and of each CCS project's effectiveness in mitigating climate change.

## ADOPTION AND DEPLOYMENT WITHIN THE ELECTRIC POWER INDUSTRY

Early adopters of CCS systems will likely lie outside the electric utility industry and will seek opportunities that move beyond today's niche markets in CO<sub>2</sub>-driven enhanced oil recovery. However, if there were an explicit climate policy in place that called for substantial and sustained emissions reductions, the electric power industry would likely become the largest market for CCS systems. GTSP research has shown that CCS systems will be most economic when deployed with large baseload power plants. These plants operate around the clock with only occasional brief outages for routine maintenance. For these facilities, a key criterion for locating suitable storage reservoirs is that those reservoirs have sufficient capacity to hold perhaps more than 50 years' worth of the facility's CO<sub>2</sub> plus some margin for growth. Because of this need for large quantities of reliable CO<sub>2</sub> storage, decade after decade, CCS-enabled electric power plants will most likely look to deep saline formations, which tend to offer large storage capacities.

## THE VALUE OF CONTINUED R&D

The next five to ten years constitute a critical window in which to amass needed operational experience with CCS technologies in real-world conditions. Planned CCS field demonstrations, a handful of early commercial CCS projects, and continued laboratory-based research are all needed to advance the state of the art across a number of CCS-related areas, so that CCS technologies can deploy safely and effectively in as many locales and configurations as needed to meet the challenge of stabilizing atmospheric CO<sub>2</sub> concentrations. Important areas of research identified by GTSP include the following:

- Continually improve CO<sub>2</sub> capture technologies and ensure that they are being developed and tuned to a wide array of industrial sectors that can potentially benefit by adopting CCS systems.
- Survey global candidate CO<sub>2</sub> reservoirs so that we can better understand the nature and distribution of the world's deep geologic CO<sub>2</sub> storage reservoirs. This is particularly crucial in rapidly developing countries such as China and India. Helping developing nations site new long-lived electricity generation or other

large CO<sub>2</sub>-emitting industrial facilities while giving forethought to potential deployment of CCS will allow them to avoid stranding those assets should there be a need to adopt CCS systems at those facilities at some point in the future.

- Develop a broader and more advanced set of measurement, monitoring, and verification (MMV) technologies for stored CO<sub>2</sub> than currently exists in order to meet the needs of a potential future large-scale deployment of CCS systems with CO<sub>2</sub> being stored in many different kinds of formations and circumstances. New MMV technologies need to be invented and the cost, performance, and other operating characteristics of existing MMV technologies need to be improved.
- Obtain more experience with end-to-end CCS systems in real-world conditions and make specific efforts to utilize the opportunity presented by these early commercial and research demonstration CCS facilities to increase our understanding of the behavior of CO<sub>2</sub> in the subsurface, develop a base of empirical data to facilitate the development of MMV systems and their regulation, train and educate a larger cadre of individuals who are capable of running commercial-scale CCS systems, garner public support for CCS deployment, and otherwise lay the foundation for the larger scale deployment to come.

## THE EFFORT REQUIRED FOR LARGE-SCALE COMMERCIAL DEPLOYMENT

Fulfilling the potential that the large-scale use of CCS technologies could hold will take significant effort. Despite recent technical successes and growing budgets for the development and critical field demonstration of CCS technologies, much hard work remains to transition them—perhaps quickly—from their current status as potential solutions to climate change to safe, effective, and trusted cornerstones of the global energy system. If the world can do this, then our research suggests that CCS systems hold promise to be an economic, cost-effective means for facilitating the stabilization of greenhouse gases in the atmosphere as part of a portfolio of technologies to address climate change.

# 1

# What

## is Carbon Dioxide Capture and Storage?

A complete end-to-end CCS system is a dedicated assemblage of various technologies and components—many of which are already used in other settings—working together to prevent CO<sub>2</sub> from entering the atmosphere. This section opens with an overview of the technologies that would comprise a fully functional CCS system, along with an assessment of the current state of the art for each of them.

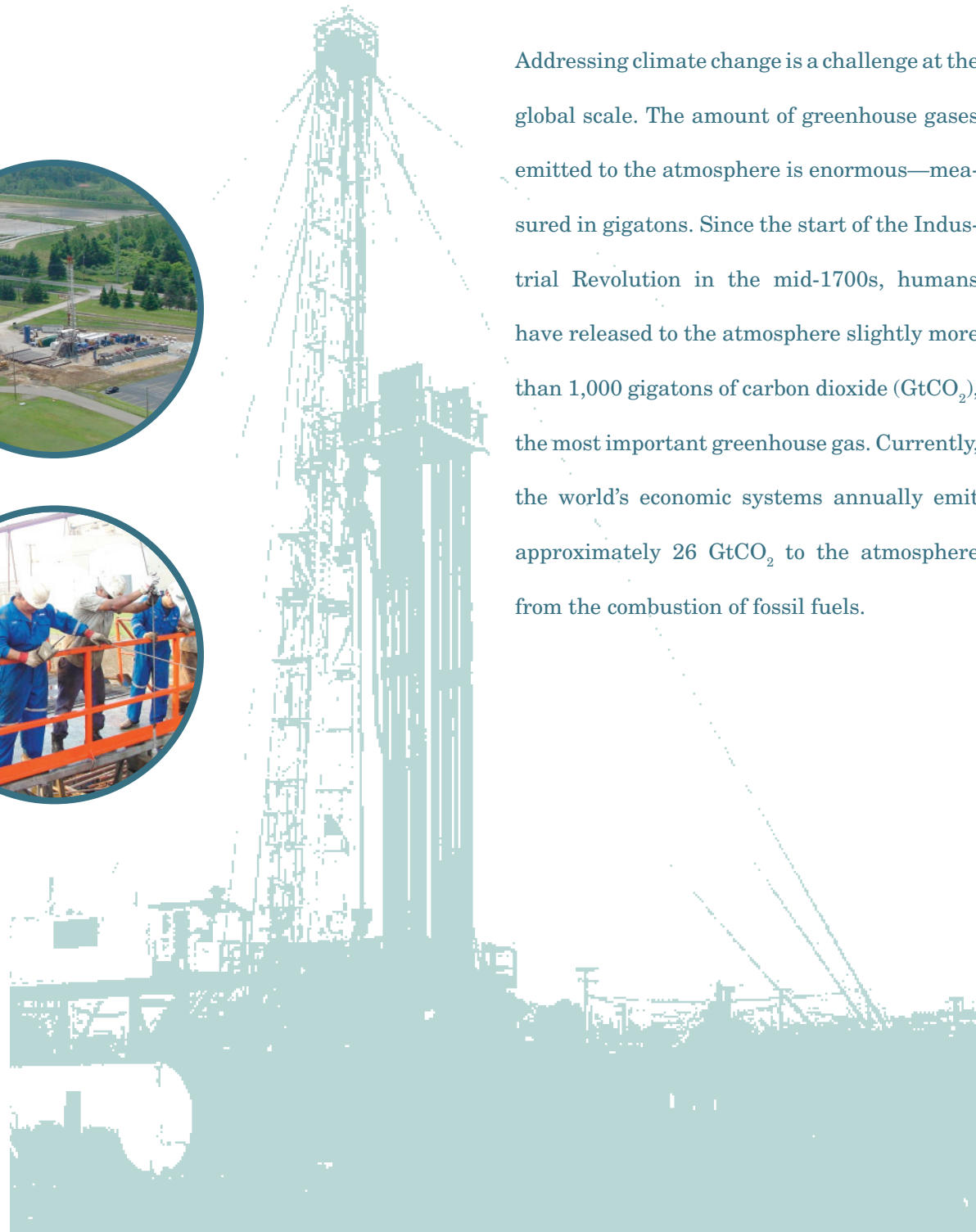
A principal focus of this section is to describe candidate CO<sub>2</sub> storage reservoirs and the process by which CO<sub>2</sub> is injected and stored in these formations. These candidate reservoirs are located thousands of feet below the surface.

Their depth and the confining layers of dense rock (often called caprocks) that lie above them serve to isolate the candidate CO<sub>2</sub> storage reservoirs and provide the principal means of trapping the injected CO<sub>2</sub> in the deep subsurface over the long term.

This chapter also discusses the issue of verifying permanence; that is, how will operators of future CCS facilities demonstrate that the CO<sub>2</sub> that they have injected into the deep subsurface is staying in the target injection zones? Further information about technical terms and concepts introduced in this section can be found in the appendices.

## THE CHALLENGE—CLIMATE CHANGE, TECHNOLOGY, AND CARBON DIOXIDE CAPTURE AND STORAGE

Addressing climate change is a challenge at the global scale. The amount of greenhouse gases emitted to the atmosphere is enormous—measured in gigatons. Since the start of the Industrial Revolution in the mid-1700s, humans have released to the atmosphere slightly more than 1,000 gigatons of carbon dioxide (GtCO<sub>2</sub>), the most important greenhouse gas. Currently, the world's economic systems annually emit approximately 26 GtCO<sub>2</sub> to the atmosphere from the combustion of fossil fuels.



Assuming continued economic, population and technological growth, including the continued development and deployment of cleaner and more efficient energy technologies, global CO<sub>2</sub> emissions could rise to as much as 5 times their current level by the year 2050 and then double from that level by 2100. Thus, in the absence of explicit efforts to address climate change, total cumulative emissions from fossil fuel combustion over this coming century could reach as high as 9,000 GtCO<sub>2</sub>.

However, to stabilize CO<sub>2</sub> concentrations in the atmosphere “at a level that would prevent dangerous anthropogenic interference with the climate system” (consistent with the overarching goal of the United Nations Framework Convention on Climate Change, which has been ratified by 189 nations) would necessitate that global CO<sub>2</sub> emissions over the course of this century total no more than 2,600 to 4,600 GtCO<sub>2</sub>. The need to avoid the release of thousands of gigatons of CO<sub>2</sub> to the atmosphere over the coming century implies a significant change in the way that energy is produced and consumed around the globe.

There is a broad consensus in the technical literature that the key to making this large-scale transition in the energy economy will be the development and deployment of a broad portfolio of advanced energy technologies. Part of this portfolio will involve continued improvements in energy efficiency in homes, offices, and automobiles, as these technologies not only reduce CO<sub>2</sub> emissions but also help to improve economic efficiency, competitiveness, and local environmental quality. Renewable energy, advanced bioenergy and biotechnologies, advanced transportation including hydrogen production and fuel cells, and nuclear power have also been shown to be core aspects of this broad global portfolio of energy technologies.

To have a meaningful impact on climate change, each core element of this portfolio must be capable of deploying at a scale that matters. One way to think about whether a given advanced energy technology can meet this criteria is to ask whether commercial deployment of the technology has the potential to cost-effectively reduce greenhouse gas emissions by *a gigaton or more per year*.

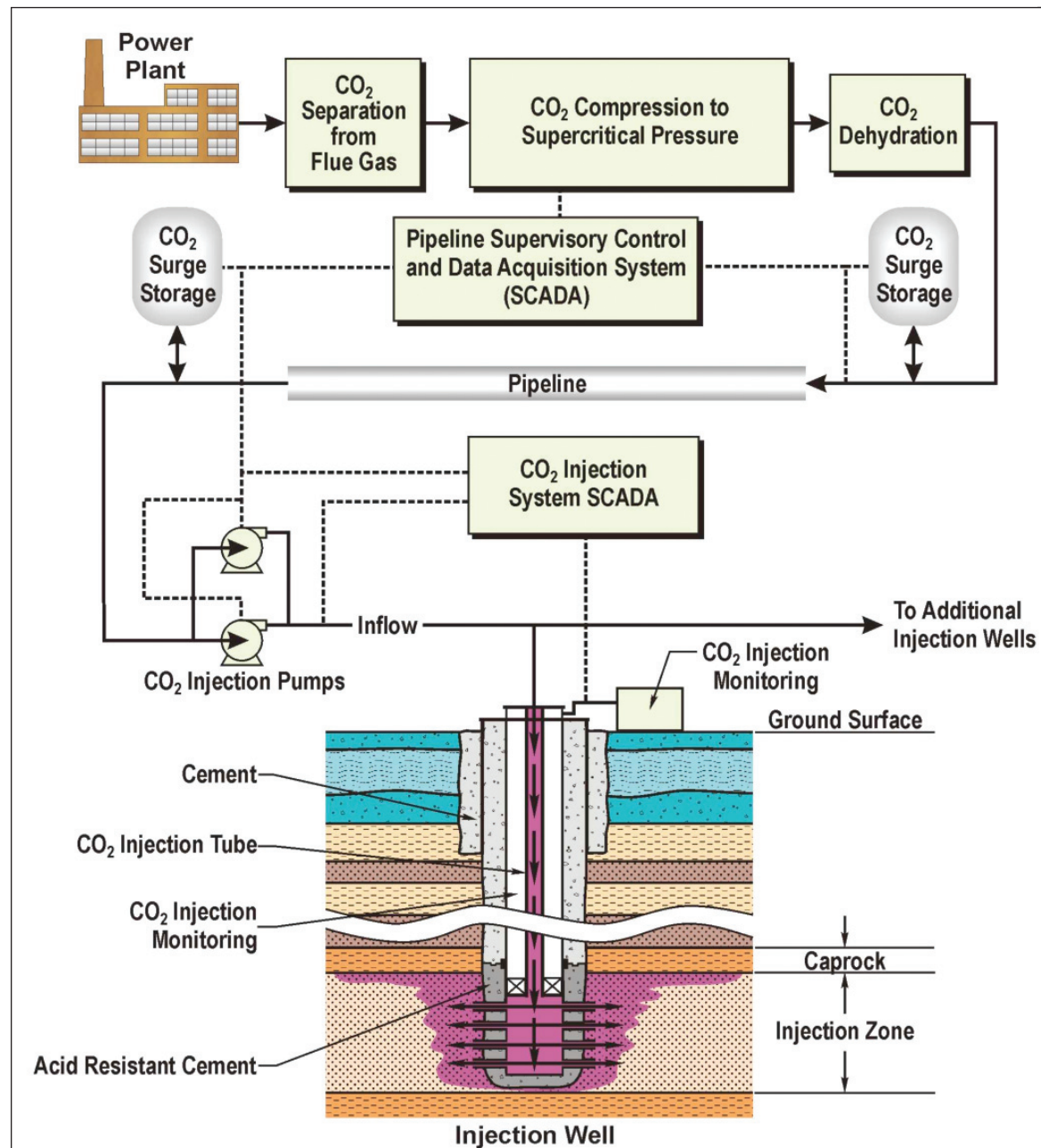
**The need to avoid the release of thousands of gigatons of CO<sub>2</sub> to the atmosphere over the coming century implies a significant change in the way that energy is produced and consumed around the globe.**

Carbon dioxide capture and storage (CCS) represents another candidate component of this larger portfolio of advanced energy technologies and climate policies needed to bring about the stabilization of atmospheric CO<sub>2</sub> concentrations. CCS systems are specifically designed to remove CO<sub>2</sub> from the flue gases and various process streams of large power plants and industrial facilities and safely deposit the CO<sub>2</sub> in secure storage sites deep underground—thus keeping it out of the atmosphere. At present, there are more than 8,100 large CO<sub>2</sub> point sources on Earth comprising primarily large fossil-fired power plants and other large industrial facilities. These facilities collectively emit approximately 15 GtCO<sub>2</sub> annually. Many of these power plants and industrial facilities are believed to be near suitable candidate CO<sub>2</sub> storage reservoirs.

CCS technologies, the focus of this report, have the potential to prevent many hundreds to thousands of gigatons of CO<sub>2</sub> from reaching the atmosphere over the course of this century and thus they clearly pass this “gigaton or more per year” test.



## CCS COMPONENTS AND THE STATE OF THE ART



### The Whole System

Global experience with complete end-to-end CCS systems is at present quite limited. When compared to the kinds of CCS systems needed to deliver significant CO<sub>2</sub> reductions—a gigaton or more per year—the CCS systems that exist today are very small, and many of the individual system components can be viewed as first-generation technologies. In particular, a strong focus on CO<sub>2</sub> capture and MMV will help bring about successive generations of more effective, economical and reliable technologies. But even when component technologies work well, they need to work well within an integrated CCS system—and at a scale far larger than any of the systems in operation today. The challenge of moving from today's limited experiential knowledge base to the massive CCS systems that would be needed to contribute to climate mitigation is the focus of this report.

### CO<sub>2</sub> Capture

For some CO<sub>2</sub> emissions mitigation applications, first-generation CO<sub>2</sub> capture systems already exist and can be purchased from commercial vendors. There are even a few operational coal- and natural gas-fired power plants that apply CO<sub>2</sub> capture systems to a small portion of the plants' emissions to serve niche industrial CO<sub>2</sub> markets, and there are natural gas processing plants that routinely capture and separate CO<sub>2</sub> and sell it for various industrial uses.

But the cost, performance, and other operating characteristics of these first-generation CO<sub>2</sub> capture systems need to be improved in order to enable CCS systems to deploy to their full market potential. The scale of today's CO<sub>2</sub> capture systems is also considerably smaller than the scale needed to address climate change concerns. CO<sub>2</sub> capture is and will likely remain an area of intense CCS research.

### Ancillary Systems

CO<sub>2</sub> compressors, booster pumps, surge tanks, and other equipment are all off-the-shelf technologies that can be considered routine aspects of future commercial CCS operations.

### CO<sub>2</sub> Transport

Transporting CO<sub>2</sub> is an established practice. Currently, more than 3,000 miles of dedicated CO<sub>2</sub> pipeline exist in the United States alone. Modern control technologies help to ensure pipeline integrity and safety—a pipeline section that is damaged can be quickly shut down, limiting the loss of CO<sub>2</sub>. The principal issue for CO<sub>2</sub> transport is not research and development but rather potential obstacles in the siting and placement of potentially large CO<sub>2</sub> pipeline networks that would likely be needed as CCS systems begin to deploy at a significant scale.

### CO<sub>2</sub> Injection into Deep Geologic Formations

The most likely CO<sub>2</sub> storage sites are deep geologic formations. The technologies to inject CO<sub>2</sub> into these formations exist today and are routinely used in the oil and gas industries. In this sense, CO<sub>2</sub> injection can be considered an established technology, although ways to optimize injection, such as using lateral wells and injecting into multiple vertically stacked reservoirs, still need to be better understood. The continued development and field demonstration of these more advanced drilling and CO<sub>2</sub> injection techniques could facilitate the use of CCS in a much broader range of locales, a necessary step if CCS technologies are to deploy on a large scale.

### Measurement, Monitoring, and Verification (MMV)

MMV technologies, crucial elements of a complete CCS system, are not as easily described as "established technologies." Some off-the-shelf MMV technologies can be applied to ensure safe and effective storage of injected CO<sub>2</sub> in certain classes of formations and under specific circumstances (e.g., seismic imaging of CO<sub>2</sub> that has been injected into a deep saline formation or a depleted oil field). But that alone is not sufficient to meet the MMV needs of a future large-scale deployment of CCS in many varied locales and circumstances. MMV is, and will continue to be, an active area of intense research; new MMV technologies need to be developed and the cost, performance, and other operating characteristics of existing MMV technologies need to be improved. In addition to this laboratory and field research effort to create new and better MMV technologies, prospective industrial users and regulators also need to create a shared vision of what it means in practice to measure, monitor, and verify CO<sub>2</sub> that has been injected into the deep subsurface.

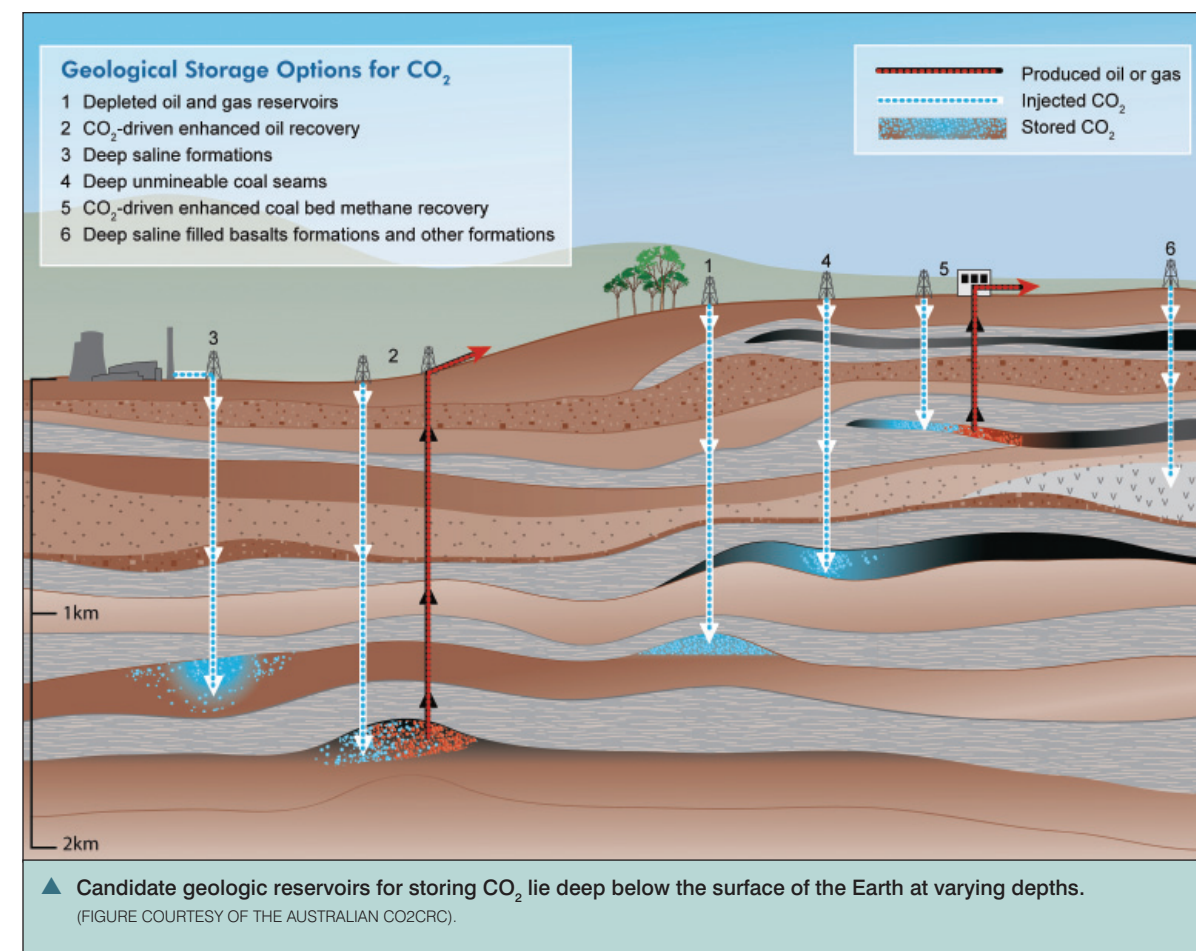
## GOING DEEPER: CANDIDATE GEOLOGIC CO<sub>2</sub> STORAGE FORMATIONS

The deep geologic formations identified as candidates for long-term CO<sub>2</sub> storage were deposited tens to hundreds of millions of years ago. Similar deep geologic formations have been used for oil and gas production and for fluid storage for more than a century. But only recently have researchers understood the potential value of these formations as tools in addressing climate change.

Like nearly all other natural resources, CO<sub>2</sub> storage reservoirs are highly heterogeneous in quantity, quality, and distribution (see the maps on pages 25 and 26). The figure below and table on the next page describe some the key characteristics of those classes of geologic formations that are being examined as candidates for long-term CO<sub>2</sub> storage.

In most cases, CO<sub>2</sub> is injected as a supercritical fluid, which means that it is dense like a liquid, but has a gas-like viscosity that allows it to flow very easily through pipelines and into the target storage formation. Maintaining the CO<sub>2</sub> as a supercritical fluid in the storage formation typically can be accomplished in reservoirs that are at depths greater than 800 meters (0.5 miles) below the surface of the Earth.

Candidate CO<sub>2</sub> storage reservoirs are separated from the surface and from sources of fresh water by thousands of feet of layered rock. Some layers are very permeable and porous, allowing the CO<sub>2</sub> to be injected and stored in the empty spaces between grains in the rock. Other layers are denser, effectively isolating the CO<sub>2</sub> storage reservoirs from the shallower groundwater reservoirs. These intervening dense rock layers (often called caprocks) provide the principal means of trapping the CO<sub>2</sub> in the deep subsurface over the long term.



## PRINCIPAL CANDIDATE GEOLOGIC CO<sub>2</sub> STORAGE RESERVOIRS

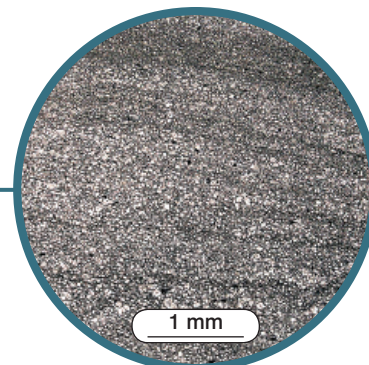
(see appendix for sources and assumptions)

Type of Reservoir	General Characteristics	Principal Trapping Mechanism	Theoretical Global Capacity (GtCO <sub>2</sub> )	Theoretical U.S. Capacity (GtCO <sub>2</sub> )
<b>Deep Saline Formations</b>	Sandstone and carbonate (limestone or dolomite) rocks with void spaces inhabited by salty water. Injection of waste fluids into deep saline formations (DSFs) is a common practice in many parts of the world.	Hydrodynamic, dissolution, mineralization	9,500	3,630
<b>Depleted Natural Gas Reservoirs</b>	Once the formation has been stripped of its natural gas, it essentially behaves like a DSF in terms of CO <sub>2</sub> storage. Depleted natural gas formations are often used for natural gas storage.	Hydrodynamic, dissolution, mineralization	700	35
<b>Depleted Oil Reservoirs</b>	Once the recoverable oil has been produced from the formation, CO <sub>2</sub> may be stored in the available pore space. CO <sub>2</sub> injection can also be used to recover additional oil that was left behind during primary production. Oil producers have 30+ years of experience using CO <sub>2</sub> -driven enhanced oil recovery (EOR) in areas of North America, but there has been little focus on demonstrating the retention of CO <sub>2</sub> or the use of these depleted oil fields as a long-term means of isolating CO <sub>2</sub> from the atmosphere.	Hydrodynamic, dissolution, mineralization	120	12
<b>Deep Unmineable Coal Seams</b>	Methane is found on the surfaces of coal. However, those surfaces have a chemical preference for CO <sub>2</sub> , which when injected induces the coal to release its methane while adsorbing the injected CO <sub>2</sub> instead. At present, CO <sub>2</sub> -driven enhanced coalbed methane recovery (ECBM) with simultaneous CO <sub>2</sub> storage is an emerging technology.	Primarily chemical adsorption	140	30
<b>Deep Saline-Filled Basalt Formations</b>	Permeable, porous "interflow" zones provide storage capacity while impermeable "massive" zones separate interflows and keep CO <sub>2</sub> from migrating out of the storage zones. Although these formations are similar to DSFs, basalts are rich in iron and other elements that allow for the inclusion and permanent storage of CO <sub>2</sub> in carbonate minerals, so the mineralization potential in these formations tends to be much higher.	Hydrodynamic, dissolution, mineralization	Unknown	240
<b>Other (Salt Caverns, Organic Shales, etc.)</b>	Salt caverns, organic shales, methane hydrate-bearing formations and other geologic media may provide novel niche CO <sub>2</sub> storage options.	Various	Unknown	Unknown

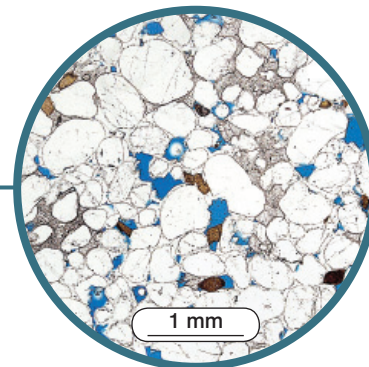
## WHAT DOES A CO<sub>2</sub> STORAGE RESERVOIR LOOK LIKE?

A key mechanism for storing CO<sub>2</sub> in deep geologic formations and ensuring that it stays there is a system of layered, deeply buried, permeable rock formations that serve as the CO<sub>2</sub> storage reservoir, overlain by impermeable caprocks which serve to keep the injected CO<sub>2</sub> in place. A thorough evaluation of these formations and their ability to accept and retain injected CO<sub>2</sub> must be an essential component of site assessment before any CO<sub>2</sub> is injected. Here we take a closer look at these formations.

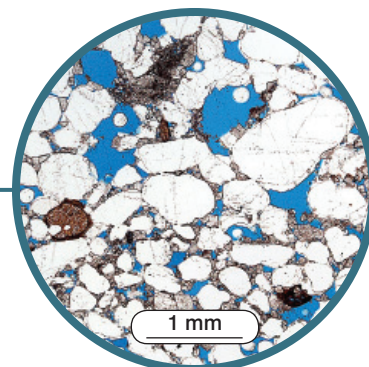
**Microscopic view of a caprock.** The grains making up this rock are densely packed with few interconnected pore spaces. The low permeability of these rocks makes them ideal barriers to prevent the migration of CO<sub>2</sub> out of the target storage formation. Examples include shale and dense carbonates.



**Microscopic view of a medium-grained sandstone that would serve as a good CO<sub>2</sub> storage reservoir.** The individual grains making up this rock are much less tightly packed than in the caprock. The blue areas are voids in the rock that are filled with water that is not suitable for drinking or irrigation because of high concentrations of salt and other minerals. Injected CO<sub>2</sub> would move into and reside in these void spaces, over time dissolving in the formation water and reacting with the water and surrounding rocks to form stable compounds called carbonates.



**Microscopic view of a coarse-grained sandstone that would serve as an excellent CO<sub>2</sub> storage reservoir.** Note that here the individual grains making up this rock are even less tightly packed than in the previous sample. This looser packing means that all of the voids are well connected to each other, allowing the injected CO<sub>2</sub> to more easily move through the host formation. Thus, more CO<sub>2</sub> can be injected and at a higher rate than in a formation composed of a medium-grained sandstone.



## CO<sub>2</sub> INJECTION INTO A DEEP GEOLOGIC STORAGE FORMATION

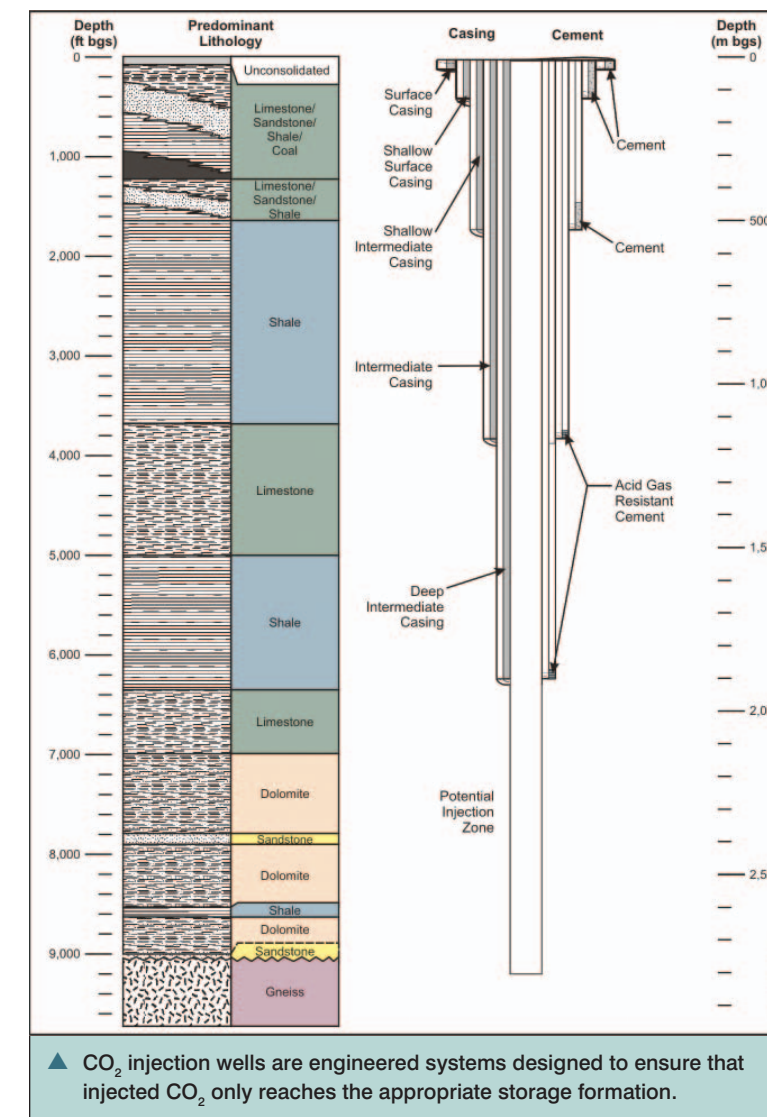
As can be seen from the schematic below, CO<sub>2</sub> injection constitutes a highly engineered system. A CO<sub>2</sub> injection well is actually composed of several casings that help to ensure that the CO<sub>2</sub> only enters the intended injection zone or zones (in this graphic, the yellow bands at left are candidate injection zones) and does not interfere with sources of drinking water, which are much shallower than candidate CO<sub>2</sub> storage formations.

Many of the technologies needed to safely inject CO<sub>2</sub> into these deep geologic formations exist today and are

drawn from technologies, techniques and industrial best practices that are routinely used in the oil and natural gas production industries. While CO<sub>2</sub> injection can be considered an established technology, the large-scale deployment of CCS systems as a central component of a global climate change mitigation response is potentially so large that it requires the continued development and field demonstration of more advanced drilling and CO<sub>2</sub> injection techniques, to allow for the greatest possible utilization of available CO<sub>2</sub> storage capacity, and to allow a wider range of CO<sub>2</sub> storage reservoirs to be pressed into service if needed.

The schematic also shows clearly that the CO<sub>2</sub> injection well traverses many thousands of feet of various geologic strata before reaching the target CO<sub>2</sub> storage formations, the yellow bands in the figure. The rocks

that make up these formations are ancient and deeply buried. For example, the Cambrian-age sandstone (the lowermost yellow band)—a potential CO<sub>2</sub> storage reservoir nearly two miles below the surface—was deposited about 500 million years ago as life on our planet was transitioning from single-celled organisms to a more diverse set of biota. The sandy beach that eventually became part of the Ordovician sandstone (the second-lowest yellow band) predated the emergence of terrestrial plants by at least ten million years. Over hundreds of millions of years these loose, sandy beaches have been compacted under enough younger sediment to turn them into consolidated rock formations capable of storing CO<sub>2</sub> over the long term.

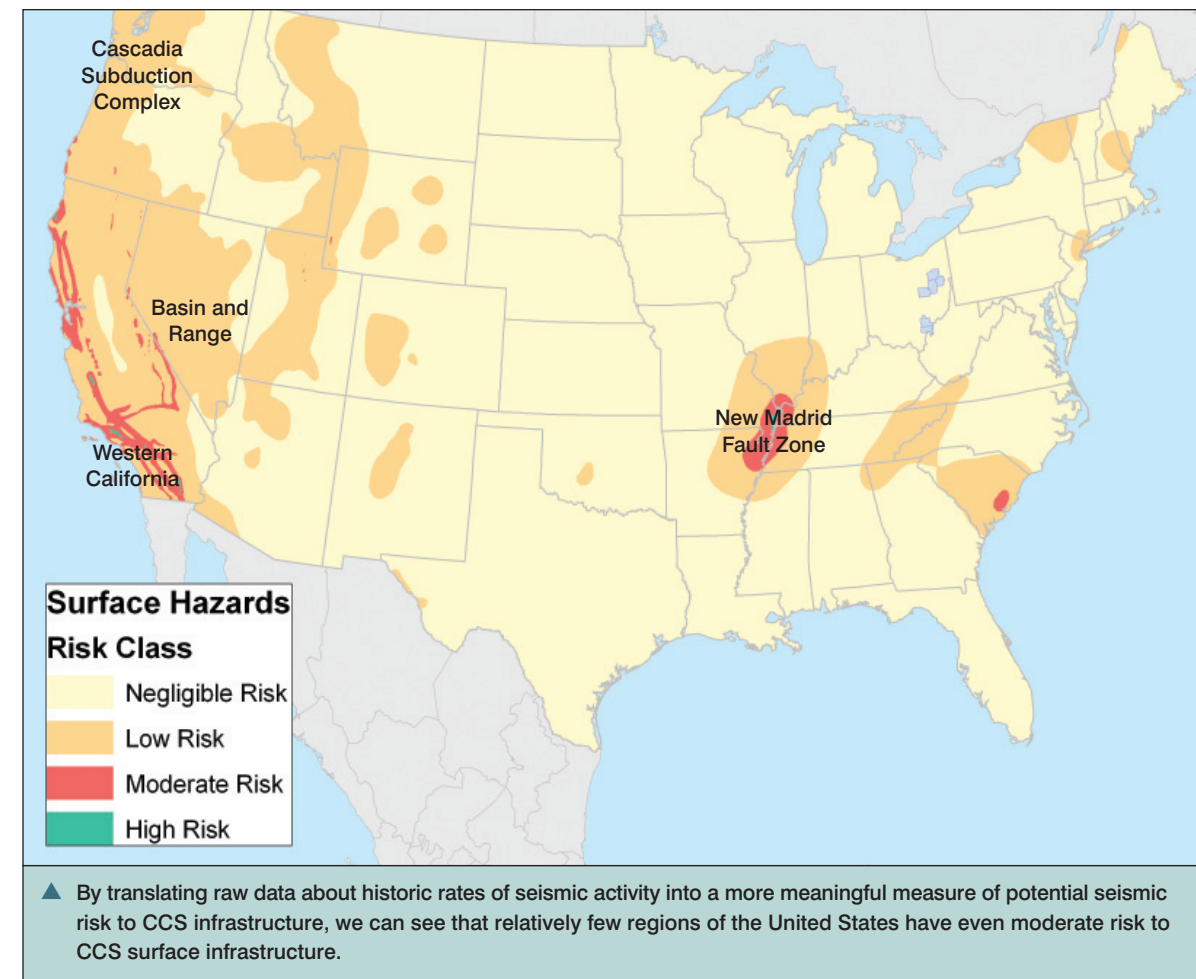


## CO<sub>2</sub> STORAGE: THE ISSUE OF PERMANENCE

At a properly designed and well-managed CO<sub>2</sub> storage site, the chance of CO<sub>2</sub> leakage should be small; thus, concerns about catastrophic release are likely unfounded. Properly-designed sites will have one or more injection zones that can accept and store large quantities of CO<sub>2</sub>, overlain by suitable caprocks, and will not be located in areas that have a high incidence of seismic activity. The features and attributes of storage formations and caprocks were discussed in the previous section. Here we focus on the issue of seismicity and the permanence of the stored CO<sub>2</sub>.

Fortunately, within the United States there are relatively few areas where seismicity would be a significant concern (as the map shows), allowing for CCS deployment across a wide range of locales. This type of assessment has not been completed for other regions of the world.

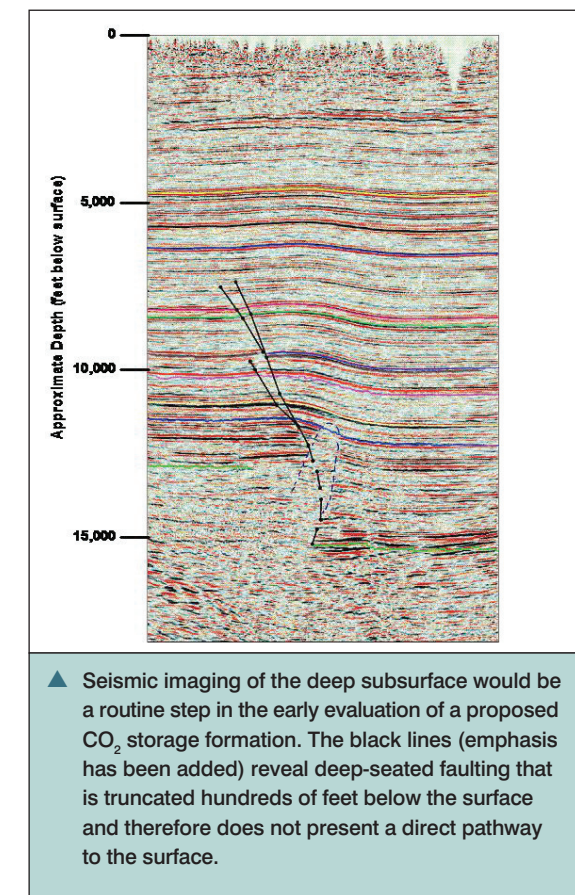
CO<sub>2</sub> storage sites can be designed against sudden large releases by avoiding areas with significant risk of seismicity and by mitigating leakage pathways such as faults and abandoned wells. Seismic surveys can be undertaken at candidate sites to assess whether there are any faults that might allow injected CO<sub>2</sub> to migrate out of the target injection zone. Seismic surveys, however, are just one aspect of a comprehensive pre-injection site evaluation that would need to be performed at each prospective CO<sub>2</sub> storage site. This pre-injection site evaluation would also need to identify the extent and condition of any abandoned wells (e.g., decades-old oil and gas production wells). Adequate sealing of abandoned wells that penetrate the storage zone would need to be assured to prevent these man-made structures from becoming pathways for CO<sub>2</sub> to migrate back to the surface.



Measuring, monitoring, and verification (MMV) systems will be needed to ensure that injected CO<sub>2</sub> remains in the target formation. Some technologies needed to monitor certain aspects of CO<sub>2</sub> storage are commercially available. However, the large-scale deployment of CCS technologies will depend in part on developing a much more robust and accurate suite of MMV technologies. Sites will draw from this suite to create tailored, site-specific MMV systems that will be designed to detect potential leaks long before they pose any danger to drinking water supplies or surface ecosystems.

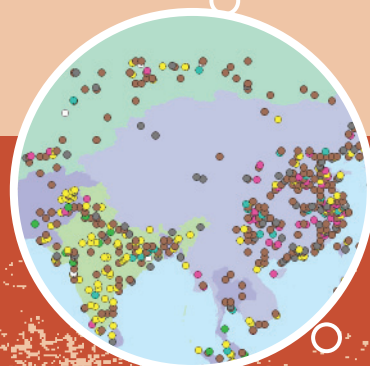
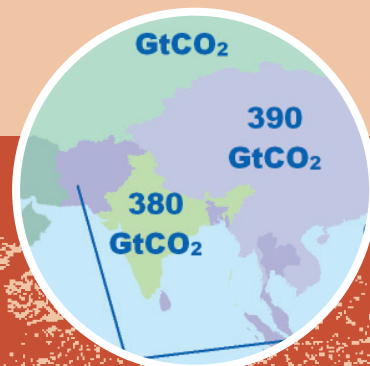
While the issue of leakage from CO<sub>2</sub> storage in deep geologic formations remains a subject of debate and intense research, several points are worth stressing:

- Because the majority of any potential large-scale CCS deployment is still likely decades away, we can use the next decade's worth of planned field experiments and potential early commercial CCS deployments to fundamentally improve our knowledge base about this key issue. There is a pressing need to amass field data to better bound likely leakage rates.



- Sudden releases of CO<sub>2</sub> are unlikely. To the extent that leakage does occur, the most likely pathways are transmissive faults and unsecured abandoned wells. In order to migrate back to the surface, a molecule of CO<sub>2</sub> would have to find its way through many layers of low-permeability rock, through which it might move only centimeters per century. Finding its way to the surface by moving upward through thousands of meters of solid rock could take millennia.
- CO<sub>2</sub> leakage from deep geologic formations is therefore not principally about human health and welfare today. The concern relates to slow, undetected leakage and how that might impact the climate for future generations.
- Discussions of leakage should also be paired with discussions of possible remediation measures, their strengths and weaknesses, and how these measures would be applied in the event that some CO<sub>2</sub> does escape from the storage formation.
- Tools and data exist that allow potential CO<sub>2</sub> storage project operators to assess candidate sites and the presence of any potential natural or manmade pathways that might allow CO<sub>2</sub> to migrate out of the target deep geologic storage formation. Although not foolproof, these tools and industrial best practices will help to greatly minimize potential issues with CO<sub>2</sub> storage.
- The likelihood and extent of any potential CO<sub>2</sub> leakage should slowly decrease as a function of time after injection stops. This is because the formation pressure will begin to drop to pre-injection levels, as more of the injected CO<sub>2</sub> dissolves into the pore fluids and begins the long-term process of forming chemically stable carbonate precipitates.

# 2



# Market

## Potential of CCS Systems

CCS systems must work well and efficiently—but that is not enough for them to play a role in addressing climate concerns. To play this role, CCS systems must fill a market need; they must help industry curtail greenhouse gas emissions while simultaneously delivering the products and services that customers want and expect. In addition, CCS systems—including verified suitable geologic storage reservoirs—must also be available both when and where needed. Large CO<sub>2</sub>-emitting industrial facilities exist all over the world; most belong to the electricity generation sector, but others support a wide range of other important industrial sectors. There also appears to be an abundance of large potential geologic CO<sub>2</sub> storage sites distributed

around the world. The capacity of these formations is likely more than enough to meet conceivable CO<sub>2</sub> storage needs from industry for a century or more.

This section presents a market analysis which shows that these candidate deep geologic CO<sub>2</sub> storage formations exist in close proximity to many power plants and industrial facilities throughout the world. Thus, it is conceivable that thousands to tens of thousands of CCS systems could deploy, if needed, providing the likely scale of deployment required (a gigaton or more per year of CO<sub>2</sub> emissions reductions) for CCS to be a significant component of the global climate change mitigation portfolio.

## WHERE IN THE WORLD ARE THE POTENTIAL STORAGE SITES FOR CARBON DIOXIDE?

Candidate geologic CO<sub>2</sub> storage reservoirs exist across the globe, and in many key regions they appear to be in the right places to meet current and future demand from nearby CO<sub>2</sub> emissions sources. In fact, there is likely more than enough theoretical CO<sub>2</sub> storage capacity in the world to meet projected needs for at least the next century.

While there remains a significant amount of field validation to be performed surrounding global geologic CO<sub>2</sub> storage potential, and while debate persists within the scientific community about the methodologies used to compute these theoretical storage capacities, our first-order estimates of theoretical geologic CO<sub>2</sub> storage capacity suggest a resource base that could potentially accommodate nearly 11,000 GtCO<sub>2</sub> worldwide. One way to understand the immense size of this potential resource is to realize that, across a wide range of possible future energy and economic scenarios and across hypothetical scenarios used to model CO<sub>2</sub> stabilization from 450 to 750 ppm, the demand for CO<sub>2</sub> storage space is estimated to not exceed 2,220 GtCO<sub>2</sub> over the course of this century. In a world in which there is a broad portfolio of complementary carbon management technologies that can be drawn upon (e.g., energy efficiency, renewable energy, nuclear power), it would appear that the deployment of CCS systems will not be constrained by a lack of overall storage capacity. Therefore, these technologies should be able to deploy to the extent that deployment makes economic sense in fulfilling a given climate stabilization goal.



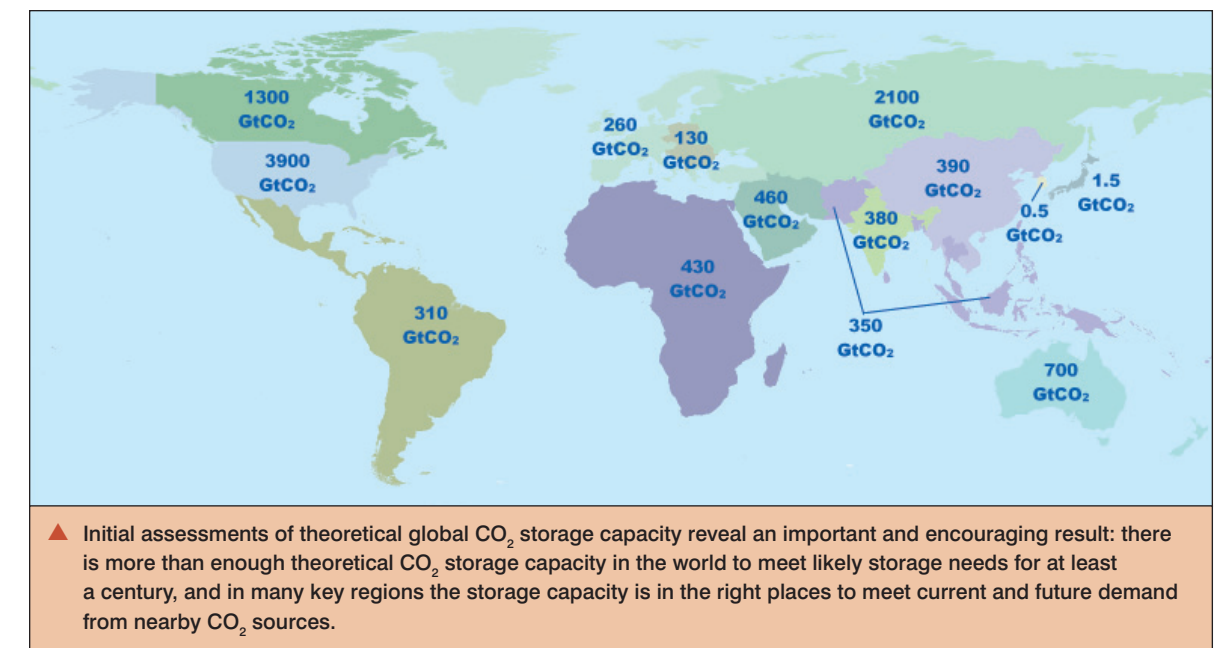
Substantial CO<sub>2</sub> storage capacity within a nation could be viewed as a very valuable domestic natural resource. For example, regions that have an abundance of CO<sub>2</sub> storage capacity can likely rely on a broader mix of fuels to power their economies and avoid the premature retirement of fossil-fired capital stock to meet tighter emissions constraints in the future.

However, even nations that do not have substantial CO<sub>2</sub> storage resources can benefit from CCS technologies through the purchase of lower-cost emissions credits made possible by CCS use in other nations.

The important issue is not whether a given country has more or less storage capacity than another country, but rather whether it has *enough CO<sub>2</sub> storage capacity* to meet its needs. This depends upon what other mitigation options are available to that country, as well as economic and demographic trends over the course of this century and the stringency of future greenhouse gas regimes—not a simple comparison of one country's theoretical storage capacity with that of another country. GTSP research indicates that:

- The United States, Canada, and Australia likely have more than enough theoretical CO<sub>2</sub> storage capacity to meet their needs for this century and perhaps beyond.
- Countries such as Japan and Korea will likely see their future use of fossil-energy technologies—and therefore the mix of energy technologies they can use—more constrained under future greenhouse gas policies than if they had more onshore geologic CO<sub>2</sub> storage capacity than they are currently thought to possess.

Whether the rest of the world has sufficient storage capacity depends on how much of their *theoretical* storage capacity can be used. At this point in time, there is a lack of high-quality data upon which to base statements about how much usable CO<sub>2</sub> storage capacity is available in rapidly developing, fossil fuel-rich regions of the world like China and India, as well as other regions that would appear to be candidates for CCS deployment. Therefore, one near-term, high-priority research task is to survey global candidate CO<sub>2</sub> reservoirs, since the availability, quality and distribution of these reservoirs directly impact the future evolution of the energy infrastructures in many nations.

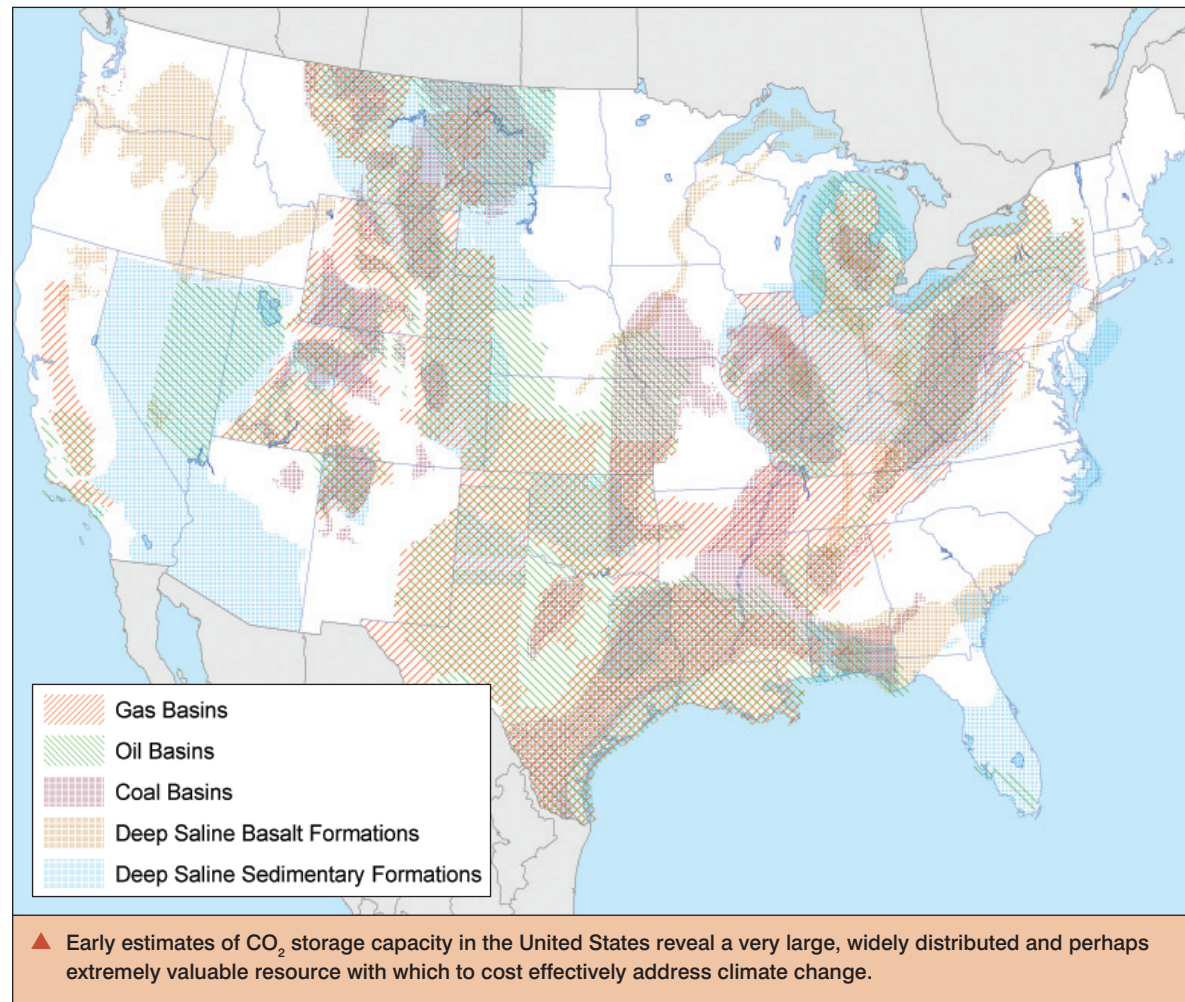


**The United States is fortunate to have an abundance of theoretical CO<sub>2</sub> storage potential, well distributed across most of the country.**

## POTENTIAL GEOLOGIC CO<sub>2</sub> STORAGE RESERVOIRS IN THE UNITED STATES

The United States is fortunate to have an abundance of theoretical CO<sub>2</sub> storage potential, well distributed across most of the country. Our preliminary and ongoing assessment of candidate geologic CO<sub>2</sub> storage formations reveals that the formations studied to date contain an estimated storage capacity of 3,900+ GtCO<sub>2</sub> within some 230 candidate geologic CO<sub>2</sub> storage reservoirs (see map below):

- 2,730 GtCO<sub>2</sub> in onshore deep saline formations (DSFs), with perhaps close to another 900 GtCO<sub>2</sub> of storage capacity in offshore deep saline formations



- 240 GtCO<sub>2</sub> in onshore saline-filled basalt formations
- 35 GtCO<sub>2</sub> in depleted gas fields
- 30 GtCO<sub>2</sub> in deep unmineable coal seams with potential for enhanced coalbed methane (ECBM) recovery
- 12 GtCO<sub>2</sub> in depleted oil fields with potential for enhanced oil recovery (EOR)

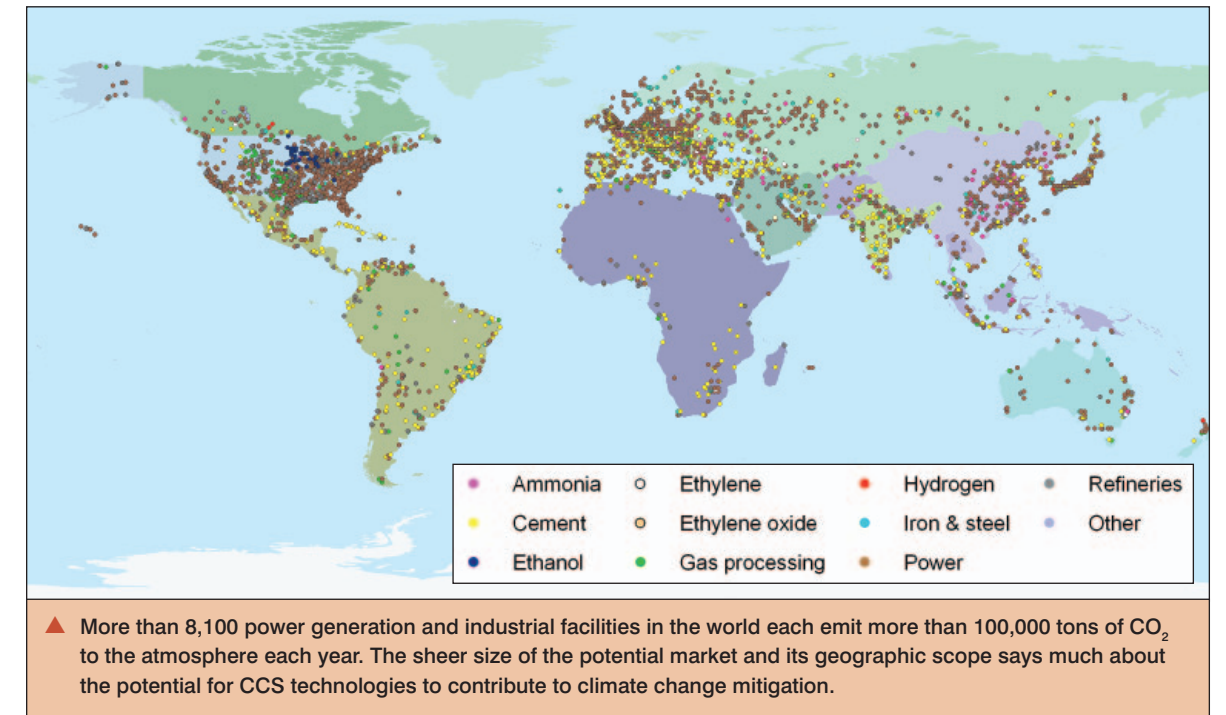
Together, these candidate CO<sub>2</sub> storage reservoirs within the United States represent a valuable and very large natural resource that may play a potentially critical role in cost-effectively bringing about deep and sustained reductions in greenhouse gas emissions. These candidate CO<sub>2</sub> storage formations underlie parts of 45 states and two-thirds of the land mass of the contiguous 48 states. In total, these formations may be capable of storing the United States' current CO<sub>2</sub> emissions from large stationary point sources for hundreds of years to come. The highest capacity of the U.S. candidate CO<sub>2</sub> storage formations is found DSFs, and some individual DSFs can store hundreds of gigatons of CO<sub>2</sub>.

## WHO AND WHERE ARE THE POTENTIAL CUSTOMERS FOR CCS?

In a carbon constrained future, a global market for CCS technologies will likely exist across a number of different industrial sectors. Although the fossil-fired power market (and perhaps future fossil-based syn-fuels or hydrogen production markets) would undoubtedly be the largest market for CCS technologies, other sectors of the economy will see that adopting CCS systems could represent a cost-effective and robust means of achieving deep and sustained emissions reductions while simultaneously serving their customers' needs.

In the year 2000, there were more than 8,100 documented large CO<sub>2</sub> point sources in the world, each of which emitted more than 100,000 tons of CO<sub>2</sub> to the atmosphere.

- Collectively, these large CO<sub>2</sub> point sources emitted approximately 15 GtCO<sub>2</sub> into the atmosphere, which is more than 60% of all global anthropogenic CO<sub>2</sub> emissions in that year.



- Fossil fuel-fired power plants accounted for the largest fraction (60%) of these CO<sub>2</sub> point sources and accounted for an even larger share of the emissions (71%).
- Natural gas processing plants accounted for less than 10% of the estimated emissions, while cement plants (6%), refineries (5%) and steel mills (5%) accounted for smaller but still significant shares.
- Roughly speaking, high-purity CO<sub>2</sub> source streams exhibiting a low cost of CO<sub>2</sub> capture (e.g., ammonia, ethanol, ethylene oxide, natural gas processing units and hydrogen production facilities) combined to account for 11% of both total sources and annual emissions.
- The 500 largest CO<sub>2</sub> point sources on the planet contributed 42% of all emissions from the 8,100 large stationary sources. These 500 largest emitters are overwhelmingly coal-fired power plants and they and the other fossil-fired power generation units combined to represent 78% of total emissions from these largest sources.
- As can be seen from the map on the previous page, these large CO<sub>2</sub> point sources are heavily concentrated in a few regions of the world: the United States (20% of CO<sub>2</sub> emissions), OECD Europe (12%), China (18%) and India (4%). These four regions alone account for 54% of the emissions and 52% of the existing large CO<sub>2</sub> point sources in the world. The last two regions—China and India—are particularly important future markets for CCS technologies given their rapid growth.

## POTENTIAL CCS CUSTOMERS IN THE UNITED STATES

The United States represents a critical prospective market for CCS technologies. As was the case with the preceding global snapshot of CO<sub>2</sub> point sources, the large CO<sub>2</sub> point sources in the United States represent a highly heterogeneous set of potential CCS opportunities. As can be seen from the figure at right, the contiguous United States has approximately 1,715 large CO<sub>2</sub> point sources that collectively emit more than 2.9 GtCO<sub>2</sub>/per year.

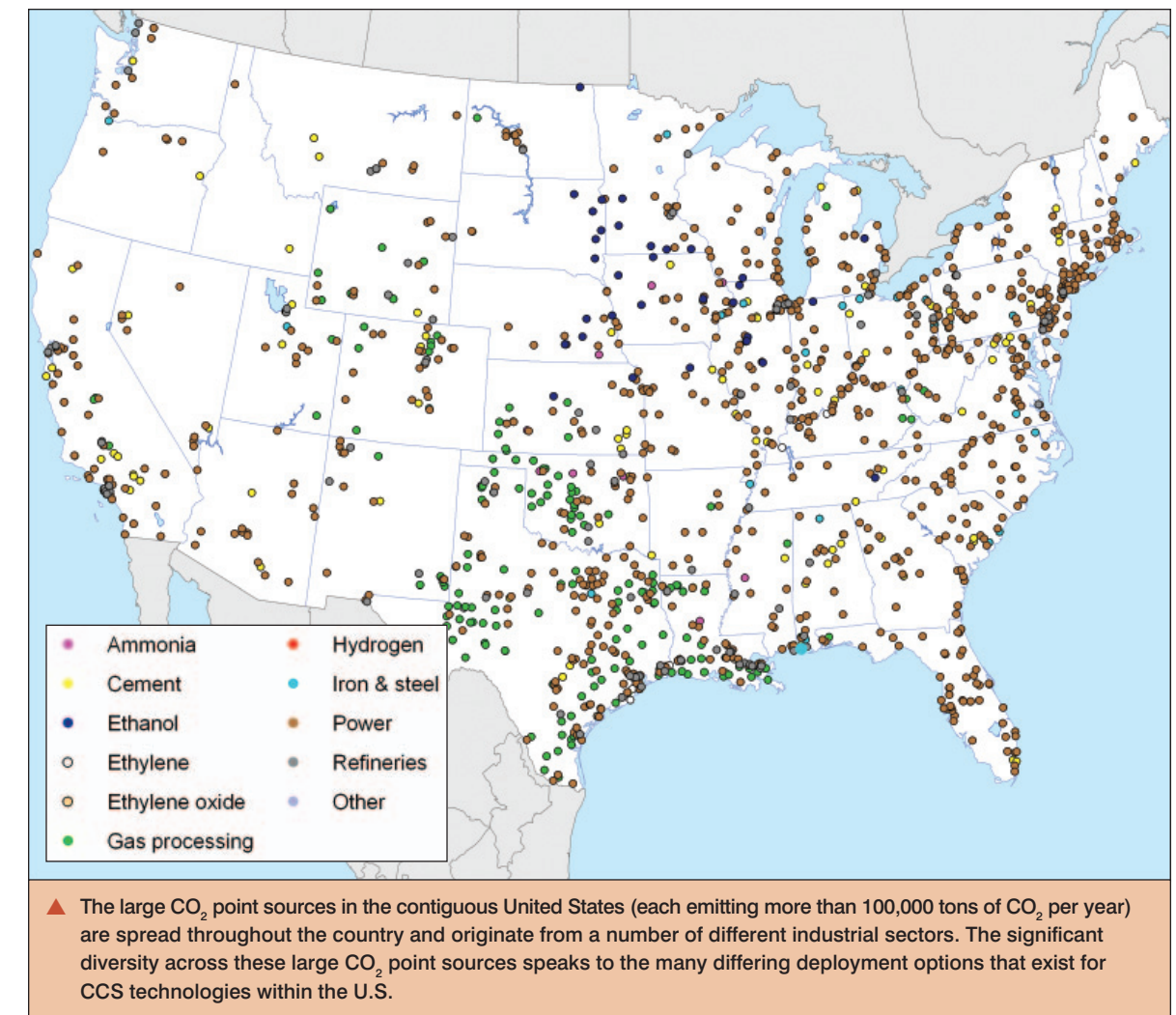
CO<sub>2</sub> point sources that produce a high-purity carbon dioxide stream are often seen as potential early adopters for CCS deployment. This is because, as the next section details, the cost of capturing CO<sub>2</sub> from a given source is a function of the concentration of CO<sub>2</sub> in the facility's emissions. Roughly speaking, large high-purity (and low cost of capture) CO<sub>2</sub> sources within the United States total 349 (20% of the sources) and account for 6% of the total emissions.

One of the principal benefits associated with the potential deployment of CCS technologies relates to its ability to deliver deep emissions reductions when applied to the largest CO<sub>2</sub> point sources. For example, in the United States:

- The 100 largest CO<sub>2</sub> point sources (6% of all facilities) account for 39% of total annual CO<sub>2</sub> emissions; 79% of these are power plants—all of them coal-fired.
- The 500 largest CO<sub>2</sub> point sources (29% of total) account for 82% of annual emissions; 78% of these are power plants, most coal-fired.

Within the United States, the potential application of CCS systems to the 500 largest CO<sub>2</sub> point sources could potentially yield substantial CO<sub>2</sub> reductions, since fully 95% of these sources are within 50 miles of a candidate CO<sub>2</sub> reservoir. Those 500 facilities represent trillions of dollars of productive industrial infrastructure (power plants, refineries, and other facilities). This demonstrates the potential leverage that CCS can provide when applied to a relatively manageable subset of large point sources.

**Fully 95% of the largest U.S. point sources are within 50 miles of a candidate CO<sub>2</sub> reservoir.**





# 3

# Costs of CCS Components

Next to questions like, “Will CCS really work?” and, “Is there enough CO<sub>2</sub> storage capacity in the world to make this worthwhile?” the most common question about CCS technologies relates to the cost of constructing and operating these systems.

In addition to the technical considerations presented in the previous section, firms must consider whether CO<sub>2</sub> capture is technically and economically feasible for a specific power plant or other large industrial source, as well as

the costs of transporting it to a suitable reservoir, injecting it into the deep subsurface, and maintaining it there. Each of these site-specific factors will play a critical role in determining whether CCS technologies will be adopted by existing CO<sub>2</sub> sources as well as power plants and other industrial facilities that will be built in the coming decades. This section focuses on what is known about the cost of deploying CCS technologies.

## THE COST OF CO<sub>2</sub> CAPTURE

For the vast majority of CCS applications, the cost of CO<sub>2</sub> capture is the largest contributor to overall CCS system cost and thus should be a focus of cost reduction efforts. The cost of CO<sub>2</sub> capture depends in large measure on the pressure and concentration of CO<sub>2</sub> in the flue gas or process stream from which the CO<sub>2</sub> is being separated. As a general rule, it is cheaper to capture CO<sub>2</sub> from a purer and higher-pressure CO<sub>2</sub> stream, as it

requires relatively less processing and compression before it is ready to be introduced into a CO<sub>2</sub> pipeline. The table on the facing page presents an overview of CO<sub>2</sub> capture technologies and costs described by the technical literature for a variety of large anthropogenic CO<sub>2</sub> sources that could be considered candidates for adopting CCS technologies in a greenhouse gas-constrained world. As the table shows, the cost of CO<sub>2</sub> capture varies considerably across these various types of large CO<sub>2</sub> point sources.



## THE COST OF CO<sub>2</sub> CAPTURE FOR VARIOUS INDUSTRIAL PROCESSES

(see appendix for sources and assumptions)

Plant Type	Capture Process(es)	Cost Estimates for Capture & Compression	Factor(s) Driving Cost of Capture and Compression
Steam Rankine Power	Chemical Absorption (amines)	\$25–\$60/tCO <sub>2</sub>	CO <sub>2</sub> content in flue gas stream, capital cost and energy requirements for solvent cycling
IGCC Power	Physical Absorption	\$25–\$40/tCO <sub>2</sub>	CO <sub>2</sub> content in flue gas stream, capital cost
Refinery Flue Gas	Chemical Absorption/ Flue Gas Recycling	\$35–\$55/tCO <sub>2</sub>	CO <sub>2</sub> content in flue gas stream and capital cost, energy requirements for solvent cycling (if applicable)
Steel	Flue Gas Recycling/ Chemical Absorption	\$20–\$35/tCO <sub>2</sub>	CO <sub>2</sub> content in flue gas stream and capital cost, energy requirements for solvent cycling (if applicable)
Cement	Flue Gas Recycling/ Chemical Absorption	\$35–\$55/tCO <sub>2</sub>	CO <sub>2</sub> content in flue gas stream and capital cost, energy requirements for solvent cycling (if applicable)
Ethanol (Fermentation)	NA	\$6–\$12/tCO <sub>2</sub>	No capture cost for pure CO <sub>2</sub> stream; compression cost only
Ethylene Oxide (Process Stream)	NA	\$6–\$12/tCO <sub>2</sub>	No capture cost for pure CO <sub>2</sub> stream; compression cost only
Ammonia (Reformer Gas)	NA	\$6–\$12/tCO <sub>2</sub>	No capture cost for pure CO <sub>2</sub> stream; compression cost only

CO<sub>2</sub> capture costs also vary considerably within technology classes. Therefore, when considering the cost of deploying CCS systems, decision makers must understand the specific circumstances under which the CCS unit will be deployed. For example, they would need to know not only whether a coal-fired power plant is a pulverized coal (PC) or Integrated Gasification Combined Cycle (IGCC) power plant but also what the plant's vintage and efficiency are, whether SO<sub>2</sub>, NO<sub>x</sub> and other emissions controls are already in place, and whether the CO<sub>2</sub> capture system will be mated to an existing plant or designed for a plant that has yet to be built, before being able to estimate the cost of CO<sub>2</sub> capture for any given facility.

The costs in the table assume that commercial (off-the-shelf) or near-commercial technologies are utilized. Ongoing research is designed to bring forward advanced and less costly CO<sub>2</sub> capture technologies. There is widespread agreement that such advancements will help accelerate CCS deployment, and that deployment will push the cost of CO<sub>2</sub> capture down through a process known as “learning by doing.” There is significant value in efforts designed to continually improve CO<sub>2</sub> capture systems in terms of lowering the cost of employing them in the real world. Technologies that are capable of lowering the cost of CO<sub>2</sub> capture systems will not only lower the cost of deploying CCS systems at specific

facilities but will also lower the overall societal cost of addressing climate change by as much as one-third if large-scale deployment of CCS technologies occurs during this century. This equates to potentially hundreds of billions, if not trillions of dollars in potential savings.

In addition to lowering the cost of CO<sub>2</sub> capture it is also important to continually increase the capture efficiency or percent of CO<sub>2</sub> captured from the target flue gas or process stream. This may be most important for power

plant-based CCS applications given the large size of these facilities and their collective emissions contribution. Currently available technologies are likely to capture approximately 90% of the inlet CO<sub>2</sub>, while the remaining 10% is released to the atmosphere. In a carbon-constrained world, any CO<sub>2</sub> released to the atmosphere would be taxed like any other greenhouse gas emission. As carbon permit prices rise, which would be necessary for stabilizing CO<sub>2</sub> concentrations, this seemingly small amount of CO<sub>2</sub> released to the atmosphere could have a profound impact on fuel choice and generation technology selection. Because power plants are very long-lived, proposals to build CCS plants that would capture only a modest fraction of a plant's emissions might not prove economic in the long term.



## COSTS OF CO<sub>2</sub> TRANSPORT AND STORAGE

As described previously, the geologic CO<sub>2</sub> storage resource is vast, and in many parts of the world this storage resource appears to be advantageous in its geographic distribution with many large CO<sub>2</sub> point sources in close proximity to candidate geologic CO<sub>2</sub> storage reservoirs. However, the characteristics of these candidate CO<sub>2</sub> storage reservoirs in terms of their quality, quantity, capacity, and value varies tremendously across the globe and even within specific regions, just as the distribution of other natural resources varies—for example, gold, oil, coal, or sunshine.

Therefore, the cost to access CO<sub>2</sub> storage capacity will also vary from region to region. The key factors in determining the cost of CO<sub>2</sub> transport and storage are the proximity of the CO<sub>2</sub> source to the selected CO<sub>2</sub> storage reservoir and the characteristics of the reservoir that is selected for CO<sub>2</sub> injection.

There is a general consensus within the technical community that most CO<sub>2</sub> will be transported from its point of capture to a suitable deep geologic storage reservoir via land-based pipelines. Already, approximately 3,000 miles of dedicated CO<sub>2</sub> pipeline deliver CO<sub>2</sub> to commercial CO<sub>2</sub>-EOR projects within North America, in areas such as the Permian Basin of West Texas and southeastern New Mexico, the Rocky Mountain Region of Utah, Wyoming, and Colorado, and to the Weyburn Field in Saskatchewan. The longest of these dedicated CO<sub>2</sub> pipelines, the Cortez pipeline, delivers CO<sub>2</sub> over a distance of 500 miles.

This operational experience with CO<sub>2</sub> pipelines and the similarity in terms of construction and operational costs between CO<sub>2</sub> pipelines and natural gas pipeline networks provides a robust set of data that can be used to estimate future CO<sub>2</sub> transportation costs. CO<sub>2</sub> transport costs via pipeline are a function of the distance between the CO<sub>2</sub> source and its geologic storage reservoir.

**Already, approximately 3,000 miles of dedicated CO<sub>2</sub> pipeline deliver CO<sub>2</sub> to commercial CO<sub>2</sub>-EOR projects within North America.**

The cost also depends upon the diameter of the pipeline (which is a function of how much CO<sub>2</sub> the pipeline must carry, i.e., its design mass flow rate), with larger pipelines experiencing some economies of scale. Recent history of natural gas pipeline land construction costs, while highly variable, suggest that capital costs for these transport pipelines are on the order of \$40,000/mile per inch of pipeline diameter. So, assuming a large CCS-enabled power plant produces 10 million tons of CO<sub>2</sub> per year, the main trunk pipeline (approximately 26 inches in diameter) used to carry the CO<sub>2</sub> to its reservoir would cost roughly \$1.2 million per mile to construct. Circuitous routing or challenging terrain could significantly increase the cost.

For CO<sub>2</sub> storage, one of the most significant characteristics impacting overall economics revolves around whether the storage reservoir is capable of producing a valuable hydrocarbon—oil or methane—in response to CO<sub>2</sub> injection. These reservoirs, which include maturing oil fields and certain classes of unmineable coal seams, are often referred to as “value-added reservoirs.” Other types of reservoirs, such as deep saline formations, deep saline-filled basalt formations, and depleted natural gas fields, typically would not provide value-added hydrocarbon recovery.

**...our research tells us that the greatest impact associated with CO<sub>2</sub> storage in value-added reservoirs could well relate to their ability to produce more domestic oil and gas...**

In North America, where we have been able to model in detail the complex interplay among the thousands of large CO<sub>2</sub> sources and the large—but nonetheless finite—candidate CO<sub>2</sub> storage formations in the region, our research tells us that the greatest impact associated with CO<sub>2</sub> storage in value-added reservoirs could well relate to their ability to produce more domestic oil and gas and not because of their ability to reduce the cost of CO<sub>2</sub> transport and storage.

The large-scale deployment of CCS systems hinges upon proving that CCS technologies can be integrated with fossil-fired electricity production (and perhaps in the future fossil-derived hydrogen production). There are a number of issues related to CO<sub>2</sub> storage in value-added reservoirs that suggest the possibility of a significant mismatch between the nearly continuous need to store large quantities of CO<sub>2</sub> from a CCS-enabled power plant and the more limited and episodic need for CO<sub>2</sub> in CO<sub>2</sub>-driven EOR and ECBM projects. Such projects

also require extensive and separate infrastructure for handling recovered oil and gas from the host storage formation; separating and recycling co-produced CO<sub>2</sub>; and handling produced waste water. All of this infrastructure requires additional financing to construct and operate and also requires core competencies that are unlikely to reside within most electric utility, cement, iron and steel firms and other potential adopters of CCS technologies.

Although gigatons of low-cost CO<sub>2</sub> storage opportunities may be associated with value-added reservoirs in North America alone, the long-term challenge presented by the need to stabilize atmospheric concentrations of CO<sub>2</sub> indicates that, because the storage capacity available in oil- and gas-bearing reservoirs is dwarfed by capacity in reservoirs that do not bear saleable products, over the long term, CO<sub>2</sub> storage in value-added reservoirs may not represent as significant a portion of total CO<sub>2</sub> stored as is widely believed. Our research suggests that all classes of CO<sub>2</sub> storage reservoirs are valuable and will be needed once CCS technologies begin their expected large-scale commercial deployment. For the rest of the larger economy and over the course of this century, our work suggests that the long-term average cost of CO<sub>2</sub> transport and storage should stay below the level of approximately \$12–\$15/tCO<sub>2</sub> for a region like North America, due largely to the abundant capacity offered by deep saline formations.

Current estimates of the cost of employing the technologies needed to measure, monitor, and verify the fate of CO<sub>2</sub> injected into deep geologic formations suggest that these costs will be small when measured on a per-ton-of-CO<sub>2</sub>-stored basis, perhaps as low as a few pennies per ton. Planned and future CCS field demonstrations and early commercial CCS deployments should help to validate these assumptions about the cost of MMV.

## PULLING IT ALL TOGETHER: THE NET COST OF CCS

So far, this section has discussed the range of expected costs for individual CCS system components, but society is most concerned with the total cost of CCS (including capture, transport, injection, and monitoring) applied to a real power plant or other industrial facility. On the next page is a cost curve for the net cost of employing CCS within the United States, given current technologies, for the 1,715 existing large CO<sub>2</sub> point sources and all of the candidate CO<sub>2</sub> storage reservoirs we have been able to identify to date. The model used to compute this cost curve, the *Battelle CO<sub>2</sub>-GIS*, was specifically built to gain understanding of the potential for CCS technologies to deploy across North America in a competitive marketplace for cost-effective emissions reductions.

Each point on the curve represents the levelized cost (in \$/tCO<sub>2</sub>) for a specific existing large CO<sub>2</sub> point source to employ CCS: capture its CO<sub>2</sub> and ready it for transport; transport the captured CO<sub>2</sub> via pipeline to a suitable candidate storage reservoir; inject the CO<sub>2</sub> into the reservoir; and measure, monitor and verify that the injected CO<sub>2</sub> remains within the target reservoir. In addition, for injection into value-added storage reservoirs, any revenues from resulting CO<sub>2</sub>-driven hydrocarbon recovery are also incorporated in the net costs. This represents an attempt to capture the full end-to-end cost of employing CCS technologies, given the inherent heterogeneity of the potential market for CCS technologies across the United States.

This “net cost of employing CCS” cost curve has four distinct regions that are worth commenting on:

- At the far left end of the curve are a few CO<sub>2</sub> capture and storage opportunities that appear to be so cheap that they fall below the x-axis, indicating that firms could make money today by exploiting these opportunities even in the absence of any explicit climate policy requiring a reduction in CO<sub>2</sub> emissions. This “low hanging fruit” can be seen in the real world today as the few tens of millions of tons of anthropogenic CO<sub>2</sub> that are currently being used in EOR projects. While these represent potential negative-cost CCS deployment opportunities, such opportunities are relatively limited and most are likely already being exploited.

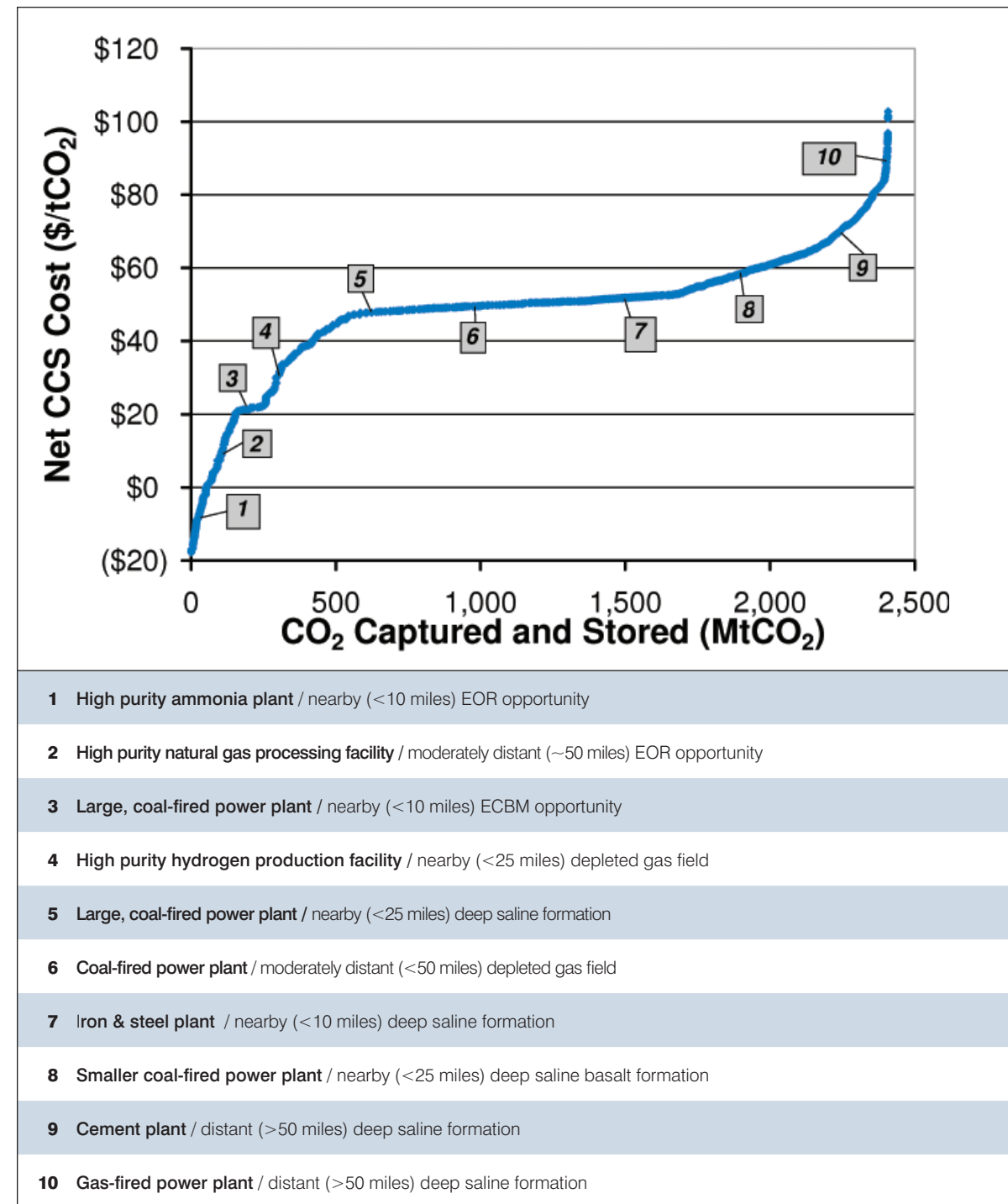


- Next in the cost curve are perhaps a few hundred million tons per year of relatively inexpensive full end-to-end CCS opportunities. This region of the cost curve is dominated by high-purity (and therefore low cost of capture) CO<sub>2</sub> point sources such as natural gas processing facilities seeking to store their CO<sub>2</sub> in nearby oil fields—and perhaps in the future as ECBM technology matures, in unmineable coal seams—where there may be some potential for offsetting revenues associated with CO<sub>2</sub>-driven EOR and ECBM production. Although these are relatively low cost options, they still have positive net costs, implying that society is unlikely to target these options in the absence of a requirement to reduce greenhouse gas emissions.

- The cost curve next transitions into a long, relatively flat region which is the domain of the large fossil-fired power plants seeking to dispose of their CO<sub>2</sub> emissions in the nation’s abundant, high-capacity deep saline formations, depleted gas fields, and deep basalt formations. Here is the potential for gigatons (that is, thousands of millions of tons) of stably priced, long-lived CO<sub>2</sub> storage. The advent and adoption of advanced CCS-enabled fossil-fired power production technologies, such as IGCC with CCS, would lower this region of the cost curve and therefore hasten the large-scale adoption of CCS systems in the United States. The slight increase in per-ton cost of CCS on this part of the curve results largely from sources becoming smaller and more distant from their best available storage reservoir.

## THE NET COST OF EMPLOYING CCS WITHIN THE UNITED STATES—CURRENT SOURCES AND TECHNOLOGY

The ten marked points on the curve are characterized below the graph by their different circumstances related to use of CCS technologies.



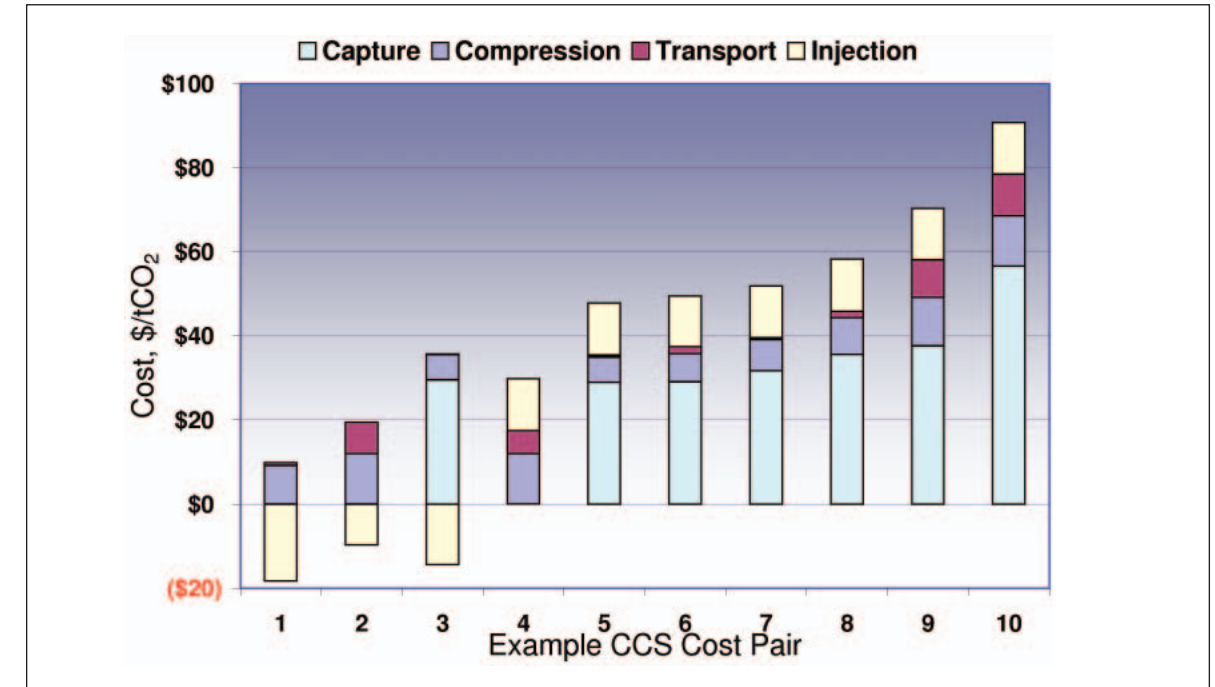
- Finally, the tail end of the curve represents an acceleration of this escalating cost trend with mostly low-purity sources of decreasing size and purity (e.g., small natural gas-fired power plants), able to access increasingly more distant storage reservoirs.

The numbers along the curve and the associated table below the graph serve to further illustrate the nature and significance of how site-specific factors and the inherent heterogeneity in the marketplace for CCS will impact the adoption of this class of technologies. These ten points have no special significance and are simply presented here to highlight how CCS technologies might deploy across the entire economy, as represented by the entire CCS cost curve. For each sample point, the text in the table states the type of large CO<sub>2</sub> point source from which CO<sub>2</sub> is being captured, the type of CO<sub>2</sub> storage reservoir that it has selected as its available lowest-cost storage option, and the required pipeline distance needed to reach the target storage

reservoir. For example, the first point on the curve represents a high-purity ammonia plant that is able to separate and compress CO<sub>2</sub> at a very low cost and store it in a nearby mature oil field where the CO<sub>2</sub> is injected to increase incremental oil recovery via EOR. These points show how the characteristics of the CO<sub>2</sub> sources, along with the storage reservoirs they are coupled with and the distance between them, change across the economy and impact the net cost of employing CCS technologies.

The chart below offers further insight into the dynamic composition of net CCS costs. For each of the ten sample points highlighted above on the cost curve, the individual capture, compression, transport and net injection cost components are presented. This figure helps to more clearly illustrate the impact individual source and reservoir characteristics have in defining the total cost for deploying CCS in a wide variety of settings

## THE NET COST OF EMPLOYING CCS: EXAMPLE COMPONENT COSTS BREAKOUT



and circumstances. For instance, note that the capture costs for these ten sources range from \$0/tCO<sub>2</sub> for the very high-purity CO<sub>2</sub> sources up to \$57/tCO<sub>2</sub> for the small and very low-purity NGCC source. Compression cost estimates vary also, depending again on the size of the CO<sub>2</sub> stream and other characteristics, roughly between \$6 and \$12/tCO<sub>2</sub>. Transport costs are driven by the mass flow rate of CO<sub>2</sub> to be transported, but also the distance between the source and its selected reservoir. Here, they range from about \$0.20/tCO<sub>2</sub> for the very large coal-fired power plant requiring minimal pipeline length, to nearly \$10/tCO<sub>2</sub> for the very small gas-fired power plant that is over 65 miles from its target reservoir.

The injection costs shown here represent the cost of injecting the CO<sub>2</sub> into the selected reservoir, including all necessary capital and operating costs for wells and distribution pipeline, as well as monitoring equipment and procedures. In addition, for value-added CO<sub>2</sub> injection for EOR or ECBM, the value of the anticipated incremental recovered oil or gas is then subtracted, thereby allowing for this net injection cost to be negative (i.e., resulting in a net profit) in some situations. For these ten sample points, the net injection costs vary from about -\$18 to \$12/tCO<sub>2</sub>, based largely on the type and characteristics of the selected reservoir (e.g., depth, injectivity, oil/gas recovery potential) and the value of any recovered oil and gas.



For all but the highest purity sources, the largest cost is related to separation of CO<sub>2</sub> from the flue or process stream. In fact, for the example curve points shown here, the cost of capture alone represents roughly 60% of the total estimated net CCS cost for the low-purity sources. This is significant, as reducing the cost of CO<sub>2</sub> capture from these low-purity sources (and from power plants in particular) would provide a significant boost to the economic viability of geologic CO<sub>2</sub> storage.

While the above analysis focuses on modeling the potential adoption of CCS technologies within the United States, it also reveals a few key points about the cost of employing CCS systems that are likely to hold true in other parts of the world:

- First, there is likely some potential for very low and even negative cost (and therefore perhaps already profitable) CCS opportunities, but these opportunities represent only a small portion of the emissions mitigation potential to be exploited. Many are likely already being utilized by the marketplace, albeit often without application of MMV systems, which would be required to demonstrate the long-term retention of the injected CO<sub>2</sub> if the primary purpose of these projects was climate protection.

- Second, while the fossil-fired power sector represents the largest potential demand for CCS, other, higher-purity large CO<sub>2</sub> point sources are likely to adopt CCS systems before electric power plants do and in doing so might lock up much of the remaining value-added CO<sub>2</sub> storage opportunities.

- Third, even under very conservative assumptions such as those used here (e.g., power plants and other large industrial CO<sub>2</sub> point sources use existing CO<sub>2</sub> capture technologies), CCS technologies appear to have great potential to cost-effectively reduce greenhouse gas emissions.

# 4



# Future

## Scale of CCS Deployment and the Path Forward

The GTSP's research on CCS affirms that this class of technologies could play a significant role in societal efforts to stabilize atmospheric concentrations of greenhouse gases. The scale of CCS deployment needed to make this significant contribution will likely require thousands of CCS-enabled plants deployed over the course of this century, beginning early enough so that gigatons of CO<sub>2</sub> per year are routinely being stored in deep geologic formations around the world by mid-century.

However, the current state of CCS commercial deployment and even early stage field research deployment represents a very small fraction of

what will be needed. This raises the question of how to expand the use of CCS technologies by orders of magnitude over the coming decades. The expansion of a new technology at that rate is not impossible, but it certainly is challenging.

This concluding section explores the factors influencing regional, sectoral, and plant-level implementation of CCS systems, factors that must be addressed to allow deployment at a scale large enough to greatly reduce the costs of reducing global CO<sub>2</sub> emissions. Also, a number of key R&D and institutional needs must be pursued in order to allow CCS technologies to deploy across a range of economic sectors.



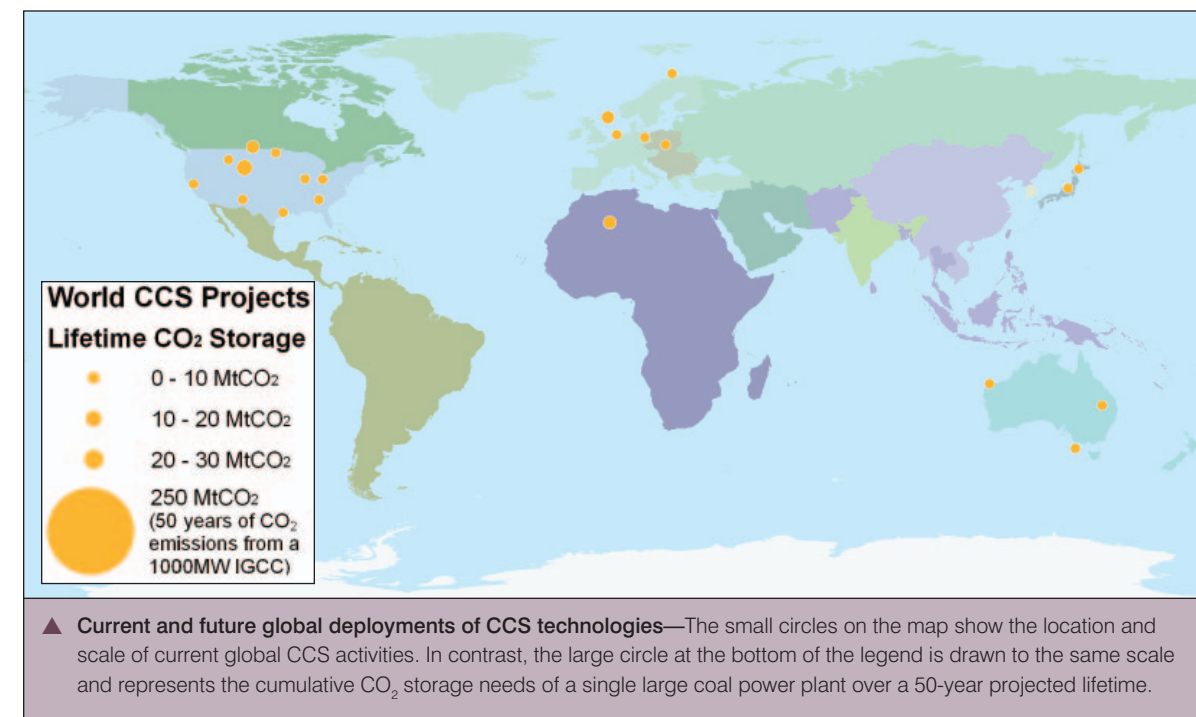
## TODAY'S CCS DEPLOYMENT COMPARED TO POTENTIAL MID-CENTURY DEPLOYMENT

This page is too small to show the full extent of the difference between CCS deployment today and its potential deployment.

The figure below shows 21 currently operational or planned CCS projects as of late 2005. Ranging from projected lifetime injection volumes of 1,000 tons of CO<sub>2</sub> (or 0.000001 GtCO<sub>2</sub>) to 26 million tons of CO<sub>2</sub> (0.026 GtCO<sub>2</sub>), these 21 projects represent a critical test bed to fundamentally advance our knowledge about how CCS systems will operate under real-world conditions.

Even the largest project on the list, which hopes to inject 0.026 GtCO<sub>2</sub> over its lifetime, will only inject one-tenth as much CO<sub>2</sub> as a 1,000 MW IGCC plant would need to inject over its 50-year projected lifetime.

However, the challenge is to deploy, not a single 1,000 MW plant, but potentially hundreds or thousands of such facilities worldwide. Indeed, the cumulative amount of CO<sub>2</sub> that would need to be stored in geologic formations over approximately the next half century under a hypothetical 550 ppm stabilization policy could be nearly 20 GtCO<sub>2</sub> in the United States and more than 100 GtCO<sub>2</sub> across the world. The challenge is not a matter of doubling or tripling or even quadrupling current deployment, but of increasing current deployment by 3 to 4 orders of magnitude. The next sections explore how the needed scale-up might occur.

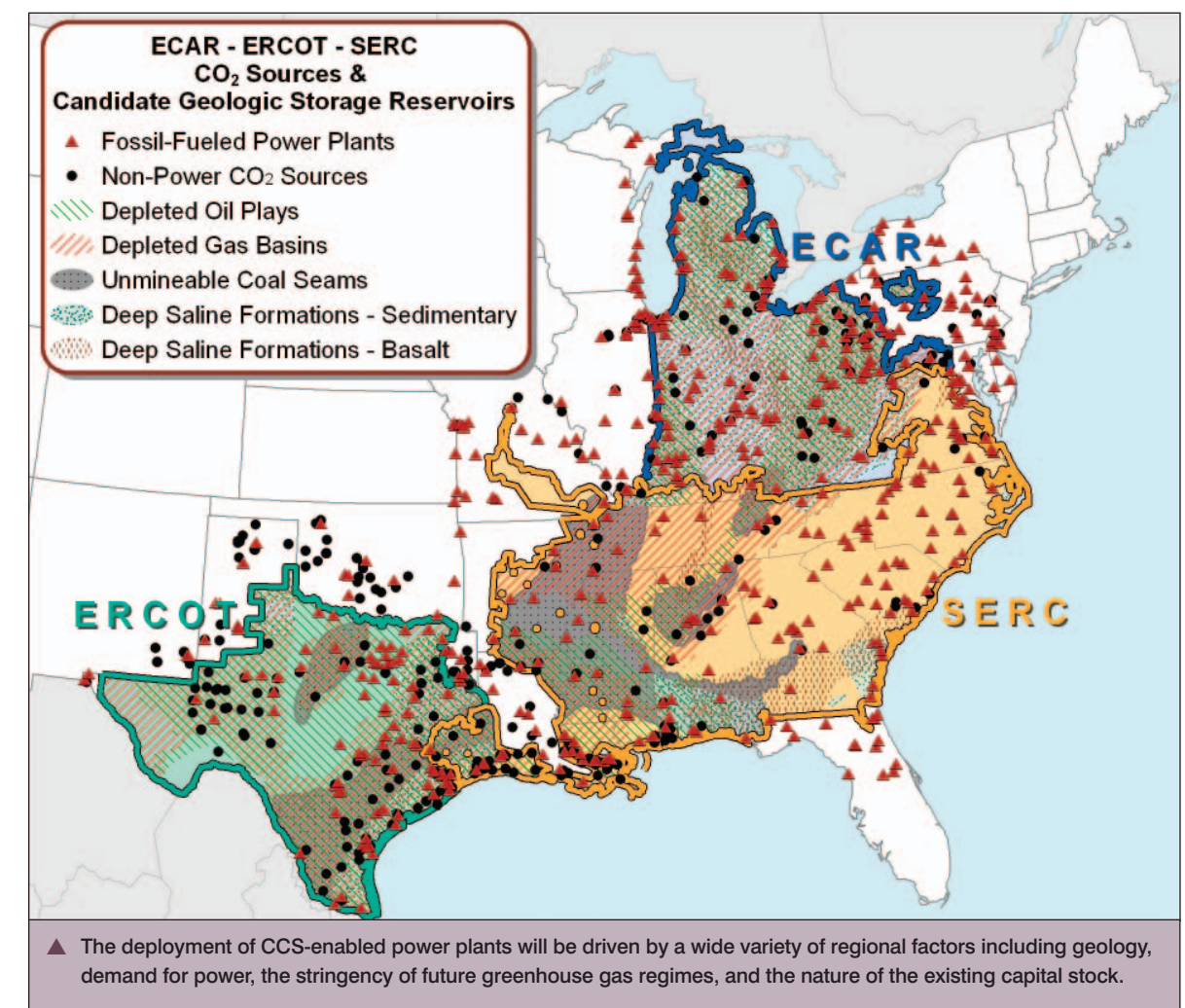


## CCS DEPLOYMENT AT THE REGIONAL AND SECTORAL SCALE

To illustrate CCS deployment at a scale that would significantly reduce CO<sub>2</sub> emissions, we have modeled the hypothetical adoption of CCS systems within three fossil-fuel-intensive electricity generation regions in the eastern United States in response to a hypothetical emissions constraint. The map below shows the regions, major sources of CO<sub>2</sub>, and potential storage sites. The specifics of the scenario being modeled here are discussed in the appendix but key attributes of the scenario include a carbon tax that starts at \$12/tCO<sub>2</sub> in 2015 and rises at 2.5% per year, and oil and natural gas prices that, while not as high as current prices, reflect current thinking that future prices for gas and

oil will remain higher than historical levels. Under this scenario, there could be approximately 150 large, coal-fired IGCC+CCS power plants operational by 2045 in just these three regions of the United States. Together these advanced coal-fired power plants would be capturing and storing nearly 900 MtCO<sub>2</sub> per year by 2045 and would have cumulatively stored over 6 GtCO<sub>2</sub> in regional geologic storage formations by 2045.

To accurately model the potential adoption of CCS technologies within these three power production regions of the United States, we included each region's unique attributes: (1) the existing electricity generating capacity—efficiency, fuel costs, operating and maintenance (O&M) costs, emissions; (2) electricity demand—both the varying nature of the electricity load profile (from baseload to peaking) and future demand growth; (3) competing technologies for new generating capacity—





capital costs, efficiency, O&M costs, emissions; (4) other market factors—fuel prices, emissions policies, cost of financing, reserve margin requirements; and (5) the characteristics of candidate CO<sub>2</sub> storage reservoirs.

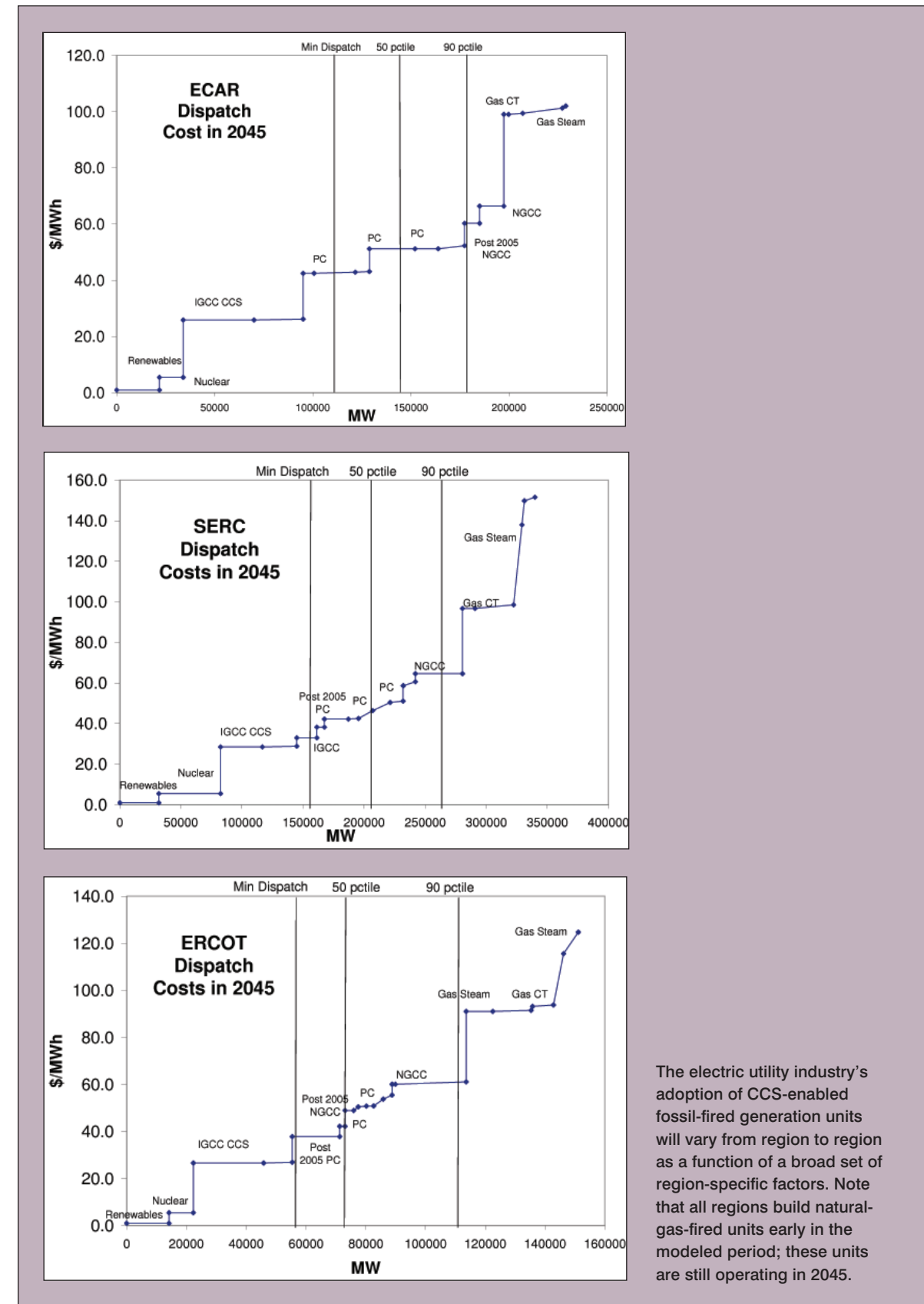
When all of these factors and the heterogeneous composition of different geographic regions are taken into account, a highly nuanced picture of CCS deployment across different regions emerges, which we will briefly discuss before focusing on the larger issues that this analysis reveals about how CCS technologies might be adopted by the electric power sector.

**ECAR:** The U.S. region located in the industrial upper Midwest (the East Central Area Reliability Coordination Agreement, or ECAR) has an electricity system that has historically been dominated by conventional coal plants. The region’s geologic CO<sub>2</sub> storage opportunities are dominated by deep saline formations, although there is some potential for value-added CO<sub>2</sub> storage. Under this scenario the deployment of CCS-enabled IGCC units could clearly be a key to decarbonizing baseload electricity generation in this region by 2045. In the early years of this scenario, when carbon permit prices are relatively low, increased demand for electricity is met mainly through new coal- and natural gas-fired generation units. The coal plants are IGCC units which eventually adopt CCS systems (thus becoming IGCC+CCS) as carbon permit prices rise. The new natural gas-fired units—that is, those built after 2005—continue to operate during the period to 2045 although their utilization rate drops, moving farther out in the dispatch curve as carbon and natural gas prices rise. Contrary to conventional wisdom, most of the existing (pre-2005) pulverized coal plants would

not be taken offline or rebuilt as IGCC+CCS; instead, the most efficient of these existing plants would continue to operate as baseload units while others become key resources in the region’s intermediate load capacity generation portfolio (see the top figure at right).

**SERC:** In the Southeastern United States (the Southeastern Electric Reliability Council, or SERC), coal-fired power plants also make up the majority of current (2005) electric generation capacity, but the region is home to substantially more nuclear and hydroelectric power than ECAR. Moreover, the region also has a significant amount of natural gas-fired generation capacity, most of which has come online very recently. Similar to ECAR, this region’s CO<sub>2</sub> storage opportunities are heavily dominated by deep saline formations; however, on average these deep saline formations (both sedimentary and basalt) are farther away from today’s fossil-fired power generation units than is generally the case in the ECAR region, implying slightly higher costs for CO<sub>2</sub> transport in this region. Under this CO<sub>2</sub> emission reduction scenario, SERC’s baseload electricity generation is characterized by 2045 principally by nuclear and IGCC+CCS, along with some renewable energy. A relatively small amount of conventional PC and IGCC without CCS is built in the post-2005 period and continues to operate in 2045 as a part of SERC’s intermediate capacity load generation. Existing (pre-2005) PC plants continue to operate but at reduced levels as these units move over time out of their former role as baseload units and transition to serve intermediate loads (see the middle figure, at right).

**ERCOT:** The region that encompasses much of the state of Texas (the Electric Reliability Council of Texas, Inc., or ERCOT) is home to significantly more value-added CO<sub>2</sub> storage potential than either of the other regions discussed above. However, like the other two regions (and much of the United States), the majority of the region’s CO<sub>2</sub> storage potential is in deep saline formations. This third region has historically been dominated by gas and oil steam electricity production capacity. Conventional coal also fuels a substantial portion of the region’s current generation capacity,



The electric utility industry’s adoption of CCS-enabled fossil-fired generation units will vary from region to region as a function of a broad set of region-specific factors. Note that all regions build natural-gas-fired units early in the modeled period; these units are still operating in 2045.

and there has been a recent boom in new natural gas-fired capacity. Here, the principal means for reducing the region's electric utility emissions in 2045 is again a mix of nuclear, renewables and IGCC+CCS. However, in ERCOT, some new conventional coal capacity is built in the first decade under this scenario, even though its emissions will be taxed. The higher future gas and oil prices mean that some new coal capacity will be economic, as it would earn a sufficient margin in this gas-dominated electricity market to compensate for its higher emissions. In addition, the carbon permit price is not high enough in the early years to make investment in IGCC+CCS the economic choice. These new post-2005 conventional fossil-fired units continue to operate in 2045 by transitioning over time from baseload to intermediate load. Here again, rather than being scrapped, existing conventional coal plants can continue to deliver value to their owners by transitioning from baseload generation to intermediate load (see bottom figure, previous page).

The major lesson is that CCS technologies are really focused on baseload power production. The greatest amount of CO<sub>2</sub> emissions mitigation via the application of CCS technologies in the electric power sector can be achieved at the least cost by focusing on fossil-fired baseload capacity. It will be relatively more expensive to reduce CO<sub>2</sub> emissions from intermediate and peaking generation units because of their lower utilization rates. Therefore, CCS-enabled baseload power plants should be designed so that they can capture nearly all of their emissions. This is a more robust long-term strategy than the alternative of capturing closer to 50% of a unit's emissions, sometimes discussed in an effort to control the costs of CO<sub>2</sub> capture and the resulting electric power. In the long term, units that cannot capture the vast majority of their emissions are likely to become unprofitable, stranded assets.

The potential for CCS deployment in the electric power sector to be centered on decarbonizing high-capacity factor baseload plants has important implications for the possible evolution of the market for CO<sub>2</sub> storage and the kinds of CO<sub>2</sub> storage reservoirs that will likely be most relevant for this industry's needs.

Our research indicates that the overwhelming criteria for siting a CCS-enabled power plant will relate more to allowable CO<sub>2</sub> injection rates and total reservoir capacity than to potential buyers for CO<sub>2</sub>. Knowing whether a region has more or less potential for value-added CO<sub>2</sub> storage than any other region is only one of many pieces of information needed to understand the deployment of CCS-enabled electric generation systems.

Because the cost of CO<sub>2</sub> capture in the electric power sector—even including state-of-the-art IGCC+CCS—will likely be higher than the cost to capture CO<sub>2</sub> from some industrial sources, much of the value-added CO<sub>2</sub> storage capacity in a given region could already be spoken for before CCS systems begin their expected, significant deployment within the electric power sector. Large, deep saline formations will therefore likely be the CO<sub>2</sub> storage workhorse for the electric utility sector.

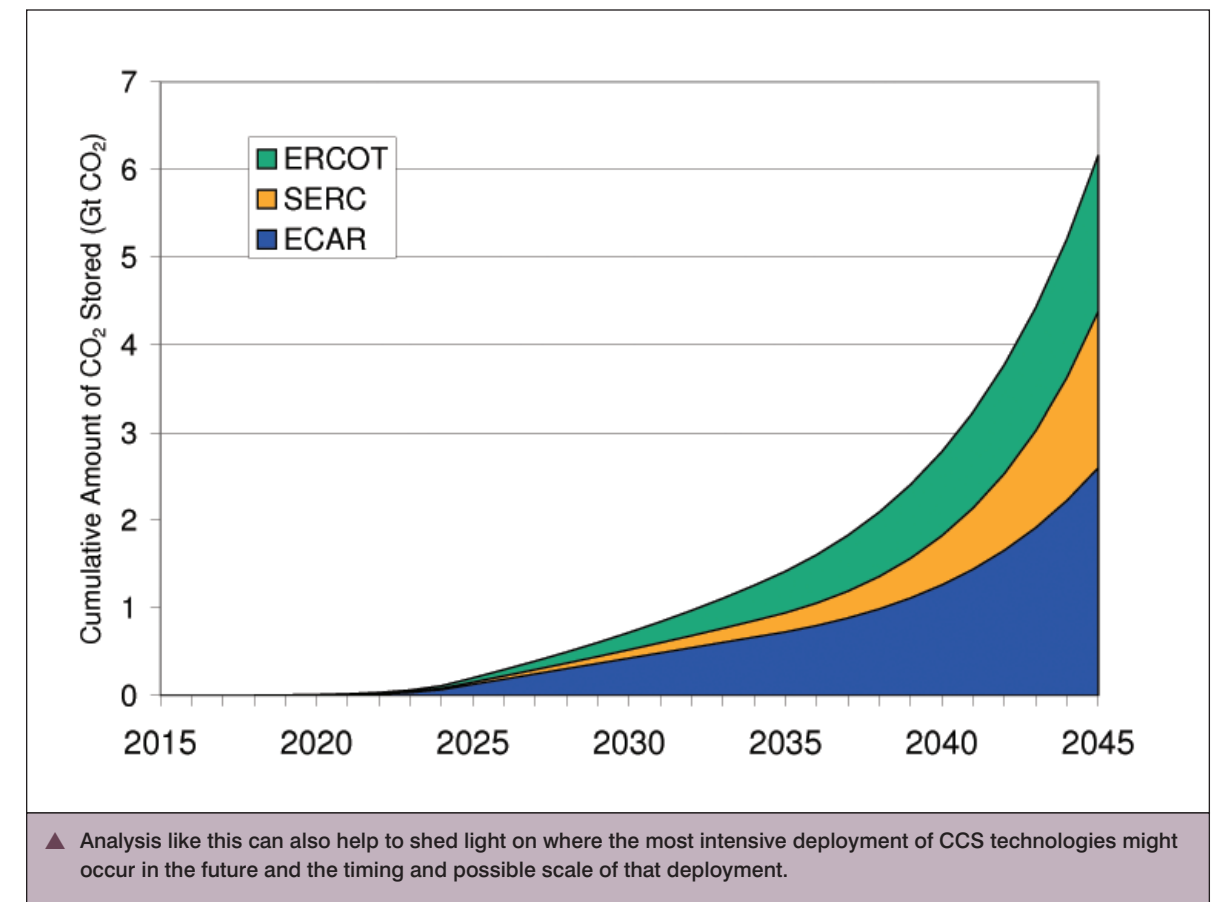
**The major lesson is that CCS technologies are really focused on baseload power production.**

In this scenario, there is a need to deploy over 150 CCS-enabled power plants in just these three regions of the United States. These units would be capable of capturing and storing more than 6 GtCO<sub>2</sub> in regional formations by the middle of this century, as shown in the graph below. But, at this point in time, we lack the physical, human and regulatory infrastructures needed to enable CCS deployment and CO<sub>2</sub> storage at this scale.

Moreover, these are not the only regions that will deploy CCS systems, nor is this a particularly aggressive CCS deployment scenario. Thus, another key finding of GTSP's CCS research is that an important dimension of CCS R&D and early field deployments is to develop tools and techniques to allow CCS to deploy in a wide variety of circumstances. CCS systems must be able to work in more than just ideal settings. The potential large-scale adoption of CCS systems by the

**CCS systems must be able to work in more than just ideal settings.**

electric utilities will depend to some degree upon the continued development of innovative technologies to allow CO<sub>2</sub> storage to be deployed at significant scale where needed, increasing effective storage capacities and CO<sub>2</sub> injection rates.





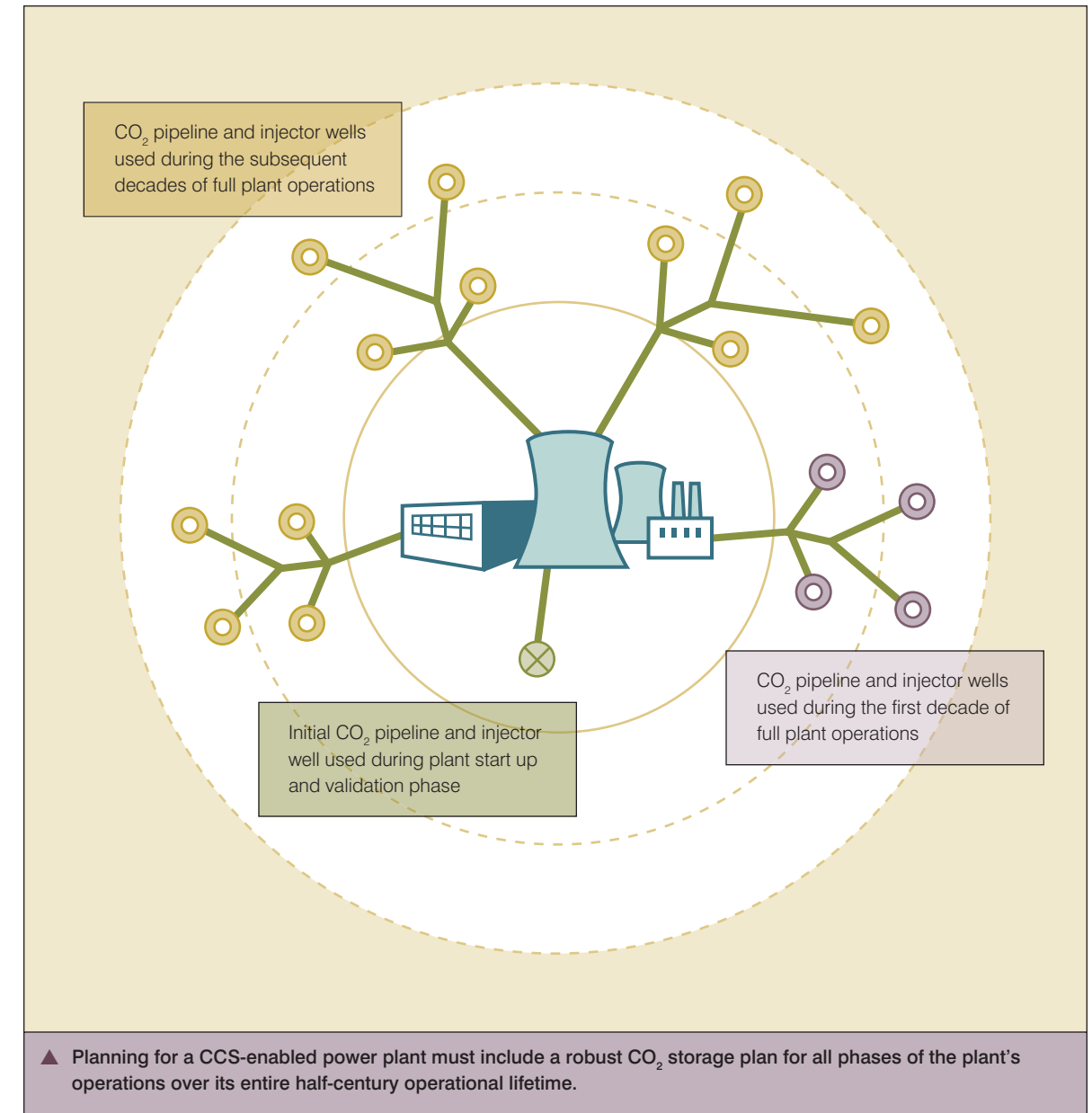
## CCS DEPLOYMENT AT THE PLANT SCALE

Each utility planning new capacity is faced with complex decisions about which fuels and technologies to invest in. Building a new, long-lived capital asset such as a power plant with the expectation of future CO<sub>2</sub> emissions constraints will add new criteria to the already complex processes of siting, construction, and operation of such facilities. New elements involved in a decision to build a CCS-enabled power plant would likely include the following:

- An assessment of how a proposed CCS-enabled power plant will impact the utility's ability to address increasingly stringent local and regional environmental regulations (e.g., regulations to address acid rain or mercury emissions) across the utility's generation fleet.
- The likelihood that the utility will be able to recover some of the costs for the more capital-intensive CCS-enabled power plant in the rate base.
- The likely market price for baseload power in the region and the generation costs for the CCS-enabled plant. That is, will the CCS-enabled plant produce competitively priced electricity in the near to mid term when CO<sub>2</sub> permit prices likely are relatively low?
- The probable scenarios for CO<sub>2</sub> permit prices, especially the price path for CO<sub>2</sub> permits over the life of the CCS-enabled power plant.
- The availability of competencies in operating a CCS-enabled power plant, either within the utility itself or from trusted vendors.
- The kinds of CO<sub>2</sub> separations processes that exist, the ability to scale them to the needed plant capacity, and the compatibility of the capture units to perform reliably around the clock and day after day consistent with being mated to a high-availability baseload power plant.
- The additional time and budget requirements for assessing candidate geologic CO<sub>2</sub> storage reservoirs at prospective power plant sites. This would need to include an assessment of the size, capacity, and physical properties of candidate CO<sub>2</sub> storage reservoirs as well as modeling to begin assessing such practical issues as the number of CO<sub>2</sub> injector wells required to handle the plant's output and whether multiple injection fields will be needed over the lifetime of the power plant (see the drawing on the next page).

- The need to acquire permits and rights-of-way for any needed CO<sub>2</sub> transport pipelines.
- An assessment of the kinds of measurement, monitoring, and verification technologies that are available, required by regulations, and that will work with the specific geologic reservoirs likely to be used to store the power plant's CO<sub>2</sub>.

These and other factors will need to be integrated into planning for a CCS-enabled plant. The timeline on the next pages gives an overview of how various aspects of this type of planning and decision making for CCS-enabled power plants may play out over the lifetime of the power plant and beyond.



**PHASES DURING THE LIFETIME OF A CCS-ENABLED POWER UNIT**

	Pre-Operational Phase (~10 years)					Operational Phase (~40–60 years)		Post-Operational Phase
	Decision to Expand or Replace Generation Capacity	Site and Power Generation System Selection	Pre-construction	Construction		Initial Plant Operations	Full Plant Operations	Plant Decommissioning and Post-Injection Monitoring of Injected CO <sub>2</sub>
<b>Business, Regulatory, and Stakeholder Issues</b>	Initiate process to begin considering various power system options (e.g., IGCC, NGCC, nuclear, wind, etc.) and candidate locations for new plant.	Begin and sustain dialogue with shareholders, regulators, local communities about the decision to proceed with construction of a CCS-enabled power plant. Permitting begins.		Regulatory oversight of construction and verification of compliance with environmental and engineering requirements.		Power plant and its associated CO <sub>2</sub> storage system begin to generate electricity and revenue.	Periodic need to communicate and demonstrate via various filings with regulators and stakeholders that CCS systems are working as expected.	Stakeholder education about post-injection safety and monitoring.  Records maintenance regarding CO <sub>2</sub> that has been injected into deep geologic storage formations.  Compliance with regulation to periodically monitor stored CO <sub>2</sub> .
<b>Power Production</b>		Down-select to a handful of candidate vendors for the power production system.	Select vendors for power plant systems and construction.	Footprint established, first unit and support facilities / infrastructure constructed.		Individual power production trains / units are brought online as they are completed.	All power production units operational.	Power plants are taken offline, and plant facilities are rehabilitated or removed.
<b>CO<sub>2</sub> Storage System</b>		Begin early analysis of site-specific CO <sub>2</sub> storage system design.  Consult existing geological expertise to see if any candidate sites can be quickly ruled out due to known subsurface issues.	Site characterization and injection planning need to begin. Because there are no current vendors offering off-the-shelf CO <sub>2</sub> storage systems, utilities will need to assemble a team of consultants and vendors to create and implement CO <sub>2</sub> storage system's infrastructure.	Injection site wells are complete with wells drilled and supporting above-ground infrastructure such as storage tanks, CO <sub>2</sub> pipeline, and wellhead facilities in place.		Small-scale CO <sub>2</sub> storage likely begins at the first few injection sites to validate CO <sub>2</sub> storage system, allow plant staff to gain familiarity with systems and allow local public and other stakeholders to become more comfortable with CO <sub>2</sub> storage at this site.	Large-scale, continuous CO <sub>2</sub> injection for many decades. As the storage capacity of any given reservoir is consumed, that reservoir and its injector wells need to be safely decommissioned and new storage reservoirs need to be brought online.	CO <sub>2</sub> injection ceases.  Surface CO <sub>2</sub> injection facilities such as pipelines and wellheads are removed.  CO <sub>2</sub> injector wells are plugged and prepared for long-term closure.
<b>Measurement, Monitoring and Verification (MMV)</b>		Solicit and incorporate feedback from stakeholders and regulators to inform design of MMV system.	Subsurface characterization performed to determine optimum injection zones and help decide what kind of MMV system is appropriate and how it should be sited.	Construct MMV systems and perform baseline characterization for system calibration and later comparison.		Routine MMV begins with the first CO <sub>2</sub> injected into deep storage reservoirs.	Continued monitoring of active injection sites. Post-injection monitoring of decommissioned (i.e., filled) storage fields.	Implementation of long-term post-injection monitoring phase begins.

## TO ENABLE THE LARGE-SCALE DEPLOYMENT OF CCS, MUCH NEEDS TO BE DONE...

Utilities and other potential users of CCS systems could be caught between *the potential of CCS technologies* to cost effectively deliver significant and sustained CO<sub>2</sub> emissions reductions as described in numerous technical papers and reports like this one and *the realities of today* where CCS deployment is quite small. The real-world knowledge gained by operating dozens of CCS-enabled facilities will be critical to transforming CCS technologies from their current status as areas of intense cutting-edge research with tremendous potential to accepted technologies that are capable of delivering results in numerous configurations and settings around the world. In order to realize a future in which CCS technologies are accepted, trusted, economic and ordinary technologies, institutions must evolve in a number of spheres: social, political, technical, regulatory, economic, and corporate.

The large-scale deployment of CCS technologies depends upon them becoming accepted, trusted, economic and ordinary technologies.

If large-scale deployment does happen, the following elements will need to be in place.

### CCS Systems Will Work and Be Accepted

**Social, political, and technical spheres:** From governance structures to popular opinion, there will need to be agreement that climate change concerns warrant a limit on cumulative emissions of greenhouse gases, and that a broad portfolio of options is needed.

**Regulatory sphere:** Governments will need to establish climate policies, legislation, and regulations that recognize CCS technologies on an equal footing with other mitigation strategies.

**Economic and corporate spheres:** Decision-makers will require a stable planning environment. They will need to know that climate policies are here to stay and that the value of carbon will rise to a level that requires investment in capital-intensive emissions-abatement technologies such as CCS systems.

### CCS Systems Will Make Economic Sense

**Social, political, and technical spheres:** Consumers must be willing to purchase products that come from CCS-enabled systems, and the technology works well and efficiently.

**Regulatory sphere:** In emissions trading systems, CCS-derived credits will need to be equivalent to other emissions offsets, including their ability to be banked and traded.

**Economic sphere:** CCS technologies must be economically competitive with other strategies for meeting corporate emissions reduction targets, including suitability for use with the corporate business models and industry-specific market circumstances such as regional power production.

**Corporate sphere:** Companies will need to understand CCS technologies and the likely future regulatory environment well enough to see a prospective CCS-enabled unit as being profitable over a significant period of its operational lifetime, thus justifying the investment and acceptance of any risk.

### CCS Systems Will Be Trusted

**Social and political spheres:** The general public will need to understand and accept that each technology employed to address climate change has strengths and weaknesses.

**Technical sphere:** CCS technologies, including those used for MMV, must have an established track record of success in the field that clearly demonstrates their ability to meet safety and efficacy standards.

**Regulatory sphere:** Regulations must contain accepted protocols and standards for geologic site characterization and selection and for the safe and effective operations of CCS systems, including the frequency of measurement and monitoring for stored CO<sub>2</sub>. Computer models and simulation tools will need to be developed and accepted by industry, regulators, and other stakeholders as valid means for qualifying prospective CO<sub>2</sub> storage sites and for predicting the movement of stored CO<sub>2</sub>.

**Economic sphere:** Financial markets and investment banks must understand CCS systems well enough to provide financing for CCS-enabled infrastructure at rates comparable to those extended to other large-scale emissions-abatement options.

**Corporate sphere:** Companies will need to either evolve a set of internal CCS core competencies or be able to work with vendors to construct and operate the CCS aspects of their plants.

### CCS Systems Will Be Ordinary

**Social and political spheres:** CCS installations must draw no more attention than any other large-scale emission abatement installation.

**Technical sphere:** CCS-enabled power plants, hydrogen production facilities, and steel mills must safely operate around the clock at hundreds or thousands of facilities in the United States and thousands or tens of thousands of facilities globally. There will need to be standardized parts, a cadre of trained professionals, established rules and regulations, and codified industry best practices that enable and support this large-scale deployment.

**Economic and regulatory spheres:** Liability stemming from CCS operations must be reasonably defined and bounded. There must be general agreement that the risk of not addressing climate change outweighs the risk of deploying and operating CCS-enabled systems.

## KEY CCS R&D AND KNOWLEDGE GAPS

A significant challenge is how to move quickly from today's important but nonetheless modest CCS deployment to the massive global deployments needed to make a substantive difference in addressing climate change. The next decade represents a critical window with which to amass needed operational experience with CCS technologies in real-world conditions. Planned CCS field demonstrations, a handful of early commercial CCS projects and continued laboratory-based research are all needed to advance the state of the art across a number of CCS-related areas such as the following:

### R&D Needs for CCS Systems Integration

► **Obtain more experience with end-to-end CCS systems in real-world conditions.** Simply moving forward with the planned commercial and research projects listed at the beginning of this section and operating these as systems under real-world conditions will be enormously beneficial and tell us much about where the key CCS R&D needs lie. The planned public-private FutureGen project, in itself, represents a significant and much-needed contribution to the technical knowledge likely to be gained from these projects.

► **Increase our understanding of the role of biomass-fired CCS energy systems in addressing climate change.** Developing a better understanding of the potential synergies and costs associated with integrated biomass energy systems that capture and store their CO<sub>2</sub> in deep geologic formations is important, as the combination of these two technologies potentially holds the key to one of the few ways to remove CO<sub>2</sub> that has already been emitted to the atmosphere.

## R&D Needs for CO<sub>2</sub> Capture

- ▶ **Continually improve capture technologies**—not only in terms of cost, energy penalty, and efficiency, but also in the percentage of the CO<sub>2</sub> stream that is effectively captured. This effort to improve capture technologies should be seen as a process and not as something that has a specific endpoint (i.e., the goal is not to reduce capture costs to some predefined level and then abandon this area of research). If the efficiency of capture systems is not continually advanced, then the options are limited for addressing climate change and ensuring that economies can continue to draw upon a diverse set of energy resources and technologies.
- ▶ **Tune capture technologies to specific industrial applications**—for example, in the cement industry, capture systems will need to be developed and demonstrated for that specific application.

## R&D Needs for CO<sub>2</sub> Transport, Storage and Injection

- ▶ **Survey global candidate CO<sub>2</sub> reservoirs**. Since the availability and distribution of this CO<sub>2</sub> storage resource directly impacts the likely evolution of many nations' future energy infrastructure, this is a near-term, high-priority task. This is particularly crucial in rapidly developing nations such as China and India. Helping developing nations site their new generation capacity while giving forethought to potential future deployment of CCS will allow them to avoid stranding those assets should CCS deployment become a reality.

- ▶ **Increase our understanding of the behavior of CO<sub>2</sub> in the subsurface**. Improved and widely accepted reservoir models are needed to help examine commercial-scale CO<sub>2</sub> storage scenarios and help predict CO<sub>2</sub> movement through deep geologic formations.
- ▶ **Improve the resolution of data on candidate geologic reservoirs**. Much of the data on CO<sub>2</sub> storage reservoirs and their potential capacities effectively treat very large geologic formations as if they were uniform across an entire basin. We know this is not the case. More detailed data at a finer scale of resolution would likely provide a more detailed and precise CO<sub>2</sub> supply cost curve, and would allow us to understand the heterogeneities that will likely impact the deployment of CCS.
- ▶ **Improve understanding of the production and cost dynamics of CO<sub>2</sub>-driven enhanced hydrocarbon recovery related to long-term CO<sub>2</sub> storage**. Much of the analysis of CO<sub>2</sub>-driven enhanced hydrocarbon recovery assumes constant incremental oil and natural gas recovery rates (as well as constant rates of CO<sub>2</sub> injection) for all years of injection into a depleted oil field or deep coal seam. However, this is not the case. In practice, production response to CO<sub>2</sub> injection is rarely immediate, but rather increases over a number of years before peaking and then declining. This could have a significant impact on the true costs of CO<sub>2</sub> storage options based on CO<sub>2</sub>-driven enhanced hydrocarbon recovery.
- ▶ **Create innovative and cost-effective CO<sub>2</sub> transport and injection strategies**. These strategies are necessary to create systems for allowing CCS deployment in the widest set of possible circumstances. The potential deployment of CCS technologies is so large that we will not have the luxury of selecting only the most ideal locations for CO<sub>2</sub> storage. For example, advances in the ability to link smaller storage fields would help tailor EOR- and ECBM-based storage strategies to the needs of large CCS-enabled power plants, which will require massive amounts of storage capacity. Technologies for drilling horizontal wells or for injecting into two or more vertically stacked reservoirs would help improve the overall economics of CO<sub>2</sub> storage by reducing the costs of required capital, driving down the per-ton cost of storage.

- ▶ **Craft a strategy for remediating CO<sub>2</sub> that does not remain in the target formation**. Remediation options must be identified and prescribed for dealing with CO<sub>2</sub> that moves out of its target injection formation and that presents a sufficient concern to warrant remedial steps. What works for one scenario might not necessarily be applicable to another scenario, implying a need to understand the suite of remediation options available and the circumstances under which each would be used.

## R&D Needs for Measurement, Monitoring, and Verification of Stored CO<sub>2</sub>

- ▶ **Continue to develop new MMV technologies**. Off-the-shelf MMV technologies exist that can be applied to ensure safe and effective storage of injected CO<sub>2</sub> in certain classes of formations and under specific circumstances. But a broader and much more advanced set of MMV technologies is required to meet the needs of a potential future large-scale deployment of CCS systems with CO<sub>2</sub> being stored in many different kinds of formations and circumstances. New MMV technologies need to be invented and the cost, performance, and other operating characteristics of existing MMV technologies need to be improved. In addition to this laboratory and field effort to create new and better MMV technologies, prospective industrial users and regulators also need to create a shared vision of what it means in practice to measure, monitor, and verify CO<sub>2</sub> that has been injected into the deep subsurface.
- ▶ **Begin to evolve a better understanding of tailored site-specific MMV systems that could be deployed to meet the needs of CCS-enabled facilities**. Potential users of CCS systems will require a system-level description of packaged MMV systems and how they would deploy under a set of real-world scenarios. For example, what configuration of which set of technologies would be most appropriate for a 1,000 MW coal plant contemplating CO<sub>2</sub> storage in a deep saline formation 1,000 meters below the surface and with an average thickness of 100 meters? MMV systems can then be brought into a larger decision framework

The next decade represents a critical window with which to amass needed operational experience with CCS technologies in real-world conditions.

about the type and locations of specific facilities. In addition, different MMV packages could be more or less applicable during various stages of a CCS project's lifetime. Researchers need to answer these kinds of operational questions so that more informed and holistic decisions about CCS systems can be made.

- ▶ **Establish a base of empirical data to facilitate the development of MMV systems and regulations**. Field data and direct experiential knowledge will inform regulatory positions and attitudes about reasonable leakage rates from deep geologic CO<sub>2</sub> storage formations across a wide variety of formation classes and scenarios. These data will directly impact regulations that will drive how MMV systems are deployed in practice.

# APPENDIX 1 Acronyms and Abbreviations

<b>bbbl</b>	Barrel, as in barrels of oil	<b>MMV</b>	Measurement, Monitoring and Verification
<b>CCS</b>	Carbon Dioxide Capture and Storage	<b>MtCO<sub>2</sub></b>	10 <sup>6</sup> tons (a megaton) of CO <sub>2</sub> = million tons of CO <sub>2</sub>
<b>CO<sub>2</sub></b>	Carbon Dioxide	<b>MW</b>	Megawatt
<b>CT</b>	Combustion Turbine	<b>NGCC</b>	Natural Gas Combined Cycle power plant
<b>DSF</b>	Deep Saline Formation	<b>NGCC+CCS</b>	Natural Gas Combined Cycle power plant that also includes all of the necessary systems needed for Carbon Dioxide Capture and Storage
<b>ECAR</b>	East Central Area Reliability Coordination Agreement	<b>NO<sub>x</sub></b>	Nitrogen Oxides (formed during the combustion of fossil fuels)
<b>ECBM</b>	Enhanced Coalbed Methane Recovery	<b>O&amp;M</b>	Operating and Maintenance
<b>EOR</b>	Enhanced Oil Recovery	<b>PC</b>	Pulverized Coal power plant
<b>ERCOT</b>	Electric Reliability Council of Texas, Inc.	<b>ppm</b>	Parts Per Million
<b>ft bgs</b>	Feet Below Ground Surface, a measure of depth	<b>psi</b>	Pounds per square inch
<b>GHG</b>	Greenhouse Gas	<b>SCADA</b>	Supervisory Control and Data Acquisition System
<b>GtCO<sub>2</sub></b>	10 <sup>9</sup> tons (a gigaton) of CO <sub>2</sub> = 10 <sup>15</sup> grams of CO <sub>2</sub> (a petagram) = billion tons of CO <sub>2</sub>	<b>SERC</b>	Southeastern Electric Reliability Council, Inc.
<b>GTSP</b>	Global Energy Technology Strategy Program	<b>SO<sub>2</sub></b>	Sulfur Dioxide (formed during the combustion of fossil fuels)
<b>IGCC</b>	Integrated Gasification Combined Cycle power plant	<b>tCO<sub>2</sub></b>	Ton of CO <sub>2</sub>
<b>IGCC+CCS</b>	An Integrated Gasification Combined Cycle power plant that also includes all of the necessary systems needed for Carbon Dioxide Capture and Storage	<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
		<b>U.S.</b>	United States of America

## APPENDIX 2 Notes and References

The cover photos were taken by JJ Dooley during the spring of 2003 at the site of the Ohio River CO<sub>2</sub> Storage Project. This Battelle-led field research project—sponsored by the United States Department of Energy (DOE), American Electric Power (AEP), BP, Ohio Coal Development Office, Schlumberger, Battelle, and Pacific Northwest National Laboratory—was the world’s first geologic CO<sub>2</sub> storage assessment conducted at a modern operational coal-fired power plant, AEP’s Mountaineer power plant. This project was designed to understand the CO<sub>2</sub> storage potential at this power plant and in the greater Ohio River Valley Region, which contains one of the world’s largest concentrations of large CO<sub>2</sub> point sources that could be candidates for adopting CCS technologies in the future. Project participants completed a 9,108 ft. exploratory well, and in 2006 the data from this well are being used to conduct reservoir modeling and risk assessment, and to prepare designs and plans for a potential field-scale injection and monitoring project. To learn more about the research conducted through this project, see N. Gupta and J.J. Dooley, “The Ohio River Valley Storage Project,” *Greenhouse Issues*, no. 77 (Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme [IEA GHG], March 2005).

This report adopts the conventions of the CCS technical community which expresses values in U.S. dollars per ton of CO<sub>2</sub> (\$/tCO<sub>2</sub>) and in millions of tons of CO<sub>2</sub> (MtCO<sub>2</sub>) or billions of tons of CO<sub>2</sub> (GtCO<sub>2</sub>). Cost data can be converted to dollars per ton of carbon (\$/tC) by multiplying by 3.644 and mass data can be converted to the carbon (C) based units of the climate change technical community by dividing the mass expressed in CO<sub>2</sub>-based units by 3.664.

This report makes frequent use of a very large measure of mass known as a “gigaton.” A gigaton of CO<sub>2</sub> (GtCO<sub>2</sub>) is a standard measure for scientists and policy makers familiar with carbon management, yet for other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, “A Gigaton Is...,” PNWD-3299 (College Park, MD: Joint Global Change Research Institute, Battelle Pacific Northwest Division, July 2003).

**Section 1 notes:** As of early 2006, 189 nations, including the United States, have ratified the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which states as its goal, “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” (For more information on the UNFCCC, please see [http://unfccc.int/essential\\_background/convention/items/2627.php](http://unfccc.int/essential_background/convention/items/2627.php)). While there is general agreement that stabilization of greenhouse gas (GHG) concentrations is the best way to frame decisions about addressing climate change, there is no scientific consensus yet regarding the ideal levels of atmospheric concentrations or the potential impacts associated with higher concentrations. CO<sub>2</sub> is the most important GHG in terms of its contribution to climate change. At the beginning of the Industrial Revolution concentrations of CO<sub>2</sub> in the atmosphere were approximately 270 parts per million (ppm). Currently, CO<sub>2</sub> concentrations are around 370 ppm and rising. Whether the appropriate stabilization level is as low as 450 ppm or as high as 750 ppm, the goal of stabilization carries with it requirements to produce and sustain deep reductions in GHG emissions over the



course of this century. See, for example, T.M.L. Wigley, R. Richels and J.A. Edmonds, "Economic and Environmental Choices in the Stabilization of Atmospheric CO<sub>2</sub> Concentrations," *Nature* 379, 6562 (1996): 240-243.

Because the trapping mechanisms are different in coal-based CO<sub>2</sub> storage projects, CO<sub>2</sub> is not necessarily injected as a supercritical fluid, which means that the pressure, temperature, and depth criteria listed here do not necessarily apply for coal-based CO<sub>2</sub> storage projects. However, these criteria can still serve as useful *guidelines* for coal-based CO<sub>2</sub> storage.

The schematic of various candidate CO<sub>2</sub> storage formations has been used with permission from Dr. Peter Cook, Chief Executive of the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC).

The theoretical CO<sub>2</sub> storage capacities presented for the world and the United States represent first-order estimates based on available data. These estimates will likely evolve over time as more research and a more thorough and consistent methodology is applied globally. The methodology and subsequent analyses that led to these first-order geologic CO<sub>2</sub> storage capacity estimates can be found in the following publications:

- J.J. Dooley, S.H. Kim, J.A. Edmonds, S.J. Friedman and M.A. Wise, "A First-Order Global Geologic CO<sub>2</sub> Storage Potential Supply Curve and Its Application in a Global Integrated Assessment Model," in *Greenhouse Gas Control Technologies, Volume I*, eds. E.S. Rubin, D.W. Keith and C.F. Gilboy (Elsevier Science, 2005).
- J.J. Dooley and S.J. Friedman, "A Regionally Disaggregated Global Accounting of CO<sub>2</sub> Storage Capacity: Data and Assumptions," PNWD-3431 (College Park, MD: Joint Global Change Research Institute, Battelle Pacific Northwest Division, May 2004).
- R.T. Dahowski, J.J. Dooley, C.L. Davidson, S. Bachu and N. Gupta, *Building the Cost Curves for CO<sub>2</sub> Storage: North American*, Technical Report 2005/3 (Cheltenham, UK: IEA GHG, 2005).

- C.L. Davidson, H.T. Schaefer and R.T. Dahowski, "A First-Order Assessment of CO<sub>2</sub> Storage Capacity in U.S. Basalt Formations," in *Proceedings of the Fourth Annual Conference on Carbon Capture and Sequestration* (Alexandria, VA: May 2-5, 2005) (also available as PNNL-SA-45124, Pacific Northwest National Laboratory, Richland, WA).

Definitions of the principal trapping mechanisms associated with deep geologic CO<sub>2</sub> storage:

- Hydrodynamic trapping: involves free-phase CO<sub>2</sub> being trapped beneath a caprock which has low permeability—that is, the CO<sub>2</sub> cannot flow through the caprock, so it remains in place.
- Dissolution trapping: occurs when the CO<sub>2</sub> dissolves into the formation fluids (oil, gas, and saline water).
- Mineralization-based trapping: When this dissolved CO<sub>2</sub> reacts with minerals in the rock, other solutes in the formation fluids, or the formation fluids themselves, it sometimes forms stable minerals called carbonates in a process called mineralization. This is the most permanent form of trapping, since the CO<sub>2</sub> has been chemically incorporated into nonreactive minerals, and can no longer enter the atmosphere without undoing those chemical reactions.
- Chemical adsorption in coals: The matrixed surface of coals is often covered with methane molecules, and because the chemical bonds holding the methane onto the coal would prefer to have CO<sub>2</sub> instead of methane, the presence of CO<sub>2</sub> causes the methane to be swapped out for the carbon dioxide molecules. The degree to which CO<sub>2</sub> is preferentially adsorbed onto the surface of the coal can vary, with some coals accepting several more CO<sub>2</sub> molecules for each methane molecule released.

The three pictures showing microscopic thin sections of rock core samples are taken from the AEP-1 deep well drilled at AEP's Mountaineer Plant during 2003 (see the first note in this appendix). The images illustrate the nature of caprocks and storage reservoirs. Visible pore space in the rock thin sections is shown in blue. The top photo shows the Well Creek Shale, an impermeable caprock with essentially no pore space, at a depth of 7125 ft. The middle photo is of the Rose Run

Sandstone, a potential storage reservoir at a depth of 7771 ft. with a moderate amount of pore space. The bottom image is of a porous interval of the Rose Run Sandstone at a depth of 7763.5 ft, that is considered an excellent candidate for CO<sub>2</sub> storage. Details of the geology at this site can be found in N. Gupta, P. Jagucki, J. Sminchak, D. Meggyesy, F. Spane, R.S. Ramakrishnan and A. Boyd, "Determining Carbon Sequestration Reservoir Potential at a Site-Specific Location with the Ohio River Valley Region," in *Greenhouse Gas Control Technologies, Volume I*, eds. E.S. Rubin, D.W. Keith and C.F. Gilboy (Elsevier Science, 2005).

The schematic diagram depicting the geology and test well design is from the AEP-1 deep well drilled at AEP's Mountaineer Plant during 2003 (see the first note in this appendix). The schematic shows the major geologic layers, including caprocks and potential injection zones, observed in the well. It also shows the completion of the well down to a depth of 6285 ft using multiple carbon steel casings and a combination of regular and CO<sub>2</sub>-resistant cements. As of early 2006, the bottom 2800 ft. of this well are currently without casing. This additional casing, injection tubing, and related equipment will be installed once a final decision to proceed with an injection and monitoring phase is undertaken. Details of site assessment can be found in Gupta et al., "Determining Carbon Sequestration."

For more on the screening analysis for CCS infrastructure seismic risk, please see C.L. Davidson, R.T. Dahowski and K.P. Saripalli, "Tectonic Seismicity and the Storage of Carbon Dioxide in Geologic Formations," in *Greenhouse Gas Control Technologies, Volume II*, eds. M. Wilson, T. Morris, J. Gale and K. Thambimuthu (Elsevier Science, 2005).

Our most recent published work focusing on the economic considerations of leakage can be found in J.J. Dooley and M.A. Wise, "Potential Leakage from Geologic Sequestration Formations: Allowable Levels, Economic Considerations, and the Implications for Sequestration R&D," in *Proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies*, eds. J. Gale and Y. Kaya (Amsterdam: Pergamon, 2003).

The example of a seismic survey showing deep-seated faulting in geologic formations has been provided by Mr. William Rike, Consulting Geologist, Galloway, Ohio, and is taken from a survey in the subsurface

geologic feature known as the Rome Trough in West Virginia. The survey shows a deep normal fault through the Rome Trough structure, where sedimentary rock formations thicken to over 15,000 ft deep in the Appalachian Basin.

**Section 2 notes:** The worldwide regional estimates of CO<sub>2</sub> storage capacity presented here are taken from a recent GTSP-supported review of the published literature. We see these estimates as a first-order global CO<sub>2</sub> storage capacity assessment and expect that as more field research is conducted the precision of these estimates will improve. See Dooley and Friedman, "A Regionally Disaggregated Global Accounting."

The focus for the analysis is on sources that emit at least 100,000 tons of CO<sub>2</sub> per year (100 ktCO<sub>2</sub>/yr), which represents a minimum size threshold below which it is unlikely that the significant capital investments needed to employ CO<sub>2</sub> capture technologies would prove to be economic.

A much more detailed analysis of CO<sub>2</sub> storage capacity requirements and availability for various countries can be found in J.A. Edmonds, J.J. Dooley, S.H. Kim, S.J. Friedman and M.A. Wise, "Technology in an Integrated Assessment Model: the Potential Regional Deployment of Carbon Capture and Storage in the Context of Global CO<sub>2</sub> Stabilization," in *Human-Induced Climate Change: An Interdisciplinary Perspective* (Cambridge: Cambridge University Press, 2006).

Much of the data here on large CO<sub>2</sub> point sources and candidate geologic storage formations within the United States comes from a report that was coauthored with colleagues at other institutions and supported by the International Energy Agency's Greenhouse Gas R&D Programme. Please see Dahowski, et al., "Building the Cost Curves." Modifications made to the data following publication of the report include significantly reducing the estimated CO<sub>2</sub> emissions for all U.S. gas processing plants (based on indications that initial estimates were highly overstated) and halving the estimated storage capacity potential in U.S. deep unmineable coal seams as previous estimates appeared to be far too optimistic, given the state of development of coal seam storage and CO<sub>2</sub>-ECBM recovery. The estimates of the CO<sub>2</sub> storage capacity of North American deep basalt formations can be found in Davidson et al., "A First-Order Assessment."

The data on the global distribution of CO<sub>2</sub> point sources includes the modifications noted above for U.S. natural gas processing facilities and is primarily based upon Dahowski et al., “Building the Cost Curves” as well as periodic updates to the following dataset: International Energy Agency’s Greenhouse Gas R&D Programme, 2002, Building the Cost Curves for CO<sub>2</sub> Storage, Part 1: Sources Of CO<sub>2</sub>, Report Number PH4/9. Note that similar adjustments to the non-U.S. gas processing CO<sub>2</sub> emissions estimates were not made and therefore the estimates shown here for other regions of the world reflect higher than likely global emissions from this sector.

**Section 3 notes:** More detailed information on our research into the cost of CO<sub>2</sub> capture for various power plants and industrial facilities can be found in:

- N. Mahasenan and D.R. Brown, “Beyond the Big Picture: Characterization of CO<sub>2</sub>-Laden Streams and Implications for Capture Technologies,” in *Greenhouse Gas Control Technologies, Volume II*, eds. M. Wilson, T. Morris, J. Gale and K. Thambimuthu (Elsevier Science, 2005).
- N. Mahasenan, R.T. Dahowski and C.L. Davidson, “The Role of Carbon Dioxide Capture and Storage in Reducing Emissions from Cement Plants in North America,” in *Greenhouse Gas Control Technologies, Volume I*, eds. E.S. Rubin, D.W. Keith and C.F. Gilboy (Elsevier Science, 2005).

Our research on the need to improve the efficiency of CO<sub>2</sub> capture can be found in M.A. Wise and J.J. Dooley, “Modeling CO<sub>2</sub> Capture Efficiency: Implications of Alternative Specifications,” PNWD-3429 (College Park, MD: Joint Global Change Research Institute, Battelle Pacific Northwest Division, May 2004).

Key publications examining the cost of CO<sub>2</sub> transport and storage, including the possible value from enhanced CO<sub>2</sub>-driven hydrocarbon recovery are Dahowski et al., “Building the Cost Curves,” and the following:

- R.T. Dahowski and J.J. Dooley, “Carbon Management Strategies for U.S. Electricity Generation Capacity: a Vintage-Based Approach,” *Energy* 29, 9-10 (2004): 1589-1598.
- R.T. Dahowski, J.J. Dooley, C.L. Davidson and N. Mahasenan, “Regional Differences in Carbon Dioxide Capture and Storage Markets within the United States,” in *Greenhouse Gas Control Technologies, Volume II*, eds. M. Wilson, T. Morris, J. Gale and K. Thambimuthu (Elsevier Science, 2005).
- J.J. Dooley, R.T. Dahowski, C.L. Davidson and M.A. Wise, “CO<sub>2</sub> Transport and Storage Costs and their Impact on the U.S. Electric Utility Industry’s Carbon Management Investment Decisions,” presented at EPRI’s Ninth Annual Global Climate Change Research Seminar (Washington, DC: June 2, 2004), also available as Report No. PNWD-SA-6513, Joint Global Change Research Institute, Battelle Pacific Northwest Division, College Park, MD).

As noted in the body of the report, our work strongly suggests that in an area like North America, which has a very large and widely distributed CO<sub>2</sub> storage resource base, over the course of this century the *long-term average cost* of CO<sub>2</sub> transport and storage should stay below the level of approximately \$12–\$15/tCO<sub>2</sub>. Some projects will surely experience higher transport and storage costs than this and others will undoubtedly face lower costs. But this \$12–15/tCO<sub>2</sub> represents a realistic estimate of the upper bound on transport and storage costs that most firms will likely face.

An estimate of the cost of measurement, monitoring and verification of CO<sub>2</sub> that has been stored in deep geologic formations can be found in our report L. Smith, N. Gupta, B. Sass and T. Bubenik, *Carbon Dioxide Sequestration in Saline Formations—Engineering and Economic Assessment, Final Technical Report*, prepared for DOE’s National Energy Technology Laboratory, Contract No. DE-AC26-98FT40418.

The net cost of employing CCS within the United States was computed by employing the source-reservoir pairing method presented in Dahowski et al., “Building the Cost Curves.” A series of pairwise cost calculations was used to determine the levelized cost per ton of CO<sub>2</sub> capture, transport, and storage into geologic storage formations for existing large, stationary point sources of CO<sub>2</sub>. The crucial component of this analysis involves calculating pairwise solutions matching each source with its lowest cost, globally optimized storage option (i.e., finding the best option taking the entire system into account). Cost curves were computed by solving for the best option for each stationary source subject to a set of constraints, as follows:

- First, due to the close proximity of the large majority of CO<sub>2</sub> point sources in the United States to candidate storage reservoirs, a maximum 100-mile search radius was imposed, such that each source was able to consider selecting any potential storage reservoirs within a distance of 100 miles. This resulted in a set of CO<sub>2</sub> storage options for each source for which the net costs were determined by summing individual capital and operating costs for capture, compression, dehydration, pipeline transport, and storage, including injection, infrastructure, and measurement, monitoring, and verification, less any revenue that might be generated by recovery of incremental oil or coalbed methane as a result of CO<sub>2</sub> injection.
- Costs for capture, compression, and dehydration were estimated based on key parameters such as type of plant, CO<sub>2</sub> emissions rate, and purity of the produced CO<sub>2</sub>.
- Transport costs are based on the distance between each source and candidate storage reservoir and adjustments for differences in terrain and routing requirements.
- Storage costs vary for each individual reservoir and are based on a number of different parameters including type of reservoir, depth, and injectivity. For depleted oil fields that appear favorable for enhanced oil recovery, or coal seams expected to release methane as a result of CO<sub>2</sub> injection, the revenue associated with the hydrocarbon recovery

is estimated based on individual recovery rates for each formation (in barrels of oil or cubic feet of methane recovered per ton of injected CO<sub>2</sub>), along with the value of the recovered oil or gas.

- Summing each of these resulting cost components and subtracting the value of any recovered oil or gas arrives at a total net CCS cost, which is then levelized by applying an appropriate fixed charge rate for the project. Because each storage formation contains a finite amount of potential lifetime storage capacity, issues of reservoir filling and competition for low-cost storage are also explicitly accounted for.

**Section 4 notes:** The rationale for the particular accounting of the CCS field demonstration projects presented here is largely based upon our assessment of whether the project’s primary motivation was the application of CO<sub>2</sub> storage technologies as a means of addressing climate change. It is for this reason alone that many commercial CO<sub>2</sub>-driven enhanced oil recovery projects such as those in West Texas are not listed. While these commercial projects might confer some incidental climate mitigation benefit, that is not the primary motivation for these commercial efforts. Interested readers can consult C.L. Davidson and J.J. Dooley, “The State of CO<sub>2</sub> Capture and Storage Field Experimentation and Deployment: Summer 2005,” PNNL-15296 (College Park, MD: Joint Global Change Research Institute, Pacific Northwest National Laboratory, August 2005). The projections of possible global and U.S. cumulative CO<sub>2</sub> storage volumes are taken from J.J. Dooley, C.L. Davidson, M.A. Wise and R.T. Dahowski, “Accelerated Adoption of Carbon Dioxide Capture and Storage within the United States Electric Utility Industry: the Impact of Stabilizing at 450 ppmv and 550 ppmv,” in *Greenhouse Gas Control Technologies, Volume I*, eds. E.S. Rubin, D.W. Keith and C.F. Gilboy (Elsevier Science, 2005).

The impact that the economics of electricity dispatch might have on the deployment of CCS systems within the electric power sector and within specific regions of the United States is a rapidly evolving focus of our research. Further explanation regarding the electricity dispatch modeling follows, along with a list of our initial publications in this area.

- The specific policy modeled here assumes a carbon tax that begins in 2015 at \$12/tCO<sub>2</sub> and increases at a real, inflation-adjusted rate of 2.5% per year, reaching \$25/tCO<sub>2</sub> in 2045. This carbon tax is applied uniformly across the three regions and results in electric utility CO<sub>2</sub> emissions in 2045 approximately equal to 2005 levels.
- Investment in new nuclear and renewable power generation is difficult to model based purely on optimal investment economics, as decisions to invest in these systems often include a significant aspect of non-economic consideration (e.g., government policies, environmental concerns, or social considerations such as public acceptability) that affect their deployment. Therefore we have adopted what we believe to be aggressive but realistic deployments for nuclear and renewable energy technologies and assume explicitly that these critical technologies will play major roles in responding to a CO<sub>2</sub> emissions policy. Specifically for this study, we assume that nuclear growth is sufficient to maintain its share of total capacity in each region starting in 2015. Expansion of renewables is sufficient to reach a minimum of 10% of regional capacity by 2045 or to maintain its current share if higher. Different expansion rates for nuclear and renewables would certainly alter the CO<sub>2</sub> emissions paths, but the decision to invest in CCS for fossil power would still be based on the relative economics of the technology and emissions price and would be relatively unaffected.
- Fuel prices (gas, oil, and coal) for the period up to 2025 were taken from EIA AEO 2005 (U.S. Department of Energy, Energy Information Agency, *Annual Energy Outlook 2005 with Projections to 2025*, DOE/EIA-0383, 2005, January 2005). Fuel prices for 2025–2045 were extrapolated from the EIA AEO 2005 data covering the period up to 2025. In this scenario, natural gas prices stay above \$5/mmBtu for much of the period and increase steadily beyond \$6/mmBtu by 2015 (AEO 2005 Restricted Natural Gas Supply Case). The assumed natural gas prices—while lower than recent peak spot prices—are much higher than the average gas price of the past decade and are sufficiently high that the economic choice for many electric generation regions is to build new

coal plants, even in the face of a carbon policy such as this. As the carbon permit prices start to escalate, many older natural gas and oil steam plants begin to retire. IGCC+CCS only starts to deploy in earnest in this scenario in the 2025–2035 period as the carbon permit prices begin to escalate further. The large-scale adoption of natural-gas-fired combined cycle power plants with CCS (NGCC+CCS) would require higher carbon permit prices than assumed in this scenario. Assumed coal prices are slightly higher than those in 2005 and oil prices are assumed to stay at approximately \$40/bbl or above during the entire period (AEO 2005 High Case B).

- In building region-specific CO<sub>2</sub> storage supply curves, we have sought to account for the fact that some facilities with higher-purity CO<sub>2</sub> streams (hence, with lower-cost options for CO<sub>2</sub> capture, e.g., natural gas processing facilities, ammonia plants) exist in these regions and may likely begin capturing and storing their CO<sub>2</sub> at an earlier date when carbon permit prices are still relatively low. By deploying earlier, these lower-cost CO<sub>2</sub> capture facilities would tend to reduce the amount of EOR and ECBM-based CO<sub>2</sub> storage options that new CCS-enabled power plants are able to access when they begin capturing CO<sub>2</sub>. For the three regions modeled here, this reduction in the amount of value-added CO<sub>2</sub> storage capacity available for the electric utility industry is most pronounced in the ERCOT region.

Readers who are interested in the core methodologies and tools used to perform this electric utility dispatch modeling should consult Dooley et al., “Accelerated Adoption”; and Dahowski et al., “Regional Differences.”

Although they were not explicitly addressed in this report, we have looked at public attitudes regarding CCS deployment. The overwhelming conclusion from this work is that the public knows little about CCS and therefore there is an opportunity to positively shape public opinion about the need for and benefits of the possible large-scale deployment of CCS technologies. Readers interested in learning more may consult J.A. Bradbury and J.J. Dooley, “Who’s Talking? What Are the Issues? The Media’s Portrayal of Carbon Dioxide Capture and Sequestration in the United States,” in *Greenhouse Gas Control Technologies, Volume II*, eds. M. Wilson, T. Morris, J. Gale and K. Thambimuthu (Elsevier Science, 2005).

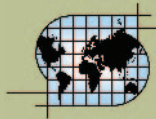
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