Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

POLICY CONTEXT OF GEOLOGIC CARBON SEQUESTRATION

The primary objective of the Framework Convention on Climate Change is the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner” (Article 2 of the FCCC).

The Convention states specifically that participating parties shall

> “Promote and cooperate in the development, application and diffusion, including transfer, of ***technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases*** … ***in all relevant sectors, including the energy … sectors***” (Article 4(c), emphasis added).[1]

Emissions from fossil fuel consumption are the largest contributor to the accumulation of greenhouse gases in the atmosphere and UCS firmly believes that reductions in these emissions must be the primary focus of activities to mitigate climate change. However, given current trends of GHG emissions in general, and continuing increases in atmospheric CO_2 concentrations in particular, UCS agrees in principle that nations should explore all environmentally sound options and opportunities for the effective long-term reduction of emission sources and the sustainable development of carbon sinks.[2] Below, approaches to geologic carbon sequestration are briefly summarized. The Additional Background provides a fully referenced assessment of these approaches.

---

[1] The subsequent Article 4(d) concerning the development and enhancements of carbon sinks and reservoirs does not explicitly mention underground formations for carbon storage such as depleted oil and gas fields, deep coal beds, or saline formations.
[2] For UCS position statement on marine sequestration, see http://www.ucsusa.org/environment/pos_marcarseq.html.

GEOLOGIC CARBON SEQUESTRATION

Geologic carbon sequestration can be broadly defined as the isolation and/or removal of carbon dioxide and its long-term storage underground to reduce or prevent the build-up of carbon dioxide in the atmosphere. The interest in this option[3] has been spawned by a number of factors, including the:

- allure to some of continuing a fossil-fuel based economy without major changes to the ways in which energy is produced and consumed;
- potential for significant emission reductions if implemented on a large, commercial scale;
- large, long-term storage capacity of known geologic formations;
- general feasibility and already quite advanced stage of development of capture, transportation, and storage technologies; and
- potential for developing economies of scale to make geologic sequestration economically more attractive than at present, and to achieve significant reductions at lower costs than strategies that do not include this option as part of the mix.

Geologic carbon sequestration involves three basic steps:

(1) ***Capture*** -- Carbon capture can occur before or after the burning of fossil fuels or biomass at point sources, such as power plants, large industries, or fossil fuel extraction and conversion sites.[4] Pre-combustion fuel separation (decarbonization) and capture is more desirable in terms of energy efficiency and because of the production of hydrogen (a GHG-free energy source) in the process. Post-combustion technologies involve the capture of the emitted waste stream and isolation of carbon dioxide from the mix of emissions. The post-combustion process is currently further developed than pre-combustion technologies and thus is more likely to be employed over the next few years. After capturing the CO_2, the gas is concentrated, compacted, and dried into a dense-phase fluid before being transported to the storage site.[5]

(2) ***Transportation*** – The capture and processing of carbon dioxide typically occurs at energy production sites (oil and gas wells, power plants). Unless the gas is immediately re-injected into active oil or gas wells or deep coal beds for enhanced oil/gas recovery, transportation in pipelines to the ultimate storage site is required.

(3) ***Storage*** – Storage typically involves the injection of the condensed carbon compound into known underground repositories, such as depleted oil and natural gas fields, land-based or off-shore deep saline formations, or deep coal beds. Depending on the type of storage, the substance either chemically reacts with (e.g., coal, silicates) or is dissolved in other substances (e.g., water) and is thereby fixed, or it is held in the porous geologic substrate. An alternative to deep-storage is the facilitation of chemical reactions between the gas and calcium or magnesium compounds to produce limestone, which then can be stored aboveground or used elsewhere.

---

[3] Under the UNFCCC Climate Technology Initiative, exploratory research and application projects on carbon capture and storage are being funded already. Moreover, the fossil-fuel industry on its own, and in public-private research and development ventures with governments in North America, Europe and Asia, is advancing research on carbon separation technologies and furthering the understanding of storage sites. In the United States, the Department of Energy is funding carbon sequestration research and development at about $19 million for FY2001 (a 19-fold increase since 1998) and has proposed to increase this funding to $40 million – 85 million/year over the next 15 years.

[4] Economically viable capture technologies from small, dispersed sites (e.g., cars) are yet to be developed.

[5] The basic chemistry of a gas hydrate is that of a gas molecule enclosed in a crystal (ice) structure.

The fossil fuel industry has used some carbon capture, transportation, and re-injection technologies for more than two decades. Capture and injection of carbon dioxide into oil, gas, and coal reserves have been integral parts of enhanced oil and gas recovery. Long-term storage underground has yet to be demonstrated. Thus, while technical feasibility has been demonstrated for some technologies already, there are still significant economic costs (e.g., for R&D, capture/separation and compression technologies, transportation) and energy efficiency losses involved. Efficiency losses of 10-20% with currently available separation technologies result in higher fuel input per unit of delivered energy. Energy penalties of this magnitude are particularly serious if safe, long-term underground carbon storage cannot be assured, i.e., if the CO_2 was quickly returned to the atmosphere (on the order of years or decades) and thus increase future greenhouse gas concentrations. A number of current research and development efforts focus on ways to lower costs, e.g. through improving the capture and compression technologies, increases in energy efficiency and increases in opportunities for economic benefits from capturing, recycling/reusing, or permanently storing CO_2.

For geologic carbon sequestration to be a promising option for climate change mitigation, it is also important to assess the potential capacity of underground formations to store carbon. Studies conducted by the International Energy Association and others indicate the following potential for underground carbon storage worldwide, the range reflecting optimistic estimates of absolute underground storage space on the high end and current economic restrictions on the low end:

Deep saline formations	100-3000 Gt C
Depleted gas wells	140-310 Gt C
Depleted oil wells	40-190 Gt C
Deep coal beds	100-300 Gt C

(1 Gt C = 1 Giga/billion tons of carbon)

The ultimate (upper end of the range) storage capacity of oil and gas fields combined may be more than 125 years of total current CO_2 emissions from fossil fuel power plants. Deep saline formations could possibly extend that capacity to store the world's carbon emissions for many decades if not centuries. Thus, geologic sequestration could potentially play a significant role in the solutions portfolio to reduce carbon dioxide emissions and concentrations. However, the upper end of this range should not be viewed as achievable, as social, environmental, political, economic, and technical factors will determine what is realistically feasible.

For example, while the potential environmental consequences and risks to public safety are generally acknowledged but frequently dismissed as minor, these environmental concerns are insufficiently studied through systematic research to date. These risks include:

Direct risks to humans

- the potential for environmental risks to humans, such as catastrophic venting of CO_2, i.e., the rapid re-release of stored gas in toxic concentrations from underground storage sites;
- the potential for potable aquifer contamination; and
- the possible risk of induced seismicity (earthquakes) due to underground movement of displaced fluids.

Environmental risks

- the yet-unknown permanence of underground carbon storage, i.e., the re-release of carbon dioxide, thus delaying, but ultimately not solving the emission problem; given the energy penalty associated with carbon separation, if stored carbon is re-released to the atmosphere over time scales of years or decades, atmospheric carbon dioxide concentrations will increase;
- continued (and possibly increased) reliance on fossil fuels with the associated adverse environmental consequences at fossil-fuel extraction sites, particularly in ecologically sensitive areas;
- adverse environmental impacts associated with extensive expansion of pipeline facilities necessary for the transfer of CO_2 to deposition sites if implemented on a large scale; and
- unknown impacts on the biological communities that live in deep saline formations and other storage sites.

Within the full portfolio of domestic and international approaches to manage carbon comprehensively, UCS views geologic carbon sequestration as one potentially viable option to achieve reductions in carbon dioxide emissions and atmospheric concentrations. In no way, however, should geologic carbon sequestration be seen as a "silver bullet" to reducing emissions, nor should it be researched and developed at the expense of other environmentally sound, technologically feasible, and economically affordable solutions to climate change. UCS views technologies and policies that prevent emissions to the atmosphere in the first place – such as improving energy efficiency (http://www.ucsusa.org/energy/energy-home.html) in power generation, transportation (http://www.ucsusa.org/vehicles/veh-home.html) and buildings, developing renewable energy (http://www.ucsusa.org/energy/0renewable.html), and protecting threatened forests (http://www.ucsusa.org/environment/forests.html) – as the safest and highest priority.

UCS supports appropriate research into all aspects of geologic sequestration, especially the

- currently largely unexplored environmental consequences, including those associated with extending fossil fuel extraction;
- capacity for safe, long-term underground storage of carbon;
- characteristics of the currently much less well understood saline formations;
- pre-combustion carbon capture (decarbonization) technologies; and the
- risks to public safety.

Such research should determine the realistic scale of using this approach within the larger portfolio of carbon management options.

ADDITIONAL BACKGROUND

In order to stabilize atmospheric concentrations of greenhouse gases, there is a need for a significant reduction in emissions of CO_2 and other greenhouse gases (IPCC, 2001). No single strategy will meet both growing energy demands and emission reduction needs (Herzog, 2000). A portfolio of strategies is required to address emissions of all greenhouse gases in the most cost-effective and environmentally sound manner. With regard to the main greenhouse gas CO_2, two sets of approaches are needed. One the one hand, we need approaches that reduce or prevent CO_2 from reaching the atmosphere – such as an increase in energy efficiency, the use of renewables, the protection of forests, and CO_2 capture during fossil fuel and electricity production. These must be combined, on the other hand, with approaches that can remove gas already emitted to the atmosphere – such as enhanced terrestrial carbon sequestration through reforestation, appropriate land use practices, or enhanced microbial or mineral carbon fixation (e.g., Socolow, 1997).

Given the fast build-up of heat-trapping gases and their concentrations in the atmosphere, the fossil-fuel-intensity of industrial processes in developed countries, the economic development and demographic growth trajectories of developing countries, and the increasing rate of climate change, there is a growing urgency to find options for large, lasting, and relatively quickly implemented emission reductions.

In the broad context of adapting and fundamentally changing the energy system that supports the world's economies, geologic carbon sequestration can be viewed as one potential, and potentially important, contribution to the much larger portfolio of carbon management and climate mitigation options. *The following sections elaborate on UCS' position statement on geologic carbon sequestration.*

Available Geologic Formations & Principal Mechanisms of Carbon Capture and Storage: An Overview

Two definitions contained in the U.N. Framework Convention on Climate Change (1992) are relevant to geologic carbon sequestration:

- A "sink" is defined as any process, activity or mechanism, which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.
- A "reservoir" is defined as a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored.

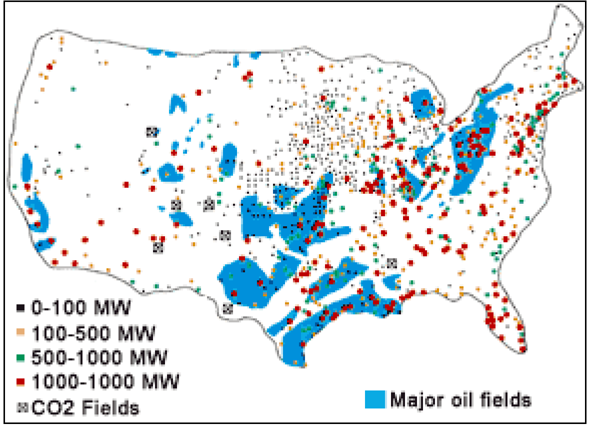
The geologic formations in which carbon could be stored would be considered the ***reservoirs***, whereas the processes of capture, separation, and injection into these reservoirs would be considered the ***sinks***. Currently, geologic sequestration research focuses on four types of reservoirs or underground storage sites for carbon:

- Active and depleted oil fields
- Active and depleted natural gas reservoirs
- Deep saline (brine) formations
- Deep coal seams or coal beds.

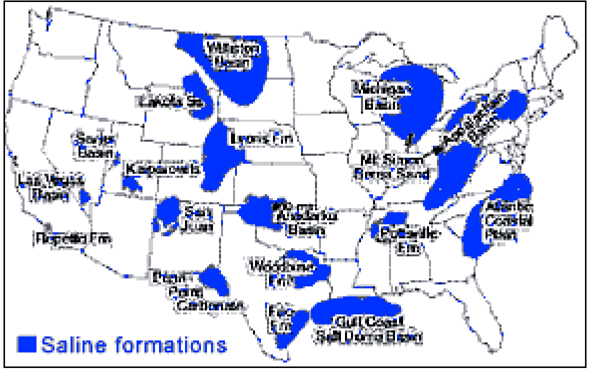
These underground formations can be land-based or beneath the ocean floor; they are widespread globally, including in the U.S. (see Figures below).

Potential Land-based Storage Sites in the U.S.

Locations of major U.S. oil fields, power plants and CO_2 fields

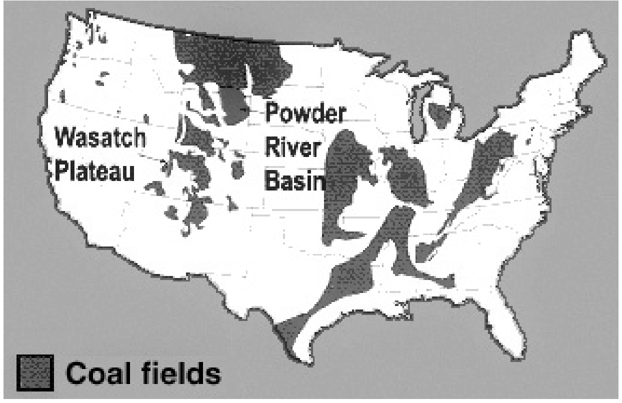


Locations of major deep saline formations in the U.S.



Source of both Figures: Preuss (2001)

Locations of major U.S. coal fields



Source: USGS (2000)

The storage potential of other geologic formations – such as salt domes or oil shales – has yet to be examined and critically assessed (Benson, 2000b).

Sink Mechanisms

The three basic (sink) mechanisms allowing carbon to be stored underground are:

- **Hydrodynamic trapping**: CO_2 can be trapped as a gas or fluid under a quasi-tight layer of rock or stored in a saline formation;
- **Solubility trapping**: CO_2 can dissolve into a fluid phase – a process used in enhanced oil recovery; and
- **Mineral trapping**: CO_2 can react with the minerals or organic matter in geologic formations and become part of the solid matter or rock.

Carbon Capture and Separation

Prior to being able to store carbon underground via any of these trapping mechanisms, the carbon must first be captured and separated from other components of the fuel or waste stream. Again, there are three fundamentally different ways to accomplish this initial step (Keith, 2001); for more detail see the section on **Technical Status and Prospects**):

- **Post-combustion carbon capture**: Fuel is burned in air and CO_2 is captured from the combustion products. This option allows current energy production facilities and other large industrial sites to be retrofitted with the necessary technology.
- **Oxyfuel**: Oxygen is first separated from air; then the fuel is burnt in pure oxygen and CO_2 captured from the combustion products.
- **Pre-combustion decarbonization**: Fuel is reformed to produce both hydrogen and CO_2. This hydrogen can be used as a carbon-free energy source.

Geologic Carbon Storage Potential

Whether or not geologic carbon sequestration can make a significant contribution to the portfolio of climate change mitigation options depends in part on the storage capacity of underground repositories. According to a comprehensive assessment by the International Energy Agency and more recent studies, research has produced a range of estimates for the global CO_2 storage capacity:

Repository	**Global Storage Capacity**
Deep saline formations	100-3000 Gt C*
Depleted gas wells	140-310 Gt C
Depleted oil wells	40-190 Gt C
Deep coal beds	100-300 Gt C

[* 1 G (Giga) ton C = 1 billion tons of carbon]

Sources: Parson & Keith (1998); IEA (1994b) from http://www.ieagreen.org.uk/removal.htm and http:///www.ieagreen.org.uk/disp2.htm)

At the high end, the storage capacity of oil and gas fields combined equates to over 125 years of total current CO_2 emissions from fossil fuel power plants (Abelson, 2000). According to one estimate there may be enough capacity in oil and gas reservoirs to sequester many decades of the world's CO_2 emissions from power plants and other industries (Sally Benson of Lawrence Berkeley National Laboratory quoted in Preuss, 2001). Depending on assumptions about total thickness of the saline formation (volume), formation properties such as porosity and permeability, and possible restrictions on use (e.g., lack of suitable seal), deep saline formations could add to this capacity such that the world's carbon emissions could be stored for centuries (Preuss, 2001). However, the upper end of this range should not be viewed as achievable, as social, environmental, political, economic, and technical factors will determine what is realistically feasible.

Technical Status and Prospects

Some of the technologies enabling geologic carbon sequestration are already in a relatively advanced stage of development; others are only in the early stages of research. The following sections provide additional background on the status quo and future prospects for the relevant steps in the process.

1. Carbon capture and separation

Carbon capture and separation is the first step toward geologic carbon sequestration. The basic idea behind it is to separate the energy function (e.g., hydrogen) from the carbon content of the fuel. An array of technologies is already available for carbon separation from flue gas and combustion products. However, the different technologies have different CO_2 concentration and waste gas stream "cleanliness" requirements. They can be applied before or after combustion, however, with implications for the energy efficiency loss. Post-combustion solvent-based separation, for example, is a relatively mature technology and involves a loss of energy efficiency (energy penalty) of about ~20% at a cost of $70-140/metric ton of carbon. More recent developments promise energy penalties <15% and overall power plant efficiencies of ~50%. Advanced separation technologies (using new solvents, membranes, low-pressure formation of CO_2 hydrates) promise energy penalties <10% (David and Herzog, 2000; Parson and Keith, 1998; Nelson, 1998). The basic technological options are as follows (Herzog, 1999; Parson and Keith, 1998; DOE, 2000b; IEA 1994a):

1. **Adsorption –** Adsorption of the gas by the use of molecular sieves – a relatively unattractive post-combustion option, due to the high energy penalty (energy efficiency loss of about 20%); but a more attractive technology if used in the pre-combustion separation process.
2. **Absorption –** Physical and chemical absorption with the help of solvents (akin to "scrubbing" of exhaust gases) is currently the most mature process, but still in need of optimization. Chemical absorption is the more energy efficient option at present.
3. **Membranes –** Separation of certain components from the gas stream along a fine membrane – still a relatively immature technology currently under development, but attractive because of a reduced energy penalty (<15% energy efficiency loss);
4. **Cryogenic fractionation –** Low temperature (cryogenic) distillation processes for highly concentrated CO_2 in flue gas; also involving a relatively high energy penalty;
5. **(Bio)Mineralization –** Chemical reaction of carbon with calcium and magnesium to produce limestone or biological incorporation and hence fixation of carbon through the metabolic process.

2. Transportation

Extensive experience with long-range pipeline transport (i.e., over hundreds of km at pressures of approximately 100 atmospheres) of super-critical carbon dioxide (a fluid) has been gathered in the context of enhanced oil recovery (EOR) (Parson and Keith, 1998). Hence, the basic technology, again, is available. However, the cost of transport increases significantly with distance, and thus should be minimized. As a result, the placement of capture sites relative to injection/storage sites is a key concern.

If geologic carbon sequestration were to become a more widely used option in the context of the climate mitigation portfolio, significant investment in a much expanded gas transportation (pipeline) infrastructure would be required to accommodate the needed capacity. However, such infrastructure expansion would also result in significant environmental impacts incurred by the construction of pipelines. This would be especially serious if done in ecologically sensitive areas.

3. Underground storage

Depleted oil and gas fields:

Depleted oil and gas fields have several advantages as storage sites. They are immediately available; their geology is fairly well known, hence there is only a limited need for exploration; and they have a seal (quasi-impermeable rock layer above the storage repository). Relative to saline formations, however, their storage capacity is relatively limited. The underlying concept is that injected CO_2 replaces recoverable hydrocarbons in the oil/gas field. In order to make best use of the storage capacity, CO_2 should be stored as a dense phase fluid (i.e., under high pressure >74 atmospheres and at temperatures >31 °C), conditions met at depths of ~800 m. About 80% of the world's oil fields are located at depth >800 m (http://www.ieagreen.org.uk/disp2.htm).

Active oil and gas fields:

Injection into active oil and gas fields to enhance fuel extraction is already a common practice in the fossil fuel industry. In that process, about half of the injected gas remains underground while the other 50% is re-released (and then captured, compressed, and reinjected again) (Hanisch, 1998). Thus, the process has an in-built inefficiency in terms of long-term storage, but also substantial cost benefits as it can enhance fuel recovery.

Deep saline formations:

Saline (brine) formations in deep layers beneath the surface potentially provide the most significant storage capacity for geologic carbon storage; however they are less well understood as storage sites than oil and gas fields. One large-scale project is in operation since 1996 (Sleipner Gas Field, Norway – run by Statoil). One million t CO_2/year is removed from the natural gas stream (through a solvent absorption process) and injected into the Utsira reservoir (saline formation) located 800 m below the seabed (Herzog, Eliason and Kaarstad, 2000). The project is an environmental award-winning operation and by many in the industry viewed as the "poster child" of sequestration in deep saline formations. Efforts are underway to explore the potential for similar projects elsewhere (e.g., Japan) (Hanisch, 1999; IEA 2001).

Deep coal seams:

Injection into deep coal beds or coal seams to enhance the release of natural gas (methane) is increasingly explored through industry and government research. Basically, injected CO_2 replaces methane contained in the coal beds at a ratio of at least 1:1 to about 3:1, depending on the characteristics of coal (Herzog, 1999, Socolow, 1997). Thus, this option enhances gas recovery associated with coal mining or allows fuel extraction from coal beds that are too deep to be extracted economically (USGS, 2000).

4. Reuse of CO_2 and Production of Useful By-Products

Currently, industry does not receive any subsidies (e.g., through market or tax incentives) to reduce or sequester carbon emissions. Thus, if geologic carbon sequestration were done today for the sole purpose of reducing emissions and atmospheric concentrations of CO_2 without any economic benefits or offsets to do so, it would be economically prohibitive. This is primarily due to the cost of carbon capture and separation which involve a significant energy and cost penalty (see Technical Status and Prospects and Economic Feasibility and Prospects). Even in the absence of special policy incentives to reduce carbon emissions, however, substantial co-benefits can be derived in the process today. Hence, reuse of CO_2 or production of useful by-products can help offset the costs of carbon capture. Several options currently exist, including:

- Enhancement of oil recovery (EOR) and – to a lesser extent – gas production. This option is used at commercial scale already, but involves the danger that future oil field operations might release the stored CO_2 into the atmosphere.
- Use of carbon dioxide as a bio-fuel to enhance the growth of plants or algae. This option might be viable only in certain locations and does not provide long-term carbon storage benefits; it is currently in use in the Netherlands (in greenhouses to enhance plant growth).
- Concentrated CO_2 can also serve as feedstock for the manufacturing of chemical products (e.g., in the food and oil industries). This option typically implies no permanent gas storage.
- Captured CO_2 can also be used to artificially induce and enhance the production of limestone, which in turn can be stored above surface or be used for construction and other purposes.

Economic Feasibility and Prospects

According to the IPCC (2001), half of the total estimated potential emission reductions possible by 2020 can be achieved with technologies and practices available today at a net benefit (i.e., the energy savings are bigger than the cost of the measures) to the extent that policies can exploit no regret opportunities. The other half can be achieved at a net direct cost of up to US$100/ton of carbon equivalent (at common discount rates over this period). Such policies might include efforts to eliminate or reduce market failures and barriers, as well as institutional hurdles that impede adoption of low-emission technologies. Other well designed policies might produce ancillary benefits such as reduction of air pollution, increased energy security, or simultaneous protection of species and habitats. Yet other instruments may provide additional revenue to governments (e.g., taxes). This assessment does not include large-scale geologic carbon sequestration, but only readily available emission reduction strategies and technologies.

In general, estimates of the costs and benefits of mitigation actions differ because of (a) how welfare is measured; (b) the scope and methodology of the analysis; and (c) the underlying assumptions built into the analysis. Despite these differences, most cost-effectiveness studies with a century time scale show that the costs of stabilizing atmospheric CO_2 concentrations increase as the concentration level declines. Different baselines, discount rates, the distribution of reductions over time, and the choice of policies and measures all affect the absolute costs (IPCC, 2001). Further, the IPCC finds that national responses to climate change can be more effective if deployed as a portfolio of emissions reduction measures -- such as taxes, tradable permits, provision and/or removal of subsidies, performance standards, energy mix requirements, voluntary agreements, and R&D and investment funds, etc.

> In this context of this larger portfolio of approaches, there is the potential for developing economies of scale to make geologic sequestration economically more attractive than at present, and to achieve significant carbon emission reductions at lower costs than strategies that do not include this option as part of the mix.

When viewed as a stand-alone option, geologic carbon sequestration for the sole purpose of climate mitigation is considered economically prohibitive at present because of the significant cost penalty that results primarily from the necessary higher energy input and expensive capture and separation technology. In principle, wide implementation of geologic carbon sequestration would have to yield either no net economic cost or even economic returns in order for it to become economically feasible.

Because geologic carbon sequestration is not employed on a large scale at present for the purpose of climate protection, available cost data are typically model-based projections or alternatively project-specific rather than global. Many estimates are incomplete, covering only some of the involved steps or cost items. Typically, the cost of geologic carbon sequestration is not assessed in the context of a portfolio of approaches, but as a stand-alone option. Moreover, economic modeling studies are difficult to compare because of differing assumptions (such as discount rates or economic incentives to reduce emissions). Whatever cost estimates are available should thus be viewed as indicative of the order of magnitude rather than of presumed current cost (for various estimates, see David and Herzog, 2000; Parson and Keith, 1998; Jepma et al.1996; IEA 1994b).

According to an assessment of available technologies by the IPCC in 1996, integrated carbon management in electric power plants with the technological capabilities at the time could reduce emissions by more than 80% (Ishitani et al., 1996)[6]. A full accounting would have to consider a broader set of technologies, including geologic carbon sequestration and the additional (potential) economic benefits of reuses of CO_2 and the production of useful by-products such as the following (Parson and Keith, 1998; David and Herzog, 2000; Herzog, 2000; Preuss, 2001):

- Enhanced oil recovery through immiscible replacement;
- Longer, more productive use of gas fields;
- Enhanced production of methane from coal beds; and
- Reduction of taxed CO_2 emissions (if such tax incentives are in place).

In a more recent, useful comparison, costs of employing geologic carbon sequestration were assessed for the electricity sector: the current average real cost is ~4 cents/kWh. Geologic carbon sequestration would add about 1-3 cents/kWh to that figure, making it roughly comparable to the cost of electricity from wind, biomass, and nuclear sources (Keith, 2001b; Herzog, 2000).

---

[6] This estimate did not include the indirect costs of long-term environmental impacts and the political cost of energy development of certain options such as nuclear, given the low public acceptability of that technology. It also did not consider the (unknown) potential environmental and political costs of geologic carbon sequestration.

Regardless of the exact costs, however, several general observations can be made from existing studies and estimates: costs tend to be lowest at large point sources where the cost of separation dominates, whereas costs tend to become higher where sources are distributed, and hence where there is a need to collect and transport carbon to a processing site. As a rule of thumb, the processes of carbon capture, separation and compression account for about 60-70% of the total economic cost, and from a purely economic point of view, are likely to be the focus of intense R&D (e.g., Herzog, 1999).

Environmental and Safety Concerns

A number of potential environmental impacts and public safety risks are currently acknowledged but require significant research in order to allow a comprehensive risk assessment of geologic carbon sequestration. Among the key concerns known at present are (Benson, 2000a; Keith, 2001c; Hovorka et al., 2000; Monastersky, 1999; Hanisch, 1998; Socolow, 1997):

Direct risks to humans

- the potential for environmental risks to humans, such as catastrophic venting of CO_2, i.e., the rapid re-release of stored gas in toxic concentrations from underground storage sites;
- the potential for potable aquifer contamination; and
- the possible risk of induced seismicity (earthquakes) due to underground movement of displaced fluids;

Environmental risks

- the yet-unknown permanence of underground carbon storage, i.e., the re-release of carbon dioxide, thus delaying, but ultimately not solving the emission problem; given the energy penalty associated with carbon separation, if stored carbon is re-released to the atmosphere relatively quickly, atmospheric carbon dioxide concentrations will increase;
- continued (and possibly increased) reliance on fossil fuels with the associated adverse environmental consequences at fossil-fuel extraction sites, particularly in ecologically sensitive areas;
- adverse environmental impacts associated with extensive expansion of pipeline facilities necessary for the transfer of CO_2 to deposition sites if implemented on a large scale;
- insufficiently understood risk of contamination of “sweet-water” aquifers overlying brine formations into which CO_2 is being pumped; and
- unknown impacts on the “deep hot biosphere” – biological communities that live in deep saline formations and other storage sites.

Thus far, these environmental risks are insufficiently studied. Moreover, the public is largely unaware of both the geologic sequestration option in general and the potential environmental and public safety risks in particular. Public opinion is thus vulnerable to be polarized around largely unexplored issues. Public perception and experience with burial of nuclear waste, the typical risk perception of catastrophic events, as well as generally negative perceptions of large-scale geo-engineering could become important factors in opinion forming and management. To date, public perception issues are almost entirely unexplored through social scientific research and mostly dismissed as government and industry embark further on developing this approach (Hawkins, 2001; Keith and Morgan, 2000).

U.S. Public and Private Sector Research

While research has been relatively low, and other countries have spent significantly more money on R&D than the U.S., the U.S. is among the leaders in the R&D of certain aspects of carbon sequestration technologies.

Within the US Department of Energy especially, carbon sequestration is a growing research focus, coordinated under two offices. The Office of Science focuses on basic research related to the carbon cycle and the oceans. The Office of Fossil Energy focuses more specifically on carbon separation and capture, geologic sequestration and other aspects of related and advanced technology development. It's program budget over the past four years has grown exponentially, and resource requirements based on current DOE program estimates, will continue to grow up to a maximum of $85 million/year in FY2008 (Ekman and Feeley (2000); DOE-NETL (2000)).

Currently, eight national DOE laboratories are involved in CO_2 sequestration research:

- Lawrence Berkeley National Lab
- Lawrence Livermore National Lab
- Oak Ridge National Lab
- Sandia National Lab
- Los Alamos National Lab
- Idaho Engineering and Environmental Lab
- Pacific Northwest National lab
- Argonne National Lab

The DOE's National Energy and Technology Laboratory (NETL) coordinates and manages these diverse research activities, most of them in collaboration with private sector companies and universities (total support for the selected projects in FY01 is $7.7 million) (The Energy Daily, 2000). The DOE also supports private sector research projects on carbon separation and sequestration (support: $15 million from DOE, $10 from private sector) (Ecoal, 2000). In addition, industry supports university based research. For example, BP and Ford together began funding a Princeton-based research project into carbon sequestration with $15 million and $5 million, respectively (Macilwain, 2000). Similar public-private R&D consortia have been formed in the US, Canada, Japan, Norway, The Netherlands and elsewhere.

Research and development efforts are growing fast, yet they are inadequate with regard to environmental risk concerns. Currently, the major research challenges include the following (compiled from Socolow, 1997; DOE, 1999a&b; Benson et al., 2000):

- Worldwide storage capacity assessment;
- Improved understanding of carbon trapping mechanisms;
- Assessment of retention rates and long-term fate of CO_2 in underground repositories;
- CO_2 waste stream characteristics;
- Development and assessment of advanced science-based capture and carbon separation approaches and technologies;
- Better understanding of saline formations as storage sites;
- Mineral sequestration;
- Environmental impacts and risks to public safety (see above);

- Field-testing in specific repositories (e.g., coal beds) – pilot-test and full-scale demonstration projects; and
- Development of performance assessment standards and reliable monitoring procedures.

Policy Issues

The interest in geologic carbon sequestration as one option in the portfolio of climate solutions[7] has been spawned by a number of factors, including the:

- allure to some of continuing a fossil-fuel based economy without major changes to the ways in which energy is produced and consumed;
- potential for significant emission reductions if implemented on a large, commercial scale;
- large, long-term storage capacity of known geologic formations;
- general feasibility and already quite advanced stage of development of capture and storage technologies; and
- potential for developing economies of scale to make geologic sequestration economically more attractive than at present, and to achieve significant reductions at lower costs than strategies that do not include this option as part of the mix..

However, many policy issues need to be resolved before the environmental, economic, political, and social feasibility of this approach can be fully assessed. These policy issues range from the environmental and safety regulations of project activities within individual nations, to policies and incentives encouraging R&D, to internationally harmonized incentives and price signals, to the implementation, monitoring and accounting issues involved in geologic carbon sequestration as a creditable climate mitigation activity, to addressing public concerns with this approach.

The regulatory infrastructure associated with injection into oil and gas formations is largely in place in most countries, including the United States (Benson et al., 2000). However, existing regulations would have to be revisited to assess needs and adjustments for large-scale deployment if the option were deemed feasible (Keith and Morgan, 2000). Should the results of the growing research in this area yield favorable economic and environmental assessments, governments would also need to create appropriate policy signals (e.g., through tax incentives or other market signals). Current estimates of such incentives to offset the cost penalty of carbon capture and underground storage range from $50 to $100/t C (Parson and Keith, 1998). Such incentives would best be directed upstream at the point of fossil fuel extraction and may include rebates or additional emission permits at the point of sequestration. In the context of international climate policy, there would also be a need to establish functional national accounting systems (Keith and Parson, 2000). Assuming a portfolio approach to climate mitigation, however,, one of the key challenges is to assess the impacts of this mitigation option on other options in the solutions portfolio, and to ensure that implementation of other environmentally sound and economically viable options would not be discouraged.

---

[7] Under the UNFCCC Climate Technology Initiative, exploratory research and application projects on carbon capture and storage are being funded already. Moreover, the fossil-fuel industry on its own, and in public-private research and development ventures with governments in North America, Europe and Asia, is advancing research on carbon separation technologies and furthering the understanding of storage sites. In the United States, the Department of Energy is funding carbon sequestration research and development at about $19 million for FY2001 (a 19-fold increase since 1998) and has proposed to increase this funding to $40 million – 85 million/year over the next 15 years.

Policy concerns go even further, however. The geologic carbon sequestration option raises long-term, intergenerational questions, especially in light of the unknowns about the long-term retention of stored carbon. “If underground repositories are not tight and carbon gets re-released, serious questions about intergenerational equity, especially because the energy penalty involved requires that more CO_2 be sequestered per unit of delivered energy than would be emitted by conventional combustion” (Parson and Keith, 1998).

References

Abelson, Philip H. 2000. Limiting atmospheric CO_2. *Science* 289 (25 August): 1293.

Benson, Sally M. 2000a. Geologic sequestration of carbon dioxide: Prospects and challenges, *EOS Transactions*, American Geophysical Union, 81(48), p. F246, November 28.

Benson, Sally M. 2000b. An overview of geologic sequestration of CO_2. Presented and published in *ENERGEX’2000: Proceedings of the 8th International Energy Forum*, pp. 1219-1225, July 23-28, 2000, Las Vegas, NV.

Benson, Sally M. et al. 2000. Carbon dioxide reuse and sequestration: The state of the art today. Presented and published in *Energy 2000: State of the Art*, P. Catania (ed.), pp. 205-226, July 23-28, 2000, Las Vegas, NV.

David, J. and H. Herzog. 2000. The cost of carbon capture. Working Paper. MIT: Cambridge, MA, available at http://www.sequestration.mit.edu

Ecoal. 2000. Harnessing energy with reduced emissions to atmosphere – the pace of research to generate dynamic solutions for coal. *Ecoal: The Newsletter of the World Coal Institute* 36 (December): 1, 6-7.

Ekman, J. and T. Feeley. 2000. *Sequestration – Progress along the road mapped. An update on the DOE roadmap process*. Department of Energy, National Energy Technology Laboratory.

The Energy Daily. 2000. DOE pushing carbon sequestration as inexpensive greenhouse solution. *The Energy Daily* (March 10).

Hanisch, Carola. 1999. Exploring options for CO_2 capture and management. *Environmental Science & Technology* 33(3): 66A-70A.

Hanisch, Carola. 1998. The pros and cons of carbon dioxide dumping. *Environmental Science & Technology* 32(1): 20A-24A.

Hawkins, David. 2001. *Stick it where? – Public attitudes toward carbon storage*. Paper Presented to the Department of Energy, May 2001. Natural Resources Defense Council, Washington, DC.

Herzog, Howard 2000. The economics of CO_2 separation and capture. *Technology* 7 (supplement 1): 13-23. Available online at: http://sequestration.mit.edu/bibliography/index.html

Herzog, Howard J. 1999. An introduction to CO_2 separation and capture technologies. Energy Laboratory Working Paper, MIT, Cambridge, MA. Available online at: http://sequestration.mit.edu/bibliography/index.html

Herzog, Howard, Baldur Eliasson and Olav Kaarstad. 2000. Capturing greenhouse gases. *Scientific American* (Feb): 72-79.

Hovorka, S.D., M.L. Romero, A.G. Warne, W.A. Ambrose, T.A. Tremblay, and R.H. Trevino. 2000. Sequestration of greenhouse gases in brine formations — possibilities and issues, *EOS Transactions*, American Geophysical Union, 81(48), p. F283, November 28.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001: The scientific basis*. Summary for Policymakers of the Working Group I contribution to the Third Assessment Report. Available online at: http://www.ipcc.ch/

IEA (International Energy Agency). 2001. Sleipner and SACS Projects Win Environmental Award. *Greenhouse Issues*, No.52. Available online at http://www.ieagreen.org.uk/ (Newsletter, January)

IEA. 2000. GHGT5 - Technology Solutions for GHG Emission Control. *Greenhouse Issues*, No.50. Available online at http://www.ieagreen.org.uk/ (Newsletter, September)

IEA. 1994a. Carbon dioxide capture from power stations. Available at: http://ieagreen.org.uk/sr2p.htm

IEA. 1994b. Carbon dioxide disposal from power stations. Available at: http://ieagreen.org.uk/sr3p.htm

Ishitani, H., T.B. Johansson et al. 1996. Energy supply mitigation options. In: *Climate Change 1995: Impacts, adaptations and mitigation of climate change: Scientific-technical analyses*. Contribution of Working Group II to the Second Assessment Report of the IPCC, pp. 587-647. WMO, UNEP.

Jepma, C.J., M. Asaduzzaman, I. Mintzer, R.S. Maya, amd M. Al-Moneef. 1996. A generic assessment of response options. In: *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Contribution of Working Group III to the Second Assessment Report of the IPCC, pp. 225-262. WMO, UNEP.

Keith, David W. 2001a. Personal communication to UCS, January 8. Cambridge, MA.

Keith, David W. 2001b. Personal communication to UCS, April 12. Cambridge, MA.

Keith, David W. and Edward A. Parson. 2000. A breakthrough in climate change policy. *Scientific American* (February): 78-79.

Keith, David W. and Granger Morgan. 2000. *Aspen Global Change Institute Summer Workshop on Industrial Carbon Management* (Workshop Overview). Workshop held July 23-28, 2000, Aspen, CO.

Macilwain, Colin. 2000. Carbon sequestration gains support. *Nature* 407 (26 October): 932.

Monastersky, Richard. 1999. Good-bye to a greenhouse gas. *Science News Online* 155(25) (June 19, 1999). Available at http://www.sciencenews.org/sn_arc99/6_19_99/bob1.htm

Nelson, Robert H. 2000. Sequestration of carbon dioxide from power plant emissions. Chapter 3 in: *Carbon sequestration: A better alternative for climate change?* Available at http://www.puaf.umd.edu/papers/nelson.htm

Parson, Edward A. and David W. Keith. 1998. Fossil fuel without CO_2 emissions. *Science* 282 (5391 (6 November)): 1053-1054.

Preuss, Paul. 2001. Storing CO_2 underground: One option for mitigating greenhouse gases. *ScienceBeat*, February 1. Available online at http://enews.lbl.gov/Science-Article/Archive/terr-sequ.html.

Schneider, Stephen H. 2001. Earth systems engineering and management. *Nature* 409 (18 January): 417-419.

Socolow, Robert (ed.). 1997. Fuels decarbonization and carbon sequestration: Report of a workshop. PU/CEES Report No. 302. Available online at http://princeton.edu/~ceesdoe/

U.S. Department of Energy, National Energy Technology Laboratory. 2000. Carbon sequestration: Overview and summary of program plans (draft). April. DOE, NETL.

U.S. Department of Energy, Office of Fossil Energy. 2000a. Carbon sequestration. Available online at http://www.fe.doe.gov/coal_power/sequestration/

U.S. Department of Energy, Office of Fossil Energy. 2000b. carbon sequestration – capture and separation. Available online at http://www.fe.doe.gov/coal_power/sequestration/sequestration_capture.shtml

U.S. Department of Energy, Office of Fossil Energy. 1999a. *Carbon sequestration: State of the science*. Available online at http://www.fe.doe.gov/techline/tl_seqrpt.html

U.S. Department of Energy, Office of Science, Office of Fossil Energy. 1999b. *Carbon sequestration: Research and development*. Available at http://www.ornl.gov/carbon_sequestration/

U.S. Department of the Interior, U.S. Geological Survey (USGC). 2000. Coal-bed methane: Potential and concerns. USGC Fact Sheet FC-123-00.