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

GTSP
Global Energy Technology Strategy Program

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April 2006

Printed in the United States of America

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_2 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_2 storage reservoirs and the process by which CO_2 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_2 storage reservoirs and provide the principal means of trapping the injected CO_2 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_2 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 ($GtCO_2$), the most important greenhouse gas. Currently, the world's economic systems annually emit approximately 26 $GtCO_2$ 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_2 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 $GtCO_2$.

However, to stabilize CO_2 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_2 emissions over the course of this century total no more than 2,600 to 4,600 $GtCO_2$. The need to avoid the release of thousands of gigatons of CO_2 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_2 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.

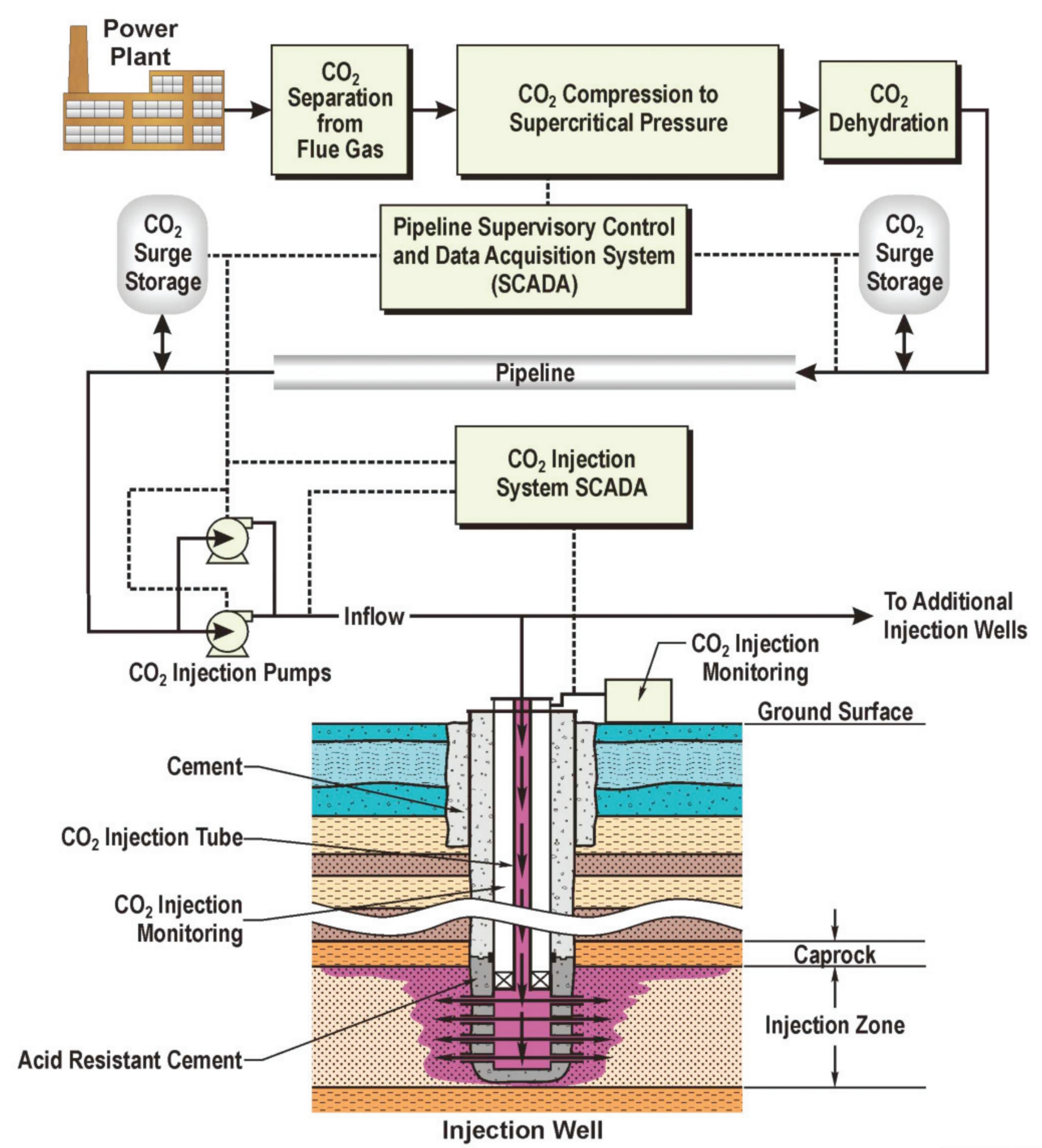
To have a meaningful impact on climate change, each core element of this portfolio must be capable of deploying at a scale that matters. One way to think about whether a given advanced energy technology can meet this criteria is to ask whether commercial deployment of the technology has the potential 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_2 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_2 concentrations. CCS systems are specifically designed to remove CO_2 from the flue gases and various process streams of large power plants and industrial facilities and safely deposit the CO_2 in secure storage sites deep underground—thus keeping it out of the atmosphere. At present, there are more than 8,100 large CO_2 point sources on Earth comprising primarily large fossil-fired power plants and other large industrial facilities. These facilities collectively emit approximately 15 $GtCO_2$ annually. Many of these power plants and industrial facilities are believed to be near suitable candidate CO_2 storage reservoirs.

CCS technologies, the focus of this report, have the potential to prevent many hundreds to thousands of gigatons of CO_2 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_2 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_2 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_2 Capture

For some CO_2 emissions mitigation applications, first-generation CO_2 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_2 capture systems to a small portion of the plants' emissions to serve niche industrial CO_2 markets, and there are natural gas processing plants that routinely capture and separate CO_2 and sell it for various industrial uses.

But the cost, performance, and other operating characteristics of these first-generation CO_2 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_2 capture systems is also considerably smaller than the scale needed to address climate change concerns. CO_2 capture is and will likely remain an area of intense CCS research.

Ancillary Systems

CO_2 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_2 Transport

Transporting CO_2 is an established practice. Currently, more than 3,000 miles of dedicated CO_2 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_2. The principal issue for CO_2 transport is not research and development but rather potential obstacles in the siting and placement of potentially large CO_2 pipeline networks that would likely be needed as CCS systems begin to deploy at a significant scale.

CO_2 Injection into Deep Geologic Formations

The most likely CO_2 storage sites are deep geologic formations. The technologies to inject CO_2 into these formations exist today and are routinely used in the oil and gas industries. In this sense, CO_2 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_2 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_2 in certain classes of formations and under specific circumstances (e.g., seismic imaging of CO_2 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_2 that has been injected into the deep subsurface.

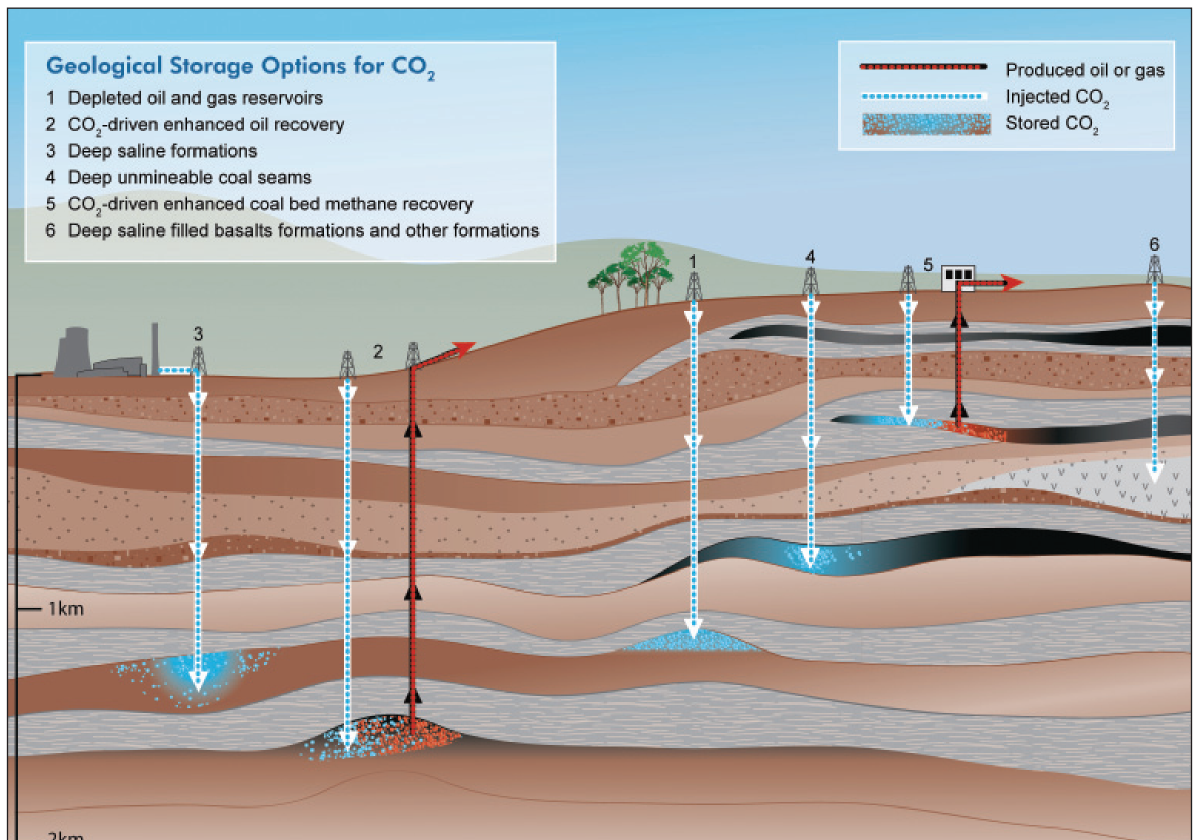
GOING DEEPER: CANDIDATE GEOLOGIC CO_2 STORAGE FORMATIONS

The deep geologic formations identified as candidates for long-term CO_2 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_2 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_2 storage.

In most cases, CO_2 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_2 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_2 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_2 to be injected and stored in the empty spaces between grains in the rock. Other layers are denser, effectively isolating the CO_2 storage reservoirs from the shallower groundwater reservoirs. These intervening dense rock layers (often called caprocks) provide the principal means of trapping the CO_2 in the deep subsurface over the long term.



▲ Candidate geologic reservoirs for storing CO_2 lie deep below the surface of the Earth at varying depths.
(FIGURE COURTESY OF THE AUSTRALIAN CO2CRC).

PRINCIPAL CANDIDATE GEOLOGIC CO_2 STORAGE RESERVOIRS

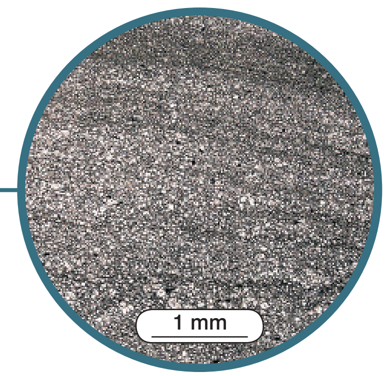
(see appendix for sources and assumptions)

Type of Reservoir	General Characteristics	Principal Trapping Mechanism	Theoretical Global Capacity ($GtCO_2$)	Theoretical U.S. Capacity ($GtCO_2$)
Deep Saline Formations	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
Depleted Natural Gas Reservoirs	Once the formation has been stripped of its natural gas, it essentially behaves like a DSF in terms of CO_2 storage. Depleted natural gas formations are often used for natural gas storage.	Hydrodynamic, dissolution, mineralization	700	35
Depleted Oil Reservoirs	Once the recoverable oil has been produced from the formation, CO_2 may be stored in the available pore space. CO_2 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_2-driven enhanced oil recovery (EOR) in areas of North America, but there has been little focus on demonstrating the retention of CO_2 or the use of these depleted oil fields as a long-term means of isolating CO_2 from the atmosphere.	Hydrodynamic, dissolution, mineralization	120	12
Deep Unmineable Coal Seams	Methane is found on the surfaces of coal. However, those surfaces have a chemical preference for CO_2, which when injected induces the coal to release its methane while adsorbing the injected CO_2 instead. At present, CO_2-driven enhanced coalbed methane recovery (ECBM) with simultaneous CO_2 storage is an emerging technology.	Primarily chemical adsorption	140	30
Deep Saline-Filled Basalt Formations	Permeable, porous "interflow" zones provide storage capacity while impermeable "massive" zones separate interflows and keep CO_2 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_2 in carbonate minerals, so the mineralization potential in these formations tends to be much higher.	Hydrodynamic, dissolution, mineralization	Unknown	240
Other (Salt Caverns, Organic Shales, etc.)	Salt caverns, organic shales, methane hydrate-bearing formations and other geologic media may provide novel niche CO_2 storage options.	Various	Unknown	Unknown

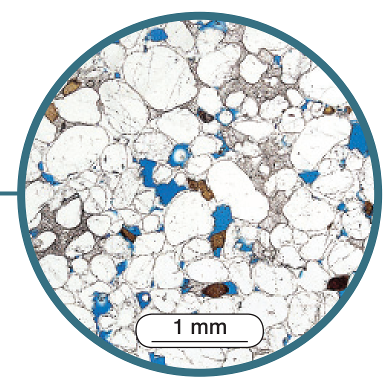
WHAT DOES A CO_2 STORAGE RESERVOIR LOOK LIKE?

A key mechanism for storing CO_2 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_2 storage reservoir, overlain by impermeable caprocks which serve to keep the injected CO_2 in place. A thorough evaluation of these formations and their ability to accept and retain injected CO_2 must be an essential component of site assessment before any CO_2 is injected. Here we take a closer look at these formations.

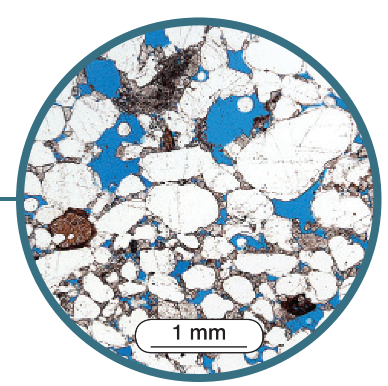
Microscopic view of a caprock. The grains making up this rock are densely packed with few interconnected pore spaces. The low permeability of these rocks makes them ideal barriers to prevent the migration of CO_2 out of the target storage formation. Examples include shale and dense carbonates.



Microscopic view of a medium-grained sandstone that would serve as a *good* CO_2 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_2 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_2 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_2 to more easily move through the host formation. Thus, more CO_2 can be injected and at a higher rate than in a formation composed of a medium-grained sandstone.

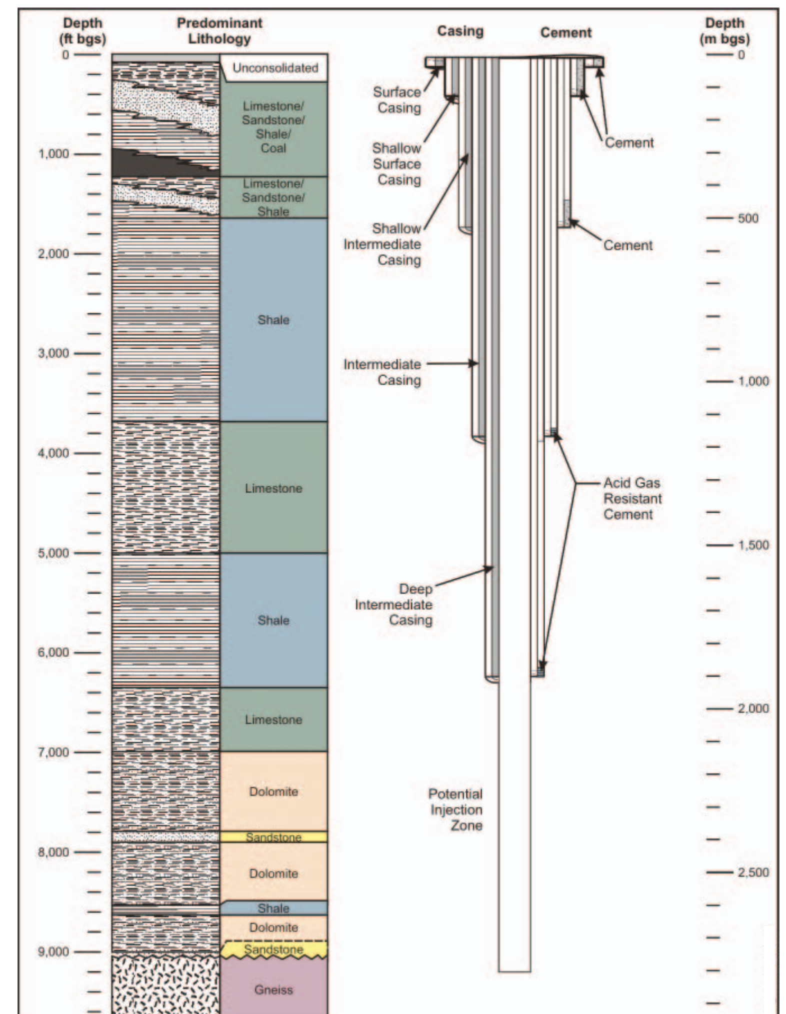


CO_2 INJECTION INTO A DEEP GEOLOGIC STORAGE FORMATION

As can be seen from the schematic below, CO_2 injection constitutes a highly engineered system. A CO_2 injection well is actually composed of several casings that help to ensure that the CO_2 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_2 storage formations.

Many of the technologies needed to safely inject CO_2 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_2 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_2 injection techniques, to allow for the greatest possible utilization of available CO_2 storage capacity, and to allow a wider range of CO_2 storage reservoirs to be pressed into service if needed.

The schematic also shows clearly that the CO_2 injection well traverses many thousands of feet of various geologic strata before reaching the target CO_2 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_2 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 Ordovican 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_2 over the long term.



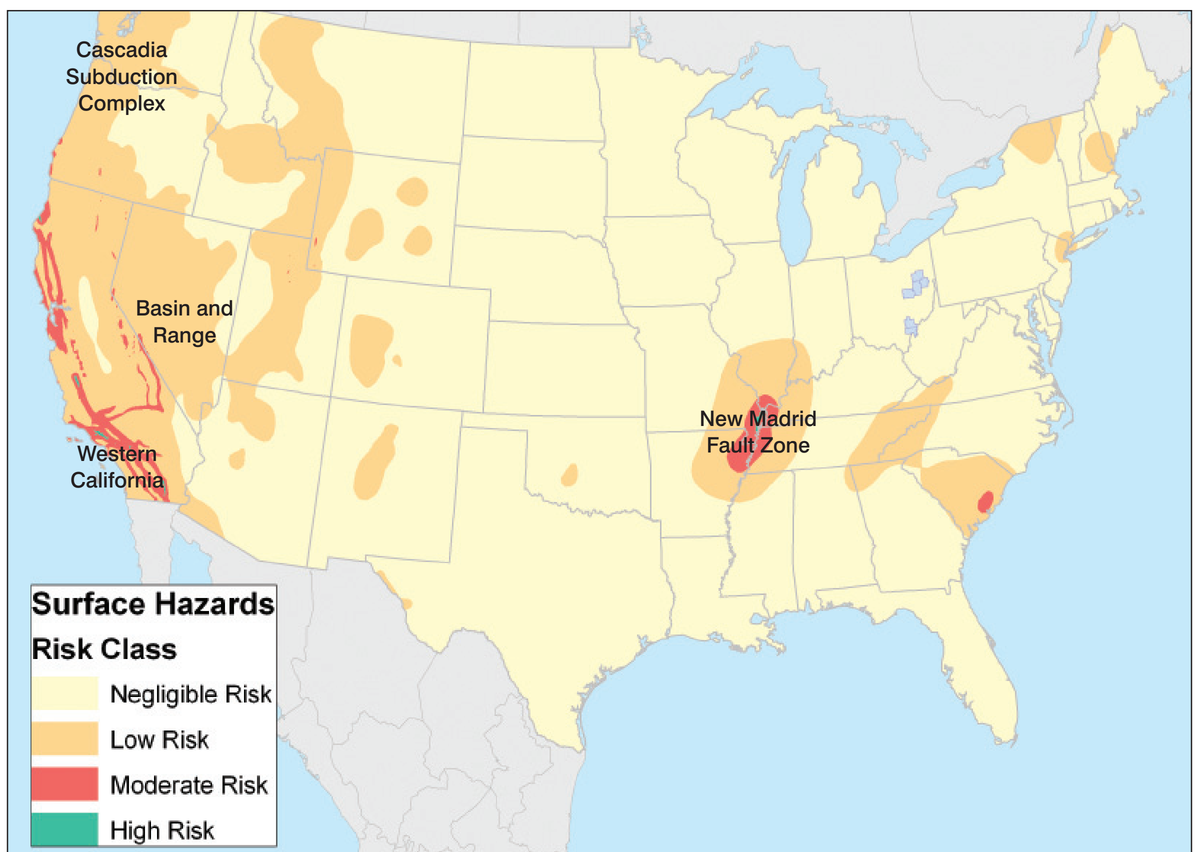
▲ CO_2 injection wells are engineered systems designed to ensure that injected CO_2 only reaches the appropriate storage formation.

CO_2 STORAGE: THE ISSUE OF PERMANENCE

At a properly designed and well-managed CO_2 storage site, the chance of CO_2 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_2, 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_2.

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_2 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_2 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_2 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_2 to migrate back to the surface.

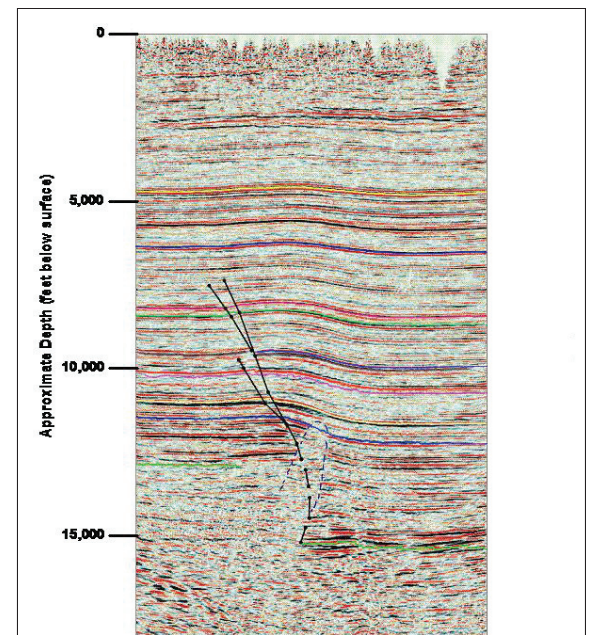


▲ By translating raw data about historic rates of seismic activity into a more meaningful measure of potential seismic risk to CCS infrastructure, we can see that relatively few regions of the United States have even moderate risk to CCS surface infrastructure.

Measuring, monitoring, and verification (MMV) systems will be needed to ensure that injected CO_2 remains in the target formation. Some technologies needed to monitor certain aspects of CO_2 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.

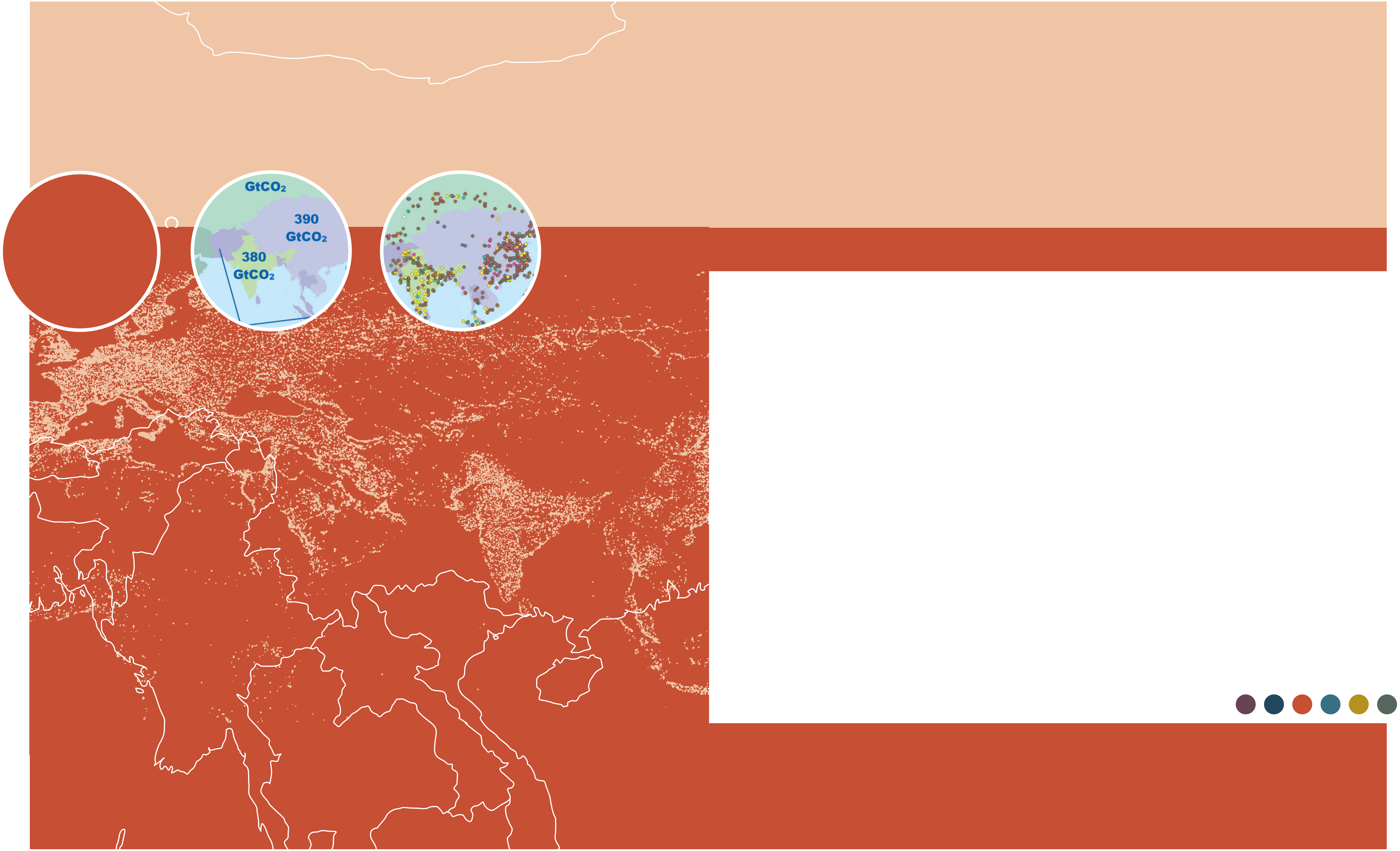
While the issue of leakage from CO_2 storage in deep geologic formations remains a subject of debate and intense research, several points are worth stressing:

- 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.



▲ Seismic imaging of the deep subsurface would be a routine step in the early evaluation of a proposed CO_2 storage formation. The black lines (emphasis has been added) reveal deep-seated faulting that is truncated hundreds of feet below the surface and therefore does not present a direct pathway to the surface.

- Sudden releases of CO_2 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_2 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_2 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_2 does escape from the storage formation.
- Tools and data exist that allow potential CO_2 storage project operators to assess candidate sites and the presence of any potential natural or manmade pathways that might allow CO_2 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_2 storage.
- The likelihood and extent of any potential CO_2 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_2 dissolves into the pore fluids and begins the long-term process of forming chemically stable carbonate precipitates.


GtCO₂
390
GtCO₂
380
GtCO₂

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

Candidate geologic CO_2 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_2 emissions sources. In fact, there is likely more than enough theoretical CO_2 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_2 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_2 storage capacity suggest a resource base that could potentially accommodate nearly 11,000 $GtCO_2$ 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_2 stabilization from 450 to 750 ppm, the demand for CO_2 storage space is estimated to not exceed 2,220 $GtCO_2$ 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.

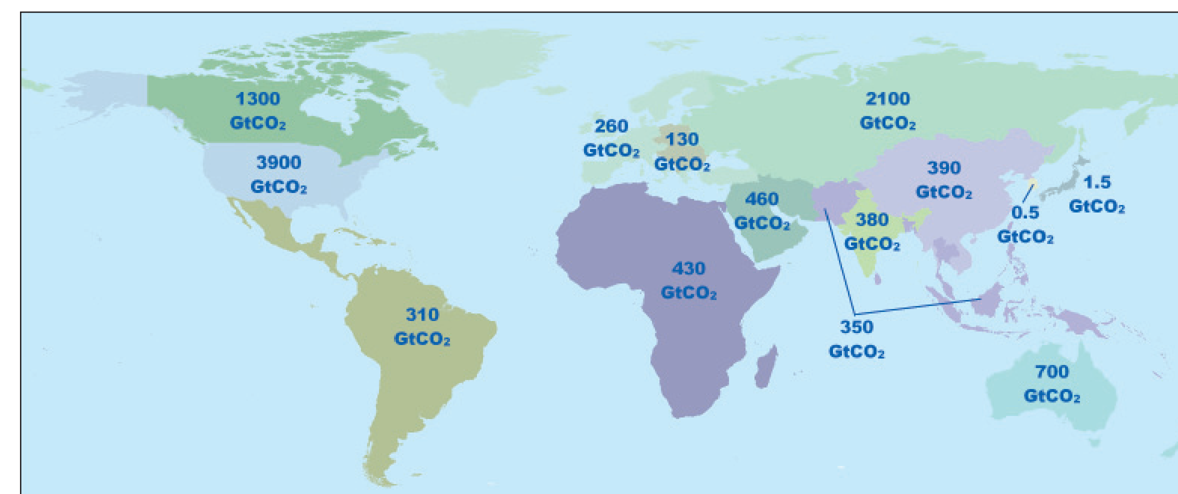
Substantial CO_2 storage capacity within a nation could be viewed as a very valuable domestic natural resource. For example, regions that have an abundance of CO_2 storage capacity can likely rely on a broader mix of fuels to power their economies and avoid the premature retirement of fossil-fired capital stock to meet tighter emissions constraints in the future.

However, even nations that do not have substantial CO_2 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_2 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_2 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_2 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_2 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_2 reservoirs, since the availability, quality and distribution of these reservoirs directly impact the future evolution of the energy infrastructures in many nations.



▲ Initial assessments of theoretical global CO_2 storage capacity reveal an important and encouraging result: there is more than enough theoretical CO_2 storage capacity in the world to meet likely storage needs for at least a century, and in many key regions the storage capacity is in the right places to meet current and future demand from nearby CO_2 sources.

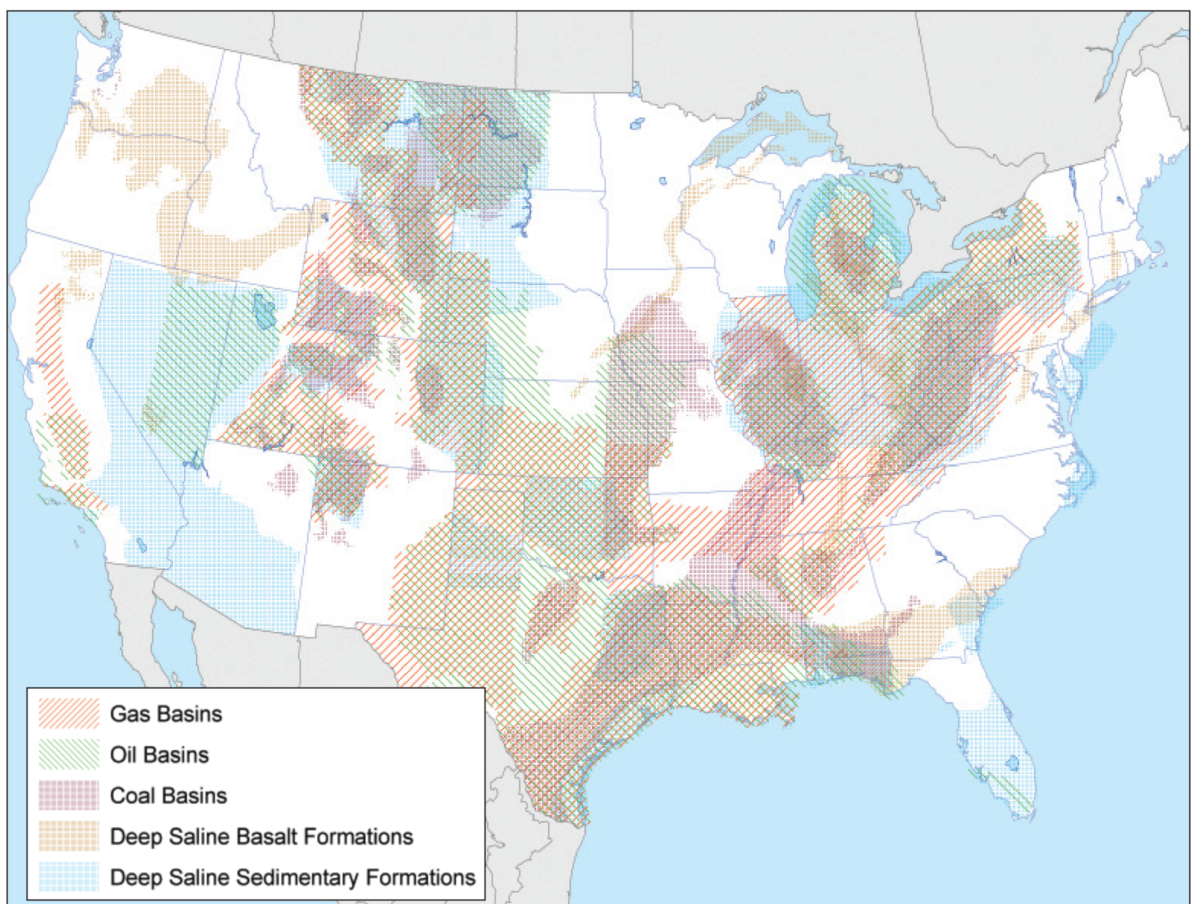
POTENTIAL GEOLOGIC CO_2 STORAGE RESERVOIRS IN THE UNITED STATES

The United States is fortunate to have an abundance of theoretical CO_2 storage potential, well distributed across most of the country.

The United States is fortunate to have an abundance of theoretical CO_2 storage potential, well distributed across most of the country. Our preliminary and ongoing assessment of candidate geologic CO_2 storage formations reveals that the formations studied to date contain an estimated storage capacity of 3,900+ $GtCO_2$ within some 230 candidate geologic CO_2 storage reservoirs (see map below):

- 2,730 $GtCO_2$ in onshore deep saline formations (DSFs), with perhaps close to another 900 $GtCO_2$ of storage capacity in offshore deep saline formations
- 240 $GtCO_2$ in onshore saline-filled basalt formations
- 35 $GtCO_2$ in depleted gas fields
- 30 $GtCO_2$ in deep unmineable coal seams with potential for enhanced coalbed methane (ECBM) recovery
- 12 $GtCO_2$ in depleted oil fields with potential for enhanced oil recovery (EOR)

Together, these candidate CO_2 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_2 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_2 emissions from large stationary point sources for hundreds of years to come. The highest capacity of the U.S. candidate CO_2 storage formations is found DSFs, and some individual DSFs can store hundreds of gigatons of CO_2.



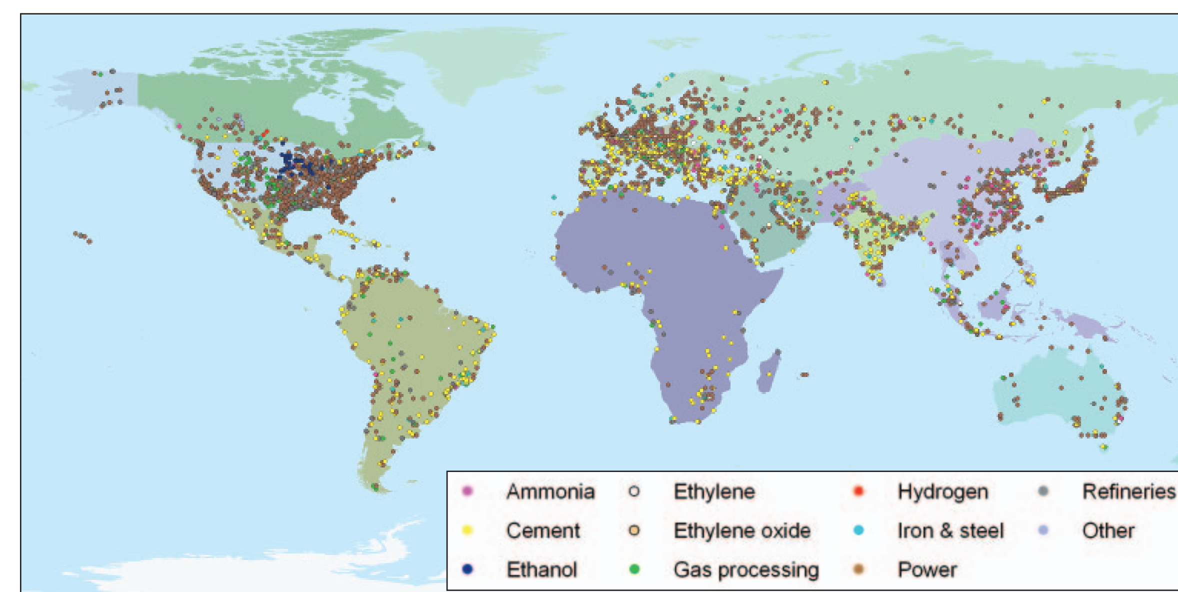
Early estimates of CO_2 storage capacity in the United States reveal a very large, widely distributed and perhaps extremely valuable resource with which to cost effectively address climate change.

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 synfuels 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_2 point sources in the world, each of which emitted more than 100,000 tons of CO_2 to the atmosphere.

- Collectively, these large CO_2 point sources emitted approximately 15 $GtCO_2$ into the atmosphere, which is more than 60% of all global anthropogenic CO_2 emissions in that year.



More than 8,100 power generation and industrial facilities in the world each emit more than 100,000 tons of CO_2 to the atmosphere each year. The sheer size of the potential market and its geographic scope says much about the potential for CCS technologies to contribute to climate change mitigation.

- Fossil fuel-fired power plants accounted for the largest fraction (60%) of these CO_2 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_2 source streams exhibiting a low cost of CO_2 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_2 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_2 point sources are heavily concentrated in a few regions of the world: the United States (20% of CO_2 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_2 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_2 point sources, the large CO_2 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_2 point sources that collectively emit more than 2.9 $GtCO_2$/per year.

CO_2 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_2 from a given source is a function of the concentration of CO_2 in the facility's emissions. Roughly speaking, large high-purity (and low cost of capture) CO_2 sources within the United States total 349 (20% of the sources) and account for 6% of the total emissions.

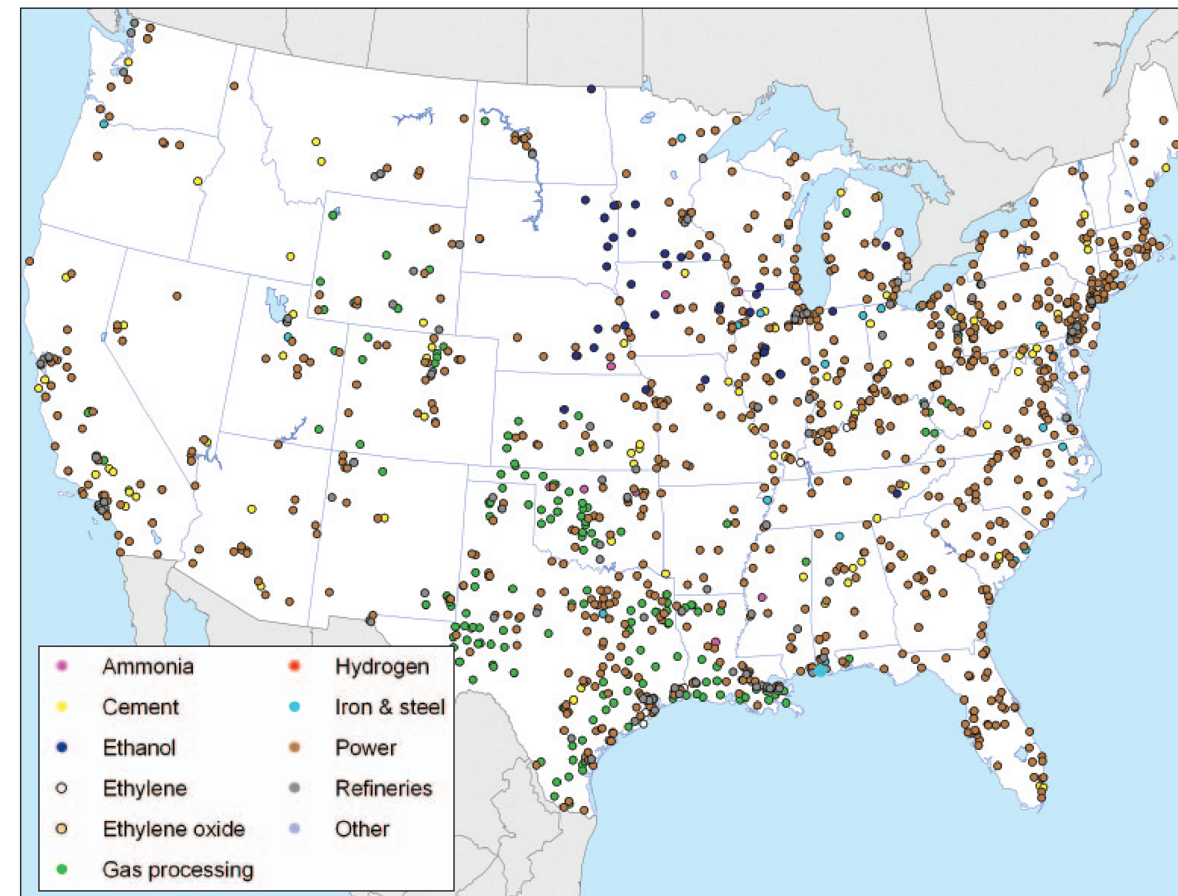
One of the principal benefits associated with the potential deployment of CCS technologies relates to its ability to deliver deep emissions reductions when applied to the largest CO_2 point sources. For example, in the United States:

- The 100 largest CO_2 point sources (6% of all facilities) account for 39% of total annual CO_2 emissions; 79% of these are power plants—all of them coal-fired.

- The 500 largest CO_2 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_2 point sources could potentially yield substantial CO_2 reductions, since fully 95% of these sources are within 50 miles of a candidate CO_2 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_2 reservoir.



The large CO_2 point sources in the contiguous United States (each emitting more than 100,000 tons of CO_2 per year) are spread throughout the country and originate from a number of different industrial sectors. The significant diversity across these large CO_2 point sources speaks to the many differing deployment options that exist for CCS technologies within the U.S.

THE COST OF CO_2 CAPTURE

For the vast majority of CCS applications, the cost of CO_2 capture is the largest contributor to overall CCS system cost and thus should be a focus of cost reduction efforts. The cost of CO_2 capture depends in large measure on the pressure and concentration of CO_2 in the flue gas or process stream from which the CO_2 is being separated. As a general rule, it is cheaper to capture CO_2 from a purer and higher-pressure CO_2 stream, as it requires relatively less processing and compression before it is ready to be introduced into a CO_2 pipeline. The table on the facing page presents an overview of CO_2 capture technologies and costs described by the technical literature for a variety of large anthropogenic CO_2 sources that could be considered candidates for adopting CCS technologies in a greenhouse gas-constrained world. As the table shows, the cost of CO_2 capture varies considerably across these various types of large CO_2 point sources.

THE COST OF CO_2 CAPTURE FOR VARIOUS INDUSTRIAL PROCESSES

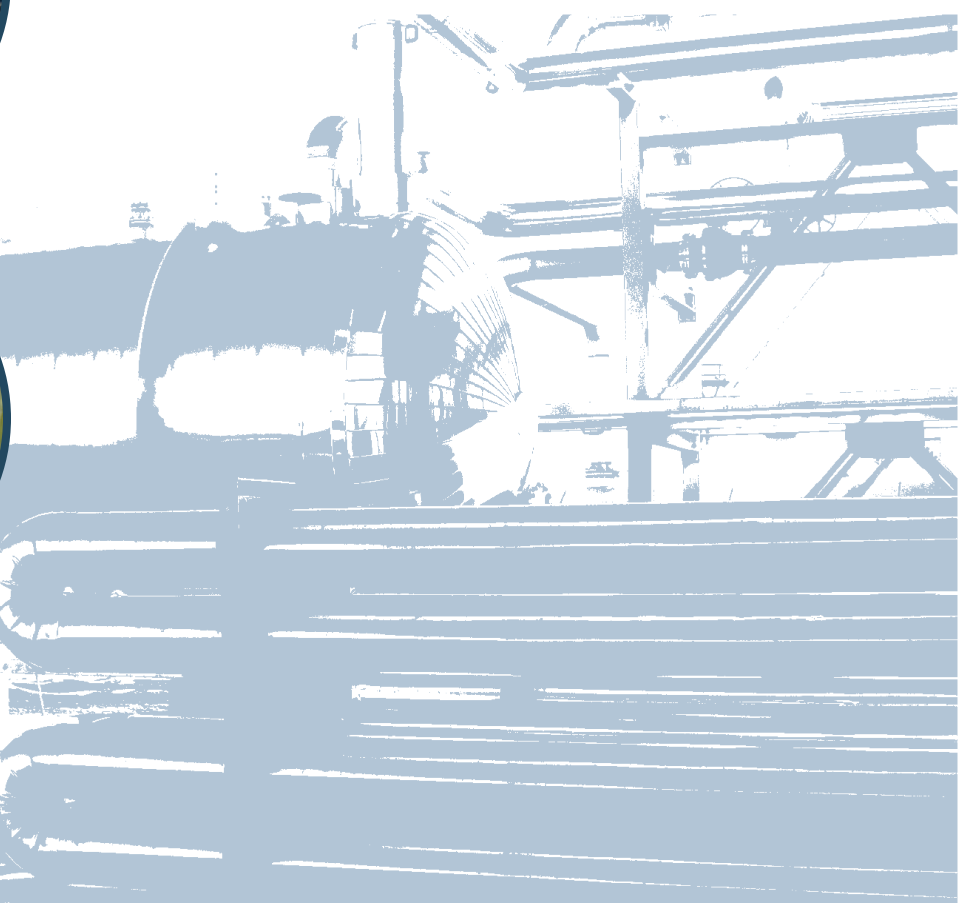
(see appendix for sources and assumptions)

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_2	CO_2 content in flue gas stream, capital cost and energy requirements for solvent cycling
IGCC Power	Physical Absorption	\$25–\$40/tCO_2	CO_2 content in flue gas stream, capital cost
Refinery Flue Gas	Chemical Absorption/ Flue Gas Recycling	\$35–\$55/tCO_2	CO_2 content in flue gas stream and capital cost, energy requirements for solvent cycling (if applicable)
Steel	Flue Gas Recycling/ Chemical Absorption	\$20–\$35/tCO_2	CO_2 content in flue gas stream and capital cost, energy requirements for solvent cycling (if applicable)
Cement	Flue Gas Recycling/ Chemical Absorption	\$35–\$55/tCO_2	CO_2 content in flue gas stream and capital cost, energy requirements for solvent cycling (if applicable)
Ethanol (Fermentation)	NA	\$6–\$12/tCO_2	No capture cost for pure CO_2 stream; compression cost only
Ethylene Oxide (Process Stream)	NA	\$6–\$12/tCO_2	No capture cost for pure CO_2 stream; compression cost only
Ammonia (Reformer Gas)	NA	\$6–\$12/tCO_2	No capture cost for pure CO_2 stream; compression cost only

CO_2 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_2, NO_x and other emissions controls are already in place, and whether the CO_2 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_2 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_2 capture technologies. There is widespread agreement that such advancements will help accelerate CCS deployment, and that deployment will push the cost of CO_2 capture down through a process known as "learning by doing." There is significant value in efforts designed to continually improve CO_2 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_2 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_2 capture it is also important to continually increase the capture efficiency or percent of CO_2 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_2, while the remaining 10% is released to the atmosphere. In a carbon-constrained world, any CO_2 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_2 concentrations, this seemingly small amount of CO_2 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_2 TRANSPORT AND STORAGE

As described previously, the geologic CO_2 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_2 point sources in close proximity to candidate geologic CO_2 storage reservoirs. However, the characteristics of these candidate CO_2 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_2 storage capacity will also vary from region to region. The key factors in determining the cost of CO_2 transport and storage are the proximity of the CO_2 source to the selected CO_2 storage reservoir and the characteristics of the reservoir that is selected for CO_2 injection.

There is a general consensus within the technical community that most CO_2 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_2 pipeline deliver CO_2 to commercial CO_2-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_2 pipelines, the Cortez pipeline, delivers CO_2 over a distance of 500 miles.

This operational experience with CO_2 pipelines and the similarity in terms of construction and operational costs between CO_2 pipelines and natural gas pipeline networks provides a robust set of data that can be used to estimate future CO_2 transportation costs. CO_2 transport costs via pipeline are a function of the distance between the CO_2 source and its geologic storage reservoir.

Already, approximately 3,000 miles of dedicated CO_2 pipeline deliver CO_2 to commercial CO_2-EOR projects within North America.

The cost also depends upon the diameter of the pipeline (which is a function of how much CO_2 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_2 per year, the main trunk pipeline (approximately 26 inches in diameter) used to carry the CO_2 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_2 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_2 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_2 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_2 sources and the large—but nonetheless finite—candidate CO_2 storage formations in the region, our research tells us that the greatest impact associated with CO_2 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_2 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_2 storage in value-added reservoirs that suggest the possibility of a significant mismatch between the nearly continuous need to store large quantities of CO_2 from a CCS-enabled power plant and the more limited and episodic need for CO_2 in CO_2-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_2; 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_2 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_2 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_2 storage in value-added reservoirs may not represent as significant a portion of total CO_2 stored as is widely believed. Our research suggests that all classes of CO_2 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_2 transport and storage should stay below the level of approximately \$12–\$15/tCO_2 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_2 injected into deep geologic formations suggest that these costs will be small when measured on a per-ton-of-CO_2-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_2 point sources and all of the candidate CO_2 storage reservoirs we have been able to identify to date. The model used to compute this cost curve, the *Battelle CO_2-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.

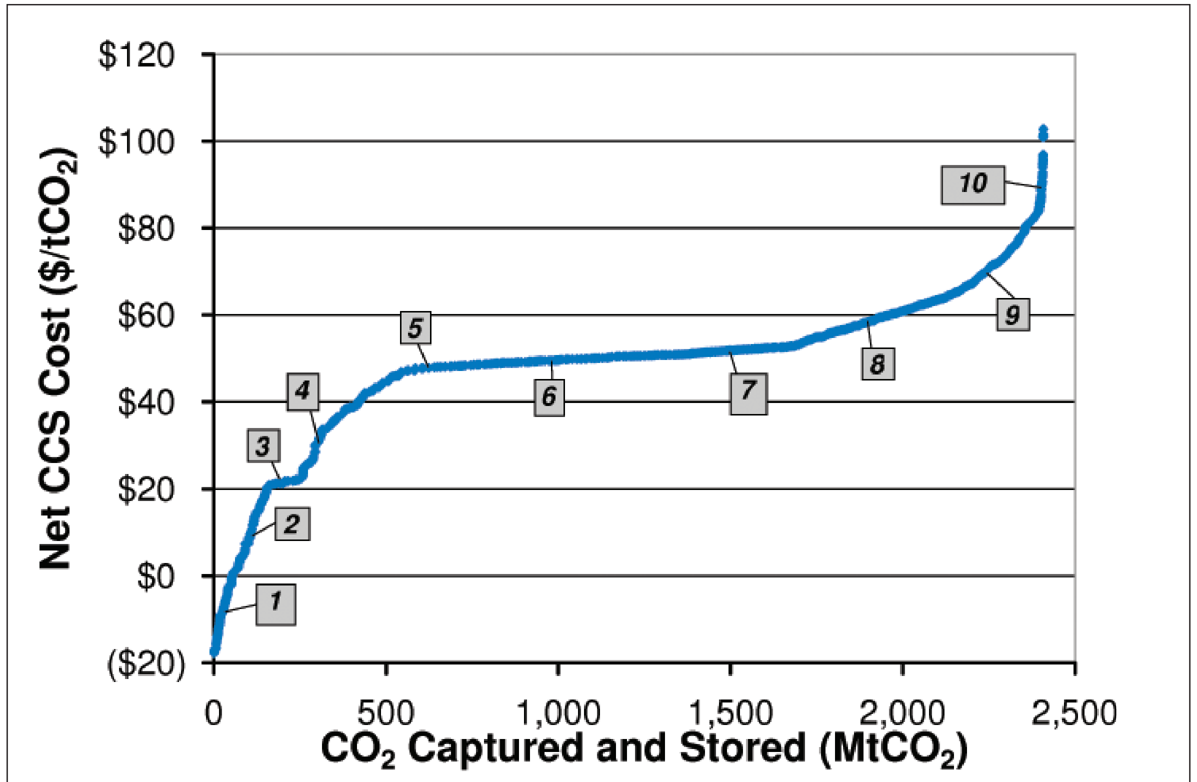
Each point on the curve represents the levelized cost (in \$/tCO_2) for a specific existing large CO_2 point source to employ CCS: capture its CO_2 and ready it for transport; transport the captured CO_2 via pipeline to a suitable candidate storage reservoir; inject the CO_2 into the reservoir; and measure, monitor and verify that the injected CO_2 remains within the target reservoir. In addition, for injection into value-added storage reservoirs, any revenues from resulting CO_2-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_2 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_2 emissions. This "low hanging fruit" can be seen in the real world today as the few tens of millions of tons of anthropogenic CO_2 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_2 point sources such as natural gas processing facilities seeking to store their CO_2 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_2-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_2 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_2 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.



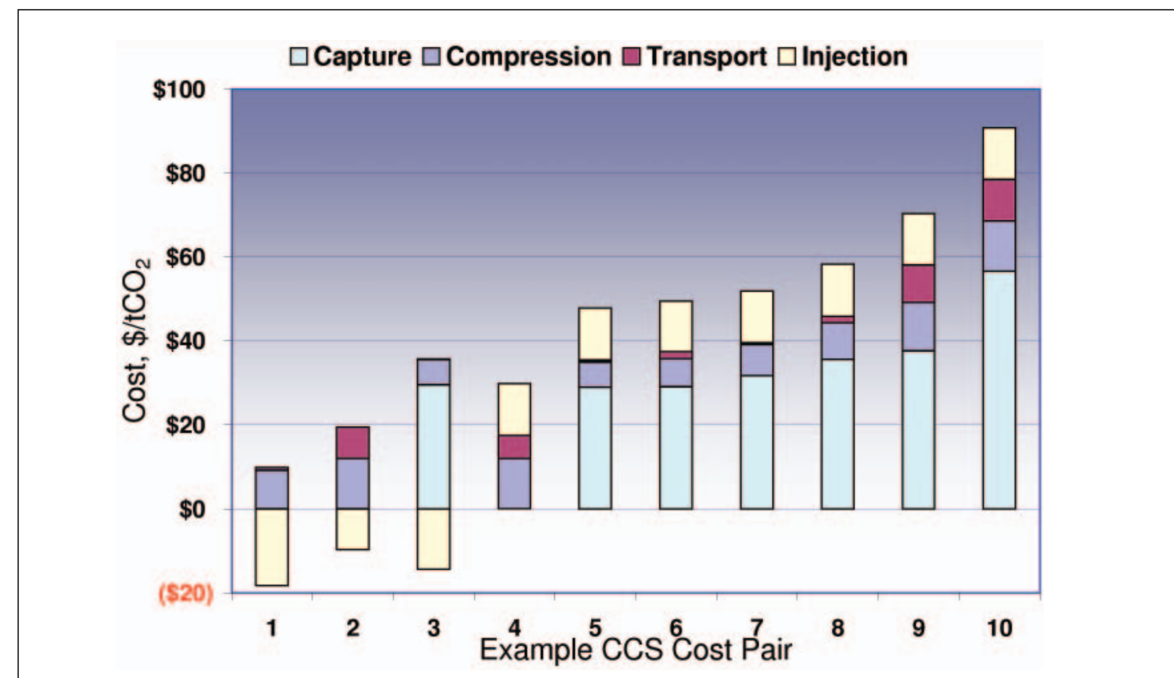
1	**High purity ammonia plant** / nearby (<10 miles) EOR opportunity
2	**High purity natural gas processing facility** / moderately distant (~50 miles) EOR opportunity
3	**Large, coal-fired power plant** / nearby (<10 miles) ECBM opportunity
4	**High purity hydrogen production facility** / nearby (<25 miles) depleted gas field
5	**Large, coal-fired power plant /** nearby (<25 miles) deep saline formation
6	**Coal-fired power plant** / moderately distant (<50 miles) depleted gas field
7	**Iron & steel plant** / nearby (<10 miles) deep saline formation
8	**Smaller coal-fired power plant** / nearby (<25 miles) deep saline basalt formation
9	**Cement plant** / distant (>50 miles) deep saline formation
10	**Gas-fired power plant** / distant (>50 miles) deep saline formation

- 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_2 point source from which CO_2 is being captured, the type of CO_2 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_2 at a very low cost and store it in a nearby mature oil field where the CO_2 is injected to increase incremental oil recovery via EOR. These points show how the characteristics of the CO_2 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 $0/t$CO_2$ for the very high-purity CO_2 sources up to $57/t$CO_2$ for the small and very low-purity NGCC source. Compression cost estimates vary also, depending again on the size of the CO_2 stream and other characteristics, roughly between $6 and $12/t$CO_2$. Transport costs are driven by the mass flow rate of CO_2 to be transported, but also the distance between the source and its selected reservoir. Here, they range from about $0.20/t$CO_2$ for the very large coal-fired power plant requiring minimal pipeline length, to nearly $10/t$CO_2$ 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_2 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_2 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 $12/t$CO_2$, 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_2 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_2 capture from these low-purity sources (and from power plants in particular) would provide a significant boost to the economic viability of geologic CO_2 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_2 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_2 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_2 storage opportunities.

- Third, even under very conservative assumptions such as those used here (e.g., power plants and other large industrial CO_2 point sources use existing CO_2 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_2 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_2 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.

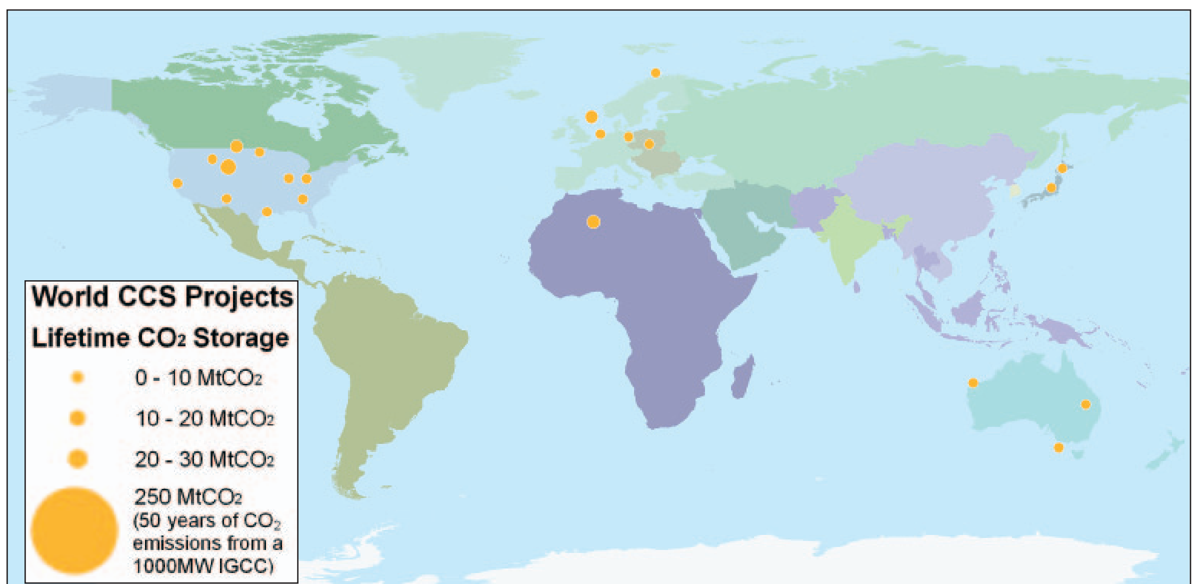
TODAY'S CCS DEPLOYMENT COMPARED TO POTENTIAL MID-CENTURY DEPLOYMENT

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_2 (or 0.000001 $GtCO_2$) to 26 million tons of CO_2 (0.026 $GtCO_2$), 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 $GtCO_2$ over its lifetime, will only inject one-tenth as much CO_2 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_2 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 $GtCO_2$ in the United States and more than 100 $GtCO_2$ 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.

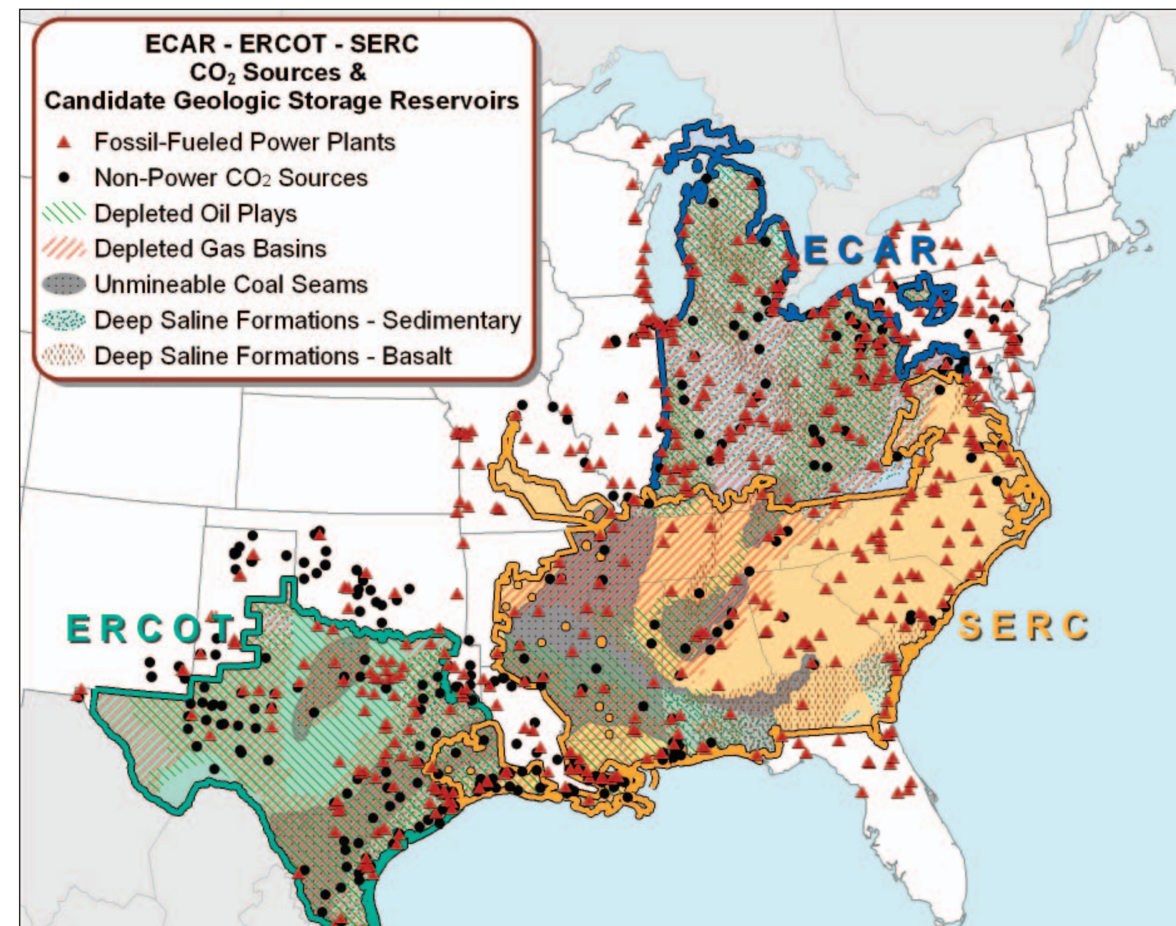


▲ **Current and future global deployments of CCS technologies**—The small circles on the map show the location and scale of current global CCS activities. In contrast, the large circle at the bottom of the legend is drawn to the same scale and represents the cumulative CO_2 storage needs of a single large coal power plant over a 50-year projected lifetime.

CCS DEPLOYMENT AT THE REGIONAL AND SECTORAL SCALE

To illustrate CCS deployment at a scale that would significantly reduce CO_2 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_2, 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_2 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 $MtCO_2$ per year by 2045 and would have cumulatively stored over 6 $GtCO_2$ 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—



▲ The deployment of CCS-enabled power plants will be driven by a wide variety of regional factors including geology, demand for power, the stringency of future greenhouse gas regimes, and the nature of the existing capital stock.

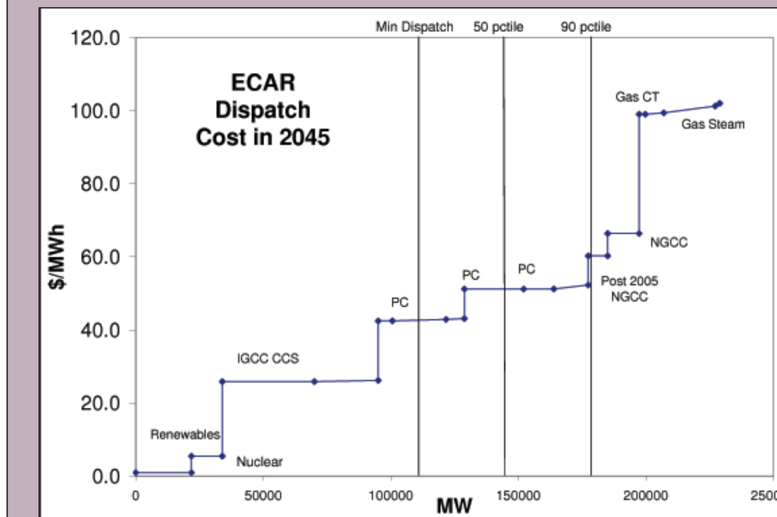
capital costs, efficiency, O&M costs, emissions; (4) other market factors—fuel prices, emissions policies, cost of financing, reserve margin requirements; and (5) the characteristics of candidate CO_2 storage reservoirs.

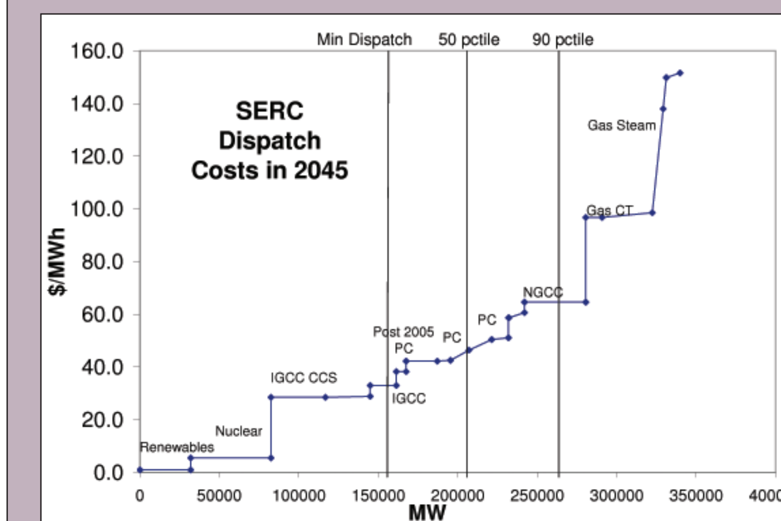
When all of these factors and the heterogeneous composition of different geographic regions are taken into account, a highly nuanced picture of CCS deployment across different regions emerges, which we will briefly discuss before focusing on the larger issues that this analysis reveals about how CCS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

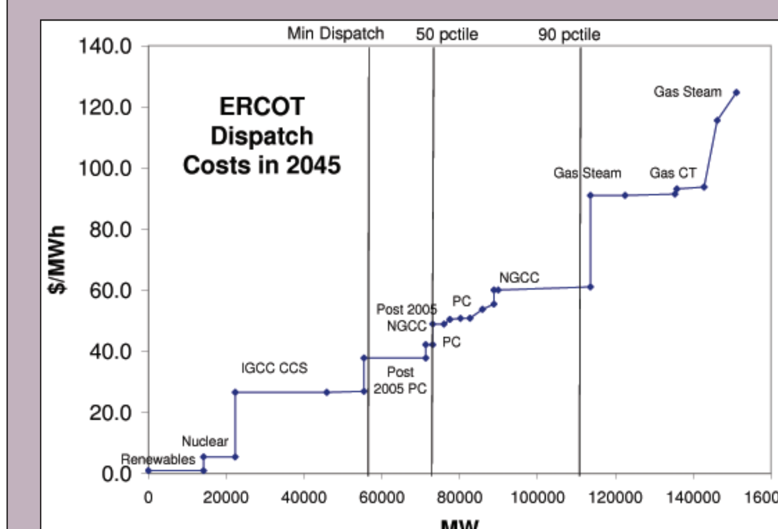
ECAR: The U.S. region located in the industrial upper Midwest (the East Central Area Reliability Coordination Agreement, or ECAR) has an electricity system that has historically been dominated by conventional coal plants. The region's geologic CO_2 storage opportunities are dominated by deep saline formations, although there is some potential for value-added CO_2 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_2 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_2 transport in this region. Under this CO_2 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_2 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_2 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 major lesson is that CCS technologies are really focused on baseload power production. The greatest amount of CO_2 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_2 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_2 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_2 storage and the kinds of CO_2 storage reservoirs that will likely be most relevant for this industry's needs.

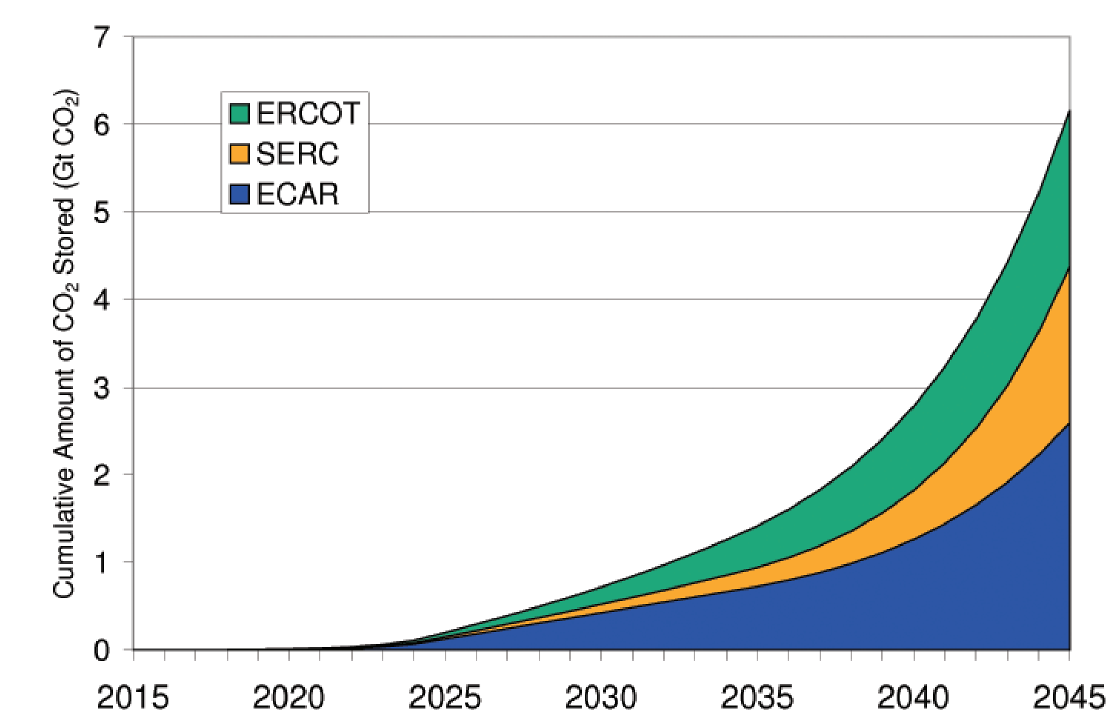
Our research indicates that the overwhelming criteria for siting a CCS-enabled power plant will relate more to allowable CO_2 injection rates and total reservoir capacity than to potential buyers for CO_2. Knowing whether a region has more or less potential for value-added CO_2 storage than any other 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_2 capture in the electric power sector—even including state-of-the-art IGCC+CCS—will likely be higher than the cost to capture CO_2 from some industrial sources, much of the value-added CO_2 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_2 storage workhorse for the electric utility sector.

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 $GtCO_2$ 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_2 storage at this scale.

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

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 electric utilities will depend to some degree upon the continued development of innovative technologies to allow CO_2 storage to be deployed at significant scale where needed, increasing effective storage capacities and CO_2 injection rates.



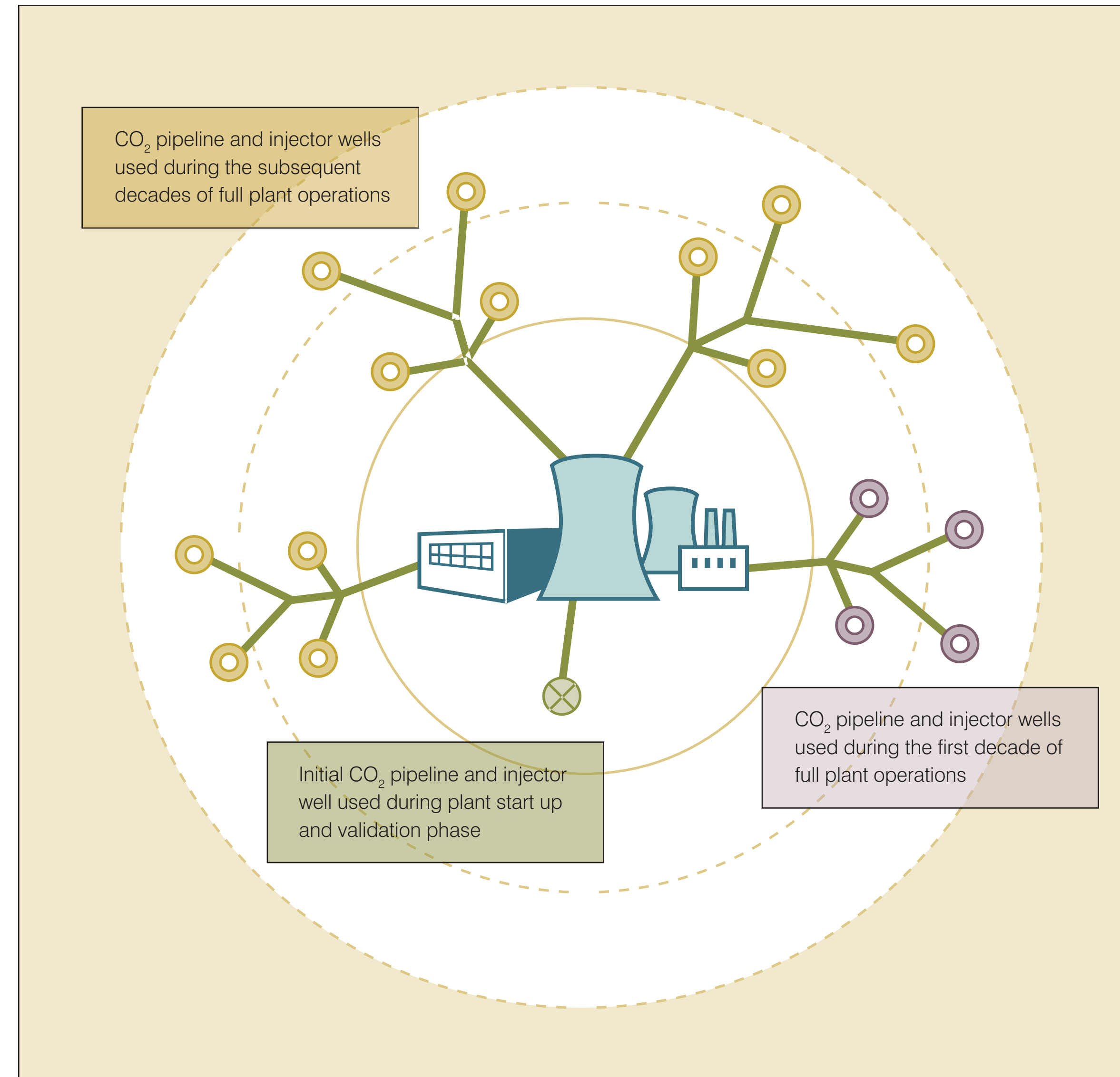
Analysis like this can also help to shed light on where the most intensive deployment of CCS technologies might occur in the future and the timing and possible scale of that deployment.

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_2 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_2 permit prices likely are relatively low?
- The probable scenarios for CO_2 permit prices, especially the price path for CO_2 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_2 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_2 storage reservoirs at prospective power plant sites. This would need to include an assessment of the size, capacity, and physical properties of candidate CO_2 storage reservoirs as well as modeling to begin assessing such practical issues as the number of CO_2 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_2 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_2.

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.



▲ Planning for a CCS-enabled power plant must include a robust CO_2 storage plan for all phases of the plant's operations over its entire half-century operational lifetime.

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_2**
Business, Regulatory, and Stakeholder Issues	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_2 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_2 that has been injected into deep geologic storage formations. Compliance with regulation to periodically monitor stored CO_2.
Power Production		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.
CO_2 Storage System		Begin early analysis of site-specific CO_2 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_2 storage systems, utilities will need to assemble a team of consultants and vendors to create and implement CO_2 storage system's infrastructure.	Injection site wells are complete with wells drilled and supporting above-ground infrastructure such as storage tanks, CO_2 pipeline, and wellhead facilities in place.			Small-scale CO_2 storage likely begins at the first few injection sites to validate CO_2 storage system, allow plant staff to gain familiarity with systems and allow local public and other stakeholders to become more comfortable with CO_2 storage at this site.	Large-scale, continuous CO_2 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_2 injection ceases. Surface CO_2 injection facilities such as pipelines and wellheads are removed. CO_2 injector wells are plugged and prepared for long-term closure.
Measurement, Monitoring and Verification (MMV)		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_2 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_2 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_2. 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_2 storage sites and for predicting the movement of stored CO_2.

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_2 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_2 that has already been emitted to the atmosphere.

R&D Needs for CO_2 Capture

▶ ***Continually improve capture technologies***—not only in terms of cost, energy penalty, and efficiency, but also in the percentage of the CO_2 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_2 Transport, Storage and Injection

▶ ***Survey global candidate CO_2 reservoirs.*** Since the availability and distribution of this CO_2 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_2 in the subsurface.*** Improved and widely accepted reservoir models are needed to help examine commercial-scale CO_2 storage scenarios and help predict CO_2 movement through deep geologic formations.

▶ ***Improve the resolution of data on candidate geologic reservoirs.*** Much of the data on CO_2 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_2 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_2-driven enhanced hydrocarbon recovery related to long-term CO_2 storage.*** Much of the analysis of CO_2-driven enhanced hydrocarbon recovery assumes constant incremental oil and natural gas recovery rates (as well as constant rates of CO_2 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_2 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_2 storage options based on CO_2-driven enhanced hydrocarbon recovery.

▶ ***Create innovative and cost-effective CO_2 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_2 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_2 storage by reducing the costs of required capital, driving down the per-ton cost of storage.

▶ ***Craft a strategy for remediating CO_2 that does not remain in the target formation.*** Remediation options must be identified and prescribed for dealing with CO_2 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.

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

R&D Needs for Measurement, Monitoring, and Verification of Stored CO_2

▶ ***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_2 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_2 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_2 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_2 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 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_2 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.

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