



*April 2009*

## **CCS 101: Greenhouse Gases, Global Warming & CCS**

*This educational paper is intended to provide an introduction (in Part I) to the subject of greenhouse gases and their contributions to global warming), and (in Part II) the nature and environmental benefits of CO<sub>2</sub> capture and storage (CCS).*

### ***Introduction***

The world is experiencing a combination of global population growth and an increase in per capita GDP, or wealth. This translates to rapid growth in overall global energy demand that may be temporarily slowed by global economic down turns. Energy is needed for all facets of our global civilization. It is needed to produce, transport, preserve, and cook our food. It is needed to improve our health and to power our medical diagnostic equipment and medical research tools. It is needed to build housing, and to light, heat, and cool our housing once it is built. It is needed to transport people and to communicate with each other. It is needed to power our industrial production.

Both domestically, and internationally, fossil fuels provide over 85% of total energy supply, and are projected to continue at that rate through 2030. Coal, for example, has been the fastest growing global fuel for the past 5 years. Overseas, China alone is adding coal-based electrical capacity equivalent to the entire U.S. coal-fired fleet every 4 years. According to British Petroleum, coal consumption in China grew 7.9% in 2007, which was the lowest growth rate since 2002.<sup>1</sup> The International Monetary Fund reports projections of 500 million new cars in China by 2050. This projected growth in energy use will lead to increases in carbon dioxide (CO<sub>2</sub>) emissions.

The existing global fleet of fossil fueled (coal, natural gas, pet coke and other fossil fuels) plants already emits large amounts of CO<sub>2</sub>. As global energy use increases, the consequences of these increases will grow. We will need ever more energy resources and we will have to deal with ever more complex environmental issues, including the production of greenhouse gases (of which CO<sub>2</sub> is the most abundant).

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<sup>1</sup> BP Statistical Review of World Energy, June 2008.

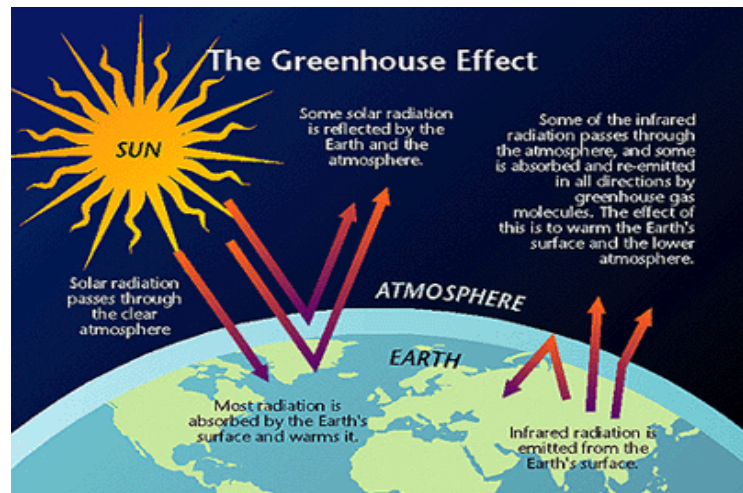
In 2004, CO<sub>2</sub> emissions by developed nations (OECD member countries) and developing countries were about equal. The DOE/EIA projects that by 2030, developed country emissions will increase by 30%, while that of developing countries will double. In response to this anticipated growth, the International Energy Agency (IEA) has called for a global “Energy Revolution” to respond to the climate change issue.

## *Part I: Climate Fundamentals*

Greenhouse gases (GHGs) include both naturally occurring and man-made gases that tend to trap the sun’s heating rays and increase global temperatures. While CO<sub>2</sub> is the most abundant man-made global GHG and the one most discussed, it is only one of many GHGs which include water vapor (H<sub>2</sub>O); methane (CH<sub>4</sub>); ozone (O<sub>3</sub>); and nitrous oxide (N<sub>2</sub>O); the group of fluorinated gases consisting of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>); and chlorofluorocarbons (CFCs).

### *The Greenhouse Effect*

GHGs act like the windowpanes of a greenhouse by allowing transmission of incoming solar energy, while blocking retransmission of the Earth’s infrared radiation back into space, causing most of the sun’s incoming energy to be retained (see U.S. Environmental Protection Agency (EPA) graphic). This is why this heat reflection process is commonly referred to as the Greenhouse Effect. The greenhouse effect is important - without it, our world would be intolerably cold with daily surface temperatures varying by hundreds of degrees (much like our atmosphere-free moon). However, too much heating is not good as well. Scientific models suggest that higher concentrations of CO<sub>2</sub>, and other GHGs, could lead to environmental effects that often are grouped under the terms "global warming," or "climate change.”



### *The Global Growth in Greenhouse Gases*

Scientists have been able to determine historic levels of GHGs from bubbles trapped in ice cores that are thousands of years old. They found that the amount of CO<sub>2</sub> in the air has varied considerably over many millennia, but has been relatively constant for the last ten thousand years until the industrial revolution. They also found that global atmospheric concentrations of CO<sub>2</sub>, methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) have increased markedly since 1750 and now considerably exceed pre-industrial values. Since the 1750s, the world’s population has grown approximately six-fold, and the use of coal, oil, natural gas, and industrial chemicals has increased much more in order to meet the growing global demand for energy to

heat and light our homes, to provide our food, to drive our vehicles, and to power our computers, televisions, air-conditioners, vacuum cleaners, medical equipment, and other things we depend on in our daily lives.

### *Key Greenhouse Gas Emissions*

Man-made, energy-related CO<sub>2</sub> emissions accounted for more than 80% of the total U.S. man-made GHG emissions in 2006. The two largest contributors to U.S. emissions were coal-fired power plants (27% of total U.S. GHG emissions) and petroleum-based transportation sources (28% of total emissions).<sup>2</sup> Natural gas using sources also contributed substantially to the CO<sub>2</sub> inventory. Various legislative proposals have called for reductions in U.S. emissions of up to 80% by 2050. Clearly, such goals cannot be achieved without dramatic reductions in all energy sectors, especially the power and transportation sectors. For the power sector, the rapid growth of carbon free generation options (nuclear power, renewable energy) will help, but most credible analyses show that development and deployment of CCS technology will be necessary to meet such goals. The absolute need for affordable CCS technologies in other countries, like China, is necessitated by the greater reliance of those countries on coal, and their continuing rapid growth in coal use.

### *The Greenhouse Gases & Global Warming*

While most GHGs occur naturally, and are necessary to maintain life as we know it, there are concerns due to elevated levels of GHGs caused by human activities. GHG levels in the atmosphere have significantly increased above the pre-industrial era level – annual emissions of CO<sub>2</sub> from human activity have increased from an insignificant level two centuries ago to over 33 billion tons worldwide today. This increase of GHGs is considered by many scientists to contribute to global warming, and could cause unwelcome global shifts in regional climates.

CO<sub>2</sub> is the most frequently cited GHG. Naturally occurring GHGs, such as water vapor, also strongly contribute to the greenhouse effect. Water vapor is the most important GHG in terms of the naturally occurring greenhouse processes (and can actually contribute to both global warming and global cooling). As atmospheric temperatures rise, more water is evaporated from rivers, oceans, soil, etc., leading to a higher concentration of water vapor in the atmosphere. That causes more infrared energy radiated from the Earth to be absorbed, further warming the atmosphere, which in turn increases the amount of water vapor in the atmosphere, and so on — a phenomenon known as a positive feedback loop. On the other hand, as water vapor levels increase in the atmosphere, more of it will eventually condense into clouds, some of which (the lower level clouds) are better able to reflect incoming solar radiation — in turn allowing less thermal energy to reach the Earth's surface and heat it. There is a great deal of scientific uncertainty in defining the extent and importance of this cloud-based feedback loop. In the future, monitoring atmospheric processes involving water vapor will be crucial to fully understand the complexity of the feedbacks in the climate system. While we have good atmospheric measurements of key GHGs such as CO<sub>2</sub> and methane, our ability to measure global water vapor is poor, so we can't be sure how much atmospheric concentrations of this most abundant GHG have changed over the years.

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<sup>2</sup> Emissions of GHG in the U.S. – 2006, USDOE/EIA, November 2007.

As the name, global warming, suggests, this is a global phenomenon which requires a global solution. The global atmosphere is indifferent as to the global locations and source of GHGs, especially CO<sub>2</sub>. CO<sub>2</sub>, for example, has the same effect on the average global temperature whether its release is due to land use changes in the United States, generating electricity in China, natural gas heating of homes in Europe, deforestation in the Amazon, or operating automobiles anywhere in the world.

### *The Global Warming Challenge*

In testimony before the Senate Committee on Environment and Public Works' Subcommittee on Public and Consumer Solutions to Global Warming and Wildlife Protection, NRDC President Frances Beinecke testified<sup>3</sup> *“that the time for action on global warming is now. Climate scientists warn us that we must act now to begin making serious emission reductions if we are to avoid truly dangerous global warming pollution concentrations... A growing body of scientific research indicates that we face extreme dangers to human health, economic well-being, and the ecosystems on which we depend if global average temperatures are allowed to increase by more than 2 degrees Fahrenheit from today's levels. We have good prospects of staying below this temperature increase if atmospheric concentrations of CO<sub>2</sub> and other global warming gases are kept from exceeding 450 ppm CO<sub>2</sub>- equivalent and then rapidly reduced. To make this possible requires immediate steps to reduce global emissions over the next several decades, including action to halt U.S. emissions growth within the next few years and then cut emissions by approximately 80% by mid-Century.”*

### *The Global Warming Solution*

There is no easy or inexpensive solution to dramatically reducing the atmospheric levels of CO<sub>2</sub>. Global population and energy demand will continue to grow. The global energy demand is such that we will need to use all of our energy resources, including our global fossil energy resources. Non-fossil fuel options to minimize GHG emissions include energy efficiency improvements; the shift to less carbon intensive fuels such as nuclear power and renewable energy sources; reduction of non-CO<sub>2</sub> GHG emissions; and changes in land use practices that currently result in global deforestation. No single technology or policy option will provide all of the emission reductions needed to accomplish stabilization of atmospheric concentrations of GHGs. In combination, however, these options could achieve a range of stabilization levels. Enhanced energy efficiency and increased renewable energy production will reduce CO<sub>2</sub> emissions, but according to IEA, energy efficiency and renewable energy alone do not have the potential to reduce global CO<sub>2</sub> emissions to the International Panel on Climate Change's (IPCC's) target level.

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<sup>3</sup> Frances Beinecke, Testimony before the Subcommittee on Public and Consumer Solutions to Global Warming and Wildlife Protection Committee on Environment and Public Works, “America's Climate Security Act”, October 24, 2007. [http://docs.nrdc.org/globalwarming/glo\\_07102401A.pdf](http://docs.nrdc.org/globalwarming/glo_07102401A.pdf).

With regard to fossil fuel options, we will need to increase the efficiency with which we use coal, oil, and natural gas and will need to capture and store much of the CO<sub>2</sub> that is generated when they are used. Coal, for example, is critical to meeting U.S. and global energy needs. It is a low-cost, secure domestic fuel that provides over half of the electricity generated in the United States (over 80% of the coal mined in the United States is used to generate electricity). Capturing CO<sub>2</sub> from oil combustion will be more problematic, since most oil is used in transportation where capture systems are impractical. This suggests that electric vehicles, which will transfer the CO<sub>2</sub> burden back to the electric power sector, may be the only effective solution for personal transportation, which amplifies the importance of developing pragmatic CO<sub>2</sub> solutions for power generation. The cited NRDC testimony also recognizes that *“Perhaps the most important performance standard for the energy production sector is for coal-fired electric generation. It is critical to recognize that continued investments in old technology will “lock in” high carbon emissions for many decades to come and create a tremendous economic burden. This is particularly so for the next generation of coal-fired power plants. Power plant investments are large and long-lasting. A single plant costs around \$2 billion and will operate for 60 years or more. If we decide to do it, the United States and other nations could build and operate new coal plants that return their CO<sub>2</sub> to the ground instead of polluting the atmosphere. With every month of delay we lose a piece of that opportunity and commit ourselves to 60 years of emissions. The International Energy Agency (IEA) forecasts that more than 20 trillion dollars will be spent globally on new energy technologies between now and 2030.”*

## *Part II: Carbon Capture and Storage (CCS)*

Carbon dioxide capture and storage (or sequestration) is a process consisting of separating CO<sub>2</sub> from other gases at emission sources, transporting it to a storage location, and ensuring the long-term isolation of CO<sub>2</sub> from the atmosphere. Independent and respected international organizations have reached the conclusion that global growth in CO<sub>2</sub> cannot be avoided without the rapid development and deployment of affordable CO<sub>2</sub> capture and storage technology (CCS). The IEA states, “CCS development is critical to reducing CO<sub>2</sub> emissions.” In its scenario to reduce GHG emissions by half by 2050, CCS technology is the largest single contributor to the needed reductions. The IPCC won the 2007 Nobel Peace Prize for their work on climate change. Their 2006 assessment of CO<sub>2</sub> capture and storage, authored by 32 experts from around the world, also concluded that CCS is a critical GHG mitigation technology that can contribute up to 55% of the cumulative global mitigation effort. Many other agencies have also underscored the need for CCS, including the EPA, the DOE/EIA, the World Coal Institute, the United Nations (via the Framework Convention on Climate Change (UNFCCC) and other documents), the IPCC, the European Commission (EC), the U.S. Pew Centre on Global Climate Change, and others. The World Wildlife Fund (WWF) cites CCS as one of six key solutions to global warming.

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

Because power plants constitute a large portion of CO<sub>2</sub> emissions (and are large stationary sources that lend themselves to CCS), most CCS studies have focused on systems to capture CO<sub>2</sub> from power plants, particularly coal-based power plants. In order to properly address climate change concerns, the reader should bear in mind that CCS technology will also have to be applied to natural gas-fired power plants, and large industrial emitters, like refineries, natural gas processing plants and cement plants, in order for aggressive GHG emission reduction targets to be met.

The basic approach to CO<sub>2</sub> capture from a coal-based power plant depends largely on the power plant design. For most existing power plants, the CO<sub>2</sub> is captured from the plant's exit gas stream and a type of capture called "post-combustion capture" is the technology which is applied. This capture technology resembles pollution capture systems for traditional pollutants like SO<sub>2</sub>, although the complexity and cost is much greater. In advanced power plants, such as integrated gasification combined cycle power plants, which first gasify coal and then use the synthesis gas to produce power in a system employing both combustion turbines and steam turbines, the preferred option is to capture the carbon from synthesis gas prior to its combustion. Hence, these systems are called "pre-combustion" capture systems. This approach has distinct economic and technological advantages. There is also interest in advanced power systems that burn coal with pure oxygen. These "oxy-combustion" or "oxy-fuel" systems, as they are called, result in a combustion gas that is very high in CO<sub>2</sub> concentration, so separating the CO<sub>2</sub> is much easier. They are also projected as having economic advantages.

## *CO<sub>2</sub> Capture Technology Status*

In general, most of the discussed capture systems have been demonstrated or have been shown to work at small scale. Some capture technologies (such as Rectisol and Amine Scrubbers) have been operated commercially in other applications. None has been integrated into a commercial scale power plant to capture the generated CO<sub>2</sub>. Various studies have estimated the current cost of capture and storage of CO<sub>2</sub> to be in the range of 60-90% increase in electricity costs, compared to a traditional pulverized coal power plant without CCS. Much work is under way to bring down these costs (as well as associated energy penalties). In addition, good progress is being made in developing new, innovative technologies that could dramatically improve the cost and energy penalties for CO<sub>2</sub> capture with both gasification and combustion based systems, such as oxygen membranes, chemical looping, and advanced CO<sub>2</sub> compression technology. The control of CO<sub>2</sub> from existing plants presents special challenges, due to possible land availability and other limitations.

## *Transport*

CO<sub>2</sub> is compressed to about 2000 pounds per square inch, or about 150 times atmospheric pressure, for transport via steel pipelines. At this pressure, the gas becomes a "supercritical" liquid, meaning it can be pumped like a liquid, but has very low resistance to flow, like a gas. Pipelines for transport of CO<sub>2</sub> are a mature technology. There are about 4,000 miles of such pipelines in the United States today.

## CO<sub>2</sub> Storage

The ability of a geologic site to store CO<sub>2</sub> depends on several factors, especially the geologic porosity and permeability of the selected site. Storage sites for CO<sub>2</sub> can be found in many locations, including ancient sedimentary basins that probably looked similar to what we see today on the surface, such as beach sand. If a glass were to be filled with beach sand, no matter how tightly the grains of sand were packed, spaces would always remain between the grains. If water was then poured into this sand filled glass, the water would fill the spaces between the grains. The sand would appear to “absorb” a considerable amount of this water. Close to 40% of the volume of the glass would be made up of this poured water. The glass of sand, in this example, would be referred to as having a porosity of about 40%. This is very similar to geologic porosity that is found in nature. It is very important when seeking a good storage site because this is the space into which the CO<sub>2</sub> would be injected. See Figures 1 and 2 on pages 12 and 13 for an illustration of geologic storage of CO<sub>2</sub>.

Over millions of years these sediments get buried deeper and deeper into the earth. Ideal sediments are typically deeper than 3,000 feet. However, as the sediments get progressively deeper, or depending on how they were formed, the grains in the sediments can get crushed and, thereby the porosity and the volumes of CO<sub>2</sub> that can be stored could be diminished. It is possible for the porosity to drop to lower than 10%. If the porosity drops to these very low levels, there isn't sufficient space or capacity for practical CO<sub>2</sub> storage. Therefore, ideal CO<sub>2</sub> storage sites would be those containing sediments that have retained higher levels of porosity.

Another critical factor is permeability. Permeability is the ease with which fluids can flow through the sediments. Imagine a glass full of large marbles and then a glass full of sand. Both can have a similar 40% porosity. However, when you try to fill each with water, the one with the large marbles will fill much quicker and easier. The water flows faster through the marbles because the pathways between the marbles are bigger and therefore easier to pass through than those of the sand. The rule is generally that bigger grains mean greater permeability so ideal CO<sub>2</sub> storage sites would have deposits where the grains are big enough to allow the CO<sub>2</sub> to flow through with ease. If the grains get too small and the flow is too restricted then the injection of large volumes of CO<sub>2</sub> will require too many wells and will end up being too costly.

The CO<sub>2</sub> pressure at the surface injection point typically will be comparable to the pressure within the earth at a depth of one mile, or about 150 times atmospheric pressure, which is not overly high. The depth to which it will be injected will vary, ranging between 1,000 and 10,000 feet below the surface. Most injections will occur between 3,000 and 6,000 feet.

The force of buoyancy will cause CO<sub>2</sub> to flow upward through the porous formation and the pressure from the injection will cause it to flow laterally away from the injection point. The CO<sub>2</sub> will flow until it reaches a layer of impermeable rock that stops it. As the volume of CO<sub>2</sub> expands within a porous rock formation, various trapping mechanisms act to immobilize portions of it. It is important to note that stored CO<sub>2</sub> becomes more stable over time, thus diminishing the possibility that it will move from the

place that it is injected (especially to the surface). In fact, models show that over long periods of time (hundreds and thousands of years) the trapping mechanisms of dissolution and mineralization will act to immobilize all of the injected CO<sub>2</sub>. There are five different mechanisms that trap the stored CO<sub>2</sub> in a geologic formation:

- a) **Structural trapping.** A layer or “cap” of impermeable rock that overlies the formation of porous rock into which the CO<sub>2</sub> is injected prevents upward flow of CO<sub>2</sub>. This is the mechanism that caused natural deposits of crude oil, natural gas and CO<sub>2</sub>.
- b) **Capillary trapping.** The surface of sandstone and other rocks preferentially adheres to saline water over CO<sub>2</sub>. If there is enough saline water within a pore (75-90% of the pore volume), it will form a capillary plug that traps the residual CO<sub>2</sub> within the pore space.
- c) **Dissolution in saline water.** CO<sub>2</sub> is soluble in saline water. As it comes in contact with the saline water it dissolves into solution.
- d) **Mineralization.** Over longer periods of time (thousands of years), dissolved CO<sub>2</sub> reacts with minerals to form solid carbonates.
- e) **Adsorption of CO<sub>2</sub>.** Coal and other organically-rich reservoirs will preferably adsorb CO<sub>2</sub> onto carbon surfaces as a function of reservoir pressure.

### *CO<sub>2</sub> Storage Geology and Instrumentation*

A final important point is that every storage site will be different – even sites in similar geologic formations. Just as all rivers and beaches are different, so will be the storage sites. Though they are all different, there will be some basic geologic principles that will remain valid that will help identify those that are most suitable and the most likely patterns they will follow. We have instrumentation and technology available today that allows us to identify the best location for CO<sub>2</sub> injection, along with its geologic porosity and permeability. These technologies help to map and visualize the subsurface. They also compliment rock and fluid samples taken from the subsurface via wells.

### *CO<sub>2</sub> Storage Capacity*

Most of the existing CO<sub>2</sub> pipeline capacity carries CO<sub>2</sub> from natural underground deposits to partially depleted oil fields where the CO<sub>2</sub> is used for enhanced oil recovery (EOR). Use of EOR can produce an extra 15-20% of the original oil in an oilfield and thereby can provide an opportunity for CCS cost reduction while strengthening energy security through enhanced domestic oil production. As noted below, EOR provides considerable opportunities for storing CO<sub>2</sub> and will be especially important for early deployers of CCS. However, EOR alone will not be able to store the entire amount of the CO<sub>2</sub> being generated by power plants in the United States. In the long term, most of the CO<sub>2</sub> stored for climate change mitigation will be in deep saline formations.

The DOE’s National Energy Technology Lab’s (NETL’s) 2008 Atlas estimates the capacity of domestic storage reservoirs at over 3,000 billion metric tons of CO<sub>2</sub>. The Atlas also shows the locations of CO<sub>2</sub> sources and CO<sub>2</sub> storage opportunities. Over 95% of the estimated CO<sub>2</sub> storage capacity is in saline formations. This is a basin-level estimate based on the total pore volume and complete CO<sub>2</sub> contact with the target reservoirs. It should be considered a preliminary estimate and an upper bound. Thus the CO<sub>2</sub> storage capacity is enough to hold over 1, 500 years of power plant emissions at the 2003 level.

## Overcoming Barriers to CCS Deployment

There are a number of barriers to the wide-scale deployment of CCS. They include the high cost of currently available capture technologies, no experience operating CO<sub>2</sub> capture equipment on commercial scale power plants, as well as a lack of experience with storing extremely large volumes (3-5 million tons per year) of CO<sub>2</sub> in geologic formations. Regulatory barriers must also be overcome: an absence of rules for storage of CO<sub>2</sub> in saline formations, and for addressing long-term (hundreds of years) liabilities. There is also a lack of a CO<sub>2</sub> interstate pipeline infrastructure to transport CO<sub>2</sub> from power plants in regions that lack excellent storage options.

In the past, similar problems in the power sector have been overcome by partnerships between the private sector and public sector to advance technology, and by government policies that established regulatory frameworks to foster new solutions to benefit the public. Overcoming the CCS deployment challenges is akin to establishing a new industry, with the following challenges:

**Cost Challenge:** CCS costs and energy penalties must be greatly reduced. Compounding this challenge is the costs of capital intensive technologies, which has greatly increased in recent years due to unprecedented cost escalation in the heavy construction industry. **There are at least three opportunities for bringing down CCS cost:**

- 1. Technology Maturation:** Generally, the cost of all new technologies (including CCS technology) is the highest (and the reliability the lowest) at the time of market introduction and progressively improve as the technology matures through commercial replication and operation. Hence, one approach to reduce costs is simply to start building CCS systems using currently available technology and “learn by doing.”
- 2. Technology Advancement:** There are basically two directions in this category. The development of lower cost advanced CO<sub>2</sub> capture technologies (such as hydrogen membranes, “clathrate” technology, advanced IGCC systems, oxy-combustion systems, and other.) and, the development of system components that can bring down overall, CCS-equipped, plant costs (such as oxygen membranes, chemical looping, advanced turbines, fuel cells, advanced compression technology, etc.). Technology advancements usually require a combination of R&D (to produce a concept that works), and demonstration projects (to scale-up the technology to commercial size).
- 3. Financial Incentives:** Governments can offer a variety of financial incentives for early or accelerated demonstration and deployment of CCS technology to bring down the high initial cost (such as CCPI demonstration plant funding, tax incentives, loan guarantees, etc.). Such incentives are useful in the early stages of technology development to offset the higher risks of unproven technology, and in the early stages of technology deployment to offset the higher costs of the technology as it enters the commercial marketplace.

A combination of all three of these cost reducing mechanisms is needed to minimize both the ultimate technology cost and the time needed to reach full commercial deployment of CCS technology.

**Storage Validation (safety & permanence) Challenge:** We must globally validate the capability for storing large volumes of CO<sub>2</sub> in a variety of geologic formations over long periods of time. Also, the

heterogeneity of the global geologic resource requires a comprehensive R&D effort for fully characterizing a wide variety of geologic formations (especially saline reservoirs) through the monitoring and evaluation of injected CO<sub>2</sub> behavior.

**Risk & Liability Challenge:** The liabilities associated with the storage of CO<sub>2</sub> can be a major impediment to broad deployment of CCS technology which must and can be addressed and resolved. CO<sub>2</sub> storage must be secure for hundreds of years to be an effective climate change mitigation tool, and this timeframe exceeds the capabilities of traditional risk management mechanisms. Validating the safe and permanent storage of CO<sub>2</sub> is critically needed to be able to define/quantify risk and liability. This, combined with developing a legal CCS framework, will allow for the insurability of the projected CCS risk and liability. Defining acceptable risk and determining who will be responsible for that risk is both a legal issue and a technical one. Accelerated, broad, early global deployment of CCS may require that Governments accept some form of long term liability for CO<sub>2</sub> storage sites that have been properly operated and properly closed by an approved closure and monitoring process.

**Best Practices, Standards, Regulations Challenge:** Successful validation of long-term storage of CO<sub>2</sub> coupled with the development of low cost CCS technology will provide the basis for industry to establish “best practices.” All of this will culminate in the development of well founded standards necessary for the promulgation of regulations. While regulatory uncertainty is a barrier to CCS deployment, regulations that are not well thought out and well developed would be worse.

### *CO<sub>2</sub> Storage Technology Status*

As has been discussed above, much is already known about carbon storage. CO<sub>2</sub> has been injected underground for EOR for decades and it has been done safely. We have observed a variety of trapping mechanisms that kept naturally occurring CO<sub>2</sub> permanently contained in geologic formations. So we know it can be done, but we need to scientifically validate this capability and much work in this regard is now underway. In the United States we have had a CO<sub>2</sub> storage R&D program for a number of years and now have seven Carbon Sequestration (another name for storage) Regional Partnerships making great strides; 25 geologic CO<sub>2</sub> field tests are at various stages and 10 terrestrial sequestration tests are underway. Nine large scale field tests, injecting one million tons of CO<sub>2</sub> over several years, are set to begin injection beginning in 2009-2011.

There is consensus that permanent geologic storage of CO<sub>2</sub> has great potential for safely and permanently storing CO<sub>2</sub>. There is also reasonable confidence that there is sufficient storage capacity in the United States, Western Canada, and other parts of the world for the large volumes of CO<sub>2</sub> released by power generation and other large industrial sources. An enhanced oil recovery project (in which the United States has been participating) in the Weyburn field in Canada, has been injecting CO<sub>2</sub> produced from a North Dakota based coal gasification plant. CO<sub>2</sub> has also been injected into underground geologic structures for EOR at various U.S. locations. There are also two large overseas projects, in the North Sea and in Algeria, storing CO<sub>2</sub> into geologic structures from which the United States is receiving CO<sub>2</sub> storage data.

Thus, as the Coal Utilization Research Council (CURC) has observed, although there is reasonable confidence in the viability of long-term CO<sub>2</sub> storage, substantial financial, institutional, regulatory, and

technical challenges still remain.<sup>4</sup> Part of the effort to overcome these challenges will involve conducting an array of small-, intermediate-, and large-scale CO<sub>2</sub> injection field tests (and, as indicated earlier, some are now under way) in diverse geologies to adequately validate this technology.

### **CCS Summary Comments**

*In summary, the development and deployment of effective and low cost CCS technology is critical if we are to meet climate change goals. The validation of affordable capture technology and reliable, long-term storage of CO<sub>2</sub> will be needed to resolve CCS liability issues and to gain widespread local community acceptance of, and support for, CCS. R&D now underway in the United States and elsewhere will lead to the large-scale demonstration of large-scale power plants with integrated CCS systems and to the validation of long-term CO<sub>2</sub> storage. Ongoing R&D conducted by various public and private groups working cooperatively holds great promise for making CCS technology more affordable, but more needs to be done both domestically and globally. The rate and timing of CCS deployment will depend on the level of global investment in research, development, and demonstration in this area (which will largely determine when lower cost CCS technology will become available) and on the level of technology deployment incentives provided (which will largely determine the rate at which the new technology will be deployed).*

### **Additional Suggested Sources of CCS 101 Information**

DOE and NETL web sites, and those of their seven Carbon Sequestration Regional Partnerships, have a wealth of information on all aspects of CCS. These sites can be accessed directly or through <http://www.energy.gov> and <http://www.NETL.gov>. NETL's Sequestration Roadmap can be found on [http://www.netl.doe.gov/technologies/carbon\\_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf](http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf)

DOE/NETL's National Carbon Sequestration Database and Geographical Information System (NatCarb) is especially valuable and can be accessed through <http://www.natcarb.org>.

The seven Carbon Sequestration Regional Partnerships web sites can be accessed directly:

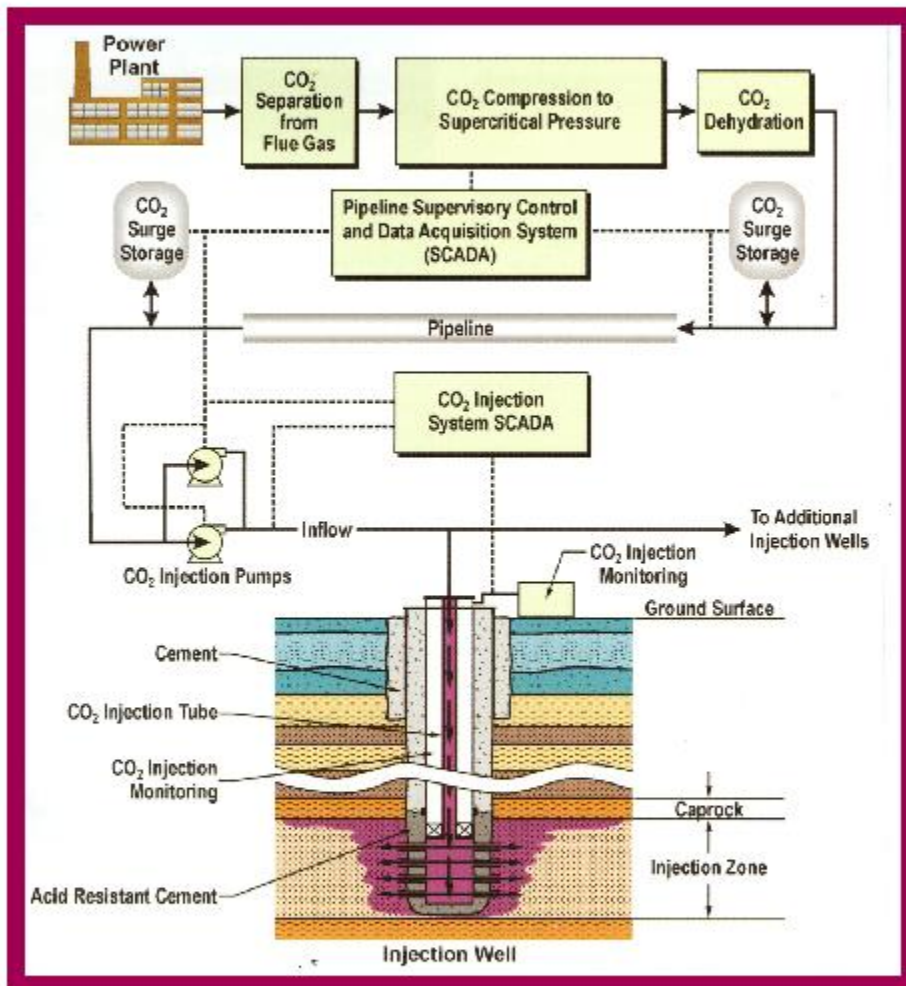
- Big Sky Partnership (Big Sky) at <http://www.bigskyco2.org>
- Midwest Geological Sequestration Consortium (MGSC) at <http://www.sequestration.org>
- Midwest Regional Partnership (MRCSP) at <http://www.mrscp.org>
- Plains Partnership (PCOR) at <http://www.undeerc.org/pcor/>
- South East Partnership (SECARB) at <http://www.secarbon.org>
- South West Partnership (SWP) at <http://www.southwestcarbonpartnership.org>
- West Coast Partnership (WESTCARB) at <http://www.westcarb.org>

USCSC educational papers on CCS can be accessed at <http://www.uscsc.org>

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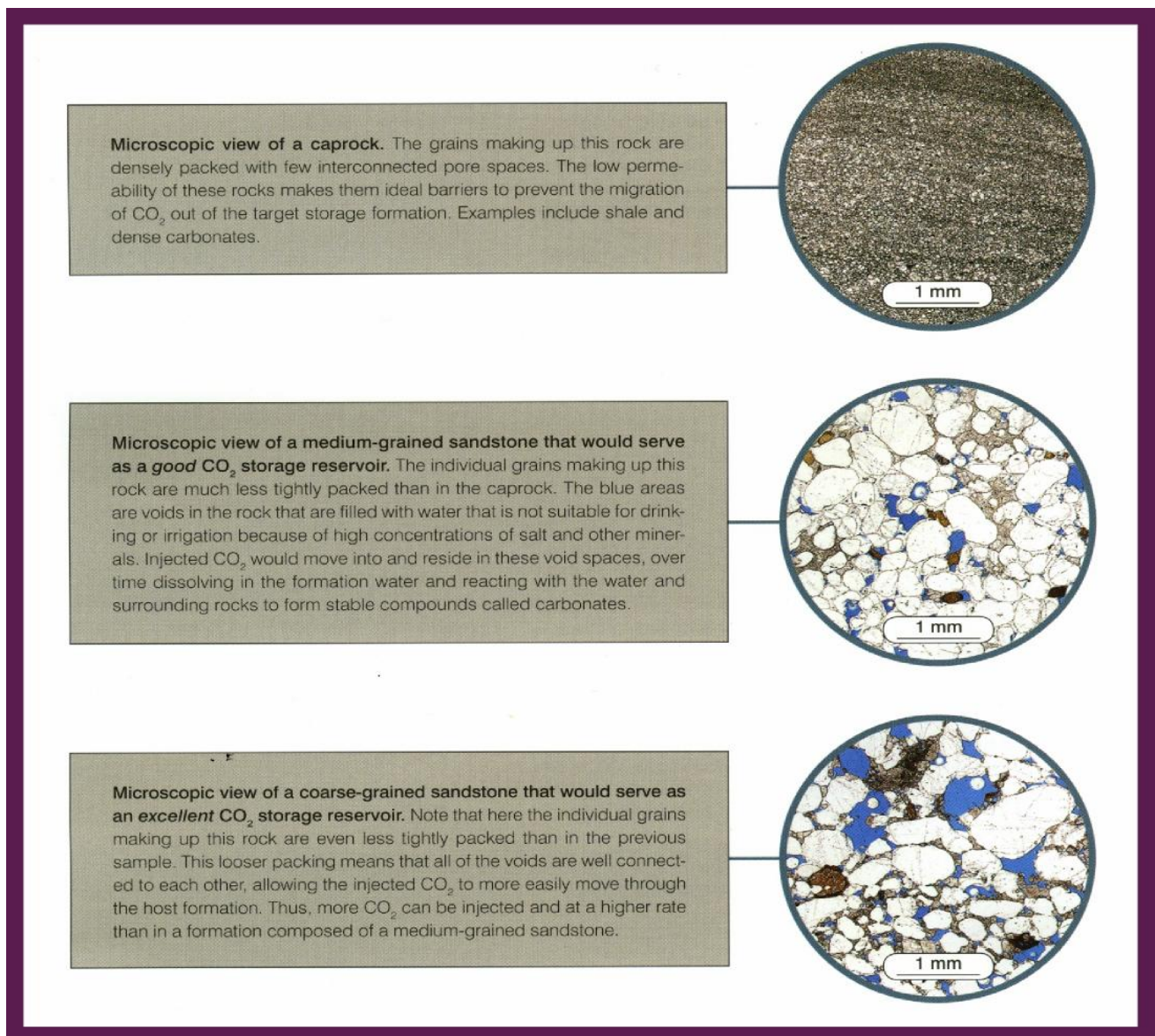
<sup>4</sup> Testimony by Ben Yamagata, Director, Coal Utilization Research Council, before the House Energy and Commerce Committee, Subcommittee on Environment and Hazardous Materials, July 24, 2008, [http://energycommerce.house.gov/cmte\\_mtgs/110-ehm-hrg.072408.ClimateChange.shtml](http://energycommerce.house.gov/cmte_mtgs/110-ehm-hrg.072408.ClimateChange.shtml) .

Figure 1  
 How does Carbon Dioxide get stored in a geologic formation?  
 Part 1: How does it get under ground?



Source: JJ Dooley, et al, "Carbon Dioxide Capture and Geologic Storage," Technology Report from the Second Phase of the Global Energy Strategy Program, April 2006

**Figure 2**  
**How is Carbon Dioxide stored in a geologic formation?**  
**Part 2: What does it look like when stored underground?**



Source: JJ Dooley, et al, "Carbon Dioxide Capture and Geologic Storage," Technology Report from the Second Phase of the Global Energy Strategy Program, April 2006

