

REFERENCE REPORT #36

CAPTURING THE GAINS FROM CARBON CAPTURE

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL
MACROECONOMIC SUGROUP
OF THE
NPC COMMITTEE ON GLOBAL OIL AND GAS

TEAM LEADERS

Douglas B. Petno
Managing Director and
Energy Group Head
J.P. Morgan Securities Inc.

Surina Shukri
Energy Investment Banking
J.P. Morgan Securities Inc.

MEMBERS

Charles E. Bishop*
Director, Economics
Marathon Oil Corporation

Marc Levinson
Economist
JPMorgan Chase & Co.

Larry G. Chorn
Chief Economist
Platts Analytics

Richard G. Newell
Gendell Associate Professor of
Energy and Environmental Economics
Nicholas School of the
Environment and Earth Sciences
Duke University

R. Dean Foreman
Senior Economist
Corporate Planning –
Economics and Energy Division
Exxon Mobil Corporation

Adam E. Sieminski
Chief Energy Economist
Global Markets/Commodities
Deutsche Bank AG

Marianne S. Kah
Chief Economist
ConocoPhillips

Katherine B. Spector
Executive Director
Global Head of Energy Strategy
Global Currency & Commodities Group
JPMorgan Chase Bank, N.A.

* Individual has since changed organizations but was employed by the specified company while participating on the study.

Capturing the gains from carbon capture

Sequestering greenhouse gas will create a major industry over the next five years

- Carbon sequestration—the burying of carbon dioxide captured from power generation and manufacturing—is likely to develop into an extremely large industry in the face of mounting concern about climate change.
- Investor interest in climate change has so far centered on utilities and fossil-fuel producers. This report seeks to widen this focus and look at opportunities for the industrial companies that are staking out roles in the infant capture-and-sequestration industry.
- Many methods of carbon capture involve integrated gasification combined cycle (IGCC) coal power plants. IGCC technology is improving rapidly and is becoming attractive to generators.
- The financial viability of carbon sequestration depends entirely upon the costs firms face for emitting carbon dioxide into the atmosphere. The projected cost of emissions may make sequestration commercially attractive in Europe as early as 2013.
- A variety of legal uncertainties must be resolved in both Europe and the US before carbon sequestration becomes practical. We expect most new US power plants to be designed to accommodate capture and sequestration at a later date, but not to have those facilities installed at the time of construction.
- We think that carbon capture and sequestration will create highly significant business opportunities for oil-field service companies with proprietary technology, such as **Halliburton** and **Schlumberger**; for construction and engineering companies with expertise in chemical engineering, such as **Washington Group** and **Fluor**; for designers and manufacturers of coal-burning power plants, notably **Alstom**, **General Electric**, and **Siemens**; for chemical companies such as **Praxair** that have expertise in membrane and filter technologies; and for oil producers that will benefit both by using carbon dioxide for enhanced oil recovery and by charging utilities to sequester CO₂.

Corporate Research

Marc Levinson^{AC}

(1-212) 622-5552

marc.levinson@jpmorgan.com



www.morganmarkets.com

J.P. Morgan Securities Inc.

See page 22 for analyst certification and important disclosures, including investment banking relationships.

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Companies mentioned in this report

Company	Analyst	Equity recommendation	Price 9-Apr-07	Involvement in carbon capture and sequestration
Alstom	Andreas Willi	UW	€ 99.75	Post-combustion capture; oxygen-fuel combustion
Chevron	Katherine Lucas	N	\$75.49	Sequestration; enhanced oil recovery
ConocoPhillips	Katherine Lucas	N	\$68.58	Gasification technology
Denbury Resources	Joe Allman	OW	\$30.84	CO ₂ pipelines; enhanced oil recovery; owns natural CO ₂ source
Dresser-Rand	Kevin Pollard	OW	\$31.68	Compression for CO ₂ pipelines and injection
Eastman Chemical	Jeff Zekauskas	N	\$65.00	Gasification; pre-combustion capture
Emerson Electric	Steve Tusa	N	\$42.72	Controls and process management for injection.
Fluor	Curt Woodworth	N	\$91.72	Design and construction of post-combustion capture
General Electric	Steve Tusa	OW	\$34.78	Standardization of IGCC plants; post-combustion separation
Halliburton	Michael LaMotte	N	\$32.60	Injection wells
Honeywell	Steve Tusa	UW	\$47.11	Methods to remove CO ₂ from flue gas in post-combustion capture
National Oilwell Varco	Michael LaMotte	N	\$79.63	Piping and coatings for CO ₂ transport and injection
Occidental Petroleum	Katherine Lucas	N	\$49.68	Enhanced oil recovery
Praxair	Jeff Zekauskas	N	\$63.72	Membranes and process design for all carbon-capture methods
Schlumberger	Michael LaMotte	OW	\$71.57	Injection wells; CO ₂ mineralization
Shaw Group	Scott Levine	N	\$29.32	Design and construction
Siemens	Andreas Willi	OW	€ 81.99	IGCC plant design and equipment
Washington Group	Scott Levine	OW	\$64.74	Design and construction

Source: JPMorgan.

The birth of a major industry

Heightened concern about climate change is giving rise to an entirely new industry dedicated to capturing and storing greenhouse gases that would otherwise be emitted into the atmosphere. Over time, we anticipate that carbon capture and sequestration (CCS) will develop into an extremely large industry, involving hundreds of chemical-type plants and extensive pipeline networks.

Many major industrial corporations are now making investments with the aim of becoming significant players in this emerging industry. In the near term, these investments are almost entirely exploratory, and we see little prospect of substantial revenue or profit over the next five years.

We think the rising cost attached to greenhouse-gas emissions could make CCS commercially attractive in Europe as early as 2013. If this judgment proves correct, and if the technology is demonstrated, contractors and suppliers may begin to book sales early in the next decade. Companies that develop expertise or proprietary technology may gain important market opportunities as the demand for carbon sequestration expands.

This report is intended to assist investors in understanding this developing market. We explain some of the processes by which greenhouse gases can be captured and stored and review the economics underlying the industry. We then look at the efforts of individual firms to become involved in carbon sequestration and offer recommendations for investors with the long time horizons essential for investment in this sector.

A response to climate change

Carbon capture and sequestration is a concept developed in response to the intense concern about climate change. Numerous scientific studies over the past two decades have found high and rising concentrations of carbon dioxide, methane, and certain other “greenhouse gases” in the atmosphere. Evidence strongly indicates that these greenhouse-gas concentrations are leading to significant rises in temperatures on earth. Most greenhouse gases persist in the atmosphere for decades or longer, so emissions today will contribute to climate change for years into the future.

Reversing global warming will require large reductions in emissions of greenhouse gases from fossil-fuel combustion. Carbon dioxide (CO₂) is the largest single contributor to the greenhouse-gas buildup in the atmosphere. Coal-burning power plants are by far the largest source of greenhouse-gas emissions (Table 1), and, because of their size, are also among the easiest sources for governments to target. For these reasons, regulatory schemes in Europe and parts of the United States, and proposed schemes in other parts of the world, devote special attention to controlling CO₂ emissions from coal-fired generation.

Table 1: Major stationary sources of CO₂ emissions worldwide

Process	Number of sources	Total emissions (Mt/yr)
Power generation	4,943	10,539
Cement production	1,175	932
Petroleum refining	638	798
Iron & steel production	269	646
Petrochemical production	470	379
Oil and gas processing	Unknown	50
Other	90	33
Ethanol and bioenergy	303	91

Source: IPCC.

In principle, CO₂ emissions from coal-burning power plants can be reduced in three main ways.

Alternative sources of power: The simplest way to reduce CO₂ emissions is to burn less coal, substituting sources of generation that have lower or no emissions, such as natural gas, uranium, and wind. We think these alternatives are unlikely to result in lower coal consumption over any meaningful time horizon, given the large installed base of coal-fired plants and the strong growth in electricity demand. In the United States, the US Department of Energy forecasts that nearly 40 gigawatts of new coal-fired capacity will come on line by 2020. Even if some of these planned units are never built, reductions in the use of coal from current levels will likely be difficult to achieve.

Greater efficiency in coal-fired generation: Technological improvements that increase the amount of electricity generated from a given volume of coal have the potential to restrain coal consumption. Efforts to improve thermal efficiency of power plants are under way at many locations. Typically, this involves installing new “supercritical” (and, eventually, “ultrasupercritical”) boilers that operate under higher pressure, or recovering and reusing heat from stack gas. These advances, which can increase generating efficiency by as much as 35%, should slow the growth of coal consumption. If, however, global coal-fired generating capacity increases 25% by 2020, as the US Department of Energy projects, improved efficiency in new and rebuilt plants is unlikely to reduce overall emissions from coal-fired plants below current levels.

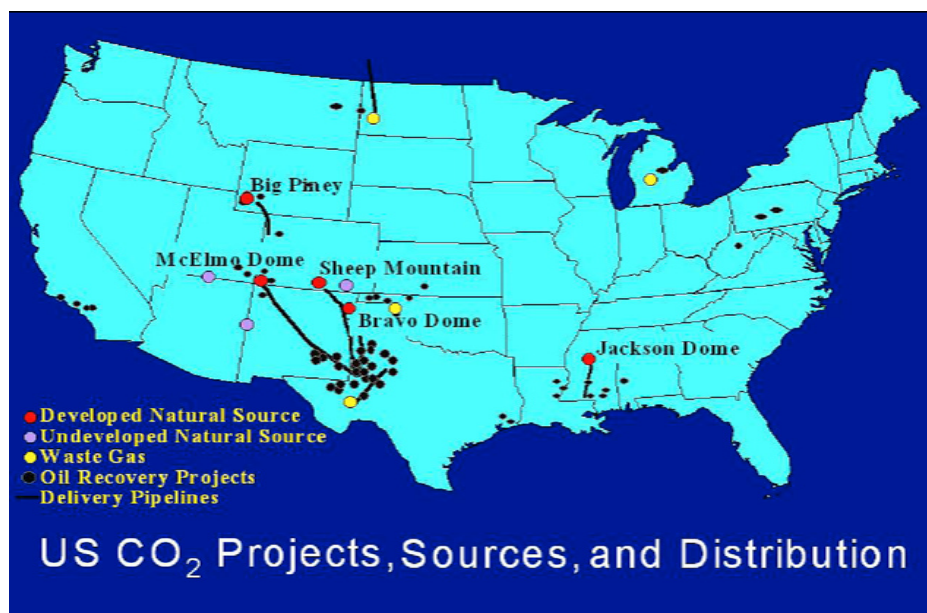
Carbon capture and sequestration: The third approach involves “capturing” carbon dioxide produced in power generation before it escapes into the atmosphere. The CO₂ can then be sequestered, or stored, in such a way that it causes no environmental harm. Sequestration would be required for several centuries, until emissions reductions have succeeded in lowering the concentration of CO₂ in the atmosphere. Capture and sequestration seem to us likely to be part of any meaningful effort to achieve absolute reductions in CO₂ emissions.

The basics of capture and sequestration

A number of projects that involve the capture and storage of carbon dioxide have been built in various parts of the world. All of these are small in scale. In the United States, carbon capture and sequestration has been in use for three decades, for

reasons unrelated to climate change. In these projects, the carbon dioxide generally is captured from natural sources and then injected into oil fields. This process, known as enhanced oil recovery, can increase the amount of oil recovered from an average field by as much as 50%. The oil producer typically pays for capture and injection, and then profits from the resultant increase in oil output. Enhanced oil recovery with CO₂ injection is in use in approximately 85 locations in the US (Figure 1).

Figure 1: Carbon capture and sequestration projects in the US



Source: Statoil.

All of the existing carbon sequestration projects are small. The largest existing project in the world, undertaken by the Norwegian oil company Statoil in the North Sea since 1996, annually separates and stores less than 1 million metric tons of CO₂ resulting from natural gas production—an amount equal to a few months’ emissions from a coal-fired generating station. The total amount of carbon dioxide being captured and stored in existing US enhanced oil recovery projects is equivalent to one or two months of a single power plant’s emissions. Three other experimental projects aimed at capturing and storing energy-related emissions are operating in Canada and Europe.

To our knowledge, no large-scale CCS system is in routine operation anywhere. Thus, while many different CCS technologies are in use or under development, none of them has been demonstrated at the scale required to serve a full-size coal-burning generating plant. The US utility industry is seeking to obtain government support for a full-scale demonstration of CCS in energy legislation now being debated in Congress.

CCS involves three distinct steps with quite different technical and economic characteristics. Capture involves separating the CO₂ from other gases at the source, purifying it if necessary, and concentrating it. This phase, which has the greatest technological content, is likely to be the province of chemical and chemical-

engineering companies. Once concentrated, the CO₂ will be handed off to a pipeline operator for delivery to a storage site. This phase requires pipeline construction, flow monitoring, and other skills in which pipeline operators specialize. The sequestration phase involves injection into the ground and long-term monitoring, and is likely to be conducted by large oil and oilfield service companies.



Carbon capture

Carbon dioxide can be captured from power plants and other sources by one of three principal methods:

- **Pre-combustion capture.** Rather than being fed directly into the power plant, 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 can 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 used today in small-scale plants that do not produce electricity. Use at larger scale requires construction of integrated gasification combined cycle (IGCC) plants, probably involving oxygen-fuel combustion. A handful of relatively small IGCC plants are in operation around the world, and generators are proposing to build approximately 25 commercial-size plants in the United States and a large number elsewhere. With present technology, IGCC plants are expected to be able to capture 75-80% of CO₂ emissions with little loss of efficiency, but a recent report indicates that recovery rates above 85% will lead to significant efficiency loss. Pre-combustion capture is also suitable for gas-fired generating plants, although with higher costs per ton of CO₂ captured.
- **Oxygen-fuel combustion.** This technology involves designing the power plant to burn coal with pure or nearly pure oxygen. If this is done, the resulting flue gas will consist principally of CO₂ and water vapor, making the CO₂ easy to capture once the water vapor is condensed. This approach requires a costly oxygen separator attached to the plant to remove nitrogen from the combustion gas. Oxygen separators can be retrofitted on existing power plants, but tend to reduce efficiency. The separation process also consumes as much as 15% of the electricity generated by the plant.
- **Flue gas separation.** Carbon dioxide accounts for 10-12% of the flue gas emitted by conventional coal-fired power plants. Separation, as the name suggests, involves capturing the CO₂ from the smokestack. Separation is essentially a chemical engineering process, in which the flue gas passes through a chemical solvent that absorbs the carbon dioxide. The solvent is then piped to an adjacent unit in which steam is used to separate out the CO₂ in highly concentrated form. The concentrated CO₂ is then compressed for shipment, while the solvent is reused. In some trials, membranes rather than steam are used to separate out the CO₂, and this approach is now the subject

of considerable research. A number of other approaches also have been tried. Some separation technologies are energy intensive, necessitating construction of a larger generating plant and partially defeating the goal of reducing CO₂ emissions.

Carbon transport

Once captured, the concentrated carbon dioxide would be transported by dedicated pipeline to a storage location. Pipeline transportation of carbon dioxide already is a technologically mature industry, with approximately 3,500 miles of CO₂ pipelines now in use in the United States. CO₂ pipelines and pipeline equipment are technically quite similar to those in use for natural gas, so there may be relatively little technological innovation in this part of the capture-and-storage process.

Expanded use of carbon capture and sequestration would likely lead to a massive expansion of pipeline networks. Some estimate that the future network for transporting CO₂ will be similar in scale to that now in place for natural gas, which in the United States now incorporates 300,000 miles of transmission pipe. We anticipate that carbon sequestration could bring significant new business for steel pipe manufacturers, manufacturers of pipe installation equipment, and pipeline operators.

Sequestration

After being transported to an injection site, the CO₂ would be injected 800 meters or more into the ground. Such injections have occurred for many years, but on limited scale. Widespread adoption of carbon capture and sequestration would lead to a quantum change in the amount of injection and will stimulate new technology to identify injection locations and monitor sequestered gas.

Currently, oil producers inject carbon dioxide as a tertiary recovery method to increase extraction from an aging field in a process known as CO₂ flooding. In this process, water is first injected to restore reservoir pressure, followed by CO₂. The concentrated CO₂ expands and reacts with the oil, lowering the viscosity, increasing the flow rate, and easing transport to the production well. Related enhanced oil recovery processes include thermal recovery and chemical injection. A well that is a good candidate for CO₂ flooding is deep (>2,000 ft), with API oil gravity greater than 22-25 degrees, and remaining oil saturation greater than 20%. While the amount of CO₂ now used in this process is small, the technology is well established.

Oil and gas fields are also being used for CO₂ storage where no enhanced oil recovery is contemplated. This mainly involves CO₂ mixed with hydrogen sulfide, which is a byproduct of oil and gas production. At some sites, this waste mixture is reinjected into the depleted oil and gas reservoirs for storage.

If CCS is to bring about significant reductions in CO₂ 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 as well. The availability of suitable underground storage space is unknown, as only isolated geological investigations have been conducted. Initially, at least, oil-field storage

seems likely to be the most viable alternative in the US, whereas saline storage appears the most promising alternative in Europe.

Scientists believe that CO₂ also could be sequestered in ocean depths. Below 3,000 meters, compressed CO₂, in liquid form, is denser than seawater. The liquid CO₂ would be expected to remain trapped for decades or even centuries. However, the CO₂ could potentially increase the ocean's acidity, with unknown consequences on marine life. In any case, the electric generators with the greatest interest in developing carbon capture and storage are aware of the potential environmentalist backlash against injecting CO₂ into the ocean, and are not actively promoting the ocean as a storage location.

One important difference between existing methods of carbon sequestration and future practices lies in the amount of monitoring required. With enhanced oil recovery, the possible escape of carbon dioxide into the atmosphere is of no great concern. If sequestration is undertaken for environmental purposes, however, those storing the CO₂ will need to make sure it remains where it was stored, potentially creating a market for new types of instrumentation.

Legal obstacles

Carbon storage faces important legal obstacles. The two most important concern liability and property rights.

Liability arises as a major issue because of the possibility of leakage from a storage reservoir over the many decades during which storage would be required. Leakage could occur either through mechanical failure or through a geological event, such as an earthquake or a volcanic eruption that could allow concentrated CO₂ to escape to the surface. Although CO₂ is not toxic, the sudden release of a large amount of CO₂ could create an intolerably high concentration of CO₂ in the air around the escape site, causing death by asphyxiation. In addition to whatever direct damage they caused, companies held liable for leakage would presumably face significant fines for discharging CO₂ into the atmosphere without permits.

Underground stores of CO₂ could also create liability even without leakage into the atmosphere. In theory, CO₂ could leach into groundwater supplies and could contribute to chemical reactions that could weaken rock structures and eventually alter the surface.

Liability shields are thus critical to the widespread use of CCS. US utilities have been unwilling to participate in large-scale CCS trials without being shielded from liability, and they envision a future in which they would shed all responsibility for the CO₂ once it enters a pipeline. The various equipment and service vendors exploring CCS, however, have been unwilling to accept unlimited liability in perpetuity. This impasse threatens to delay the development of CCS in the United States. In Europe, utilities are seeking assurances that their liability will be limited in the event sequestered CO₂ leaks into the atmosphere. European utilities have proposed a mechanism similar to that in place for nuclear power plants, under which

the utility bears the first €200 million of liability for an accident and the government is responsible for costs above that amount.

The property rights question concerns ownership of the underground spaces, known as “pore space,” into which the concentrated CO₂ would be injected. In some US states, the pore space left by oil and gas production is thought to be owned by the owner of the mineral rights. In other states, it is believed to be owned by the owner of the surface rights, and in certain states ownership is legally unclear. Large-scale sequestration of carbon dioxide cannot proceed until the courts in various states issue definitive rulings about the ownership of pore space, or until state legislatures act on the subject.

The property-rights questions are less problematic in Europe, where underground geologies are uniformly state property and mineral-rights holders control only extraction rights for a limited time period. However, CCS in Europe faces legal issues related to rights-of-way for pipelines and procedures for granting access rights to depleted oil fields and saline aquifer structures. Additionally, we expect European utilities to be at the forefront of the political push to sort out the legislative side of rights-of-way for pipelines and access rights to depleted oil fields and saline aquifer structures.

Property-rights issues may lead to the reopening of closed-in oil fields in Texas. According to a staff interpretation supplied to us by the Texas Railroad Commission, the rights to pore space in a reservoir productive of oil or gas are controlled by the owner of the mineral rights, whereas the rights to pore space in other locations are controlled by the owner of surface rights. The Railroad Commission staff cautions that it is unaware of any case law or statute that definitively addresses the issue. Under its staff interpretation, however, once the storage of carbon dioxide becomes a potential revenue source, mineral-rights owners will have an incentive to reopen low-volume wells in order to maintain control of the underground storage space.

There also are unresolved legal issues concerning the regulation of CO₂ pipelines and storage facilities in the United States. The Federal Energy Regulatory Commission (FERC), the economic regulator of interstate gas and oil pipelines, disclaims jurisdiction over pipelines carrying products that are not hydrocarbon based or are not used for energy purposes.¹ Such pipelines operating as common carriers—offering their services to any customers—have their rates overseen by the US Surface Transportation Board, but a pipeline moving CO₂ from a single power plant to a sequestration site would not face rate regulation. The US Department of Transportation’s Office of Pipeline Safety is responsible for safety regulation of interstate pipelines. It reports an average of 2-3 minor incidents per year involving CO₂ pipelines, typically involving corrosion, failed welds, or equipment failures.

Underground injection in the US is regulated by the US Environmental Protection Agency or state agencies in order to protect drinking water. However, it appears that no federal or state agency currently has authority over underground storage sites to assure that the sequestered CO₂ does not escape to the surface as a result of poor maintenance. In all probability, a new regulatory structure

1. Texas Petrochemical Pipeline LLC, 107 FERC Sec. 61, 151, May 10, 2004.

will have to be created. The European Union also has no regulator with clear authority for monitoring underground CO₂ storage sites.

The Economics of CCS: The Cost Side

The embrace of CCS, if it occurs, will be almost entirely a function of the price attached to greenhouse-gas emissions. At present, these emissions have a very low price within the European Union, and are free everywhere else in the world. As a result, users of concentrated carbon dioxide, such as oil producers pursuing enhanced oil recovery, must purchase it from electric generators, which otherwise have no reason to capture it. This situation will not persist, in our view. In the future, we believe the costs of capturing and sequestering carbon dioxide will have to be borne by owners of coal generation, not by the users of CO₂.

Capture and sequestration is not necessarily the lowest-cost means of avoiding CO₂ emissions. In fact, it would probably be quite costly if attempted with conventional pulverized-coal generating plants. However, technological innovations are expected to make some CCS technologies cost competitive, especially when they are integrated into coal-fired plants designed for capture of carbon dioxide (Table 2).

Table 2: Estimated net cost per ton of CO₂ avoided, 2030

Technology	€/t CO ₂	\$/t CO ₂
CCS on new coal plants, with enhanced oil recovery	€15-€20	\$20-\$27
Co-firing of biomass in coal plants	€20-€30	\$27-\$40
Wind power, including backup generation	€ 22	\$29
Solar	€ 24	\$32
CCS at new coal plants, no oil recovery	€25-€41	\$33-\$45
CCS retrofitted to existing coal plants, with enhanced oil recovery	€27-€40	\$36-\$53
CCS retrofitted to existing coal plants, no oil recovery	€27-€41	\$36-\$45
CCS on new gas-fired generator, with enhanced oil recovery	€30-€40	\$40-\$53
CCS retrofitted to gas-fired generators, no oil recovery	€40-€60	\$53-\$80

Source: Vattenfall, JPMorgan.

Note: Constant euros; assumed exchange rate €1=\$1.33.

Using current technology at current costs, installing and operating CCS systems will raise the cost of generation from a conventional coal plant on the order of 50%. The Intergovernmental Panel on Climate Change (IPCC), an international scientific group working on the subject, estimated in 2005 that capture and geological storage would add \$0.01-\$0.05 per kilowatt hour (\$10-\$50 per megawatt hour) to the cost of generating electricity from a conventional coal plant. JPMorgan estimates that the average cost of coal generation in the United States is around \$0.05 per kilowatt hour, including taxes and interest charges. The IPCC estimate implies an increase of 20-100% in the cost of generating electricity from coal. A survey by energy scientists at the Massachusetts Institute of Technology revealed slightly higher estimates, with the studies analyzed estimating a mean increase of 87% in the cost of conventional coal generation from adding CCS.

On a volume basis, estimates of the cost of carbon capture and storage depend heavily on specific assumptions about the generating plant. For a new plant designed with CCS in mind, the Intergovernmental Panel on Climate Change

estimates the cost of capture and storage at \$30-\$70 per ton of carbon dioxide avoided. If retrofitting of older plants is required, estimated costs are considerably higher. Vattenfall, a Swedish utility, offers estimates in a similar range, €25-€60 (\$34-\$80) per ton of emissions avoided in an existing plant, and €15-€40 (\$21-\$54) for future plants designed around CCS. “Capturing” the CO₂ is by far the most expensive part of the process, which is why new generating plants designed to facilitate carbon capture will have a significant cost advantage (Table 3).

Table 3: Estimated cost of carbon capture and storage

Process	Cost range per metric ton CO ₂ captured	Comments
Capture from power plant	\$15-\$75	Net cost compared to the same plant without capture
Transportation	\$1-\$8	Cost per 250 km via pipeline
Geological storage	\$0.5-\$8	Excludes potential revenues from enhanced oil recovery
Monitoring of storage	\$0.1-\$0.3	Depending upon regulation
Measured costs	\$16.60-\$91.30	
Costs not measured		
Liability		Availability of insurance uncertain
Remediation		Availability of insurance uncertain
Purchase of rights to underground storage		May be costly at large scale

Source: IPCC and JPMorgan.

Note: The cost per ton of emissions avoided is higher than these ranges, because of the energy required to capture and store CO₂.

All of these cost estimates omit factors that could drive the ultimate cost of carbon sequestration higher. Unless legislators limit liability for participants in sequestration schemes, the cost of insurance may be substantial, assuming that insurance is even available. There is some risk that underground storage will contaminate ground water supplies, and the potential cost of mandatory remediation will need to be factored into cost estimates. All known estimates of sequestration costs appear to assume free use of pore space or other underground storage, and this seems to us an unrealistic assumption; if CCS is undertaken on a large scale, underground sites with desirable geology will become valuable resources, and their owners can be expected to charge for their use.

The cost of carbon capture is expected to decline in the future as purpose-built generating plants arrive and as new technologies come into use. The attractiveness of carbon capture and storage depends both on such cost reductions and on the cost of the main alternative, emitting carbon dioxide into the atmosphere.

The Economics of CCS: The Payoff

Regulations are slowly beginning to attach costs to generators’ carbon-dioxide emissions. We expect that within the next six or seven years, emissions costs in the European Union will reach the level at which carbon capture and sequestration starts to become economically viable. In the United States, costs attached to CO₂ emissions are unlikely to work in favor of CCS for at least two decades, barring rapid declines in capture costs.

European Utilities Equity Research

Chris Rogers

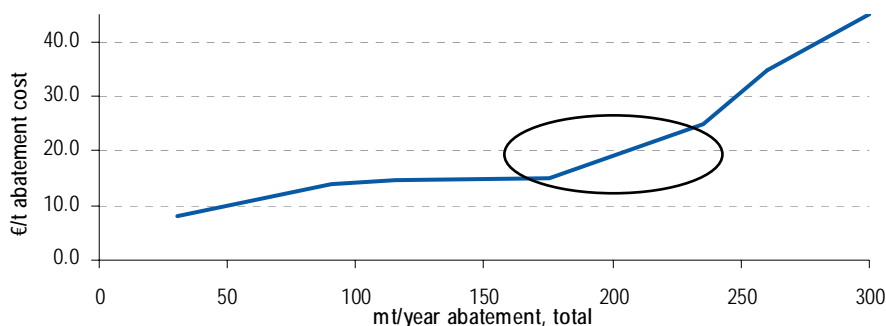
(44 20) 7325 9068
christopher.g.rogers@jpmorgan.com

Generators in the EU have been required to obtain tradable CO₂ emissions permits since 2005. Initially, each source was allocated permits based on its reported historical emissions. These reports appear to have been exaggerated, leading to an overallocation of permits. As a result, permits have traded as low as €0.75 per metric ton, a price that provides no incentive for emissions control.

In “Phase 2” of its emissions trading scheme, covering 2008-2012, the EU plans to reduce the number of permits issued. (A permit allows the holder to emit one metric ton of CO₂ during the five-year period, and is not limited to a specific year.) We believe that the number of permits available will force reductions averaging 155-210 million tons per year from current levels. In addition, airlines are to come under the scheme from 2011, increasing the shortfall by a further 85 million tons per year.²

We estimate that emissions reduction of this magnitude will bring the average cost of a permit for the 2008-2012 period to around €20 (\$26) per ton of carbon dioxide emitted (Figure 2). This will have the effect of forcing up the price of coal-fired power and will encourage utilities to shift some generation from coal to gas, where feasible. However, we do not believe that the cost of emissions permits in the 2008-2012 period will be high enough to make CCS a commercially viable alternative.

Figure 2: EU emissions abatement goal will drive cost of permits



Source: JPMorgan estimates.

The price attached to greenhouse-gas emissions in Europe is likely to make CCS far more attractive in “Phase 3” of the emissions trading scheme, starting in 2013. The waters here are somewhat murky. The EU has an announced target of reducing all greenhouse-gas emissions 20% below the 1990 level by 2020, but it is not clear whether all of that reduction will come from sectors currently covered by the emissions trading scheme (utilities, glass, paper, cement, oil refining, airlines from 2011) or whether other sectors will be required to reduce emissions as well. The EU will shift to a more ambitious target, reducing emissions 30% below 1990 levels, if a new international agreement on climate change is reached.

While the details are far from certain, we regard it as highly likely that the number of permits available for 2013-2020, on an annual average basis, will be far lower than for 2008-2012. We also think it likely that utilities, which received

2. For details on the EU emissions trading scheme, see the JPMorgan report *All you ever wanted to know about carbon trading, vol 4 pt 1*, December 14, 2006.

“free” permits to cover their historical emissions in the 2005-07 start-up phase of emissions trading and will receive “free” permits for around 65% of historical emissions in Phase 2, will be treated much less generously in Phase 3. We expect utilities will be given “free” permits equal to no more than 25-40% of historical emissions, and perhaps none at all.

We expect the price of greenhouse-gas emissions permits to average €25-40 (\$34-53) per ton over the 2013-2020 period, based on a reasonable set of assumptions. As a permit can be used at any point over those eight years, it is not necessarily the case that permit prices will rise gradually from year to year. On the contrary, prices likely will begin adjusting to the new permit regime as early as 2013.

Our forecast of permit prices indicates that some methods of carbon capture and sequestration may be commercially viable for emissions reduction in Europe as early as 2013. As the technology is proven at commercial scale, we expect to see new coal-fired plants incorporating CCS enter service in Europe as early as 2014-2015, and to account for almost new coal plants in Europe by late in the coming decade.

Our expectations of CCS in the United States are less aggressive, because we expect emissions costs to be far lower than in Europe. As a result, we expect that many new coal-fired plants will be designed to incorporate carbon capture and sequestration at a later date, but we do not think that installation of CCS will be viable in the absence of direct government subsidies.

Two regional schemes to regulate CO₂ emissions, one in the Northeast and the other in California, will soon enter into force in the US. The rules for the 10-state Northeastern scheme, known as the Regional Greenhouse Gas Initiative, will impose costs on generators' CO₂ emissions from 2009, but effectively set the maximum cost at \$7 per ton through 2018. California is to impose limits on greenhouse-gas emissions from 2012, when generators probably will become subject to a permitting system. However, detailed regulations will not be issued until 2009, so the potential cost imposed on emitters cannot readily be estimated.³

JPMorgan expects Congress to adopt a nationwide plan to control greenhouse-gas emissions within the next couple of years. This seems likely to include a national cap on emissions and a system of tradable permits, similar to the EU and RGGI schemes. However, we expect the new limits to be phased in very gradually, and to have little cost impact on generators before 2020.

Elsewhere in the world, no binding restrictions on CO₂ emissions are in place. While we expect Australia, Japan, China, and other countries to adopt emissions-trading schemes over the next few years, all of these schemes are likely to be introduced in phases in order to avoid economic dislocation. This necessarily means that the cost of emissions will remain low for the foreseeable future.

Given the low cost of carbon-dioxide emissions, carbon capture and sequestration currently make sense only for new plants with long anticipated

3. For details on pending US regulations, see the JPMorgan reports *Warming to rules on climate change*, September 27, 2006, and *Global Utilities: Trading climate change*, March 5, 2007.

lifetimes. Even then, some operators will find it preferable to build generating plants designed to facilitate carbon capture (“CCS ready”), while postponing construction of capture-and-sequestration facilities until such time as the cost of carbon-dioxide emissions justifies the expenditure. In the absence of subsidies, the economics do not justify CCS at existing facilities, except perhaps in the event of a major overhaul designed to extend plant life for decades.

We note that widespread use of CCS will also have a payoff for oil producers and service companies. On the one hand, it will lower the costs and improve the feasibility of CO₂ flooding. Currently, oil producers have to bear the cost of expensive machinery to capture carbon dioxide. Should carbon capture become legislatively mandated, this expense will be shifted on to the owners of coal-fired generators, making CO₂ flooding more affordable. Sequestering the CO₂ will provide a new source of revenue for oil producers, who will be able to charge for underground storage space, and for oilfield service companies, which may be able to modify enhanced oil recovery technology for the purpose.

The CCS Industrial Complex

As the above discussion indicates, firms participating in the carbon capture and sequestration market have few near-term revenue prospects. The International Energy Agency has identified only 18 significant CCS projects likely to get underway around the world over the next decade (Table 4). Investments related to carbon capture and sequestration should thus be regarded as developmental, as companies seek to understand the emerging market and position themselves to exploit future revenue opportunities.

Table 4: Selected demonstration projects incorporating capture and sequestration

Company	Location	Fuel	Output (MW)	Cost (millions)	Technology	Start date
BP	Peterhead, Scotland	Natural gas	350	\$400	Pre-combustion capture; oilfield storage	2010
BP	Carson, California	Petcoke	500	\$1,000	IGCC; pre-combustion capture; oilfield storage	2011
China Huaneng Group	Undetermined	Coal	100	Unknown	IGCC; pre-combustion capture	2015
E.ON	Killingholme, England	Coal	450	£1,000	IGCC; may include pre-combustion capture	2011
Scottish & Southern	Ferrybridge, Scotland	Coal	500	£250	Retrofit plant and make "capture-ready"	2011
FutureGen	Undetermined	Coal	275	\$1,000	IGCC; pre-combustion capture	2012
General Electric	Poland	Coal	1,000	Unknown	IGCC; pre-combustion capture	Unknown
Statoil	Karstø, Norway	Natural gas	430	Unknown	Post-combustion capture; possible oilfield storage	2009
Statoil	Mongstad, Norway	Natural gas	280*	Unknown	Post-combustion capture and storage	2014
Nuon	Eemshaven, Netherlands	Coal/gas/bio	1,200	Unknown	IGCC; "option to capture"	2011
Powerfuel	Hatfield, UK	Coal	900	Unknown	IGCC; pre-combustion capture	2010
Centrica/Progressive	Teesside, UK	Coal/petcoke	800	\$1,500	IGCC; pre-combustion capture	2009
SaskPower	Saskatchewan	Lignite	300	Unknown	Post-combustion or oxygen-fuel; oilfield storage	2011
Siemens	Germany	Coal	1,000	€ 1,700	IGCC; pre-combustion capture	2011
Stanwell	Queensland, Australia	Coal	100	Unknown	IGCC; pre-combustion capture and storage	2012
Statoil/Shell	Draugen, Norway	Natural gas	860	Unknown	Post-combustion capture; oilfield storage	2011
RWE	Germany	Coal	450	€ 1,000	IGCC; pre-combustion capture and storage	2014
RWE	Germany	Coal	1,000	€ 800	Retrofit; post-combustion capture or "capture-ready"	2016
AEP	Oologah, Oklahoma	Coal	450	Unknown	Retrofit with flue-gas separation; oilfield storage	2011

Source: International Energy Agency, company reports, press reports.

Note: * additional 350 MW of heat output.

These future revenue opportunities may prove to be extremely large. Carbon capture and sequestration on an environmentally meaningful scale will require the

creation of a massive industry. A conventional 500 megawatt coal-fired generating station produces more than 4 million metric tons of CO₂ per year—and there are thousands of conventional coal plants around the world. In the transportation sector alone, by some estimates, sequestering 60% of the carbon dioxide produced by US coal-fired generating plants could require as large a pipeline network as that now used to transport oil. Adding a flue-gas separation unit to a traditional 400 megawatt coal plant would cost somewhere around \$400 million.

The opportunity to cash in on CCS will extend to many different industries.

Some industries may be able to meet this potential demand with existing products; the pipelines used to transport CO₂, for example, will probably be very similar in terms of materials and construction methods to those now used for natural gas. On the other hand, the growth of CCS is likely to bring considerable innovation in chemical solvents and membranes, design and construction of oxygen and flue-gas separators, and instrumentation systems to monitor underground storage facilities.

At the moment, there is little proprietary technology at work in carbon capture and sequestration—but that is likely to change very soon. On the following pages, we highlight companies that have significant involvement in this emerging field, and describe the different areas in which they hope to obtain proprietary advantage.

Investing in CCS

Carbon capture and sequestration, much like solar power, fuel cells, and hydrogen power, offers few prospects for investors concerned about near-term cash flows and earnings. Investors with longer time horizons, however, may find it opportune to enter a sector that is likely to experience very rapid growth over the coming decade.

We recommend that investors focus on technological potential as they scrutinize companies active in CCS. Some aspects of the capture-and-sequestration process, such as capture at power plants and monitoring of sequestration sites, are likely to see considerable technological advance. Other aspects, such as transportation of concentrated carbon dioxide in pipelines, are already well understood, and may offer little opportunity for further proprietary innovations.

Below, we highlight the strategies being followed by some of the companies actively engaged in research and development related to CCS. In most instances, companies appear to be concentrating on one or another part of the process:



European Capital Goods Equity Research

Andreas Willi

(44 20) 7325 4835
andreas.p.willi@jpmorgan.com

US Integrated Oils and Refiners Equity Research

Katherine Lucas, CFA

(1-212) 622-6451
katherine.a.lucas@jpmorgan.com

US Chemicals Equity Research

Jeff Zekauskas

(1-212) 622-6644
jeffrey.zekauskas@jpmorgan.com

Carbon capture

Alstom

Alstom is developing a process that uses chilled ammonia to capture CO₂ in the post-combustion stage. This process dramatically reduces the energy required to capture and isolate carbon dioxide. In laboratory testing sponsored by the US Electric Power Research Institute and others, Alstom's process has demonstrated the potential to capture over 90% of CO₂ at a cost far below that of other technologies. Alstom believes that the main advantage of its process is that it can be used to retrofit existing coal-fired plants as well as in construction of new plants.

Alstom signed an agreement with the US utility AEP to jointly develop a full scale commercial carbon capture project of up to 200 megawatts by 2011. The project will be implemented in two phases. In phase one, Alstom and AEP will jointly develop a "validation plant" that will capture up to 100,000 tons of CO₂ per year from flue gas emitted from AEP's 1300 mW Mountaineer Plant in New Haven, West Virginia. The captured CO₂ will be sequestered in deep saline aquifers at the site. This pilot is scheduled for start-up at the end of 2008 and will operate for approximately 12-18 months. In phase two, Alstom will design, construct, and commission a commercial-scale CO₂ capture system on one of the 450 mW coal-fired units at AEP's Northeastern Station in Oologah, Oklahoma. The system, scheduled for start-up in late 2011, is expected to capture about 1.5 million metric tons of CO₂ a year, commercially validating the technology. The captured CO₂ will be used for enhanced oil recovery.

Alstom is also active in oxygen-fuel combustion in conjunction with US Department of Energy research. After pilot tests at a 3 megawatt pilot plant in Connecticut, the company is now building a 30 megawatt validation plant together with Vattenfall, a generator, in Germany, and is developing a conceptual design for retrofitting an 80 mW coal-fired boiler for oxygen-fuel firing. If built, this would be the first commercial demonstration plant of its kind in North America. According to the company, its main research in this field involves combustion efficiency, heat transfer, boiler design, and environmental equipment.

ConocoPhillips

ConocoPhillips has a gasification technology called E-Gas intended for use in IGCC plants. The technology uses pet coke, coal, and other low-value hydrocarbons to make a synthetic gas consisting mainly of hydrogen, carbon monoxide, and carbon dioxide, with lesser proportions of water, nitrogen, methane, hydrogen sulfide, and carbonyl sulfide. The CO₂ and hydrogen sulfide are then separated in a removal system using a chemical solvent, methyldiethanolamine. The remaining gas can then be used to power turbines, while the hydrogen sulfide is turned into sulfur for sale. The carbon dioxide, which represents about 20% of the volume of the synthetic gas, can be compressed and piped to a sequestration site. ConocoPhillips is seeking to license this technology, but at this point it represents a very small portion of company's business portfolio.

Eastman Chemical

Eastman has been involved in coal gasification technologies since 1983, when it opened the first US commercial coal gasification facility in Kingsport, TN. A subsidiary, Eastman Gasification Services, specializes in development of coal-gas technologies. Eastman committed the greater part of its \$43 million in 2006 research

and development spending to develop its gasification operations. Eastman has not focused on the power generation sector as a market for its technology, although its expertise in design of gasification and capture systems may be relevant for power plants designed for carbon capture and sequestration.

Eastman's main interest in gasification involves harnessing byproducts other than CO₂ for use in downstream petrochemical applications. The company sees the value in supplying CO₂ for enhanced oil recovery in the US Gulf Coast region as minor compared to that of other coal gasification byproducts produced at Kingsport. The company is currently seeking a joint-venture partner to redevelop an existing ethylene cracker in Longview, TX into a gasification unit that would produce propylene feedstock for production of oxo-alcohols and solvents; the unit could readily be adapted to capture CO₂ for sequestration in Gulf Coast oilfields. The facility is expected to come on line in 2011.

Small/Mid Cap Diversified Industrials

Curt Woodworth, CFA
(1-212) 622-6641
curtis.r.woodworth@jpmorgan.com

Fluor

Fluor's Economine process, originally patented in the 1960s, uses a monoethanolamine solvent to capture the carbon dioxide from flue gas. To date, the process has been used mainly in conjunction with natural-gas combustion, although there have been some trials with flue gas derived from coal. Fluor is involved in design and construction of the BP refinery project in Carson, CA, which incorporates carbon capture and sequestration. The latest version of its technology, Economine FG Plus, is being considered for a gas-fired combined heat-and-power plant being built by Statoil in Mongstad, Norway, at which 85% of the CO₂ emissions are to be captured and sequestered.

Electrical Equipment and Multi-Industry Equity Research

Steve Tusa
(1-212) 622-6623
stephen.tusa@jpmorgan.com

General Electric

GE is making big investments in carbon capture and sequestration, which it views as a game-changing technology. GE sees pre-combustion capture through IGCC as the biggest opportunity, potentially bringing it \$75 billion of revenue in the 2010-2020 period. Although IGCC plants now bear a 20-25% capital-cost disadvantage compared with traditional pulverized coal, GE expects that situation to reverse as the cost of IGCC technology falls and as the addition of post-combustion capture raises the cost of pulverized coal plants.

For General Electric, IGCC holds two main attractions. First, it enables the company to capture a larger share of power-plant content: some 40% of the value of an IGCC plant is made up of products that GE sells (steam turbine, generator, gas turbine, gasification island), versus only 5% of the value of a pulverized coal plant (steam turbine, generator). Second, GE anticipates rapid advances in standardization, which are expected to drive costs down. Since 2004, when it acquired the enabling gasification technology from Chevron, GE has collaborated with Bechtel to develop a standard design for commercial-scale IGCC plants. If demand shifts in favor of IGCC, we think GE will easily be able to top its record sale of 350 gas turbines in a single year, recorded in 2001. This figure would represent a doubling of the 175 units expected to be sold in 2007.

GE is heavily involved with the integration of IGCC into refineries. It is working with BP and Edison Mission Energy to convert petroleum coke from a refinery in Carson, California, into electricity in a 500 megawatt plant, with the captured CO₂ to be used for enhanced oil recovery. It is proposing to more than double the size of a 260 megawatt IGCC plant in Florida that opened in 1996, and we expect it to bid on

two IGCC commercial demonstration plants that TXU proposed to build in Texas. Last year, it established a clean coal research center in Poland, providing a base for marketing its IGCC technology across Europe.

General Electric expanded its presence in post-combustion separation technologies through the 2004 acquisition of BHA Group, which makes filtration membranes and parts for air pollution control systems. However, it appears to view post-combustion capture as a business with much less potential than pre-combustion capture with IGCC.

Electrical Equipment and Multi-Industry Equity Research

Steve Tusa
(1-212) 622-6623
stephen.tusa@jpmorgan.com

US Chemicals Equity Research

Jeff Zekauskas
(1-212) 622-6644
jeffrey.zekauskas@jpmorgan.com

Construction and Engineering Equity Research

Scott Levine
(1-212) 622-5609
scott.j.levine@jpmorgan.com

European Capital Goods Equity Research

Andreas Willi
(44 20) 7325 4835
andreas.p.willi@jpmorgan.com

Honeywell

Honeywell's UOP subsidiary, whose principal customers are in the oil refining industry, has a small US Department of Energy contract to develop a metal-based process to remove carbon dioxide from flue gas for post-combustion capture. Honeywell also owns the rights to a solvent called Selexol, made of a dimethyl ether of polyethylene glycol, which is used to remove CO₂ in the process of purifying hydrogen for use in fertilizers and refining. The process appears to lend itself to carbon capture for environmental purposes, although it is not presently being employed in that way.

Praxair

Praxair is moving aggressively into carbon capture and sequestration, as it believes that some carbon-capture technologies are closely related to its core competence in industrial combustion processes. The company is involved in all three methods of carbon capture, pre-combustion capture, oxygen-fuel combustion, and flue-gas separation. It appears to be focusing on membrane-based technologies for pre-combustion capture in IGCC plants and for oxygen separation in coal-fired plants using oxygen-fuel combustion. Praxair is also seeking to develop carbon-capture systems for industrial facilities outside the power sector in the expectation that other industries will be subject to carbon emissions controls in the future.

Praxair is currently a major supplier of CO₂ for industrial uses and for enhanced oil recovery. This business eventually may be hurt by the ample supplies of CO₂ likely to come from generating plants, but we view this as a long-term issue in the US.

ShawGroup

Shaw, an engineering and construction company that emphasizes both the electric generation and chemical manufacturing sectors, seems to us likely to take an important role in development of the CCS market. We note that the company has recently been involved in new power plant projects incorporating clean coal technologies, including the use of circulating fluidized bed boilers. Shaw also has expertise recovering greenhouse gases such as methane at landfills.

Siemens

Siemens is emphasizing IGCC technology that could eventually be used with pre-combustion capture, and is not involved in post-combustion capture. Its biggest IGCC venture is a 1000 megawatt coal gasification plant in Spreetal, Germany, to be completed by 2009 at a cost of €1 billion. Siemens acquired the technology and engineering activities of Sustec Group in May 2006, enabling it to expand in coal gasification. Sustec has received several recent orders for large gasification plants, suggesting that its GSP entrained flow gasification technology is becoming viable.

In the United States, Siemens is involved with a US Department of Energy program to develop and design a fuel-flexible advanced gas turbine as part of a capture-ready IGCC plant to be built starting in 2011-12. The company estimates the current cost of an IGCC plant at around €1,300 (\$1,800) per kW, with fairly low 40% thermal efficiency even before the efficiency loss from carbon capture is factored in. The project aims to develop an IGCC plant that would cost no more than \$1,000 per kW to build (in 2002 dollars), and that could capture 85-90% of carbon dioxide emissions without large efficiency losses.

Construction and Engineering Equity Research

Scott Levine
(1-212) 622-5609
scott.j.levine@jpmorgan.com



Oil Services & Equipment Equity Research

Kevin G. Pollard, CFA
(1-214) 965-3624
kevin.g.pollard@jpmorgan.com

Oil Services and Equipment Equity Research

Michael LaMotte
(1-214) 965-3623
michael.lamotte@jpmorgan.com



US Integrated Oils and Refiners Equity Research

Katherine Lucas, CFA
(1-212) 622-6451
katherine.a.lucas@jpmorgan.com

Washington Group

Washington Group, a US engineering and construction company with a large business in the power industry, recently formed an internal “skunkworks” within its power group to explore the ways in which CCS will impact its markets and to monitor the evolution of technology. The company has not said how it will participate from a technological standpoint, although we believe it is realistic to expect Washington Group to be involved in the engineering of clean-coal plants with a CCS component. The company expects a commercial CCS market to evolve over the next three to five years.

Transport

Dresser-Rand

Dresser-Rand specializes in compressors for the energy industry. All potential methods of carbon capture and sequestration require compressing the gas prior to pipeline transportation, continued compression while in the pipeline, and compression during the process of underground injection, whether into an oilfield or another geologic structure. Increased use of CCS would be a positive for Dresser-Rand, which already makes a range of products specifically designed to handle CO₂. The company’s leading competitors in compression equipment, General Electric and Siemens, often bundle compression with turbines and other products that Dresser-Rand does not make, which may put them in a better position to gain early sales. We expect Dresser-Rand to promote the greater efficiency of its compressors as a reason for purchasing compression separately.

National Oilwell Varco

We think increased use of carbon sequestration would be positive for providers of oilfield equipment used to transport and inject CO₂. One company that would seem well positioned is National Oilwell Varco, which makes fiberglass pipe and thermoplastic coating for the transport of CO₂.

Sequestration

Chevron

As a major oil producer, Chevron has used CO₂ for enhanced oil recovery at its Rangely field in Colorado since 1986. Chevron transports CO₂ emitted from operations at a nearby natural gas processing facility to the oil field and injects it into the formation, improving oil recovery while simultaneously sequestering CO₂ that otherwise would be emitted into the atmosphere.

Carbon sequestration may also play a major role at the Gorgon liquefied natural gas project in Western Australia, in which Chevron has a 50% interest. Although Australia presently has no regulations concerning CO₂ emissions, Chevron sought to

moderate opposition to its project by proposing to capture carbon dioxide brought to the surface along with natural gas and reinject it into a saline aquifer. In contrast to the Rangely project, sequestration at Gorgon would be undertaken entirely for environmental reasons and would not enhance hydrocarbon recovery. If Gorgon opens as planned early in the coming decade, it would be one of the largest carbon sequestration projects in the world. The project includes a significant subsurface monitoring component that could provide useful information for future sequestration efforts.

Chevron says its major research conclusion so far is that sequestration involves site-specific problems related to underground geology at particular locations. The company currently sees no appreciable earnings contribution from its carbon sequestration activities, observing that “we are in the early stages.”

Independent Exploration and Production Equity Research

Joseph D. Allman, CFA
(1-713) 216-6503
joseph.d.allman@jpmorgan.com

Denbury Resources

Denbury is an independent oil producer that specializes in enhancing recovery from mature oil fields with CO₂ injection. The company controls the only known large natural source of CO₂ east of the Mississippi, as well as a CO₂ pipeline system centered on its CO₂ source. Under present conditions, CO₂ is actually a scarce resource in key oil production areas. We estimate that Denbury can deliver compressed CO₂ from its own source to its oil fields for \$0.25 per thousand cubic feet, far below recent contract prices of \$0.45-\$1.00 per thousand cubic feet. This gives Denbury a significant cost advantage in oil production.

Most of the power plants near Denbury’s key Mississippi oil fields are gas-fired, and even if coal plants begin to capture carbon at some point in the next decade, it may not be cost-effective to deliver it to Mississippi for sequestration. We think that this will preserve Denbury’s business model for many years to come. Carbon dioxide from power plants is more likely to become available near Denbury’s fields in Texas. As this occurs, we think the company’s extensive experience injecting carbon dioxide for enhanced oil recovery will enable it to take advantage of the supplies, and also to build a cash-generating business from sequestration.

Electrical Equipment and Multi-Industry Equity Research

Steve Tusa
(1-212) 622-6623
stephen.tusa@jpmorgan.com

Emerson Electric

Emerson provided controls and process management for an EOR project at Weyburn, Saskatchewan, including systems to operate two compressors used to inject CO₂ into the field. The company expects to participate in carbon capture as part of its extensive activities in the power-generation sector, but notes that the business is not likely to become commercially viable for some time.

Oil Services and Equipment Equity Research

Michael LaMotte
(1-214) 965-3623
michael.lamotte@jpmorgan.com

Halliburton

Using depleted oilfields for CO₂ sequestration would require drilling of injection wells, and thus involve all oilfield service names. We think Halliburton would benefit from this potential market as it is already a leader in EOR project management and has a considerable suite of capabilities.

US Integrated Oils and Refiners Equity Research

Katherine Lucas, CFA
(1-212) 622-6451
katherine.a.lucas@jpmorgan.com

Occidental Petroleum

We believe that Occidental, like its peers, is interested in carbon sequestration primarily because of its ability to use captured CO₂ to enhance oil recovery in mature reservoirs. The ability to charge utilities for sequestering carbon would provide an incremental earnings contribution. Occidental is a world leader in the application of carbon-dioxide flood technology, using it extensively in the Permian Basin, which is

full of mature, long-exploited fields. Nearly half of Occidental's Permian production is from wells that use CO₂ flooding. Occidental also may be involved in the sequestration element of the proposed 500 megawatt hydrogen-fired power venture between BP and Edison Mission Energy in Carson, California. Technical studies are underway to determine which of Occidental's California oil fields would most benefit from flooding with the CO₂ to be captured at the Carson plant.

Oil Services and Equipment Equity Research

Michael LaMotte
(1-214) 965-3623
michael.lamotte@jpmorgan.com

Schlumberger

Among the oilfield service companies, Schlumberger seems to be most aggressive in developing the market for carbon sequestration. Schlumberger is part of an advanced project in Europe that is looking into the physics of mineralizing CO₂. This will be important when carbon dioxide is stored in some types of geologic structures, because the carbon dioxide can mix with water to create carbonic acid, which in turn can weaken the rock. Thus, technology needs to be developed that effectively seals the CO₂ inside a well or changes its physical properties to prevent a toxic environment. Schlumberger also is participating in Stanford University's Global Client and Energy Project, which is beginning to look into underground CO₂ sequestration capabilities. We believe Schlumberger, like Halliburton, has the subsurface skills and technologies to be a major player in the carbon sequestration market.

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Marc Levinson
(1-212) 622-5552
marc.levinson@jpmorgan.com

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