Carbon Capture & Storage Handbook

Coal's Salvation Under Strict Regulatory Regimes

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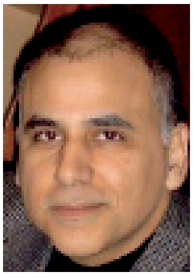
CCS: Enabling coal to compete in the low-carbon future

Government funding and a demanding public are forcing electric-power producers to reduce their reliance on fossil fuels and increase renewable-energy development. The hardest hit of the traditional generation resources in the current landscape is coal. While it is becoming increasingly clear that coal will not play as dominant a role in developed nations as it has in the past, baseload coal-fired generation is far from dead.

As Jason Makansi points out on page after page of this special report, proven technologies exist to elevate coal from its current status as the "powerplant energy source of last resort." The only question: Which of the clean-coal technologies profiled here can be implemented cost-effectively, and at the scale necessary, to compete with alternative energy resources.


Makansi

Makansi is president of Pearl Street Inc, a St. Louis-based consultancy specializing in technology deployment across the electricity value chain: fuels, generation, storage, transmission, distribution, and customer services. A chemical engineer by education, he has been closely involved with the electric-power industry for three decades and is considered an expert in emissions control technologies by his peers.

Makansi's goals in writing the *Carbon Capture & Storage Handbook*] were the following: (1) Offer a realistic assessment of the state of the coal-fired generation sector of the industry; (2) review the status of viable technologies for reducing the presence of CO_2 in the atmosphere, and (3) provide a backgrounder on the regulatory and legal challenges to the development of utility-scale CCS.

About one-third of the report focuses on the leading CO_2 capture technologies and projects of greatest relevance. The technologies are classified in three ways: Post-combustion processes, pre-combustion processes—virtually all of which involve a gasification step, and oxygen-fired combustion. Carbon capture is the most expensive portion of the CCS scheme (about three-quarters of the cost); it can increase a powerplant's footprint by up to 60%.

Thumbnail sketches are provided for nine CCS projects focused on commercial-scale operations. Names for about half the projects probably came from marketers; examples include GreenGen, FutureGen, NowGen, Trailblazer. The others are known simply by the names of the plants where they are installed: Mountaineer, Ferrybridge, Belchatow.

Think positively as you read this report. Consider CCS just one more technology the industry must develop to meet the needs of a changing world. Most likely, it will prove no more challenging to implement than pollution control systems for coal-fired plants were 30 years ago. You may recall that back then regulatory limits on particulate, SO_2, and NO_x emissions were considered by some as "impossible" to attain.

Kevin Geraghty, VP of generation for NV Energy, Las Vegas, summed up the task well at a recent industry meeting. "There has never been a time in this industry when there wasn't change," he said. The challenge is to embrace change and accomplish the specified goals with minimum cost impact while maintaining service quality and making electricity production and delivery cleaner and safer. Tall order, he acknowledged, but the engineering community is equal to the task.

Coal's Salvation Under Strict Regulatory Regimes

By **Jason Makansi,** President
Pearl Street, Inc

Introduction

Ever hear of the computer game, *SimCity*, and related games like *SimEarth*? In a fictitious version called *SimElectric*, imagine the goal is to build electricity infrastructure with a 50-year planning horizon optimized for low carbon intensity to reduce global warming impacts. One key assumption will be that half the vehicles in this fictitious world will be assumed to be electric-driven.

Three primary options for providing the electricity are:

1. Wind, hydro, solar renewable energy facilities, integrated with electric energy storage facilities to solve the variability of supply issue.
2. Nuclear powerplants with long-term spent fuel rod storage/management and integrated with fuel reprocessing plants.
3. Highly efficient gas and coal-fired powerplants with carbon dioxide capture and sequestration in underground geologic formations.

Each of these options comes framed in an exceedingly complicated matrix of technical, economic, environmental, political, and social attributes, benefits, and risks. Yet broadly, this is what the development, scale-up, and commercialization of carbon capture and storage (CCS) technologies competes against.

Keep this *SimElectric* exercise in mind as we review the status of CCS worldwide.

Stripped and bottled

CCS refers to a three-step process of removing CO_2 from fossil-fired powerplant flue gas or fuel gas (when gasification is involved), compressing the CO_2 and transporting it to a storage site, and injecting the gas into a geologic cavity for many years, then continuously monitoring the site for leakage, integrity, permeability, groundwater intrusion, etc.

While natural-gas fired gas turbine/generators and combined cycle (CCGT) plants also discharge voluminous quantities of CO_2, peaking gas turbines don't run very often and CCGT facilities discharge about half the CO_2 of an equivalent coal plant. For the most part, then, the focus for CCS is its application to coal-fired powerplants, which are generally base-loaded, and, except for nuclear plants, have much higher capacity factors than other types of powerplants.

Most experts concede that under moderate to strict regulations for carbon – such as carbon cap and trade programs or carbon taxes, CCS is coal's only salvation for the long haul, the fifty-year planning horizon mentioned above.

There is no other practical solution for dealing with the huge volumes of CO_2 discharged from fossil-fired powerplants. When you consider that one half to two thirds of the world's people get more than half of their electricity from coal, natural gas, and oil, you would hope that the development of CCS technologies would be a global priority.

On top of that, the world's appetite for electricity consumption continues to grow at 2-3% per annum, faster in the developing countries like India and China. If electric vehicles become widespread in the developed countries, this rate could increase significantly.

Power generation typically is responsible for one-third of the world's carbon intensity, transportation one-third, and industry, manufacturing, and households one-third. So make no mistake. CCS is part and parcel of the world's ability to generate electricity economically. All indications are that dealing with global warming will be the burden of the electricity business, more so if electric vehicles become part of the "solution" and replace petroleum-based transportation.

One expert at a recent CCS industry conference put it this way: Owner/operators of industrial and manufacturing facilities, also significant emitters of CO_2, can leave for countries where carbon regulations are less onerous; powerplants can't leave.

Come together

Reading newspapers isn't good for your health if you are a proponent of coal and are working to see that CCS technologies will keep coal competitive for decades to come. Coal doesn't fare well in the press. Beyond the headlines, though, are some positive stories for CCS.

Because global warming is, well, a global problem, one hopes that sustaining a place for coal in electricity production would have global cooperation. Indeed, governments in coal-rich countries with demanding energy use per capita and large numbers of potential storage sites are cooperating on CCS.

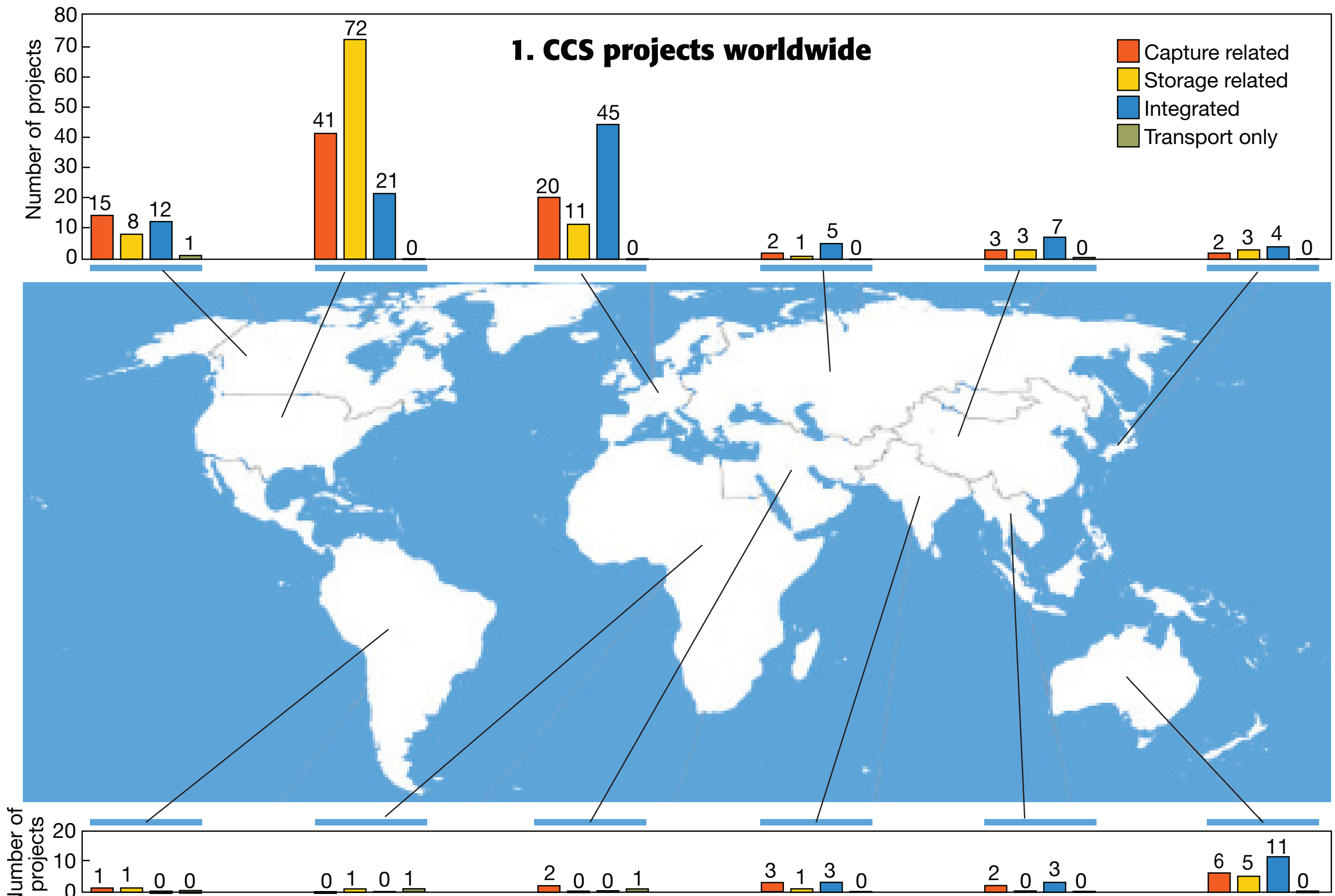
These countries include the U.S., Canada, U.K., Germany, and Australia. Countries like China and India, with vast indigenous coal reserves and explosive economic growth, are also participating in cooperative activities. It might be a stretch to say that CCS has become a *priority*. But at least there is cooperation at the policy and technical levels.

Many of these countries view CCS technology development both for application to domestic powerplants and as an export opportunity. As long as intellectual property rights are not compromised, governments are willing to assist the CCS sector in the name of economic development and global warming solutions.

Indeed, billions are already being poured in, although much more is arguably needed to meet the aggressive timetables. One analysis records more than 100 CCS projects being pursued worldwide, nine in operation, representing US\$26-billion in government support (Fig 1).

Considering that the world spends US\$8-billion annually on climate research which mostly implicates coal in electricity production, this seems to be a fair amount to spend on a sector that could go a long way towards mitigating the problem.

In June 2008, energy ministers from the G8 countries agreed to launch 20 large-



Source: International Energy Agency

Over 100 integrated CCS projects are active worldwide, with at least 200 projects demonstrating capture technology or storage processes

scale projects by 2010, and in December that same year, the EU agreed to fund 10-12 demonstration projects though none in countries outside the Union.

China needed. Without China on board applying CCS in a big way, the significance of the global effort is diminished. This year, China surpassed the U.S. in electricity consumption and, at 24% of the world's total, recently became the largest source of CO_2 into the atmosphere. Interestingly, one third of China's emissions are embedded in the nation's exports to other countries, so consumers worldwide are responsible for the externalities that remain when goods are produced inexpensively for the global market.

While the U.S., Japan, and Australia are providing equity support of projects in China, the official Chinese policy is that the developed countries must take the lead in demonstrating the technology as well as provide a "framework of incentives" for action in developing countries. In the meantime, China has undertaken a massive nuclear plant construction program, is the world's largest supplier of solar photovoltaic system components, and has embarked on an ambitious wind energy installation program as well.

EU paces. With only 12% of the world's total carbon emissions, the European Union nevertheless has most of the elements in place for robust CCS development, including carbon legislation in many countries, an EU-wide carbon trading market, companies with leading CCS technologies, initial legal and regulatory frameworks, and funded CCS programs. The EU also appears more willing to at least consider financing demonstration projects in developing countries like China.

It works now!

Perhaps the biggest myth to dispel is that CCS is a huge technology development challenge. In fact, CO_2 stripping from flue gas, CO_2 pipelining and transport, and CO_2 storage in underground formations have all been demonstrated at myriad locations around the world. The question isn't, "Can we do it?" The question is, "Can we do it at scale and compete with the other broad options for electricity generating infrastructure?"

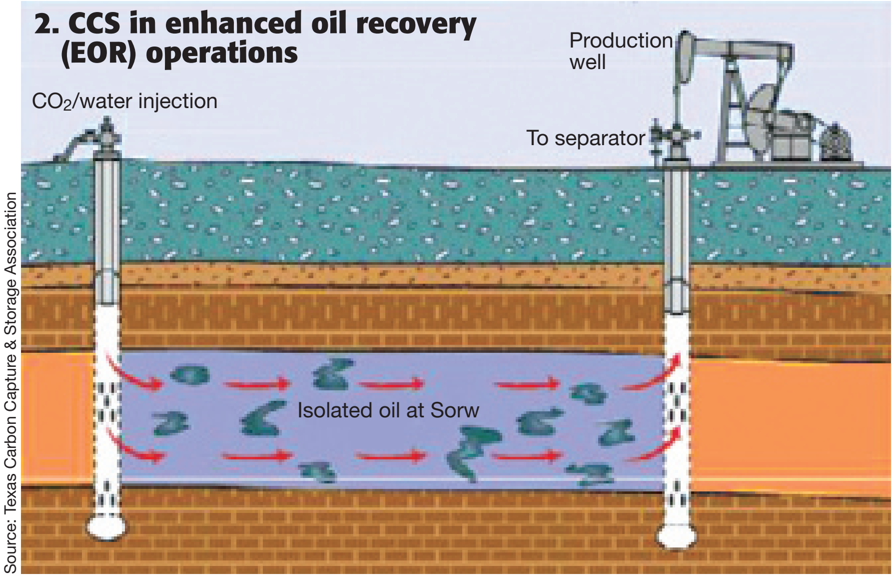
The attention of industry, government, and the public, and their funds, is needed to scale up from a 1000 ton/day CCS facility to a 10,000 ton/day capability. Accompanying that must be building confidence that the storage sites will remain sealed and safe forever or at least until a future species needs CO_2 instead of natural gas, petroleum, or salt.

Another positive development is that the timeline for having a suite of CCS technologies ready for deployment hasn't shifted. Often in these government-driven broad technology development programs, commercialization dates drift into the future.

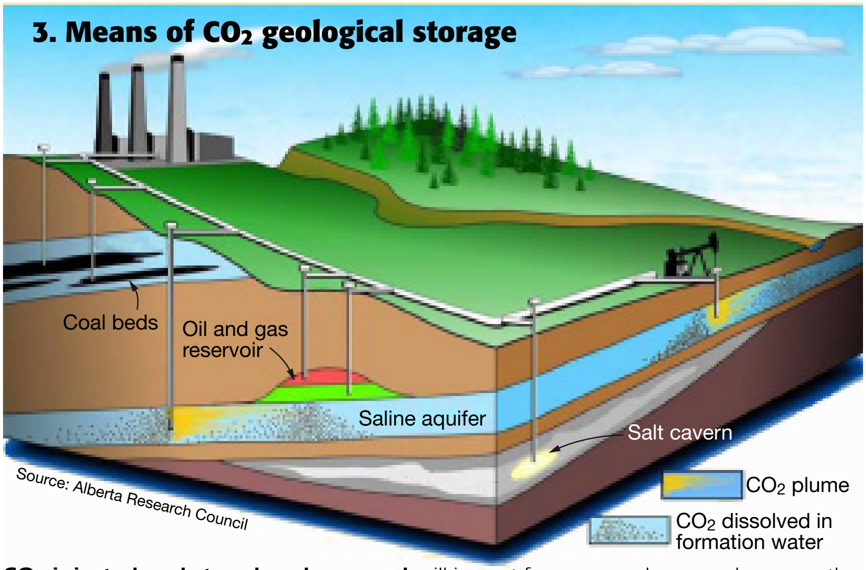
In the case of CCS, experts were saying five years ago that these technologies should be ready (at scale) by 2020 and experts appear still to be sticking to that date. Moreover, the sector appears to be comfortably transitioning from the pilot-plant state into large demonstrations with few disruptions.

One thing known for sure is that there's plenty of space to put this stuff. The worldwide volume of potential sites far exceeds projected discharges of CO_2, based on early estimates. Like all resources, the sites are not necessarily convenient to the CO_2 sources, but matching them up will be a matter of cost, not availability. Researchers worldwide are now providing more granularity to the total volumes available.

One of the places you can beneficially



CO_2 has commodity value in EOR operations, although the total volumes requiring permanent storage would quickly overwhelm this "recycling" market



CO_2 injected and stored underground will impact far more underground acreage than implied by the facilities located at the surface

use CO_2 in large quantities is in enhanced oil recovery (EOR). The Permian basin in Texas has been practicing what is known as CO_2 flooding for many years. In fact, large economical sources of CO_2 could open up EOR markets in many other places.

While powerplant CCS volumes would quickly overwhelm the market, the EOR industry is thought to be an early adopter and an excellent means for the CCS industry to gain a commercial foothold at scale (Fig 2). Tying CCS to EOR becomes an element of energy independence in countries where this is important politically.

Finally, the widespread deployment of CCS technologies is an economic development opportunity. According to one report, it would create around 800,000 permanent jobs in the U.S. alone, for manufacturing components and systems, operating CCS facilities, and managing and securing storage sites.

Add this to the jobs necessary for mining coal and running coal-fired powerplants and it becomes clear that, compared to, say, wind energy, turning coal into electricity with low carbon intensity employs lots of workers. Once you build and install a wind turbine, there's not much left to do.

In later sections of this report, half a dozen CCS projects from around the world, many with international cooperation, illustrate the impressive progress the sector has made in recent years.

Hearts and minds

To grasp the challenges confronting CCS, first understand what confronts coal-fired power in the context of our three *SimElectric* options. The majority of people today in developed countries, it seems, especially those who are privileged to vote, prefer renewable energy.

That may not be the case when millions of wind turbines and solar collector plates crowd the countryside, instead of the tens of thousands you see today. But for the most part, in the minds of the public, renewable energy facilities may be aesthetic nuisances, kill a few birds and bats, create weird strobe effects during sunrise and sunset, but they don't ravage the planet.

Extracting and mining coal involves considerable effort and expense, with negative environmental externalities (groundwater issues, for example) that are not included in the cost equation. However, mining companies have admirably demonstrated that mining sites can eventually be reclaimed and restored as if nothing occurred. One formidable challenge with CCS in winning hearts and minds is that sequestration sites must be managed and monitored *forever*. Nothing may have changed on the surface, but down below is a whole different story (Fig 3).

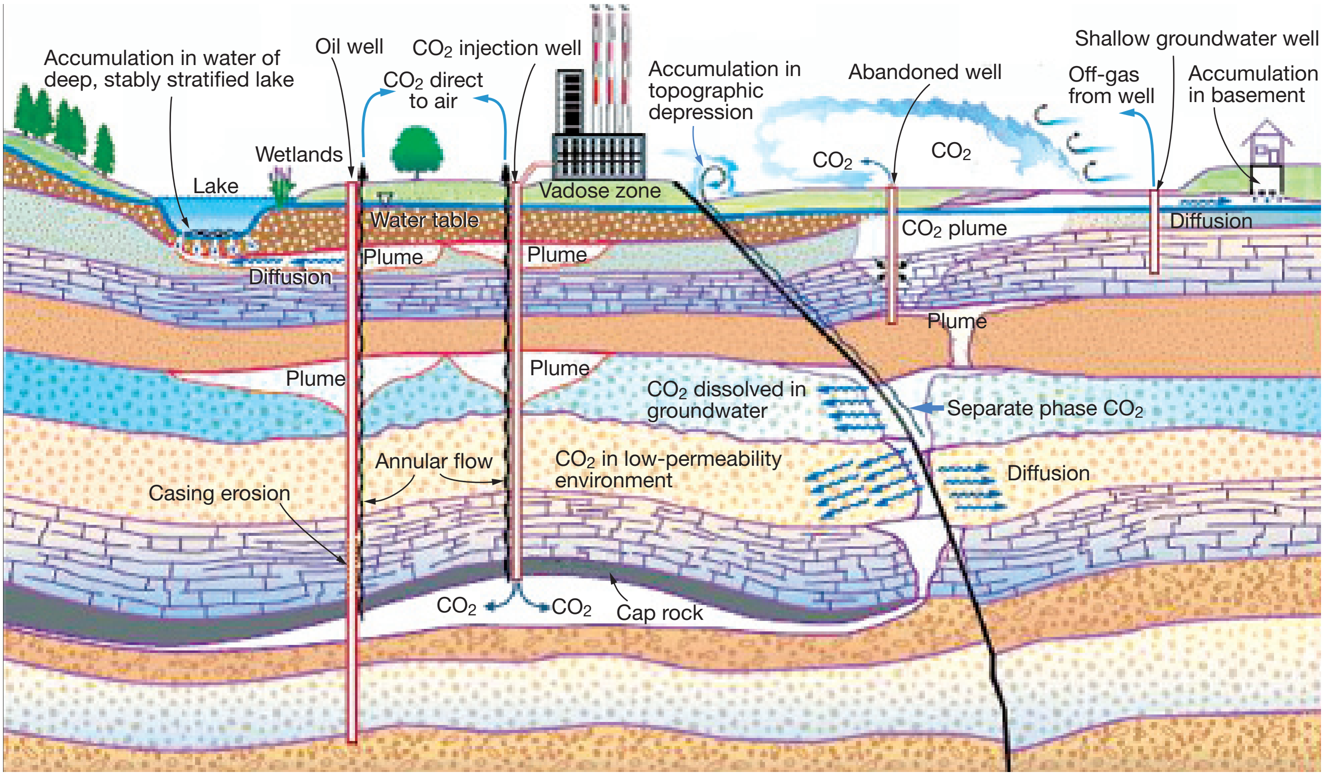
The geologic cavities targeted for CO_2 injection once were salt mines, oil and natural gas sources, aquifers, or even abandoned coal mines. With sequestration, they become repositories for the same stuff that comes out of fire extinguishers, a pressurized fluid that is heavier than air and can suffocate a population during a catastrophic leakage event, or re-enter the atmosphere under slow leakage.

To continue using coal under strict carbon regimes, people must accept that a naturally occurring underground formation will be filled with a man-made discharge stored at high pressures. People must accept that these volumes of gas will remain there to eternity, and do no harm to people, the ecology, or groundwater supplies.

You can argue that nuclear fuel also has to be mined and then the wastes managed forever. But the energy density of enriched Uranium is orders of magnitude higher than coal; therefore the total volume of waste, a solid by the way, is negligible by comparison. Far more dangerous, perhaps, but small enough that one big cavern in a remote corner of Nevada will take care of all the needs of a country like the United States for decades. And the alternative, nuclear fuel reprocessing, extends the life of the fuel rods and postpones the waste management volume issue. There is no similar such "recycling" or reprocessing of carbon dioxide.

As if that's not enough, coal already faces what the head of a U.S. electricity industry trade association called the "environmental gauntlet." Environmental restrictions – air, water, and solid waste - around coal

4. Geological challenges facing CCS projects



Underground geological structures are complicated and the movement of CO_2 may not be as predictable as desired

use are even tougher in places like Japan and Europe. Carbon regulations make a difficult situation, growing the use of coal, seemingly impossible.

And then there are those new environmental issues that people haven't given much thought to. The carbon capture processes at a powerplant could double water consumption at a time when powerplants are already under threat for discharges from once-through cooling systems, water use restrictions, and added costs for cooling towers or air-cooled condensers. And the most prevalent capture process, used for decades, involves amines as the solvent. Newer processes use ammonia.

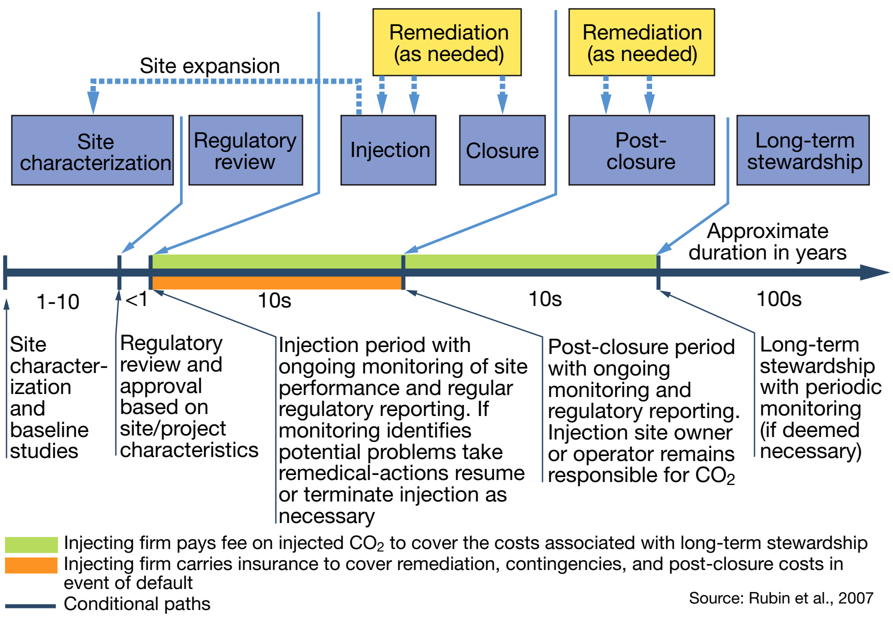
Both are toxic. At large scale, the potential for amines and ammonia to escape and cause problems in the environment only grows. One obscure blog report noted that a high profile CCS program in Scandinavia was postponed because the country's Prime Minister didn't realize that amines were potentially unsafe.

The twin challenges that will be toughest to overcome are costs of carbon capture and the regulatory and legal frameworks around sequestration sites. Decarbonizing the planet is going to be costly regardless. Wind energy appears reasonable until you begin to factor in the cost to mitigate the intermittency problems and the impacts on grid operations. New nuclear units exhibit exorbitant capital costs, and those don't account for reprocessing, and take years to permit and build but they are carbon free and will run for up to 80 years with relatively low operating costs.

When coal plants are equipped with CCS, they are no longer an obvious low-cost option. Generally, CCS will add at least 25% to the cost of electricity, and reduce the efficiency of the plant, compared to non-CCS, by 25-40%, at least until the capture processes improve. Economic analyses show that per ton prices for carbon, either through cap and trade or taxes, need to be at least US$65 to make CCS economically competitive.

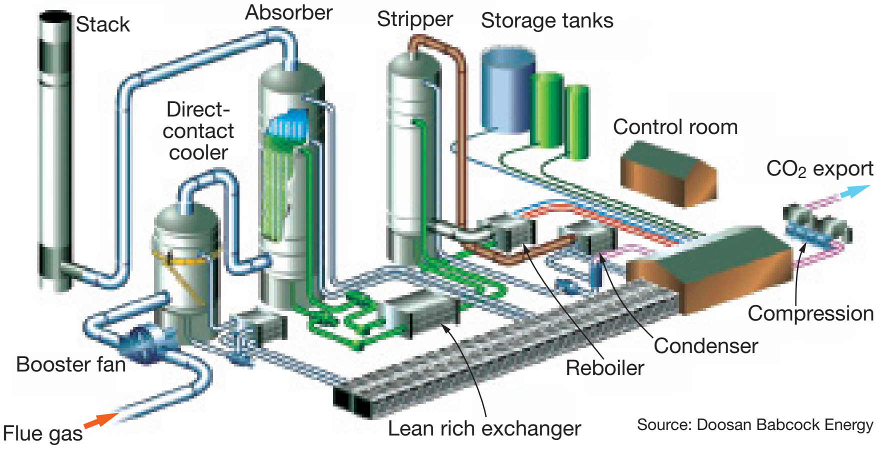
Adding yet another complicated emissions control unit to a powerplant also

5. Carbon storage site timeline



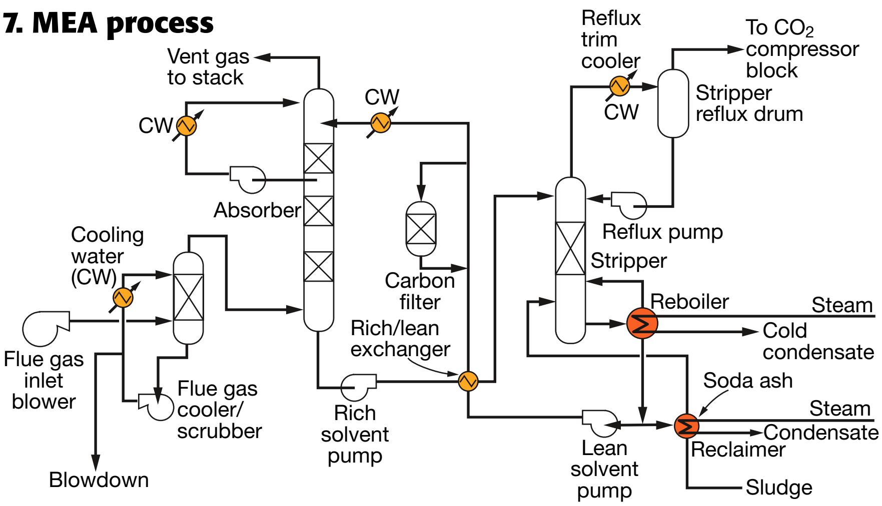
The time scales involved in opening, injecting, and closing a permanent carbon storage site are unlike any witnessed by industry, except perhaps the management of nuclear waste

6. Post-combustion carbon capture technology



The CO_2 stripping and solvent regeneration process is a common element of all CCS schemes, although there are many variations on the theme

7. MEA process



The MEA CO_2 stripping and solvent regen process has decades of experience behind it

destroys its operating flexibility. Modern powerplants already have a sulfur dioxide scrubber, selective catalytic reduction unit for NO_x removal, and other processes for hazardous air pollutants (HAPs) like mercury. It becomes difficult, for example, for a coal-fired unit to follow dispatch orders (which can be money-making functions in electricity markets) with so much baggage on the back end of the plant.

But the economic and operating issues pale in comparison to the risks and liabilities around the sequestration sites (Fig 4). In countries like China, the issue is less complicated. The state owns the land and so the state owns everything under the surface. In countries like the U.S., though, not only is property ownership private, but there can be separate owners of the rights to use the surface of the land and what's below, often called the mineral rights.

When carbon is injected and sequestered, however, it fills up all the available porous interstices far below the ground and migrates (plume movement) such that many land owners and rights holders could be affected. The regulatory issues are so complex, in fact, that they have forced vociferous private property and mineral rights advocates (such as extraction companies) into arguing that government take title to sequestered carbon (Fig 5).

As if that isn't complicated enough, the U.S. Environmental Protection Agency (EPA), in a ruling now sanctioned by the Supreme Court, has labeled carbon dioxide a "pollutant" hazardous to people. This means that sequestration sites can essentially be construed to be giant toxic dumps.

Main driver lacking

The one thing that could send the coal industry into a tailspin, oddly enough, is what will fundamentally support a robust CCS program in developed countries: a price tag on carbon. It's almost like medicine that makes you sicker before it ultimately cures you.

Unfortunately, the news here is grim. The failure to hammer out a meaningful international treaty on global climate change at the Copenhagen confab at the end of last year, combined with the inability of the U.S. Congress to pass an energy bill with substantial climate change provisions and unwillingness of China to take CCS seriously, leaves CCS with no primary market driving mechanism.

This likely means that accelerated funding from developed country governments is the only way to sustain progress in developing CCS technologies. Given that the world is only now emerging from a massive recession, one which affected the U.S. and the EU more profoundly than China or India, it is far from clear that additional money will be available, or that currently appropriated funds will even survive austerity programs and budget cuts.

Hedging your bets

Let's return to our *SimElectric* game. Deployment of nuclear and renewable energy facilities requires no carbon "solution," no additional technology to be developed comparable to what coal needs from CCS. In the developed countries, one could forecast that coal will effectively experience a "lost decade" at minimum while CCS gets developed and commercialized.

All indications are that China and India are going to build massive numbers of coal plants regardless of pleas from other governments. In this "balance of power," coal will likely increase its worldwide market share, as what the developing countries add will more than compensate for what the developed countries don't build or retire.

As a *SimElectric* player, how would you spend US$26-billion of the world's money currently allocated for CCS? Would you hedge on the future of coal with CCS? Would you double down on coal, knowing its history of providing consistently low-cost electricity? Would you accelerate the advancement of renewable energy? Would you spend it making sure the world's spent nuclear fuel rods are reprocessed and managed into eternity?

Perhaps the rest of this report will help you answer these questions.

CO_2 capture technologies

Generally, CO_2 capture technologies are classified in three ways: Post combustion processes; pre-combustion processes, virtually all of which involve a gasification process; and oxygen (oxy)-fired combustion. In the overall CCS scheme, capture is the most expensive element, taking up to 75% of the cost and adding up to 60% to the powerplant footprint.

Every option requires a CO_2 stripping and solvent regeneration process (Fig 6); the question becomes what else is done upstream to reduce the cost and complexity of the process. Thus, the core technological challenge with CCS is to scale up existing stripping and regeneration processes by an order of magnitude, no small feat, and squeeze cost out of the process.

Post-combustion technologies can be best understood as a downstream pollutant removal process, similar in objective to flue-gas desulfurization (FGD), selective catalytic reduction (SCR) for NO_x removal, and an electrostatic precipitator or fabric filter for flyash removal.

The essential challenges, from a process design perspective, are that the CO_2 is dilute, only 15% concentration; the CO_2 partial pressure is low, typically less than 0.15 atm; the flue gas temperature is relatively high; and other constituents in the flue gas hamper the removal of CO_2.

While fully commercial systems are offered for post-combustion removal, they are expensive and extremely parasitic. The energy penalty ranges from 25-37% for a coal-fired plant, 15-24% for a gas-fired plant. All of them have in common a gas-liquid contacting vessel called an absorber column. They are capable of delivering a relatively pure stream of carbon dioxide. In the case of EOR, that could be an asset. However, for sequestration, a relatively pure stream isn't necessary as long as the other constituents are not toxic in the environment.

Commercial processes are further distinguished between those that use physical solvents and those that use chemical solvents. In the physical category, the Selexol process employs a mixture of dimethyl ethers of polyethylene glycol; the Rectisol process employs chilled methanol.

For both, regeneration of the solvent requires energy, usually supplied as steam taken from the powerplant (and therefore not available to generate power). Another option for physical solvent is propylene carbonate. Since CO_2 adheres more weakly to this solvent compared to Selexol or Rectisol, the solvent can be regenerated with less energy.

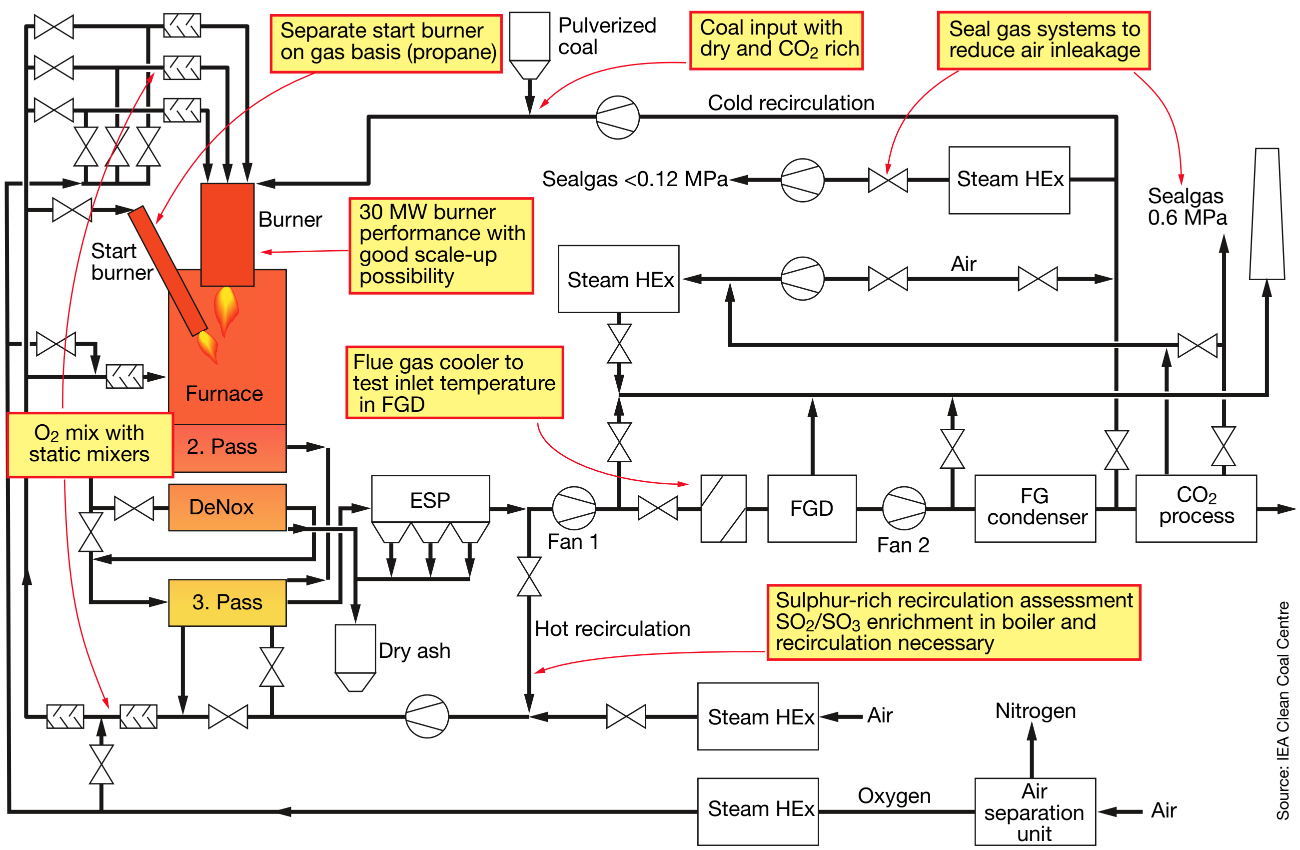
Commercial chemical solvent processes are all variations of an amine-based solvent, including mono-ethanol amine (MEA), di-ethanol amine (DEA), and methyl di-ethanol amine (MDEA), often with other compounds in the mixture that improve performance. Each of these solvents forms bonds with CO_2 of relative strength but all are considered weak bonds, which makes it easy to strip off the CO_2 in the regeneration step, usually by applying heat.

The MEA process (Fig 7) is over seven decades old. A chemical solvent process based on the conversion of carbonate (potassium) to bicarbonate in the presence of CO_2 significantly reduces energy consumption.

Another class of chemical solvent technologies involves the use of ammonia. In addition to its process features, ammonia handling and storage is familiar to modern powerplants because of its use in NO_x removal. Similar to the potassium carbonate process, ammonia carbonate reacts with CO_2 to form ammonia bicarbonate, which reportedly involves a lower heat of reaction, but can also react with other flue gas constituents to form fertilizer byproducts. One version of the process, called the chilled ammonia process (CAP), is getting traction in the U.S., as noted in the later section on projects.

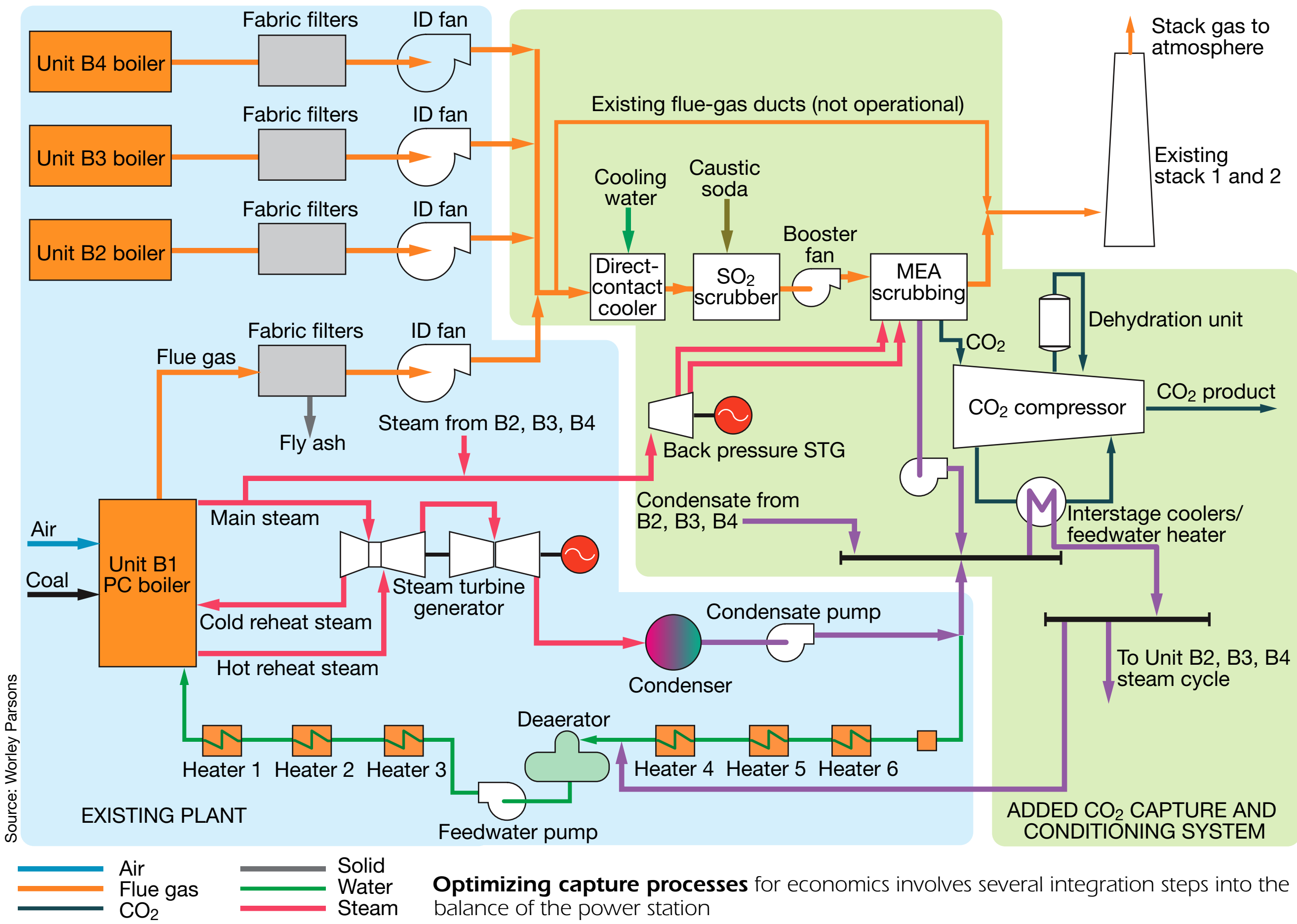
When considering post-combustion technologies, some perspective is in order. The first FGD processes applied at full scale to powerplants often involved parasitic power penalties of up to 10% of station output. Since then, process enhancements and better process energy management

8. Schematic of the Schwarze Pumpe pilot plant



Oxy-fuel combustion of pulverized coal is relatively simple in theory but does involve extensive modifications and additions to a basic power station

9. CO_2 capture retrofit



Optimizing capture processes for economics involves several integration steps into the balance of the power station

has reduced this to 1-2%. CO_2 capture processes under active development, and which can be considered close to commercial, can already reduce the penalty to 10-15%.

Pre-combustion removal processes are also widely demonstrated and used commercially because CO_2 and other impurities have been stripped out of gaseous fuels for decades. The essential advantage, compared to post combustion, is that the gasifiers operate at elevated pressures (500-1000 psig) so the CO_2 partial pressure is higher in the resulting fuel gas stream, and the CO_2 is not as dilute. This reduces the size and cost of process vessels.

Syngas from a coal gasifier generally contains hydrogen and carbon monoxide. The water-gas shift reaction (in which water and carbon monoxide react to form hydrogen and carbon dioxide) is employed upstream of the CO_2 stripping unit. Many of the processes described under post-combustion would be applied in different ways.

Although the removal of CO_2 is easier from an integrated-gasification combined cycle (IGCC), the rest of the scheme is far more complex than a traditional powerplant. Until the threat of carbon legislation became real, power companies were loath to make the transition to coal gasification because of the high capital costs and process complexity compared to the standard bearing pulverized-coal fired boiler with steam turbine/generator.

IGCC has been in earnest development for the worldwide power industry for at least three decades, yet commercial projects are few and far between. Now, as evidenced by our projects section, many new facilities planning to demonstrate CCS are based on IGCC.

Oxy-fuel combustion, the third CCS technology category, was originally conceived as a boiler retrofit strategy, but there's no reason why it couldn't be designed into a new powerplant. Instead of burning fuel with air in the furnace, an air separation plant is employed to produce oxygen (greater than 95% purity) for the combustion process.

Today's boilers typically are not designed to withstand the higher operating temperatures that would result under O_2 combustion, so the O_2 is diluted with recycled flue gas to keep combustion conditions similar. The process concentrates the CO_2 in the flue gas up to 90%. The air separation plant could require between 23-37% of the station power.

Pilot-scale oxy-fired combustion has been conducted in Europe on boilers up to 20-MW size. A side benefit is that NO_x emissions from the plant would be drastically reduced because air-fed combustion is so rich in nitrogen (a portion of the NO_x originates with the nitrogen in the fuel, however). One attraction of this oxy-fuel approach is that the powerplant remains familiar to owners and operators.

Flue-gas recirculation is practiced for NO_x control at many facilities so this aspect of the process is also well-known. In the original design, the entire boiler and gas handling equipment would all be smaller and less costly. On the other hand, flue gas recirculation also concentrates other pollutants, such as SO_2 and SO_3, and the footprint could increase by up to 150%. Flame stability in the burners may also be an issue.

Integrating oxy-fuel combustion into a new or existing powerplant involves substantial new equipment and process modifications (Fig 8), not the least of which would be the addition of the air separation plant.

From a practical standpoint, boiler suppliers are many years away from being able to guarantee the design and performance of an oxy-fuel boiler at scale suitable for CCS. Of the options available for carbon capture, this one has probably made the least progress over the last several years.

No clear winner. From an owner/operator perspective, it would be difficult to identify a preferred option from the ones described above. Electric utilities, responsible for the vast majority of powerplants around the world, are typically not innovators and even if they wanted to be, the regulatory process often precludes any appetite for technological risk. Imagine having an organization honed over decades, familiar with boilers and steam turbines, having to transition to what amounts to a coal-fired refinery! Thus many innovations for CCS are in the works, though space does not permit discussion.

All of these processes involve substantial changes to a "traditional" powerplant. Some of the major issues include:

- Some processes are more sensitive to impurities in the flue gas than others, especially sulfur. Depending on what FGD systems are already present, additional sulfur removal may be a pre-step to actual CO_2 capture. Some specifications require sulfur to be present at less than 10 ppm.
- The CO_2 capture process at the backend could constrain the front end of the plant, e.g., fuel flexibility. Burning of some coals would require more air flow than others, and change the CO_2 loading in the flue gas.
- Ammonia can be an expensive commodity, especially since it usually is derived from natural gas, which is volatile in price. Also, amines are in one sense higher forms of ammonia, so presumably they are derived from ammonia as well.
- While adding one of these processes solves the problems of one pollutant, they expand the number of other potential pollutants. Permitting would have to take into account ammonia and several new volatile organic compounds (VOCS), hazardous air pollutants (HAPs), and sludge and liquid wastes.

To extract efficiencies and lower costs, each of these processes will have to be integrated into the powerplant (Fig 9) to optimize for utilities – steam, condensate, air, etc.

The pioneers

As mentioned in the introduction, CCS has been practiced for many years, albeit at smaller scale than what will be needed to arrest global climate change impacts. Dozens of EOR sites around the world, mostly in the U.S., sequester CO_2 in depleted oil fields. However, only four of these sites source the CO_2 from an industrial facility producing it as a byproduct.

It should be pointed out that none of these facilities represent large-scale *post-combustion* capture from a coal-fired powerplant. And none of them have conducted the monitoring and verification to prove that the CO_2 remains in a contained state.

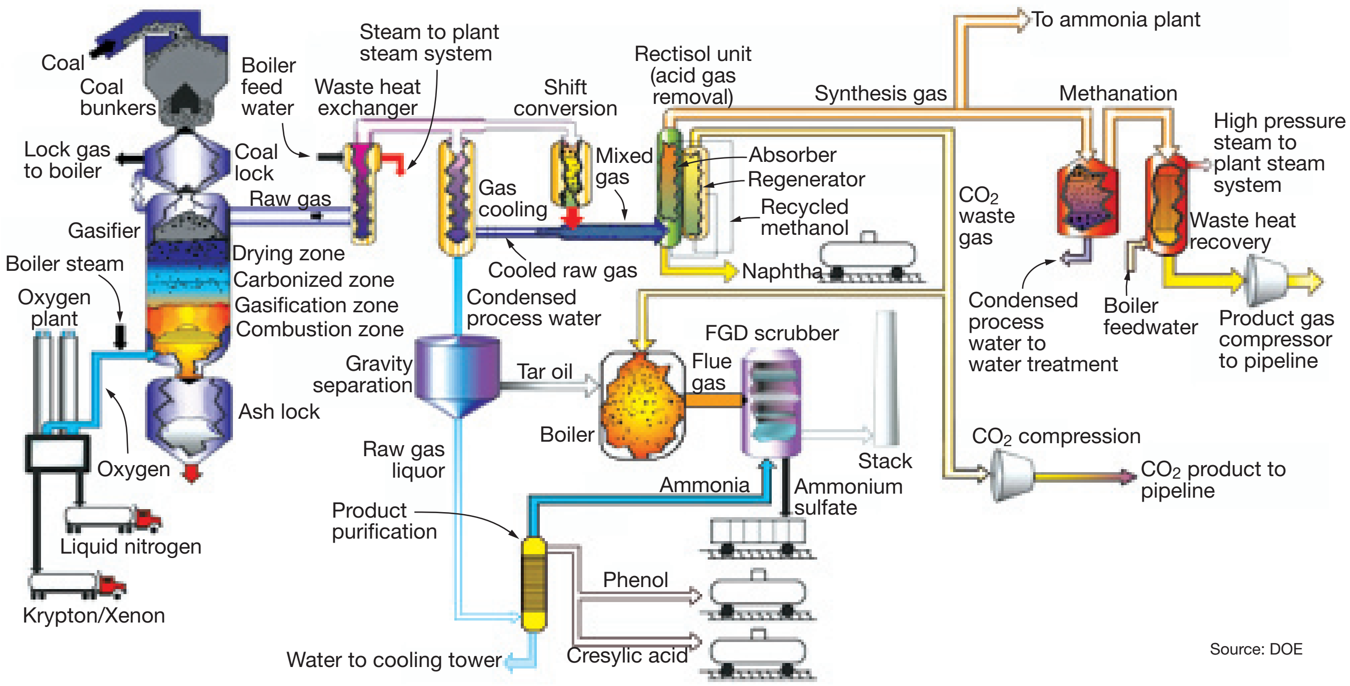
Weyburn/Dakota Gasification. An excellent place to "kick the tires" on CCS is the Dakota Gasification Facility, Beulah, North Dakota. Ironically, this project was funded through an earlier government-funded advanced coal processing initiative called the Synfuels Program. The coal gasification project (Fig 10) was built in the mid 1980s and converts coal to a synthetic fuel gas equivalent to natural gas. A Rectisol-based pre-combustion process removes sulfur, naphtha, and CO_2.

At the turn of the last decade, a deal was struck for Dakota Gasification, owned and operated by Great Plains Energy, to ship its CO_2 to the Weyburn oil field in Canada for EOR operations conducted by Encana Corp. As a result, a 325-km pipeline was built that transports 2.7-million m^3/day to the Weyburn field. More than 16-million tons of CO_2 have been sequestered since then, and millions more barrels of oil have resulted from a field once in decline. CO_2 emissions from the gasification facility have been reduced by 45%.

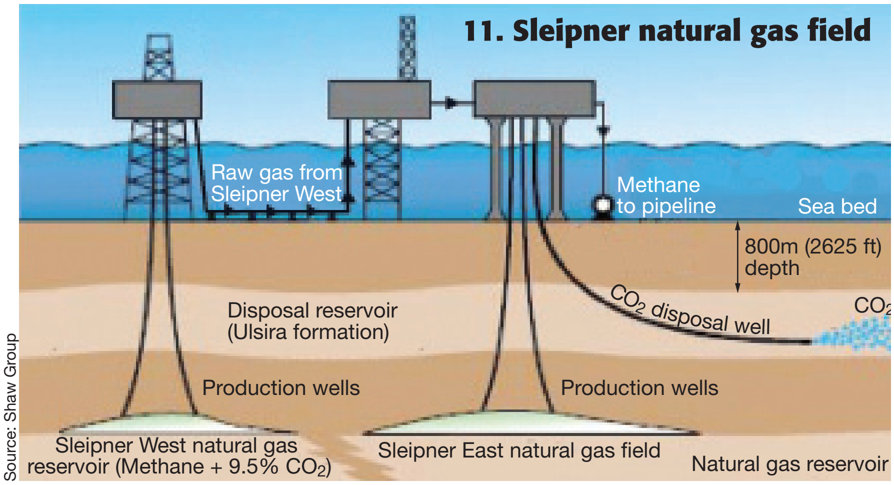
An important activity at Weyburn, funded through an international consortium, is a comprehensive monitoring and site characterization program. While every sequestration site is unique, Weyburn apparently has characteristics that will allow researchers to make generic conclusions applicable to other sites.

Under investigation are: the mechanisms at play in the reservoir, reaction of CO_2 with

10. Dakota Gasification Facility



The Dakota Gasification Facility is a true pioneer in the commercialization of CCS and advanced coal processing technology



CO_2 from the Sleipner natural gas field *in the North Sea is sequestered in a saline formation near the gas reservoir*

compounds comprising the formation, the migration paths of the CO_2, leakage potential over time, and the structural integrity of the geologic formation. Unlike Weyburn, virtually all EOR CO_2 injection operations have been optimized for oil recovery, not for long-term storage of CO_2.

Little focus is on transport of CO_2 because pipelining the material is well-proven; however, few people know the details. The Dakota-Weyburn pipeline, for example, is constructed of carbon steel, buried at a depth of 4-10 ft, the diameter runs between 12-14 inches, and the thickness of the pipe and the depth of burial increases significantly at water, road, and railroad crossings. Operating pressures are between 2700 and 3000 psig. A booster compressor station is located about halfway, and twelve remotely controlled main line valves allow isolation of parts of the pipeline for repair or during emergencies.

Sleipner/Snohvit. The North Sea has been one of the world's most active areas for oil/gas drilling and exploration. In 1996, Statoil began a program to remove carbon from a CO_2-rich (9.5%) natural gas resource. Around 1-million tons/yr are captured and sequestered in a deep (1000 m or 3000 ft below the sea floor) saline formation in a stratum above where the natural gas reservoirs are located (Fig 11). Ultimately, 20-million tons are expected to be permanently stored, with 8-million already down below.

The motivation for Statoil to undertake this project was clear: The Norwegian government imposed a US$55/ton carbon tax. A special offshore platform was built to separate the CO_2. Additional cost to remove the CO_2 and transport it underground is reported to be US$100-million. The formation won't be filling up anytime soon; it has a capacity to sequester an estimated 600-billion tons of CO_2.

It is also the subject of intensive monitoring by squads of international scientists and engineers. One critical reason for long-term monitoring is that as CO_2 at very high pressure is injected into a saline aquifer, the overall density of the rock and pore spaces decreases, affecting the strength of the formation and its ability to resist gravitational forces.

When Statoil built Europe's first large-scale liquefied natural gas (LNG) facility at Snohvit, CCS was included there as well, although, at 700,000 tons/yr, the scale of the CCS is somewhat less than Sleipner. Snohvit came online in 2008. This year, Statoil reported that there was less storage capacity in the target depleted gas reservoir than originally calculated and Statoil is now investigating ways to expand reservoir volume.

Both Sleipner and Snohvit employ a "conventional" amine-based process to capture the CO_2 from the natural gas.

Relevant projects

As mentioned earlier, getting CCS technologies to scale is the immediate challenge. Fortunately, the efforts to do so span the globe. Here's quick tour of projects focused on commercial-scale operations.

GreenGen. If for no other reason than the country in which it is located, the GreenGen project in China has the eyes of the CCS sector upon it. Ultimately, a 1050-MW coal-fired powerplant with "near-zero" emissions will be operating near Tiajin (southeast of Beijing). It is described as "China's centerpiece initiative to advance near-zero emissions, coal-fueled generation with hydrogen production, and carbon capture and storage."

The first 250-MW unit is under construction and agreements are reportedly in place for two 400-MW future units. Peabody Energy (St. Louis, MO, U.S.), the largest private sector coal company that mines the energy for 2% of the world's electricity, holds a 6% equity stake in the project. All other joint-venture partners are Chinese firms.

The technology used at GreenGen is an IGCC, anchored by a dry, two-stage, 2000 ton/day, oxygen-blown coal gasifier, coupled with hot-gas cleanup unit, all reportedly based on Chinese intellectual property. The second stage of the project will be to actually build and demonstrate the carbon capture technology.

Later stages will include testing of a hydrogen-fed fuel cell generating system and the sequestration of the CO_2. Ultimately, the goals of the project are a 55-60% efficient powerplant with over 80% of the carbon captured and stored by the year 2020.

FutureGen. In contrast to GreenGen, the U.S. government's flagship CCS project, FutureGen, has been reincarnated several times involving different sites, different technologies, and different participants. The latest arrangement, announced by the Department of Energy in August, involves the repowering of a 200-MW coal unit in Illinois for oxygen-fed combustion, a new boiler, an air separation unit, CO_2 capture and purification, compression, and sequestration via a 175-mile pipeline.

However, one hitch in the project, dubbed FutureGen 2.0, is that the pipeline will be funded separately. In a CCS project costing US$1.2-billion, it is certainly curious why the CO_2 pipeline would be funded separately. FutureGen 1.0 was to be an IGCC facility.

NowGen. Other participants in the FutureGen competition didn't necessarily waste their time. One, Summit Texas Clean Energy LLC, parlayed its FutureGen effort into a US$350-million grant from DOE to develop a 400 MW IGCC facility which will send 3-million tons of CO_2 annually at 90% capture rate to EOR producers in the area. NowGen not only will gasify coal but petroleum coke as well, and will produce hydrogen as well as other synfuel products for fertilizer processors.

Of note is that CO_2 sales are expected to increase revenues by 50% over electricity sales. The huge penalties associated with CCS are evident as the net electric output of the facility will be only 245 MW. Siemens will be supplying the gasification technology and the power generation island, including gas turbines modified to burn high hydrogen content syngas. Fluor Corp. is the project design engineering firm. The Linde Rectisol process will be employed for CO_2 separation. Groundbreaking is expected in 2011.

Gorgon. The source of carbon for the largest CCS project in the world isn't a grid-connected powerplant (although a 400-MW powerplant will serve the facility), but a massive US$37-billion natural gas extraction and development facility, so huge in fact that three global petrochemical giants – Shell, Exxon Mobil, and Chevron – have come together to build the facility. It is said to be located in Australia's largest undeveloped gas field.

Natural gas will be extracted through sub-sea (1350 m deep) facilities 250 km from the coast, then processed and fed to three 5-million ton/year liquefied natural gas (LNG) trains located on Barrow Island. Interestingly, Barrow Island is not only home to the country's largest on-shore operating oil field but is a class A nature reserve. Up to 3.3-million metric tons of CO_2 in a supercritical state will be injected annually in a deep geologic structure (known as the Dupuy formation) beneath Barrow Island.

Although the state government has not yet provided a "post-closure indemnity" for the sequestration site, the Commonwealth government passed in 2008 the Offshore Petroleum and Greenhouse Gas Storage Act. It allows the federal government to take on post-closure liability for CCS projects.

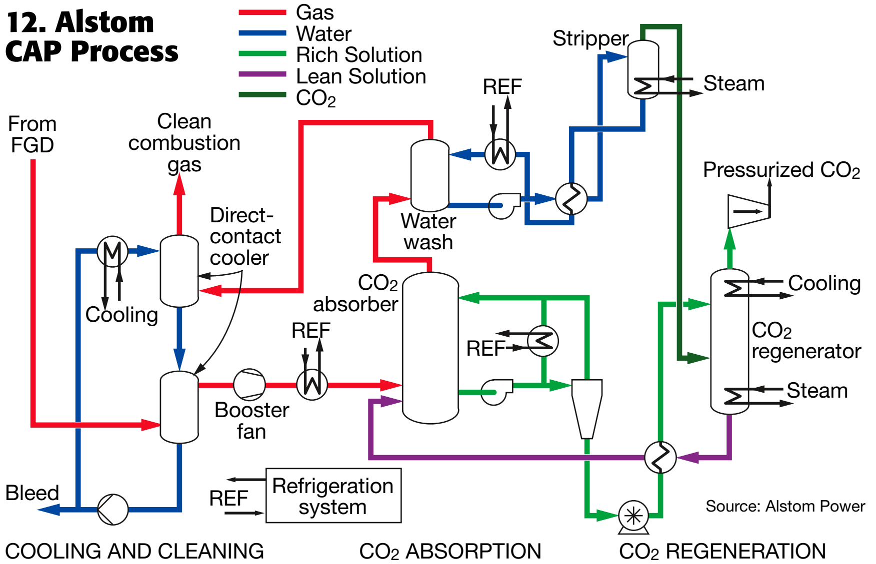
General Electric has secured US$1.1-billion worth of equipment supply for Gorgon, along with Hyundai Heavy Industries Co, with a one billion plus supply package. According to one report, the amount of carbon that will be sequestered at Gorgon is like taking two-thirds of the automobiles in Australia out of circulation. The facility is expected to be processing first gas in 2014.

Trailblazer. Unlike most CCS projects involving huge global players or electric utilities, Trailblazer, near Sweetwater, Texas, is being developed by a relatively small but highly successful independent power firm in the U.S., thus far with no government support. This 600-MW (net) supercritical coal-fired boiler and powerplant will ship 85-90% of its CO_2, 5.75-million tons/yr, to the Permian basin in Texas for EOR.

Arch Coal Corp., supplying the Powder River Basin (PRB) coal from Wyoming, has a 35% equity interest in the project. The net reductions in output from CCS are evident in this project; gross output is 765 MW. Final air permit is expected at the end of this year. The U.S. EPA apparently has granted Tenaska, Inc. a waiver for this project's air quality permit if built with 85% carbon capture. The CO_2 used in EOR flooding could yield an additional 10-million barrels of oil annually.

Mountaineer. The largest coal-burning electric utility in the U.S., American Electric Power Company, Inc. (AEP), has a long-term program for developing CCS, beginning in 2009 with the first fully-integrated CCS project in the country, a 30-MW pilot plant slipstream from the 1300-MW Mountaineer coal-fired unit (West Virginia) that began operating last year. The storage medium is a deep saline sandstone formation 1.5 miles below the powerplant site.

12. Alstom CAP Process



The chilled ammonia process may dramatically reduce the parasitic energy consumption of carbon capture but has to date only been demonstrated at pilot scale

Alstom's chilled ammonia CO_2 stripping process (Fig 12) is employed, which essentially uses the carbon dioxide to convert an ammonia carbonate reagent into ammonia bicarbonate. In later steps, the reagent is regenerated, and the CO_2 is compressed and shipped underground. Compared to amine-based processes, the chilled ammonia process reportedly "dramatically reduces the energy required to capture carbon dioxide and isolates it in a highly concentrated high pressure form."

In 2015, the next phase is scheduled to begin operating, a 235-MW equivalent facility capturing and storing 1.5-million metric tons of CO_2 annually. Up to 90% of the CO_2 can be removed from the flue gas with this process. The second phase of the project will be half-funded by the DOE to the tune of US$334-million. Mike Morris, AEP CEO, reported in March that the pilot plant has been working "quite nicely."

AEP and Alstom are pursuing a similarly sized demonstration at its Northeastern powerplant in Oklahoma, where the CO_2 will be used in EOR operations. That unit is expected to start up next year.

Ferrybridge. Described as one of the largest polluters in the UK, the Ferrybridge station will have one of its 500-MW coal-fired boilers retrofitted with supercritical technology to save 0.5-million tons CO_2 annually, and then add a pilot scale CCS system for another 1.2-million tons CO_2 removal. This project is expected to start up in 2011 or 2012.

Belchatow. This huge coal-fired powerplant in Poland, one of the world's largest, also has the distinction of being one of the largest polluters in the world. The site produces 30-million metric tons annually of CO_2. Now, thanks to funding from the EU, the plant will install and demonstrate an advanced amines-based CO_2 stripping process from Alstom and Dow Chemical Company that will take 100,000 tons per year out of the atmosphere. In a second phase, scheduled for 2015, that technology will be scaled up to remove CO_2 from a planned 860-MW supercritical Lignite-fired unit.

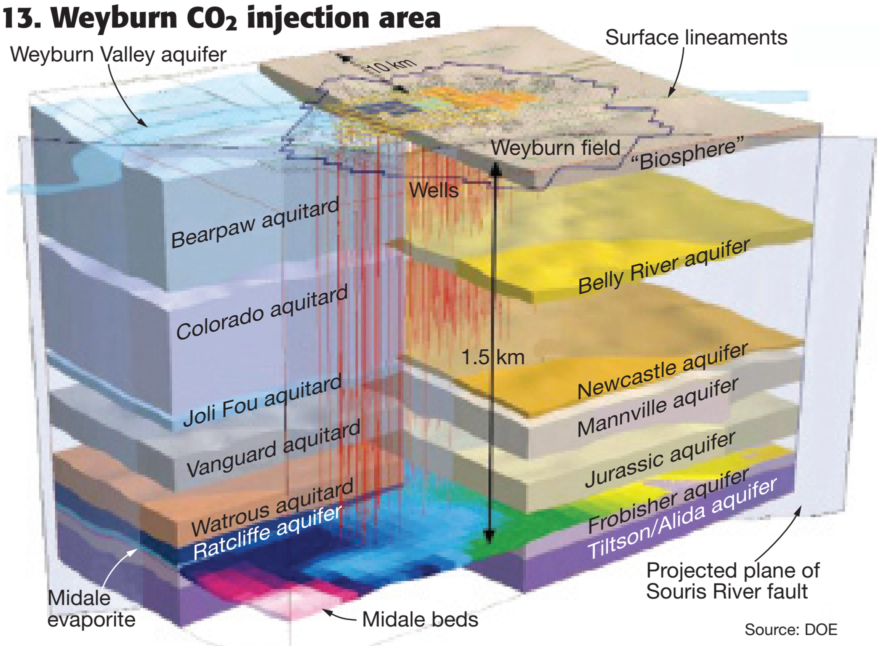
Pioneer. In Canada, TransAlta Corp.'s Keephills coal-fired powerplant, Unit 3, is the site of what could be one of the largest integrated CCS facilities in the world. Step one is to apply Alstom's chilled ammonia process at pilot scale and remove 1 million tons/year of CO_2. Most of the CO_2 will be purified for use in nearby EOR fields, the balance injected nearly 2 miles into a storage medium below the plant.

Geotechnical, legal, institutional, and financial issues

Of the three components of CCS – capture, transport, and storage – the last involves the greatest amount of uncertainty and risk. From the most cynical view, storage involves placing huge volumes of what has been defined as a "hazardous pollutant" into natural geologic formations with the expectation that the volume will remain where it is supposed to be *forever*.

Implied is the notion that permanent sequestration has no practical endpoint, at least with respect to the continued monitoring and verification of site integrity. This creates a seemingly insurmountable liability.

13. Weyburn CO_2 injection area



This 3-D model was constructed based on data from approximately 1000 wells at the Weyburn (Canada) CO_2 sequestration site. The model significantly extends beyond the boundaries of the actual injection area

Although most CCS experts concede that no comprehensive legal and regulatory framework exists for permanent sequestration, precedents are available to create one. The International Energy Agency listed the development of legal frameworks an area where significant progress has been made over the last several years.

In Europe, the EU issued its "Directive on the Geologic Storage of CO_2" in January 2008, and implementation by the member countries is scheduled to begin this year. The law is restrictive. Storage in saline aquifers and depleted oil/gas fields is not permitted. The only sanctioned storage or use is in EOR or hydrocarbon recovery, and is considered to be as much recycling as it is permanent storage.

The final framework is expected to include a 90% purity level for the injected CO_2. Regular inspection and reporting on the site will be required. Owner/operators will be responsible for the post-closure period. Only after all evidence indicates complete containment of the CO_2 can responsibility for the site be transferred, such as to a government agency.

Australia has established a regulatory framework at the national level for offshore carbon storage. Individual Australian states, notably Victoria and Queensland, have issued regulations for onshore storage. Laws were passed in 2008. The process the Australians followed was to amend the federal Offshore Petroleum Act of 2006 to accommodate CO_2 injection. The government of Norway followed a similar path in developing the legal framework for Sleipner and Snohvit.

U.S. developments. The U.S. EPA has a regulatory framework for injecting other materials into underground structures. It is called the Underground Injection Control Program (UIC), created under the 1974 Safe Drinking Water Act. In recent years, EPA released a proposed rule for CO_2 sequestration under UIC, which establishes a sixth class of injection well.

However, UIC has a relatively narrow purpose—to protect drinking water sources. States that have extensive oil/gas wells and geothermal resources could use the body of regulations and laws around these resources as a start or even a guide for carbon storage.

States that competed for the U.S. FutureGen project got a head start in establishing a regulatory framework for permanent CO_2 storage. Both Illinois and Texas, for example, passed legislation that transferred title of the CO_2 to the state government; Illinois considers it "transferred" at the time of injection, Texas at the time of capture. Thus, all long-term liabilities and risks have been transferred away from the owner/operator. At least a dozen states are developing carbon sequestration regulatory frameworks.

An Interstate Oil and Gas Compact Commission (IOGCC) task force on Carbon Capture and Geologic Storage produced a model legal and regulatory regime for CO_2 sequestration. Among its recommendations:

- Control of storage space and pore space is necessary – they should be acquired as part of the initial storage site licensing process, using eminent domain powers typical of natural gas storage if necessary.
- Create an industry-funded, state-administered trust fund to provide the necessary long-term post-closure monitoring and verification activities and funds.
- States should provide the "cradle to grave" oversight and assume legal responsibility after a ten-year minimum post-closure evaluation period.

In some states, government indemnification against the liability may raise constitutional issues. The state of New York, for example, may be constitutionally prohibited from transferring the liability for long-term carbon storage from a private corporation to the state government.

Obviously, a sequestration site's subsurface "footprint" can be huge. It is impractical to monitor the site and obtain regular readings from enough points to lend confidence that the integrity of the entire structure is sound. Therefore, the industry will have to construct and rely on geotechnical models (Fig 13).

Achievements in the oil & gas industry should be noted here. The modeling and mapping necessary to characterize and subsequently exploit underground petroleum and natural gas resources is sophisticated and accurate. It seems reasonable to expect that the same tools and techniques can apply to geologic CO_2 storage.

The three principal formations targeted for permanent CO_2 storage are EOR or depleted oil/gas reservoirs, unmineable coal seams, and saline formations. From a permanence standpoint, depleted oil/gas fields are considered best because the geology presumably has been capable of sequestering those materials at relatively high pressures and volumes for millennia. These sites also benefit from extensive evaluations conducted to develop the fields in the first place.

However, the number of such sites is limited and not necessarily located where powerplants are. The other big challenge is that, despite the decades of experience with CO_2 injection for EOR, there is no verification about how much of the CO_2 remains trapped in the formation or even protocols to make such a determination.

Similarly, coal beds typically have methane associated with them that can be recovered using CO_2 injection. The world has vast known deep coal seam resources, but only a few experiments have been conducted to determine whether methane can be economically recovered and whether CO_2 can be sequestered. Little, too, is known about CO_2/coal interactions.

Saline formations, porous rock such as sandstone and limestone saturated with brine, show the greatest volumetric potential for sequestering large volumes of CO_2. For example, about two-thirds

Acronyms

AEP	American Electric Power Company, Inc.
ATM	Standard atmospheric pressure
CAA	Clean Air Act
CAP	Chilled ammonia process
CCGT	Combined-cycle gas turbine
CCS	Carbon capture and storage
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
DEA	Di-ethanol amine
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic precipitators
FGD	Flue-gas desulfurization
HAPs	Hazardous air pollutants
IGCC	Integrated gasification combined cycle
IOGCC	Interstate Oil and Gas Compact Commission
LNG	Liquefied natural gas
MDEA	Methyl di-ethanol amine
MEA	Mono-ethanol amine
PRB	Powder River Basin
RCRA	Resource Conservation and Recovery Act
SCR	Selective catalytic reduction
Sorw	Residual oil saturation after waterflood
UIC	Underground Injection Control Program
VOCS	Volatile organic compounds
VSP	Vertical seismic profiling

of the land mass of the U.S. is thought to have saline formations underneath the surface.

For the most part, these formations are not well-characterized and the chemical and physical interactions of the CO_2 with the brine and the minerals are unknown. Perhaps the biggest risk is that there is no assurance of a permanent seal, which is presumed with a depleted oil & gas reservoir.

Several different types of monitoring are required to ensure the integrity and stability of the site (Fig 14). For example, initial site characterization is critical for establishing the baseline conditions against which later measurements will be compared. After closure of the site to injection, atmospheric, near-surface, and sub-surface monitoring continues to check for leakage and integrity. But probably the most important monitoring takes place during injection to understand how the CO_2 "plume" is migrating underground.

Legal. The well-worn phrase, "not in my backyard," the generic rallying cry for opponents of powerplants (or any other infrastructure for that matter), may take on an entirely new meaning with the advent of coal sequestration. Just like developers of facilities at the surface have to acquire property rights, often from multiple landowners in the case of transmission lines and wind farms, owner/operators of CO_2 storage sites have to negotiate for subsurface rights.

With little knowledge about how the CO_2 plume will migrate, this can be quite a liability into the future. CO_2 volumes could contaminate the mineral resources of a given mineral-rights owner, or an owner could make claims to this effect. CO_2 volumes can "impair" or cause injury to the use and value of land at the surface. To avoid these risks, some new version of government eminent domain may have to be invoked.

Financial. Investors, of course, seek to avoid all risk themselves and transfer it to other parties to a deal. With so many uncertainties and open-ended questions, it is no surprise that private capital has fled the coal-fired power industry. In fact, in the U.S., at the height of Wall Street's arrogance in 2008, three major investment firms issued their "carbon principles," essentially stating that they would not invest in coal plants until CCS was commercially viable.

Given that carbon capture at scale at the time was not anticipated until 2020, coal as a fuel for electricity was marginalized for at least a decade. And if viability includes an appropriate and accepted legal and regulatory framework, or in the eyes of investors little risk on them, well, the marginalization of coal could be understood to be indefinite.

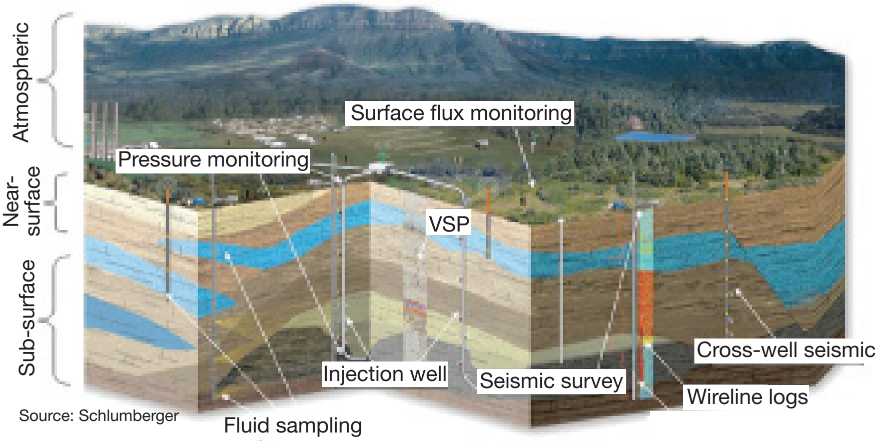
Even without the uncertainties, just the added costs alone make investors skittish about coal plants. A 600-MW coal plant with full CCS will cost between US$1-2 billion and 25-40% of that cost is attributed to the CCS equipment.

There is also a 30% increase in operating costs attributed to the CCS, and if the experience in the FGD industry is an indicator, these costs are anything but predictable for the first wave of CCS-equipped plants. On top of these costs are the added expenses for post-closure monitoring and verification. All of these costs increase debt service and have to be recovered in project revenues. All of the risks have to be born.

Every vendor and participant to a project will be concerned about getting drawn into protracted legal disputes and litigation over what happens at the storage site long-term. Insurance premiums will be astronomical until insurers are confident about the risks they are insuring against.

As mentioned earlier, because of EPA's definition of CO_2 as a pollutant, storage sites can be considered, in the worse case, massive hazardous waste sites, subject to the Resource Conservation and Recovery Act (RCRA) in the U.S., Clean Air Act (CAA),

14. Geologic monitoring tools



Several types of monitoring will be necessary to ensure integrity of the site post-closure

CERCLA liabilities on the release of reportable quantities of hazardous substances from the site, and myriad common law statutes such as nuisance, negligence, trespassing, hazardous activity, and others.

Transport. Getting the CO_2 from the powerplant to the storage site is considered the easiest of the three "steps" in CCS. However, it is far from a no-brainer. While there is nothing sexy or even controversial about transporting CO_2 from powerplant to storage site, at scale, the infrastructure will resemble the natural gas pipeline system, which was built over a one-hundred year period in the U.S.

There are 300,000 miles of interstate gas pipelines in the U.S., Europe, Australia, and Japan also have extensive gas-transport infrastructure. Estimates show that recovering CO_2 from all the powerplants in the U.S. would require an infrastructure one-third the size of the U.S. gas pipeline infrastructure and twice as large as the petroleum transport and delivery infrastructure.

Just to mention one legal hurdle, gas pipelines can acquire rights through federal or state eminent domain laws in the U.S. CO_2 transport facilities are not yet afforded such luxuries.

All of these non-technical issues pose an interesting philosophical dilemma for countries with competitive market economies and private property ownership. All the activities upstream of the CO_2 injection and sequestration are the responsibility of "private" enterprise but the management of the principal waste byproduct that of government. Thus, coal-fired power generation becomes similar to the nuclear power sector, because the government takes title to the "waste."

The only clear path to a viable coal-to-electricity industry appears to be, at best, one that is more regulated and government controlled, and, at worst, an industry sector, much like defense, that is a ward of the state.

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