Carbon capture and sequestration

A report for the London Accord

Carbon capture and sequestration – the process of separating, transporting, and storing carbon dioxide from power generation and manufacturing plants – has the potential to develop into an extremely large industry in the face of mounting concern about climate change. This report, one in a series prepared as part of the London Accord, examines the potential opportunities for investors as carbon capture and sequestration passes through a developmental phase and then comes into widespread use.

Here are the main points:

- **Large increases in coal-fired generation will be required to meet anticipated growth in electricity demand to 2030, even under aggressive assumptions about conservation and the development of renewable energy.**

- **Capturing and burying the carbon dioxide associated with coal combustion may be the most feasible way of accommodating increased coal-fired generation in a world of carbon constraints, until such time as sufficient electricity is available from non-emitting sources.**

- **Carbon capture and sequestration serves no purpose other than emissions reduction, so will be feasible only to the extent that taxes or permit fees make emissions costly.**

- **A sustained price for CO_2 emissions above $45 per ton is a necessary but not sufficient condition for adoption of carbon capture by investor-owned companies.**

- **Adoption of carbon capture and sequestration will require technological development as well as the resolution of complex legal and regulatory issues.**

This report has been prepared by JPMorgan Economic Research analyst Marc Levinson for the London Accord.

Abstract

Carbon capture and sequestration – the process of separating, transporting, and storing carbon dioxide from power generation and manufacturing plants – has the potential to develop into an extremely large industry in the face of mounting concern about climate change. Widespread adoption of this method of greenhouse-gas control may become economically feasible once the cost attached to carbon dioxide emissions moves above $45 on a sustained basis. However, considerable technological development and resolution of critical legal issues will be essential before carbon capture and sequestration can come into widespread use.

Why CCS?

Carbon capture and sequestration (CCS) is a concept developed in response to the intense concern about climate change. Although several "greenhouse gases" emitted as a result of human activity are known to contribute to climate change, carbon dioxide (CO_2) is by far the most important.

Electric generation is the single largest source of CO_2 emissions worldwide, accounting for an estimated 41% of total emissions. Two-fifths of the world's electricity is generated from coal, but coal-fired generating stations are responsible for approximately 70% of the power sector's emissions.

Large increases in coal-fired generation will be required to meet anticipated growth in electricity demand over the next quarter-century, even under aggressive assumptions about energy conservation and the development of renewable sources. The International Energy Agency's reference case outlook (its midrange scenario) foresees that the amount of electricity generated from coal will double by 2030, with coal's share of all power production rising from the current 40% to 44%, and the US Energy Information Administration takes a similar view (Table 1). The need to use coal to meet rapid increases in electricity demand is in obvious conflict with efforts to reduce the volume of greenhouse gasses released into the atmosphere.

Table 1. World electricity generation by fuel

	2004 output (bil mWh)	2004 share of total	2030 output (bil mWh)	2030 share of total
Coal	6,723	40.5%	13,650	44.5%
Natural gas	3,230	19.5%	7,423	24.2%
Renewables	3,086	18.6%	4,804	15.7%
Nuclear	2,619	15.8%	3,619	11.8%
Oil	937	5.6%	1,178	3.8%

Source: US Energy Information Administration, May 2007.

In principle, there are two methods of breaking the link between coal-based generation and CO_2 emissions.

- Increase the efficiency of coal generation. This is already occurring with the use of high-pressure boilers and heat recovery, but the 25% efficiency increase projected by the U.S. Department of Energy to occur by 2020 will be insufficient to reduce emissions from coal-fueled plants below current levels, given the anticipated increase in coal generating capacity.

- Capture the carbon dioxide associated with coal combustion before it escapes into the atmosphere, and then store it underground so that it does not add to the radiative forcing that is responsible for global warming. This is the rationale for CCS.

CCS is conceptually quite distinct from the many forms of "renewable energy" that are presently arousing intense investor interest. Renewables offer alternative methods of producing a desired commodity, namely energy. While their economic viability will vary from time to time, depending upon the relative prices of energy from other sources, their fundamental purpose is to meet actual demand. CCS, in contrast, serves no demand. It it purely an environmental measure, and will be developed only if regulation makes it less costly to install CCS than to emit CO_2 into the atmosphere. Without such regulation, CCS has no reason to exist.

CCS also has potential applications in natural gas generating plants and in industrial plants that produce CO_2 emissions. In particular, CCS may be viable for some oil refineries and steel mills within the next decade.

Over time, the capture and sequestration of carbon dioxide emissions from power plants is likely to develop into an extremely large business. It will probably go hand in hand with an entirely new generation of coal-fueled power plants, and will create important opportunities for pipeline suppliers and operators, oilfield service companies, chemical and filter companies, and the engineering and construction firms with the expertise to tie the various components together.

However, the scale, time frame, and location of potential CCS projects remain highly uncertain. The underlying technologies are still in developmental stages, and major legal issues are unresolved. Carbon capture and sequestration thus presents a difficult target for investors. While the long-term opportunities are great, the prospects over a ten-year time horizon are modest. The prospects over a twenty-year horizon, by contrast, are quite substantial.

The basics: Carbon capture

CCS involves three distinct steps with quite different technical and economic characteristics: capture, transport, and sequestration. No single company has or is likely to have adequate expertise in all of the requisite technologies, so the eventual commercial adoption of CCS will almost certainly require cooperation among multiple firms specializing in various aspects of the process.

The most difficult and costly part of CCS is capturing carbon dioxide from a power plant or an industrial source. This can be done in one of three principal ways:

- **Flue gas separation.** This is the traditional approach to air pollution control, in which pollutants are captured from waste gases on their way out the stack. CO_2 accounts for 10-12% of the flue gas emitted by conventional coal-fired power plants, and 3-6% of the flue-gas stream in gas-fired power plants. CO_2 can be separated from the rest of the flue gas stream by passing it through a chemical solvent containing amines or ammonia. The solvent absorbs the carbon dioxide, and the other waste gases are then routed through standard pollution-control processes. Steam or membrane systems are used to separate the CO_2 from the solvent. The concentrated CO_2 can then be compressed for shipment, while the solvent is reused. The great advantage of flue gas separation is that it could be added on to existing pulverized-coal generating plants and hence is not dependent upon improvements in generation technology. However, relatively high construction costs and high operating costs due to its energy intensity are expected to make flue gas separation a relatively unattractive approach to CCS in the power industry.

  Flue-gas separation technologies hold more promise in industry. CO_2 makes up approximately 27% of the flue gas from steel-mill blast furnaces, 33% of the gas from cement calcinators, and half or more of the flue gas stream in refineries.[1] These higher CO_2 concentrations may make these sectors more attractive candidates for flue gas separation technology than power plants.

- **Oxygen-fuel combustion.** Oxy-fuel technology involves burning coal in the presence of pure or nearly pure oxygen. If this occurs, the resulting flue gas will consist principally of CO_2 and water vapor, making the CO_2 easy to capture once the water vapor is condensed. Oxygen-fuel combustion, which is already applied in some industrial uses, requires a costly oxygen separator at the plant to remove nitrogen from the combustion gas. Oxygen separators also could be retrofitted to existing pulverized coal plants, but at considerable expense.

[1]. Estimates of CO_2 share in flue gas taken from Murlidhar Gupta et al, "CO_2 Capture Technologies and Opportunities in Canada," September 2003, available online at http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2trm/pdfs/co2_capture_strawman_feb2004.pdf, and Melanie Collison, "Buying Time," *Oilweek Magazine*, March 2007.

- **Pre-combustion capture.** Rather than being fed directly into a boiler, coal can be gasified into a "syngas" composed predominantly of hydrogen and carbon monoxide. This gas can be "water shifted" to produce a mixture of carbon dioxide, hydrogen, and other gases. The carbon dioxide could then be captured for storage, while the hydrogen could be put through a turbine or fed to fuel cells to generate power. Gasification technology is presently used in several small-scale plants that do not produce electricity. Use at larger scale in power generation requires construction of a new type of generating facility, known as an integrated gasification combined cycle (IGCC) plant, probably with oxygen-fuel combustion. A handful of relatively small IGCC plants are in operation around the world, but none operates at modern commercial scale. Pre-combustion capture is also suitable for gas-fired generating plants, although with higher costs per ton of CO_2 captured.

None of these technologies is capable of capturing all of the CO_2 emitted from fuel combustion. In the power industry, studies suggest that capturing more than 90-92% of CO_2 emissions from a power plant dramatically reduces the generator's operating efficiency. Similar ratios are likely to apply in other industrial sectors. Most current projects aim to capture around 90% of the CO_2 that would otherwise be emitted into the atmosphere.

In addition, all methods of carbon capture are themselves energy-intensive. In the power sector, carbon capture will require construction of generating plants 15-30% larger than would otherwise be needed. As a result, the CO_2 emissions avoided from any installation will be much lower than the emissions captured. To provide a simple example, a plant that captures 90% of CO_2 emissions but has a 20% energy penalty will achieve an emissions reduction of 88%, compared with a plant that sells the same amount of power but has no carbon capture.

The need for increased energy production to meet the power needs of the carbon capture facility raises the effective cost of carbon capture. The relevant variable in evaluating the viability of carbon capture is not the cost per ton of carbon dioxide captured, but the invariably much higher cost of carbon dioxide emissions avoided. A 20% assumed energy penalty means that the cost per ton of CO_2 avoided is 20% higher than the cost per ton captured. This distinction is frequently neglected in discussions about the viability of carbon capture.

Table 2. Impact of energy penalty on costs at hypothetical generating plant

CO_2 emissions from generation (tons/year)	1,000,000
Assumed energy penalty	20%
CO_2 emissions from generation plus capture (tons/year)	1,200,000

Annualized cost of capture, including capital	$60,000,000
Cost per ton of CO_2 captured	$50
Cost per ton of CO_2 avoided	$60

Source: JPMorgan.

Source: AEP.

There may also be significant opportunities to capture carbon dioxide in sectors other than power generation. The cost of CO_2 capture depends on the purity and pressure of the gas stream, as a purer, higher-purity stream requires less processing and compression. Some chemical, cement, and steel plants may particularly lend themselves to carbon capture.

The Basics: Carbon Transport

Once captured, purified, and compressed at the plant site, the carbon dioxide will have to be transported to a storage location. While the liquefied CO_2 could be shipped via barge, rail tank car, or even road transport, in practice pipelines are likely to provide the lowest-cost means of transportation of large volumes.

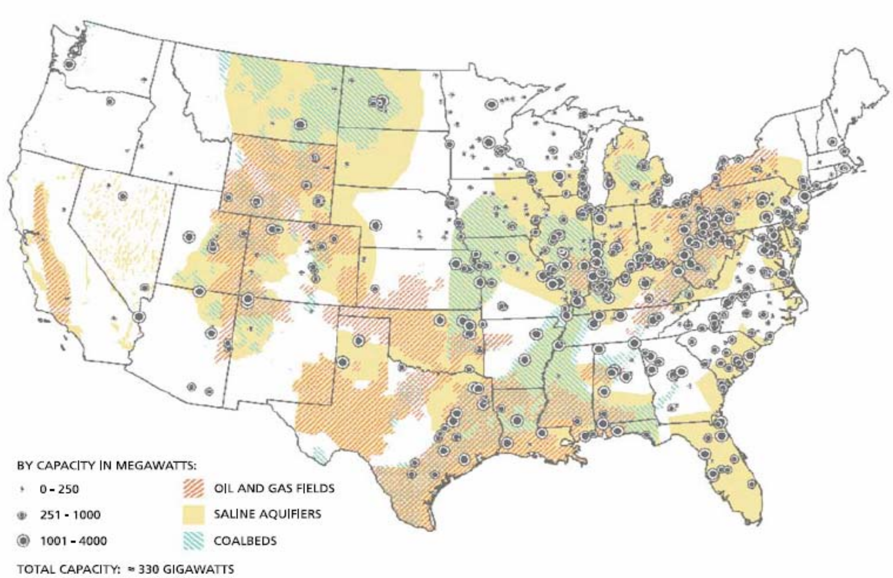
Pipeline transportation of liquid carbon dioxide already is a technologically mature industry. In the United States, approximately 5,500km of carbon dioxide pipelines are in use, principally in oil fields. Smaller CO_2 pipeline networks have been constructed in Europe and the Middle East. The pipelines and associated equipment are technically similar to those in use for natural gas, so the transportation aspect of carbon capture and storage appears to have relatively few technological uncertainties but also relatively little opportunity for technical innovation.

Expanded use of carbon capture and sequestration would lead to a massive expansion of pipeline networks. The eventual size of those networks could approach those currently transporting oil and natural gas.

The cost of building CO_2 pipelines, like that of building natural gas pipelines, will depend principally upon distance and pipeline diameter. One recent estimate puts the cost of constructing a pipeline 26 inches in diameter—large enough to handle the CO_2 produced by a large IGCC plant—at around $1.2 million per mile in the US, or approximately $60 million for a 50-mile pipeline. This would be only a few percentage points of the $1.4 billion or so such a plant would be expected to cost. Total transport costs would likely range from less than one dollar to several dollars per ton of CO_2, depending upon the source and the distance.

Transport is thus likely to be a far less costly aspect of CCS than capture in the power industry. Electric generators can be expected to consider proximity to CO_2 storage locations as a factor in siting future generating plants. This will minimize transport costs in the event CCS becomes commercially viable. However, many large existing coal-fired plants in areas such as the Southeastern United States are not located atop geologic formations suitable for storing CO_2, and transport may prove costly if carbon capture is attempted at those locations (Figure 1).

Figure 1. Potential sequestration sites and existing coal-fired power plants in US



Source: National Petroleum Council.

Transport costs may loom larger if CCS is attempted at industrial facilities. Few new steel mills, chemical plants, and cement plants are being built in North America, Europe, or Japan. Existing plants were typically sited with access to end markets, raw materials, or ocean transport as principal concerns, and plant locations may be a considerable distance from geological structures suitable for storing carbon dioxide. This may inhibit the adoption of CCS at such plants, as the cost of building several hundred miles of pipelines and related compression facilities to transport CO_2 may be prohibitive.

At this stage, it appears likely that CO_2 pipelines will be built to serve specific sources under long-term arrangements. Although some CO_2 pipelines presently operate as common carriers, offering services to all shippers with gas to transport, utilities and owners of industrial plants will want to assure adequate transportation capacity in order to avoid the costs that eventually will be associated with venting CO_2 into the atmosphere. Long-term contracts for pipeline capacity seem likely to be the instrument of choice.

The Basics: Sequestration

Following transportation to an injection site, the CO_2 would be injected 800 meters or more into the ground. Injection, like transportation, involves well-established technology. However, widespread adoption of CCS would lead to a vast increase in the amount of injection and would impose new requirements for site selection and post-injection monitoring. In addition, sequestration, the underground storage of carbon dioxide, is surrounded by technical and legal uncertainties that will have to be resolved before large-scale CCS gets underway.

Currently, oil producers inject CO_2 to increase the flow from aging oil fields, a process known as enhanced oil recovery or CO_2 flooding. In this process, water is first injected to restore reservoir pressure, followed by concentrated CO_2. As the CO_2 expands, it reacts with the oil, lowering the viscosity and increasing the flow rate. A well that is a good candidate for CO_2 flooding is more than 2,000 feet deep, with API oil gravity greater than 22-25 degrees and remaining oil saturation greater than 20%. Approximately 4% of US oil production now comes from enhanced oil recovery.

The amount of CO_2 now injected to enhance oil recovery in this way is small; a single IGCC power plant would probably produce more CO_2 in a year than is currently used at all US injection sites combined. CCS will thus entail the boring of large numbers of injection wells. The number required will depend not only on the amount of carbon dioxide to be sequestered, but also on the injection pressure permitted by regulators: with lower pressure, more wells will be required for a given amount of CO_2. Although the scale of injection activity will be vastly larger than is the case today, existing injection technology will probably be adequate.

Increased use of carbon dioxide injection could bring substantial benefit in terms of oil production, and the resultant increase in revenue could cover part of the cost of carbon capture. A recent estimate found that enhanced oil recovery could make feasible the recovery of 25 billion additional barrels of oil from six existing US oilfields. This equates to 12 years of current annual production. Enhanced recovery could also make it easier to increase production from higher-cost domestic sources, such as heavy oil reserves and oil sands.[2]

Carbon sequestration, however, is not relevant to the commercial requirements of the oil industry. Under current circumstances, oil producers are interested only in oil output, and have no further concern about the fate of the injected CO_2. If the injected gas escapes into the atmosphere, either through wells or through geologic faults, the oil producer faces no costs or consequences.

In a world in which carbon dioxide emissions are restricted or taxed, the economic imperatives will be very different from those currently faced by oil producers using CO_2 for enhanced oil recovery. Injection sites will have to be selected carefully with a view to avoiding the escape of stored CO_2 rather than for maximum oil production. Although one

[2]. US Department of Energy, "Undeveloped Domestic Oil Resources," February 2006.

recent report contends that “with relative ease present technology could be modified to emphasize such storage,” the potential costs imposed on oil producers are uncertain.[3] The sequestered gas will have to be monitored for several centuries, potentially at the oil producers’ expense.

Aside from enhanced oil recovery, several trial projects carbon sequestration projects are underway. The largest, undertaken by the Norwegian oil company Statoil in the North Sea since 1966, annually stores less than 1 million metric tons of CO_2 resulting from natural gas production. Other trials are underway in Australia and Canada. None of these trials, however, begins to approach the size required to store the CO_2 produced by a single medium-sized power plant.

If CCS is to bring about significant reductions in CO_2 emissions, very large amounts of storage will be required, probably far outstripping the amount available in oil fields. Carbon dioxide also could be stored in abandoned coal mines, in depleted natural gas fields, and in very deep saline formations. Which type of location would provide the lowest-cost storage over the very long run remains an active subject for investigation. Although revenue from enhanced recovery could offset the cost of CCS, oil and gas reservoirs do not necessarily offer the least-cost storage, as many underground reservoirs are too small to sequester meaningful amounts of CO2.[4]

The availability of suitable underground storage space varies greatly by location, depending upon geology. In the United States, large amounts of suitable storage appear to be available in the Southwest and West, but little in the Northeast and Midwest.[5] In Europe, saline storage generally appears to be the most promising alternative for storage, although some gas fields may also serve the purpose. Geology beneath Japan and Korea appears to be unsuitable for large-scale storage of CO_2. China and Australia are believed to have large amounts of potential storage space. In all of these regions, investigation of potential storage space for CO_2 is fragmentary, and more detailed research may reveal additional locations suitable for sequestration.

Although there is considerable experience with carbon dioxide injection, there is no experience with sequestration. Several experimental projects are now underway, but sequestration is not yet ready for permanent employment at commercial scale. Improved

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[3]. National Petroleum Council, *Facing the Hard Truths about Energy* (Washington 2007), p. 5-10.
[4]. Robert Dahowski and Stefan Bachu, “Timing of reservoir availability and impacts on CO2 storage in the Alberta Basin, Canada,” *Proceedings of the Eighth International Conference on Greenhouse Gas Control Technologies*, 2006.
[5]. Marshall Wise et all, “Modeling the impacts of climate policy on the deployment of carbon dioxide capture and geologic storage across electric power regions in the United States,” *International Journal of Greenhouse Gas Control*, Vol. 1 (2007), pp. 261-270.

technology for monitoring sequestered CO_2 also will be required for CCS to become commercially viable.

Critical legal issues

The feasibility of CCS depends upon the resolution of complex and novel legal issues. At this point, we are aware of no jurisdiction anywhere in the world in which the legal issues relating to CCS have been formally addressed, much less resolved. Until and unless this occurs, CCS presents an extremely risky undertaking that is unlikely to be attractive to private capital.

The novel legal concerns surrounding CCS can be divided into three principal categories: ground-use rights, liability for injury to people and property, and liability for unauthorized release of greenhouse gases. In addition, there are more conventional legal issues, such as manufacturers' willingness to warrant that their costly equipment will capture CO_2 at stated efficiency and cost. As these latter concerns are in principle similar to those surrounding commercialization of many new technologies, we focus here on the frontier issues that relate specifically to CCS.

Ground-use rights

Almost all jurisdictions have a method for assigning ownership of mineral rights, to determine who has the right to profit from mining and oil and gas exploration. With respect to carbon capture and sequestration, though, the legal question concerns ownership not of minerals underground, but rather of "empty" geologic structures, such as rock pore spaces and salt domes, that potentially could be used to store carbon dioxide.

While liquids such as wastewater, chemical waste, and CO_2 have been disposed of by injection for many years, ownership of underground structures has not been a major concern, because the supply of underground space is large relative to the volumes injected. In the event of severe constraints on greenhouse-gas emissions, however, the volume of CO_2 that could be sequestered underground may extremely high. The ownership rights could then become quite valuable. Some rights owners will likely be in a position to charge rent for the storage of CO_2 in underground spaces, making litigation over legal ownership a distinct possibility.

Even more important, in terms of the development of CCS, is the prospect that the owner of underground storage rights could refuse to permit CO_2 storage in geology under its control. Consider, for example, a situation in which landowners are deemed to control the use of geologic structures beneath the surface. In such a situation, a single recalcitrant owner could conceivably block the establishment of a large CO_2 storage reservoir underlying the holdings of many surface rights owners. As no present mechanism requires that a surface-rights owner be informed of injection beneath nearby lands, an owner might discover only after the fact that sequestered CO_2 has migrated into formations that it controls by virtue of surface-rights ownership.

These legalities may be quite complicated to sort out. In Texas, which probably has more wells injecting CO_2 than any other jurisdiction due to the use of CO_2 for enhanced oil recovery, pore space in a reservoir producing oil or natural gas is controlled by the owner of the mineral rights, whereas pore space not associated with energy production is controlled by the owner of the surface rights. If underground structures become valuable due to their potential as CO_2 reservoirs, it is conceivable that owners of currently unexploited mineral rights will start or resume production in order to control lease rights for carbon sequestration.

At this juncture, it seems highly likely that in many countries carbon sequestration, at least beneath land, will require the compulsory purchase of rights to use underground geologic formations and lay CO_2 pipelines. The definition and valuation of underground storage rights to be acquired by compulsory purchase may present new legal issues that have not been clarified anywhere, insofar as we are aware. Compulsory taking of properties or easements for energy pipelines is not new, but existing laws may not provide such authority for CO_2 pipelines. New legislation will probably be required to address these issues wherever carbon sequestration is to be attempted.

Even where legal issues may appear to be political factors could well muddy them. In much of the world, including most of Europe and US offshore waters, mineral rights are legally owned by governments but have been leased, often for very long periods, to oil and gas producers. The lease prices do not reflect the value of CO_2 storage. If storage space becomes highly valuable, there undoubtedly will be political pressure to reassess lease terms in order to keep leaseholders from reaping windfall profits.

Liability

Carbon dioxide is neither toxic nor explosive, and would therefore seem to present fewer concerns about legal liability than, say, nuclear power or petroleum refining. Yet liability issues already appear to pose a very large obstacle to the developments of carbon capture and sequestration. These issues almost certainly will require legislative intervention to resolve in every jurisdiction around the world.

The root of liability concerns is simple enough: once pumped underground, carbon dioxide will have to be sequestered for centuries, if not millennia, in order to avoid adding to the stock of greenhouse gases in the atmosphere. In insurance parlance, liability for damage resulting from CO_2 sequestration has an extremely long tail.

Any number of risks to life and property due to CO_2 sequestration are imaginable. A geologic event that perforates the earth's crust, such as an earthquake or a volcano, could allow extremely concentrated CO_2 to rush to the surface, asphyxiating people or animals. Sequestered CO_2 could interact with other compounds to eat away at rock far underground, eventually causing the collapse of structures on the surface. CO_2 in storage could migrate into areas that supply drinking water, requiring costly cleanups.

There is no reliable basis for estimating the probability or severity of such events. This extreme uncertainty, along with the very long-tailed exposure, will make it impossible to create a fully private market to insure liability risks from carbon sequestration.

Unmeasurable and uninsurable liability risk over a very long period, no matter how small, is an almost insurmountable barrier to the development of carbon capture and sequestration. Without liability protection, no party will be willing to hold ownership of large amounts of concentrated CO_2. Some US utilities have indicated that they are unwilling to make CO_2 available for sequestration unless they are relieved of ownership at the power-plant fence. The oil producers and oilfield service companies that presumably would be paid to inject and sequester the carbon dioxide, however, have said they are unwilling to remain legal owners of stored CO_2 over centuries.

Resolution of this conundrum is likely to require government actions on several fronts:

- **Creation of government reinsurance schemes that cap private liability.** One model for this is the US Price Anderson Act (more formally known as the Nuclear Industries Indemnity Act). This law, dating to 1957 and renewed most recently in 2005, limits the liability of nuclear plant operators. This effectively leaves the US government as the insurer of last resort in the event of a catastrophic accident and thus provides a subsidy to the nuclear power industry, but without such a subsidy private investment probably would not have entered the nuclear sector.
- **Clarification of legal jurisdiction, of entitlement to compensation, and of limits to compensation.** CO_2 sequestration sites are unlikely to be confined by national or sub-

national boundaries, creating the possibility that a single event could result in litigation in multiple courts under a variety of laws. The development of CCS would be aided by laws or agreements clarifying legal jurisdiction. Legislators may also wish to specify the types of harm for which compensation will be paid, liability for punitive damages, and caps on the amount any individual can receive in compensation for injury from a CCS-related accident.

- **Procedures to ensure ongoing maintenance and monitoring.** After injection, carbon dioxide will need to be monitored to make sure it remains in the desired storage reservoirs, and periodic maintenance and repairs may be required at well sites that could provide avenues for leakage into the atmosphere. It is highly likely that some of the companies responsible for managing sequestration sites will perform their duties poorly or even go out of business over the centuries during which the CO_2 will have to remain sequestered. Governments will need to create funding mechanisms to ensure maintenance and monitoring of storage sites over the very long term, with the ancillary affect of reducing the likelihood of incidents that could result in damage to people or property.

Emissions costs

There is a high probability that at least some sequestered carbon dioxide will return to a gaseous state and escape into the atmosphere. This would not necessarily require a major incident triggering the sudden release of a large volume of gas. A much more likely scenario involves the leakage of very small amounts of CO_2 over long period. This could occur, for example, as individual CO_2 molecules work their way upward through many layers of rock or find pathways to the surface through abandoned wells. Even if the annual rate of escape were very low, the cumulative volume of gas reaching the atmosphere over the period of a thousand years could be substantial.

If CO_2 emissions have a significant cost attached—and carbon sequestration is unlikely to be undertaken unless governments impose such a cost—then the party responsible for the sequestered CO_2 could face a requirement to obtain permits for the escaped gas. In the event of a large escape, the cost could be unmanageable. According to one estimate, a 1,000 megawatt IGCC plant might produce 260 million tons of CO_2 over a 50-year working life, all of which presumably would be sequestered at a single location.[6] If a geological event or an accident were to trigger the release of that entire amount and the emitter had to pay $100

[6]. This estimate taken from J.J. Dooley, R.T. Dahowski, C.L. Davidson, M.A. Wise, N. Gupta, S.H. Kim, E.L. Malone, "Carbon Dioxide Capture and Geologic Storage," Battelle Memorial Institute, April 2006, p. 44.

per ton to acquire the requisite permits, the out of pocket cost would be a staggering $26 billion. If the release were to occur in the more distant future, when the amount of permitted emissions is likely to be much lower, the cost of acquiring permits could be far greater.

It is unclear whether routine monitoring will be able to detect the leakage of CO_2 in small volumes, much less quantify it with the precision necessary to determine how many emissions permits are needed. Again, costs are impossible to estimate with any precision, but an example may indicate the size of the potential bill. If we assume a sequestration site has 260 million tons of CO_2 in storage and that 1/10,000 of that amount escapes each year, the annual leakage volume would be 26,000 tons. At a price of $100 per ton, the cost of this leakage would be $2.6 million per year, but if the cost rises significantly over time, as seems likely, the total cost over a long period could be quite high.

Questions relating to the acquisition of emissions permits to cover escape or leakage will probably need to be addressed legislatively before commercial carbon capture and sequestration gets underway. Although leakage issues may appear minor so far as any individual sequestration project is concerned, the collective amount of leakage from many sequestration sites could be large enough to hinder efforts to limit atmospheric concentrations of CO_2. In addition, the diversion of emissions permits to cover leakage from sequestration could result in higher permit prices for other emitters.

The costs of CCS

At the current stage of development, estimates of the cost of carbon capture and sequestration are entirely speculative. Several trial efforts are underway to capture carbon from natural gas and oil processing, but none of them approaches commercial scale. Carbon sequestration is now being attempted, but the volumes involved are small. The legal issues surrounding sequestration have not been resolved, so the costs involved in purchasing the rights to use geologic structures or to finance a perpetual fund to assure monitoring and maintenance are now known. It is entirely likely that establishment of at least the first few carbon sequestration sites will involve prolonged environmental reviews, public hearings, and litigation, significantly increasing the start-up costs.

In the power-generation sector, most studies indicate that carbon dioxide can be captured most economically from purpose-built plants, rather than being retrofitted to existing generating plants. The technology that appears to be most efficient for this purpose is integrated gasification combined cycle, with coal as the energy source.

Coal-fired IGCC plants do not burn coal to produce energy, as occurs in traditional pulverized coal plants. Rather, the coal is gasified, a process that essentially breaks the fuel apart under heat and pressure, with only a small amount of direct combustion. The process triggers various chemical reactions that end up with the formation of "syngas," composed primarily of hydrogen and carbon monoxide. The syngas is cleaned to extract chemical byproducts. When oxygen (rather than simply air) is used in the gasifier, the syngas contains a large amount of carbon dioxide, which can be removed and purified at this stage. The remaining gas mixture is then passed through turbines to generate electricity.

IGCC technology is not new, and is employed in a handful of generating plants now operating in Europe, Japan, and the United States. These plants have had the sorts of teething problems to be expected from an emerging technology, including poor initial reliability. Most of the existing IGCC plants are far smaller than the average new pulverized-coal plant (Table 3). No existing IGCC plant captures and purifies carbon dioxide.

Table 3. Existing IGCC plants

Project	Year operational	Net output (MW)	Primary feedstock	Capital cost/MW
Polk County (US)	1996	250	Coal	$1.6 million
Wabash River (US)	1995	260	Petcoke	$1.7 million
Delaware (US)	2002	160	Fluid petcoke	$2.4 million
El Dorado (US)	1996	35	Various	$2.2 million
IASB (Italy)	1999	512	Asphalt	$2.3 million
Falconara (Italy)	2000	550	Heavy oil	$1.5 million
Elcogas (Spain)		335	Coal, petcoke	$2.7 million
Negishi (Japan)	2003	342	Asphalt residue	$1.0 million
Alexander (Netherlands)	1994	253	Coal	

Source: Adapted from Eric Williams et al, "Carbon Capture, Pipeline and Storage: A Viable Option for North Carolina Utilities," Nicholas Institute,
Duke University, Working Paper CCPP 07-01, March 8, 2007.

Cost estimates are very sensitive to assumptions about design, operating efficiency, discount rates, and technological development. Nonetheless, they uniformly show that experts expect carbon capture to add significantly to the cost of power plant construction.

- In the United States, one recent study estimated the cost of retrofitting a 450 megawatt pulverized-coal plant to capture 90% of CO_2 emissions to be at least $420 million, or roughly $1 million per megawatt. This equates to an increase of approximately 60% over the cost of building such a plant without carbon capture.[7]

[7]. National Energy Technology Laboratory, "Carbon Dioxide Capture from Existing Coal-Fired Power Plants," DOE/NETL 401/120106, December 2006.

- Estimates made by various US suppliers in 2000 put the cost of a 500 megawatt IGCC plant equipped for carbon capture in the range of $1.6 million per megawatt, at a time when building a traditional pulverized coal plant was estimated to cost approximately $1.2 million per megawatt, a 33% capital cost penalty.[8]
- Earlier this year the US utility AEP suggested a much smaller construction cost differential. AEP, which plants to build trial IGCC plants with small-scale carbon capture, projects a cost of $1.9 million per megawatt for an IGCC plant and $1.7 million per megawatt for traditional coal plant, a cost penalty of only 12%.
- Based on recent proposals in Europe, JPMorgan estimates that building early IGCC plants will cost nearly 90% more than building conventional pulverized coal plants of similar output. We project European IGCC plants to cost approximately €2 million ($2.8 million) per megawatt, compared with roughly €1.1 million ($1.5 million) per megawatt for coal plants without CCS.
- The German utility RWE has estimated the investment required to build a new coal-fired power plant to be €1.20 million per megawatt without carbon capture, but €1.68 million per megawatt with carbon capture—a 40% construction-cost penalty.[9]

The loss of energy in the carbon capture process increases the relative cost disadvantage of the IGCC plant, as the plant must more megawatts of generating capacity to produce the same amount of power for transmission to customers. AEP estimates the normalized cost of generating power from an IGCC plant with carbon capture, including capital-cost allowances, to be €20 ($29) per megawatt hour above the cost of pulverized coal without carbon capture (Table 4). JPMorgan estimates that the initial European IGCC plants will have a cost disadvantage of €16-17 ($22-24) per megawatt hour of output versus traditional coal plants. In either case, these differentials are quite large, implying each unit of electricity generated from a new IGCC plant will cost approximately 50% more than from a new pulverized coal plant without CCS.

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8. US Environmental Protection Agency, "Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies," EPA-430/R-06/006, July 2006, Appendix A.
9. See comments of RWE manager Hans-Wilhelm Schiffer in International Energy Agency, "Expert Workshop on Financing Carbon Capture and Storage: Barriers and Solutions," Report 2007/9, July 2007, p. 16.

Table 4. Estimated costs associated with new generating plants

	Pulverized Coal	Integrated Gasification Combined Cycle (IGCC)	Natural Gas Combined Cycle (NGCC)
Nominal Capacity (MW)	600	600	600
Plant Cost ($ million/kW)	$1.7	$1.9	$0.48
Cost of Electricity, without CO2 capture ($/MWh)	$58	$63	$90
Cost of Electricity, with CO2 capture ($/MWh)	$94	$87	$137

Source: AEP.

As IGCC is a relatively new technology, it is highly likely that technological improvements will reduce unit costs over time. The extent to which this will occur, however, cannot be predicted with any reliability. One recent US Department of Energy study estimates that the real cost per megawatt of IGCC plants will decline by only 16% through 2030. This is a relatively sluggish rate of improvement for a new technology, and indicates that there is little expectation of advances that would lead to large construction-cost declines.[10]

We have not identified reliable estimates of the cost of incorporating carbon capture technology into industrial facilities, such as chemical plants, steel mills and paper mills. Many such facilities produce relatively concentrated streams of CO_2, simplifying the capture process; indeed, some chemical plants are designed specifically to capture CO_2 as a byproduct for sale to the oil industry. However, few new steel mills and chemical plants are being built in the US and Europe, so any new carbon-capture facilities will have to be attached to older plants not designed for the purpose.

Will CCS make sense?

The economic viability of carbon capture and sequestration depends upon the cost per ton of CO_2 emissions avoided, relative to alternatives. At present, the most attractive alternative in all locations outside Western Europe is venting CO_2 into the atmosphere, as so doing entails no cost to the emitter. As regulations elsewhere begin to attach costs to CO_2 emissions, the economic viability of CCS will depend upon the magnitude and anticipated increase in those costs and the relative attractiveness of other methods of reducing emissions, such as using renewable technologies to generate electricity or relocating industry to jurisdictions where emissions are unregulated.

[10]. See US Department of Energy, National Energy Modeling System 2007, "Electricity Market Module," DOE/EIA-0554, April 2007, p. 48.

The relevant cost for purposes of analysis is not the cost per ton of CO_2 sequestered, but rather the cost per metric ton of CO_2 avoided. In a regime in which a permit must be purchased for each ton of CO_2 emitted, such as the European Union's Emissions Trading Scheme, the number of tons of emissions avoided equals the number of permits that would have to be purchased in the absence of CCS, and therefore represents the relevant number for purposes of cost comparison. We recall that the cost per ton avoided is likely to be significantly higher than the cost per ton sequestered in many cases, especially in power generation, because the carbon-capture facility itself consumers so much electricity.

Despite the very large number of unknowns, early estimates of the cost of CCS per ton of emissions avoided are surprisingly consistent. One recent US study projects the total cost of capture and sequestration from a newly build IGCC generating plant to be in the range of $37 to $55 per metric ton of CO_2 sequestered. Assuming a 20% energy penalty, this translates to $44-$66 per ton avoided. The projected cost for CCS from chemical plants is much lower, because capture is much simpler (Table 5).

Table 5. Estimated cost of CO_2 capture and sequestration from various industrial processes in US

Per ton CO_2

Plant type	Capture and compression,	Transport and sequestration	Total cost per MT captured	Total cost per MT avoided	Main Factors Driving Cost
Ammonia	$6-$12	$12-$15	$18-$27	$18-$27	No capture cost for pure CO_2 stream,
Ethylene oxide	$6-$12	$12-$15	$18-$27	$18-$27	No capture cost for pure CO_2 stream
Ethanol	$6-$12	$12-$15	$18-$27	$18-$27	No capture cost for pure CO_2 stream
Cement	$35-$55	$12-$15	$47-$60	$54-$69	High capital costs for chemical absorption from flue gas
Steel	$20-$35	$12-$15	$32-$50	$37--$58	High capital costs for chemical absorption from flue gas
Refinery	$35-$55	$12-$15	$47-$70	$54-$80	High capital costs for chemical absorption from flue gas
IGCC power	$25-$40	$12-$15	$37-$55	$44-$66	High capital cost for physical absorption from flue gas

Source: J.J. Dooley et al, "Carbon Dioxide Capture and Geologic Storage," Battelle Memorial Institute, April 2006., and JPMorgan. Cost per ton avoided assumes 20% energy penalty for IGCC, 15% energy penalty for flue gas absorption, no energy penalty for chemical streams.

Recent research by JPMorgan reaches similar conclusions with respect to European power generation. The projected cost of CCS in Europe is €30, or $42, per ton of CO_2 emissions avoided (Table 6).[11]

Table 6. Estimated cost of CO2 capture and sequestration in Europe
Per ton CO_2 avoided

Plant type	Capture and compression	Transport	Sequestration	Total
IGCC power	€24	€2.4	€3.3	€29.7

Source: JPMorgan.

All of these estimates are probably on the low side, for several reasons. First, they make no attempt to calculate legal, planning, and regulatory costs. These are likely to be quite burdensome for companies developing CCS, especially for early projects, unless governments agree to pay them. Second, the estimates assume no cost for resolving the liability concerns described above. This cost could be negligible if governments agree to cover the risks, but it could be high if governments decline to do so. Third, these estimates assume a relatively low long-term cost for sequestration. This assumption may not prove correct; it is at least imaginable that sequestration will have a rising cost curve as more desirable sites are used up and later projects face higher ground rents or more difficult geological conditions.

The costs of some CCS projects look to be well above these estimates. The largest industrial CCS project now underway is being constructed by Statoil, the Norwegian state-owned oil company, in conjunction with a new combined heat and power station at an existing refinery in Mongstad, Norway. The plant is initially to capture 100,000 tons of CO_2 per year from the power station, but may eventually be expanded to capture the much greater CO_2 emissions from the refinery itself. The Norwegian government has estimated the all-in cost of capturing and sequestering one metric ton of CO_2 from the power station to be Nkr500 (€62, $85) when the facility opens in 2010.

Additionally, none of these cost estimates appears to factor in the cost of purchasing emissions permits for that portion of CO_2 that cannot be captured and sequestered. Assuming that a power plant is able to capture 90% of the CO_2 produced and taking a 20% energy penalty into account, CO_2 emissions with CCS will be 12% of those that would have been produced by the same facility without carbon capture. At a $40 per ton permit price, such a plant will have to pay $4.80 ($40 x .12) per ton of CO_2 that would have been produced in the absence of carbon capture. This cost must be considered in evaluating whether it would be cheaper to purchase permits for all emissions rather than installing CCS.

[11]. JPMorgan Research, "All you ever wanted to know about carbon trading 5.0," August 10, 2007.

Conclusion

The best available cost estimates indicate that carbon capture and sequestration from power plants will cost \$40-\$55 per ton of CO_2 captured. Adding in the cost of emissions that CCS is unable to capture raises the overall cost of CCS at power plants by approximately 12%, generating cost estimates in the \$45-\$61 range. As noted above, the costs could be considerably higher if the developers of CCS facilities must bear large expenses related to regulation, liability, and the acquisition of underground storage rights.

If these estimates are accurate, will not be economically viable unless the cost of emissions permits consistently exceeds \$45-\$50 per metric ton of CO_2. At lower permit prices, capture and sequestration is not a cost-effective option.

CCS is currently viable only in Norway, which imposed a tax of €40 per metric ton of CO_2 emitted from offshore oil operations. It is this tax, along with the potential for using CO_2 in enhanced oil recovery, that motivates Statoil's particular interest in carbon capture.[12]

In the European Union, according to various private projections, permit prices could reach the \$40-\$50 range during Phase 3 of the Emissions Trading Scheme, which covers the period 2013-2020. Beyond 2020, as the number of permits is further reduced and the cost per permit moves higher, CCS should become financially attractive in Europe. Given the long lead times involved in planning and constructing power generation facilities, generators subject to the Emissions Trading Scheme may find it desirable to start on CCS projects over the next few years. Chemical plants in Europe, which have lower capture costs, may find it worthwhile to embrace CCS even earlier.

Based on existing legislation and regulations, CCS seems unlikely to be economically viable outside Europe between now and 2030. No other jurisdiction in the world seems likely to have a carbon emissions price exceeding \$45 per ton by 2020. Many pending proposals in the United States would lead to per-ton prices in that range or higher during the 2030-2050 period, but at present no laws or regulations that would accomplish this are in force.[13] Nor are we aware of similar laws or regulations enacted in other countries. As a result, the price signals that could stimulate adoption of CCS are absent.

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[12]. See comments of Statoil manager Michel Myhre-Nielsen in International Energy Agency, "Expert Workshop on Financing Carbon Capture and Storage: Barriers and Solutions," Report 2007/9, July 2007, p. 18.
[13]. Sergey Paltsev et al., "Assessment of U.S. Cap-and-Trade Proposals," MIT Joint Program on the Science and Policy of Climate Change, Report 146, April 2007, available at http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt146.pdf.

A sustained price for CO_2 emissions above $45 per ton is a necessary but not sufficient condition for adoption of CCS by investor-owned companies. Adoption of CCS will be conditioned upon resolution of concerns about regulatory delays, liability, and the financial consequences of the leakage of sequestered CO_2. These issues have yet to be addressed anywhere.

Given these obstacles, along with the fact that some key technological aspects remain unproven, CCS is unlikely to contribute to stabilizing atmospheric concentrations of CO_2 over the next two decades.[14] However, there is a high probability that construction of CCS facilities will get underway in Europe within the next decade, providing opportunities for investors in companies that may design and manage construction of such facilities, make appropriate equipment and chemical solvents, and bring expertise in injection and underground monitoring.

[14]. See, for example, World Resources Institute, "The Future of Coal under a Carbon Cap and Trade Regime," September 14, 2007, available at http://pdf.wri.org/20070914_submission_houseeigw.pdf.

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