Carbon Capture and Storage

MEETING THE CHALLENGE OF CLIMATE CHANGE

IEA GREENHOUSE GAS R&D PROGRAMME

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International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy programme. The IEA fosters cooperation amongst its 26 member countries and the European Commission and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

IEA Greenhouse Gas R&D Programme

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Executive Summary

Avoiding severe global climate change is an enormous challenge. Greatly reducing man-made carbon dioxide (CO_2) emissions is central to meeting that challenge.

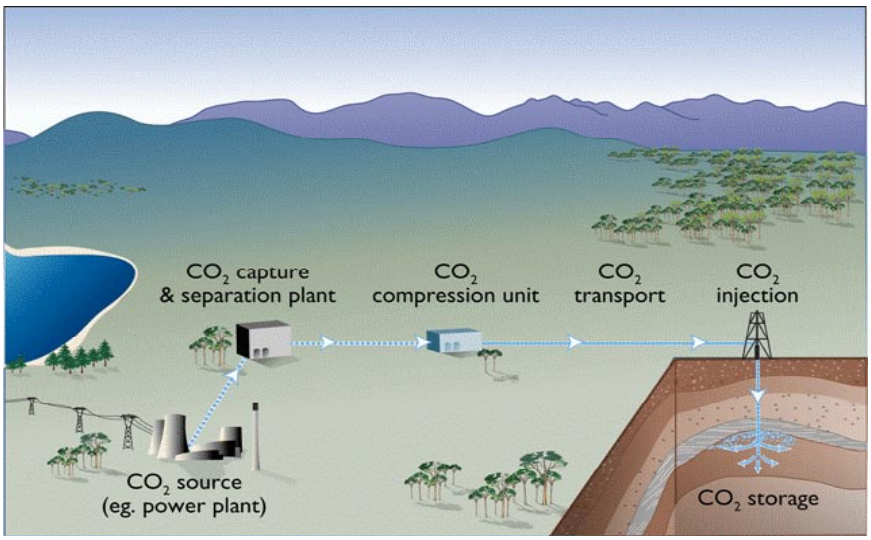
Carbon Dioxide Capture and Storage (CCS) is one of the measures necessary to reduce CO_2 emissions. CCS is the separation and capture of CO_2 from power generation or industrial processes and the transport and permanent storage of that CO_2 in deep underground rock formations. CCS is an integrated system with three stages: capture from a source, transport and geologic storage.

Why CCS Is Needed

Over the next half century, the use of widely-available and relatively inexpensive fossil fuels for power generation and industry is likely to grow substantially throughout the world and particularly in developing countries. Growing fossil energy use, however, could greatly increase CO_2 emissions. Yet, the Intergovernmental Panel on Climate Change (IPCC) projects that 2000 emission levels must be cut by half or more by 2050 to avoid the most serious consequences of climate change. CCS is the only technology that will enable large-scale fossil fuel power generation and several vital industries to continue to be economically viable while reducing their CO_2 emissions in a carbon-constrained world.

Cost of CCS

The cost of CCS varies widely with the CO_2 source, the capture method, the distance to the storage site and the characteristics of the storage reservoir. Most of the cost is in the capture stage. CCS costs are expected to decrease with technology development and experience. When commercial, CCS costs will likely be well within the range of many of the other measures necessary to mitigate climate change—less expensive than some, more expensive than others.



In CCS, CO_2 is captured before it can be emitted into the atmosphere. It is then compressed and transported to the injection site. The CO_2 is injected into deep underground rock formations, where storage is monitored and verified.

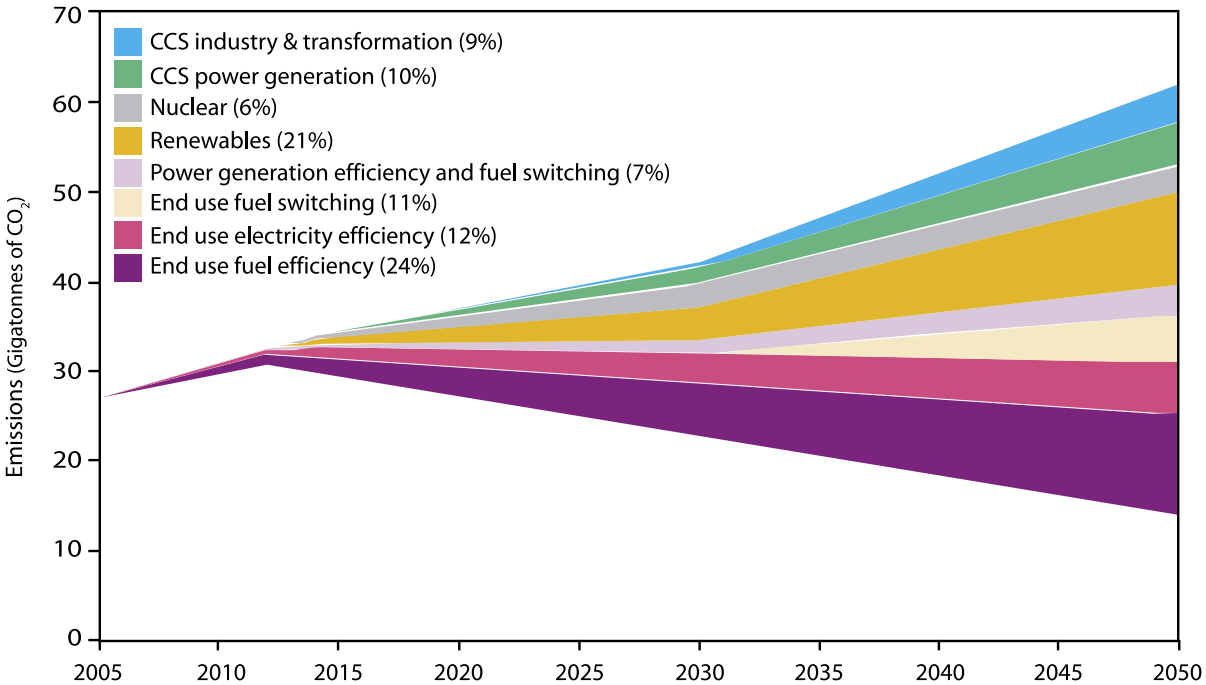
Image Source: CO2CRC

CCS will be a highly cost-effective emissions reduction measure. According to a study by the International Energy Agency, CCS in the power generation and industrial sectors is anticipated to create 19 percent of CO_2 emissions reduction needed in 2050 for only 6.7 percent of the required investment in CO_2 emissions reduction. The same study also shows that the cost

of cutting CO_2 emissions in half by 2050 would nearly double without CCS.

Readiness of CCS

Each CCS stage has been used separately for decades for other purposes. The first commercial, integrated CCS projects are now in operation. These projects are in a few industrial applications such as natural gas processing and ammonia production. The first commercial CCS projects in the power sector will likely go on line in the 2010s. CCS can be ready for widespread commercial use in power generation by about 2020 and widespread commercial use in industry somewhat later. That timeframe will enable CCS to contribute a major share of the needed emissions reduction.



An analysis by the International Energy Agency shows that CCS in both power generation and industry, when implemented along with energy efficiency and renewable energy sources, can create most of the emissions reductions needed to cut emissions in half by 2050. CCS alone can create 19 percent of the emissions reduction in 2050.

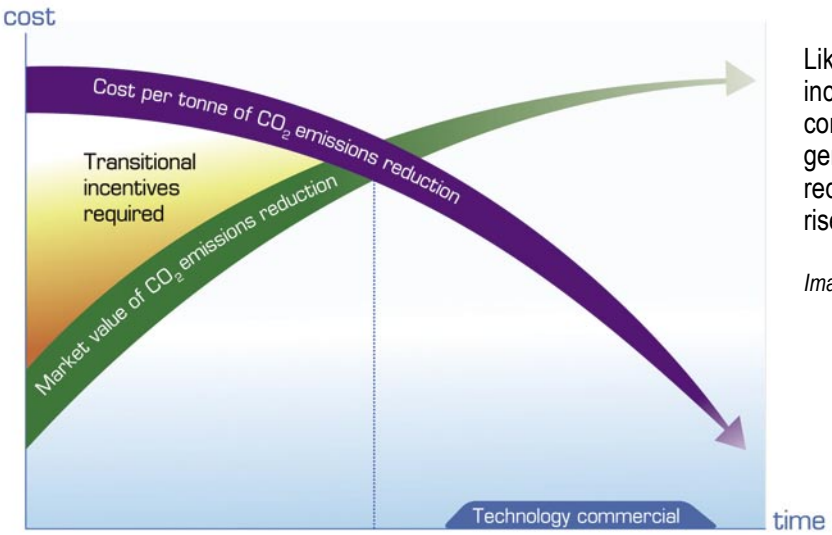
Image Source: Based on International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

Coal Gasification Plant with CO_2 Capture

CO_2 Storage Injection Site

CO_2 has been captured since 2000 at this commercial coal gasification plant in North Dakota, USA, and piped to Saskatchewan, Canada, where it is stored in depleting oil fields. Currently, 2.8 million tonnes per year of CO_2 are disposed of in this way. Many other CCS projects will become commercial in the coming years.

Image Sources: Dakota Gasification Company and IEA Weyburn-Midale Monitoring Project, Final Phase.



Like other emissions reduction measures, transitional incentives will be required before CCS becomes commercially viable in applications such as power generation. Such incentives will no longer be required when the value of CO_2 emissions reduction rises above the cost of CCS.

Image source: Bluewave Resources, LLC and CO2CRC.

Most commercial projects will be new facilities designed with CCS. Some new power plants built as capture-ready and some currently-existing facilities will likely be suitable for CCS retrofitting. Capture-ready power plants are plants built without capture, but which have the capability of being retrofit when the necessary regulatory and economic drivers are in place. Specifications for what makes a plant capture-ready are now being developed.

CCS will become widely commercially viable when the cost of CO_2 emissions—as set, for example, by the price of allowances in an emissions trading program or by a carbon tax—is above the cost of CCS. The cost of CCS is also expected to decline as the technology is developed and there is more experience using it. Until then, transitional incentives will be needed to ensure that demonstration and early commercial projects are developed. Renewable energy technologies, such as solar and wind power, similarly need early incentives.

What It Will Take

Further progress will be required to achieve the timely and widespread commercial use of CCS. Both technical progress and the development of enabling institutional frameworks will be needed.

The major technical requirements for broadening the use of CCS are reducing capture costs, demonstrating long-term storage in diverse geological settings, integrating the entire system, and achieving scale. All are considered to be achievable in the near future. Meeting these requirements necessitates further research and development; fully-integrated, commercial-scale demonstration projects; and participation by both government and the private sector.

Intensive work is being done around the world to advance CCS technology. Rapid technical progress is already improving effectiveness, efficiency and cost, as well as applicability to different emission sources and geologic formations. A large and growing number of scientists, engineers and geologists now devote their efforts to all aspects of CCS. CCS has become a high priority for many governments and companies. Major international collaborations are taking place.

Enabling institutional frameworks would consist of effective and appropriate laws and regulations, private and public sector institutions that can implement and finance CCS, and public understanding and support for CCS. Efforts are underway in many countries to develop each of those.

Reflecting the importance now being given to CCS, the G8 leaders at their 2008 meetings in Japan supported actions to advance CCS globally, including the development of at least 20 fully-integrated, commercial-scale demonstration projects.

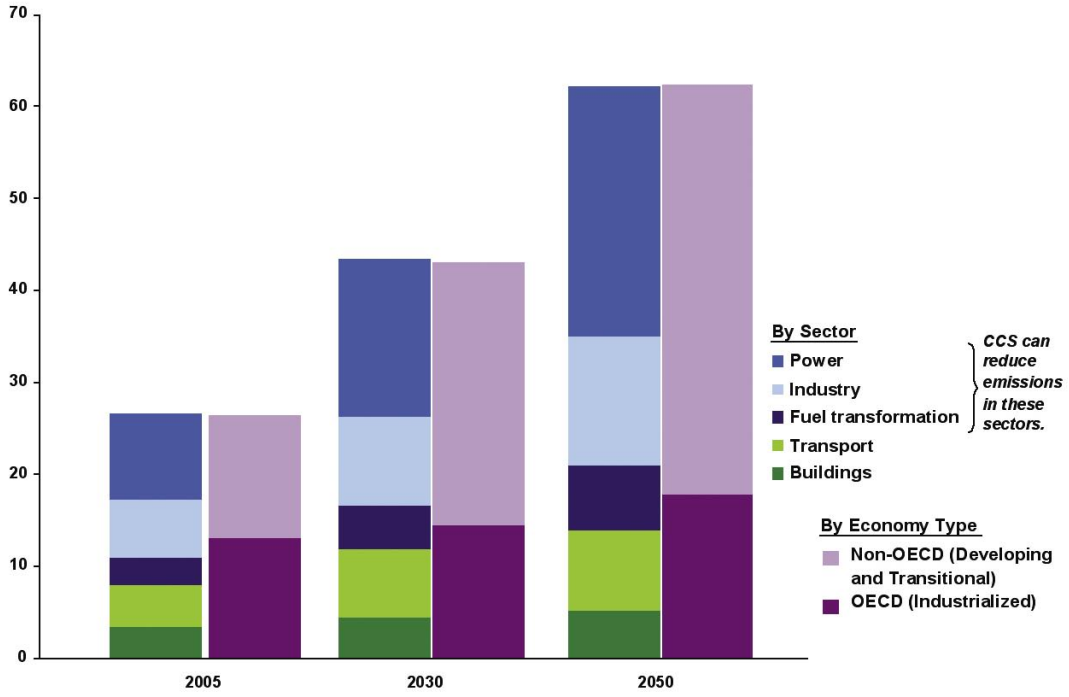
CCS can be an important, cost-effective and timely part of the solution to climate change. Making CCS widely commercially viable by about 2020 is achievable with sustained, global efforts by governments and industry. Such efforts are now underway throughout the world.

Carbon Capture and Storage can be an important, cost-effective and timely part of the solution to climate change.

Why Carbon Dioxide Capture and Storage is Needed

Carbon Dioxide Capture and Storage (CCS) is the separation and capture of CO_2 from power generation or industrial processes and the transport and permanent disposal of that CO_2 in deep underground rock formations. CCS is one of many actions necessary to stabilize greenhouse gas concentrations in the atmosphere. It will significantly reduce emissions from the power generation and industrial sectors, a fact that is being increasingly recognized and acted upon throughout the world.

Avoiding severe global climate change is an enormous challenge. Greatly reducing man-made carbon dioxide (CO_2) emissions is central to meeting that challenge. The Intergovernmental Panel on Climate Change (IPCC) estimates that CO_2 emissions must be reduced 50 to 85 percent by 2050 compared to 2000 levels. That reduction will keep the global mean temperature rise below 2.0 to 2.4°C, where severe impacts begin. Yet, the trend in global CO_2 emissions is a continued rapid rise for the foreseeable future. To date, industrialized countries have emitted most of



Current trends in global CO_2 emissions to 2050: Rising significantly. Most of this increase will be primarily in developing countries.

Image Source: Based on International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

the CO_2. Emissions from developing countries, however, are growing much faster and their emissions will overtake those of the industrialized countries in the near future.

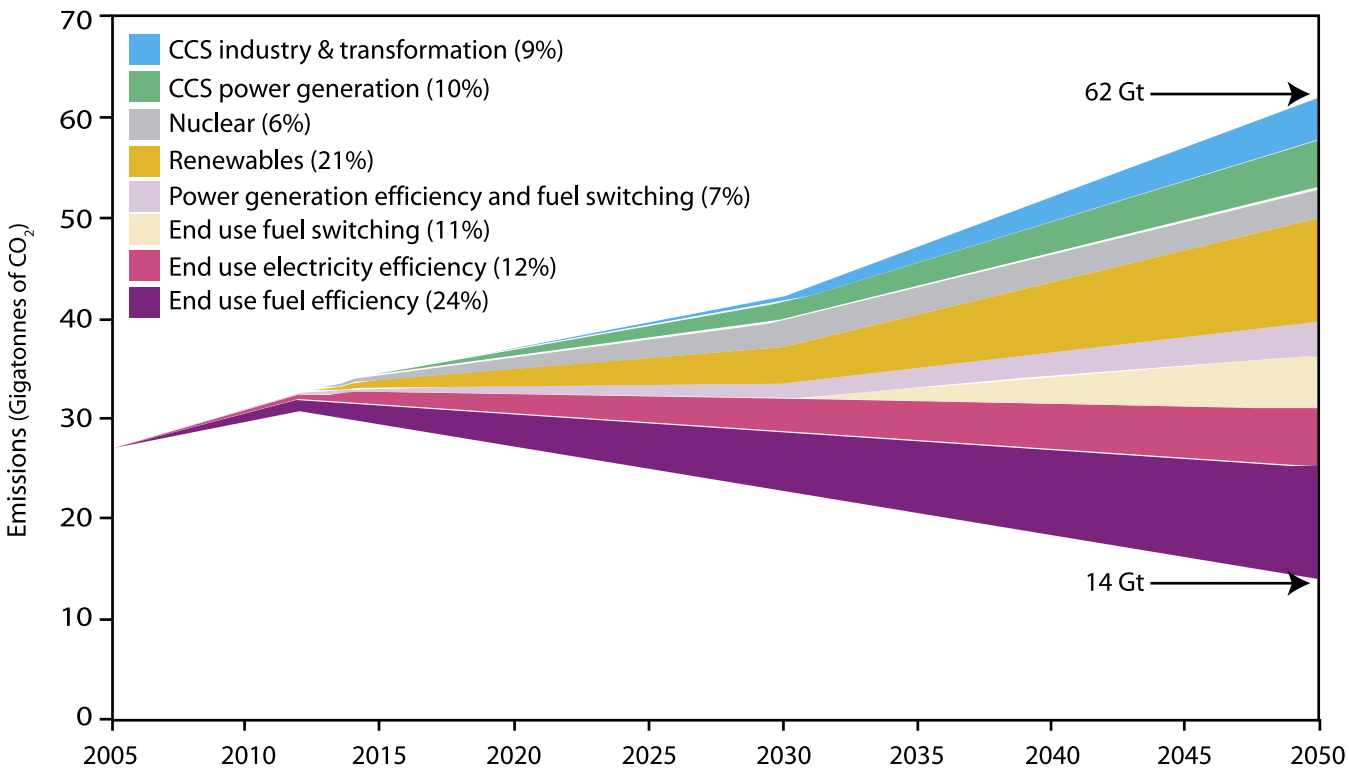
The scale of the required reduction in CO_2 emissions is enormous. Adequately reducing CO_2 emissions will require global efforts in virtually every economic sector—power, industry, fuel transformation, transport, and buildings—in both industrialized, transitional and developing economies. Human activity globally currently releases about 28 gigatonnes of CO_2 ($GtCO_2$) per year into the atmosphere. Cutting this in half or more would bring emissions to 14 $GtCO_2$ or below by 2050. This is a reduction of at least 48 $GtCO_2$ below the 62 $GtCO_2$ projected for 2050 under current trends. Cumulatively, at least about 600 Gt will have to be cut over the entire period.

How big is a gigatonne of carbon dioxide (1 $GtCO_2$) emissions reduction?

A Gt is 1 billion (10^9) tonnes (metric tons) or 10^{12} kilograms. (1 kilogram = 2.2 pounds) But what does 1 $GtCO_2$ really mean in terms of emissions reduction? Emissions reduction of 1 $GtCO_2$ per year is the equivalent of:

- ✓ Building 1,036,000 Megawatts (MW) of wind farms (current world total: 14,000 MW);
- ✓ Applying CCS to 137 coal plants, each 1,000 MW (11 percent of the current world total);
- ✓ Increasing efficiency of the world's 500 million automobiles by 7.3 km/liter (10.8 mpg);
- ✓ Reforestation of 90,000,000 hectares (222,390,000 acres), about 10 percent of the area of Brazil; or
- ✓ Biomass plantations on 48,000,000 hectares (118,000,000 acres), about the area of Spain.

If all five of these measures were implemented for 30 years, that would be 150 $GtCO_2$, about one quarter of the minimum needed.



An analysis by the International Energy Agency shows the measures needed to cut emissions in half by 2050. Most of the needed emissions reduction can be achieved by CCS in the power generation and industrial sectors, energy efficiency and renewable energy sources.

Image Source: Based on International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

Many different measures are necessary to reduce greenhouse gas emissions. These measures include increasing energy efficiency in all sectors; using renewable energy sources such as wind, biomass, geothermal and solar energy; switching to low- or no-carbon fuels; and implementing carbon dioxide capture and storage. It is also necessary to reduce emissions of other greenhouse gases such as methane and nitrous oxide and to enhance natural sinks for CO_2 such as rainforests.

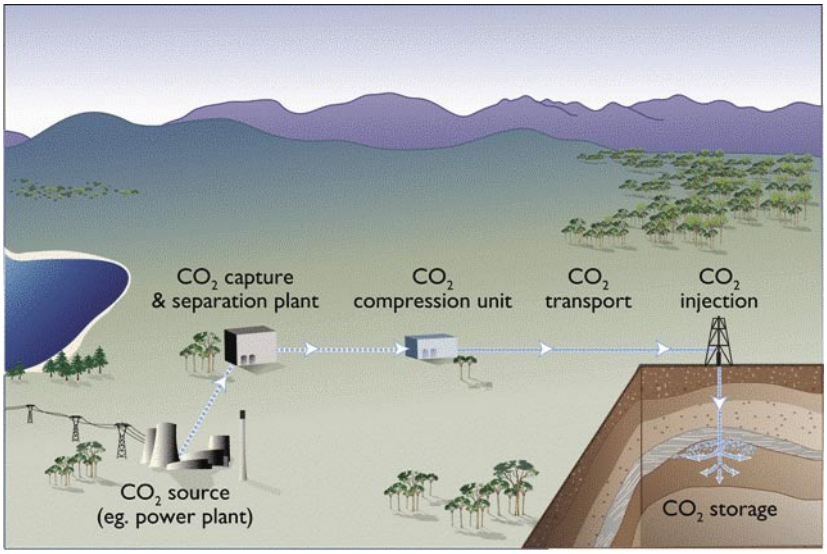
The Role of Carbon Dioxide Capture and Storage

Carbon Dioxide Capture and Storage (CCS), also known as Carbon Capture and Sequestration, is the separation and capture of CO_2 from power generation or industrial processes and the transport and permanent storage of that CO_2 in deep underground rock formations. By preventing CO_2 emissions from large facilities from entering the atmosphere, CCS is potentially a powerful tool for combating climate change.

CCS has three basic stages: capture, transport and geologic storage. All three are evolving rapidly as research and development proceeds. Many technology options for capture are emerging; most CO_2 will be transported by pipelines; and knowledge of how to conduct geologic storage is increasing.

In CCS, CO_2 is separated from other gases at a large facility such as a power plant before it is emitted into the atmosphere. The CO_2 is then compressed into a very dense supercritical fluid state and, if necessary, transported for injection. At the injection site, the supercritical fluid CO_2 is injected under high pressure into a deep underground geologic formation for very long-term storage. That geological formation may be a deep saline formation or a depleting oil or natural gas field at least 0.8 kilometers (2,600 feet) below the surface of the earth where the pressure will ensure the CO_2 will stay in a supercritical fluid state. CO_2 may also be stored in unmineable coal seams at somewhat shallower depths using a different storage process.

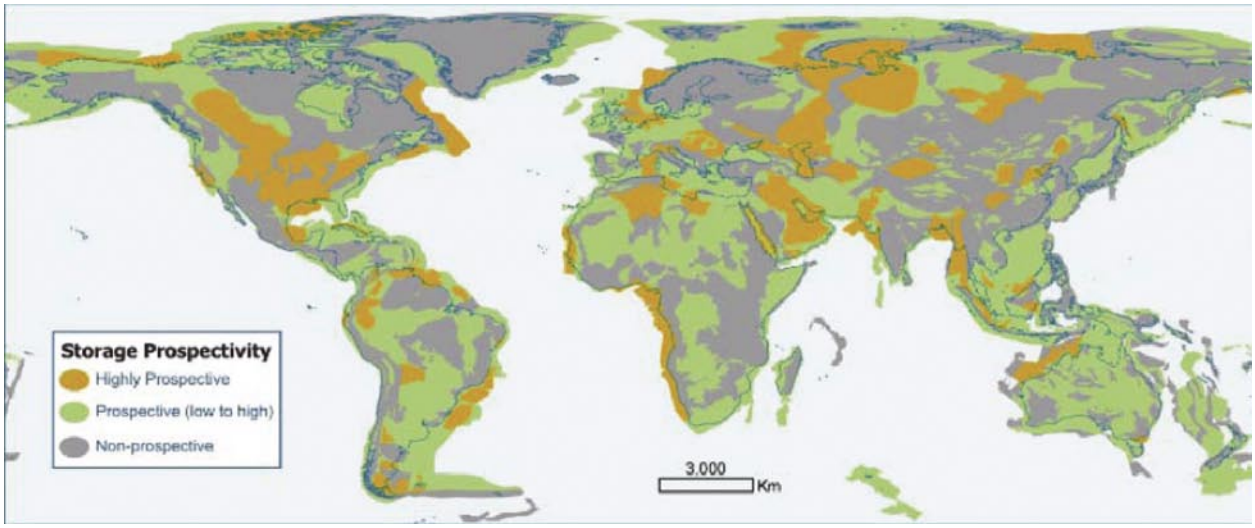
The Annex "Advancing CCS Technology" provides a detailed explanation of how CCS works and how it is being improved.



In CCS, CO_2 is captured before it is emitted into the atmosphere, compressed, transported to the injection site and then injected underground in suitable deep rock formations.

Image Source: CO2CRC

Most credible projections indicate that fossil fuels will continue to be the world's dominant energy source until at least mid-century. Even with recent price increases, fossil fuels are abundant and relatively low cost. As a result, most countries will not be able to substantially reduce their dependence on fossil fuels over the next several decades. Renewable energy sources may take decades to significantly penetrate the global energy market. Developing countries, particularly China and India, have made huge



Prospective sites to store CO_2 are located throughout the world.

Source: Bradshaw, J. and Dance, T. (2004): "Mapping geological storage prospectivity of CO_2 for the world's sedimentary basins and regional source to sink matching," in (E.S. Rubin, D.W. Keith and C.F. Gilboy eds.), GHGT-7, Proc. Seventh International Conference on Greenhouse Gas Control Technologies, Vancouver, B.C., Canada, September 5-9, 2004.

strides in developing their economies and need inexpensive energy to continue development. They will continue to use fossil fuels.

CCS is one of many measures needed to combat climate change. Each measure is necessary but, by itself, insufficient. Each measure addresses only part of the problem. Many measures are necessary to create the required total cumulative emission reduction. All are needed.

Other than increasing efficiency, CCS is the only CO_2 mitigation measure that reduces emissions from large stationary industrial sources that utilize fossil fuels. CCS can prevent further de-stabilization of the climate from the continued use of fossil fuels and can be a bridging technology to widespread use of renewable and alternative energy sources. Used with sustainable biomass, CCS can make an even greater contribution to reducing the concentrations of CO_2 in the atmosphere by actually removing atmospheric CO_2.

CCS is needed to reduce CO_2 emissions in several energy and process industries. The industries from which CO_2 may be captured include power generation, oil and gas production, iron and steel, cement, chemicals, and pulp and paper. These industries are vital to both economic and human welfare in industrialized and developing countries. CCS is the only means for these industries to continue operation while still substantially reducing CO_2 emissions beyond reductions through increasing efficiency and switching to low-or no-carbon energy sources. Not having CCS available would significantly increase cost, difficulty and time required to achieve the required emissions reduction.

The IPCC has identified nearly 7,900 existing sources as potential candidates for CCS. Each emits over 0.1 million tonnes per year of CO_2. These have total emissions of 13.5 $GtCO_2$ per year, nearly half of the current total of man-made emissions. This is shown in Table 1.

Many more large stationary sources are expected to be built in the coming decades, especially in developing countries. Most of these large stationary sources are power plants, but many others are industrial facilities in various process industries as well as extractive industries such as oil and gas production. In power generation, CCS can reduce CO_2 emissions from plants that burn fossil

fuels or biomass. CCS can also be used for large biomass fermentation or bioenergy facilities that emit large amounts of CO_2. Most CCS is likely to be used for new facilities, but under the right conditions, it may be retrofit to existing facilities. Retrofits may be more difficult because most existing facilities were not designed for CCS, may not have the space and were not sited with proximity to geologic storage in mind.

CCS is anticipated to be capable of removing a large amount of the CO_2 that would otherwise be emitted into the atmosphere from large power generation and industrial sources. IEA projects that by 2050, CCS for power generation could remove about 4.8 $GtCO_2$ per year and CCS for other industrial sources could remove about 4.3 $GtCO_2$ per year. Together, that would be about 19 percent of the total emissions reduction needed in that year (48 $GtCO_2$) to stabilize the climate.

Suitable geologic formations are located all over the world. Likely global storage capacity is estimated to be equal to several hundred years of the total emissions from potential sources. The IPCC estimated storage capacity at a minimum of 1,678 $GtCO_2$ and potentially much higher. Current emissions from large stationary sources are 13.5 $GtCO_2$ per year.

Need for CCS: Increasingly Recognized

The need for CCS to reduce CO_2 emissions from large stationary facilities is being recognized. CCS was first seriously considered as an option for reducing CO_2 emissions in the mid-1990s. At that time, it was generally perceived to be a highly speculative concept. Few scientist and engineers were working on it and it was not a priority for any governments or private companies. The first major commercial CCS project, Sleipner, began operation in 1996 in response to a carbon tax imposed by the Norwegian government on offshore oil and gas production.

Since those early days, extensive work efforts have gone into CCS. The results so far have been highly positive: a profusion of technology options emerged; several commercial projects began operation, are under construction or are planned; and CCS is now a high priority for many governments and companies.

Today, governments, research institutions, industrial firms and environmental groups in both industrialized and developing countries are working to bring CCS into widespread commercial use. Thousands of engineers and scientists are now focusing their efforts on CCS. CCS is increasingly supported by experts on climate change. Initiatives such as the IEA Greenhouse Gas R&D Programme (IEAGHG) and the Carbon Sequestration Leadership Forum (CSLF) are fostering international collaboration. The goal is for CCS to enter widespread commercial use by about 2020, about a dozen years from now.

Table 1. Potential Capacity for Geologic Storage ($GtCO_2$)

Reservoir Type	Lower Estimate	Higher Estimate
Oil and Gas Fields	675*	900*
Unmineable coal fields	3 to15	200
Deep Saline Formations	1,000	Uncertain but possibly 10,000

*These numbers would increase by 25 percent if "undiscovered" oil and gas fields are included in this assessment.

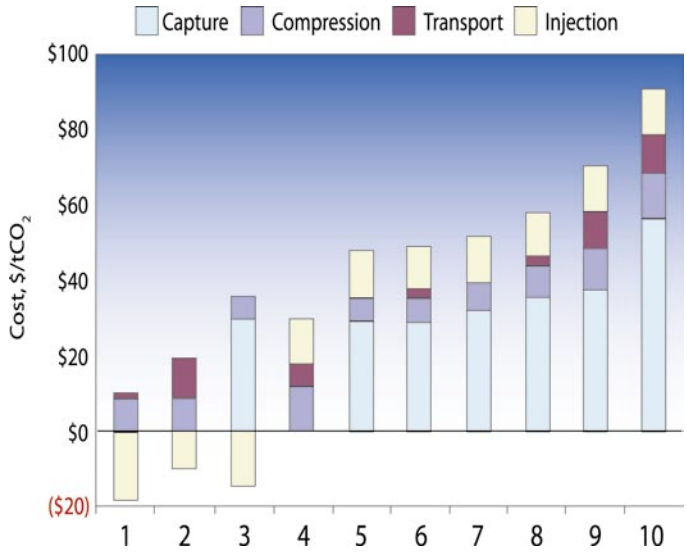
Source: IPCC, Special Report on Carbon Dioxide Capture and Storage, 2005. (The estimates in this 2005 report are based on published sources now several years old. Since then, considerable effort has gone into exploration and estimates today would probably be much higher.)

Cost of CCS

The cost of CCS varies widely among projects. The affordability of CCS depends on its cost compared to the costs of the other greenhouse gas abatement options needed to adequately cut emissions. It will likely be more expensive than some other options and less expensive than others. Future costs are likely to be reduced as the result of R&D as well as incremental improvements.

The costs of all three CCS stages—capture (including compression), transport and storage—vary considerably. Accordingly, so does the cost of the total system. The cost of CCS depends on many factors. These factors include type and size of source, type of capture process, distance to injection site, location onshore or offshore, injection depth, required monitoring, and level of integration. For sources such as power plants, capture is the dominant cost element. It accounts for 70 to 80 percent of total costs, although this percentage varies substantially. The range of total costs for CCS systems is wide, from negative (i.e., making a profit through CO_2 sales) to quite high.

Near-term opportunities for commercially-viable CCS projects tend to have low capture costs and substantial revenues from sales of the captured CO_2. Facilities with low capture costs have a CO_2 stream that is highly concentrated and already at high pressure. Examples include facilities whose commercial purpose is to separate CO_2 from natural gas as well as ammonia and hydrogen production facilities. CO_2 may be injected into depleting oil fields to increase production in a process known



1. **High purity ammonia plant** nearby, EOR
2. **High purity natural gas processing facility** moderately distant, EOR
3. **Large coal-fired power plant** nearby, ECBM
4. **High purity hydrogen production facility** nearby, depleted gas field
5. **Large coal-fired power plant** nearby, deep saline formation
6. **Coal-fired power plant** moderately distant, depleted gas field
7. **Iron and steel plant** nearby, deep saline formation
8. **Smaller coal-fired power plant** nearby, deep saline basalt formation
9. **Cement plant** distant, deep saline formation
10. **Gas-fired power plant** distant, deep saline formation

The total cost of CCS and its components varies with the location and source as well as the distance to and type of storage. At the low end is a negative total cost (a net profit) for an ammonia plant with nearby EOR. Such plants already operate commercially. At the high end is a natural gas plant distant from a saline formation. Costs will decline as CCS technology matures. (These cost estimates are for sites in the United States using technologies and costs as of 2006. These costs are now out of date but illustrate the wide range and diverse makeup of potential CCS costs.)

Source: JJ Dooley et al. "Carbon Dioxide Capture and Geologic Storage: Core Elements of a Global Energy Technology Strategy to Address Climate Change," Battelle Memorial Institute, April 2006.

as Enhanced Oil Recovery (EOR). Similarly, CO_2 may be injected into depleting natural gas fields in Enhanced Gas Recovery (EGR) or into methane-bearing coal seams for Enhanced Coal Bed Methane (ECBM). Revenues can be earned by selling the CO_2 for EOR, EGR or ECBM.

Cost-Effectiveness of CCS

CCS is a cost-effective measure to reduce CO_2 emissions compared to other needed CO_2 abatement measures. Energy Technologies Perspectives, 2008, a comprehensive study of the global role of technology in a sustainable energy future,[1] clearly shows the cost-effectiveness of CCS. This study projects the measures and technologies required to reduce CO_2 emissions by half or more by 2050 (the minimum goal set by the IPCC) for the lowest cost. It then identifies the work activities needed to commercialize the full set of required technologies quickly enough to achieve that reduction. All major economic sectors— transportation, buildings, industry, energy transformation and power—are considered. The study compares three future scenarios:

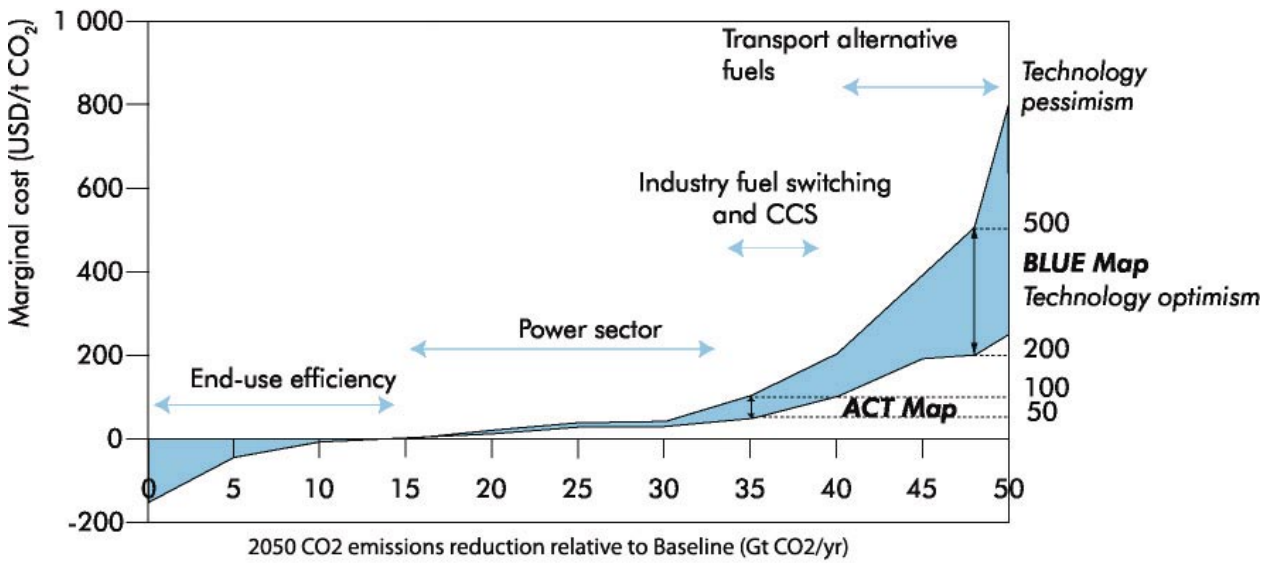
1. The Baseline scenario represents the current, unsustainable trends of rising energy consumption and CO_2 emissions. In this "business-as-usual" scenario, CCS and other advanced technologies do not reach widespread commercial use. Global CO_2 emissions rise to 62 $GtCO_2$ per year by 2050.
2. In the ACT Map scenario, only technologies that already exist or are in an advanced state of readiness are used to bring CO_2 levels back to 2005 levels by 2050. This is not sufficient to meet even the minimum IPCC goal.
3. In the BLUE Map scenario, emissions are cut to 50 percent of 2005 levels (about 14 $GtCO_2$ per year) by 2050 through new technologies such as CCS and the "urgent implementation of unprecedented and far-reaching new policies in the energy sector." The total emissions reduction in 2050 is 48 $GtCO_2$ per year—sufficient to reach the minimum IPCC goal.

CCS is only one of many technologies considered in the Energy Technologies Perspectives, 2008 study. Both the ACT Map and BLUE Map scenarios require substantial investment (US$17 trillion and US$45 trillion respectively through 2050) in a wide variety of technologies. The BLUE Map scenario, in particular, requires extensive efforts to develop a broad portfolio of technologies, not just CCS. For both the ACT Map and BLUE Map scenarios, the range of abatement costs is estimated under two sets of assumptions about technology trends: "technology optimism" and "technology pessimism."

The cost of CCS is in the mid-range of the needed emissions reduction measures. The range of costs of measures for reducing emissions under both the optimistic and pessimistic cases in both the ACT Map and BLUE Map scenarios are shown in the figure on page 8. The least-cost measures in all cases are to increase end-use efficiencies, but increasing efficiency is not sufficient to adequately reduce emissions. Power sector measures (mostly CCS) are needed under both optimistic and pessimistic assumptions. In both scenarios, they are in a cost-effective range.

The same study shows that the cost of reducing CO_2 emissions to half their current level would nearly double without CCS (US$394 per tonne versus US$200 per tonne). As Table 2 shows, if CCS does not become available, emissions will be nearly 50 percent higher at the cost of US$200 per tonne (20.4 versus 14.0 $GtCO_2$ per year).

[1] International Energy Agency, Energy Technology Perspectives, 2008: Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008.



This figure from Energy Technology Perspectives, 2008 shows why CCS will be a cost-effective measure for cutting emissions in half by 2050 (a 48GtCO_2 per year total emissions reduction called the BLUE Map scenario). The blue shaded area shows the cumulative emissions reduction that can be achieved in 2050 at different costs of emissions reduction. Measures are arrayed in order of increasing cost from left to right. Costs under the most optimistic technology assumptions are at the bottom of the blue shaded area and costs under the most pessimistic assumptions are at the top. CCS is in the mid-range of costs of all the measures needed to achieve the 48 GtCO_2 per year emissions reduction. Not only is CCS needed, but even more expensive measures will also be needed. This is the case regardless of whether optimistic or pessimistic technology assumptions are made.

Image Source: International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

CCS represents only a fraction of the total effort required to stabilize the climate. Efforts will also be required to develop and commercialize many of the other technologies needed to combat climate change, although CCS will be one of the more cost-effective measures. Advances in energy efficiency, renewable energy sources and other technology will all require extensive development. Investments in new and replacement infrastructure will be needed in every sector. IEA's Energy Technology Perspectives, 2008 study estimates that a total of US$45 trillion will be needed by 2050 to cut CO_2 emissions to half their 2005 levels. The predominant investment will be in the transportation sector due to the large projected expansion of that sector in developing countries.

Less investment is required in CCS to produce a gigatonne of emissions reduction than is required for some other necessary abatement options.

Table 2. Comparison of Global Emissions Reduction and Cost in 2050 with and without CCS

	BLUE Map Scenario	BLUE Map Scenario with no CCS
Emissions Reduction in 2050 (GtCO_2/yr)	48	41.6
2050 Emissions (GtCO_2/yr)*	14.0	20.4
Marginal cost to meet target (US$/tonne CO_2)	200	394

* These are the emissions at the BLUE Map scenario marginal cost of US$200/tonne CO_2. The 14 GtCO_2/yr target can only be met at the marginal cost of US$394/tonne CO_2 in the BLUE Map Scenario if there is no CCS. All costs are in constant 2007 US dollars.

Source: Table 2.5 of International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

As such, it is an efficient investment. A total of US$45.0 trillion is required between now and 2050 to combat climate change. Of that, US$3.0 trillion is required for CCS—US$1.4 trillion in power generation and US$1.6 trillion in industry/fuel transformation. CCS represents just 6.7 percent of the global investment to reduce CO_2 emissions. Yet CCS will create 9.1 $GtCO_2$ per year of emissions reduction in 2050, which is 19.0 percent of the total global emissions reduction. This is shown in Table 3.

Understanding CCS Cost Estimates

Published estimates of CCS costs vary widely and are often difficult to reconcile. Cost estimates for technologies such as CCS, which are at an early phase of maturity, are more uncertain than for mature technologies. Estimates for CCS projects are usually based on hypothetical plants for which engineers and cost estimators have less experience than with comparable existing technologies. The cost of building a power plant with CCS, for example, is much more difficult to estimate than the cost of building a power plant without CCS. Plants with CCS have more options and there is a lack of experience building such plants. Much less is known about the ultimate plant design and project execution. As CCS matures, the uncertainty associated with cost estimates will decrease.

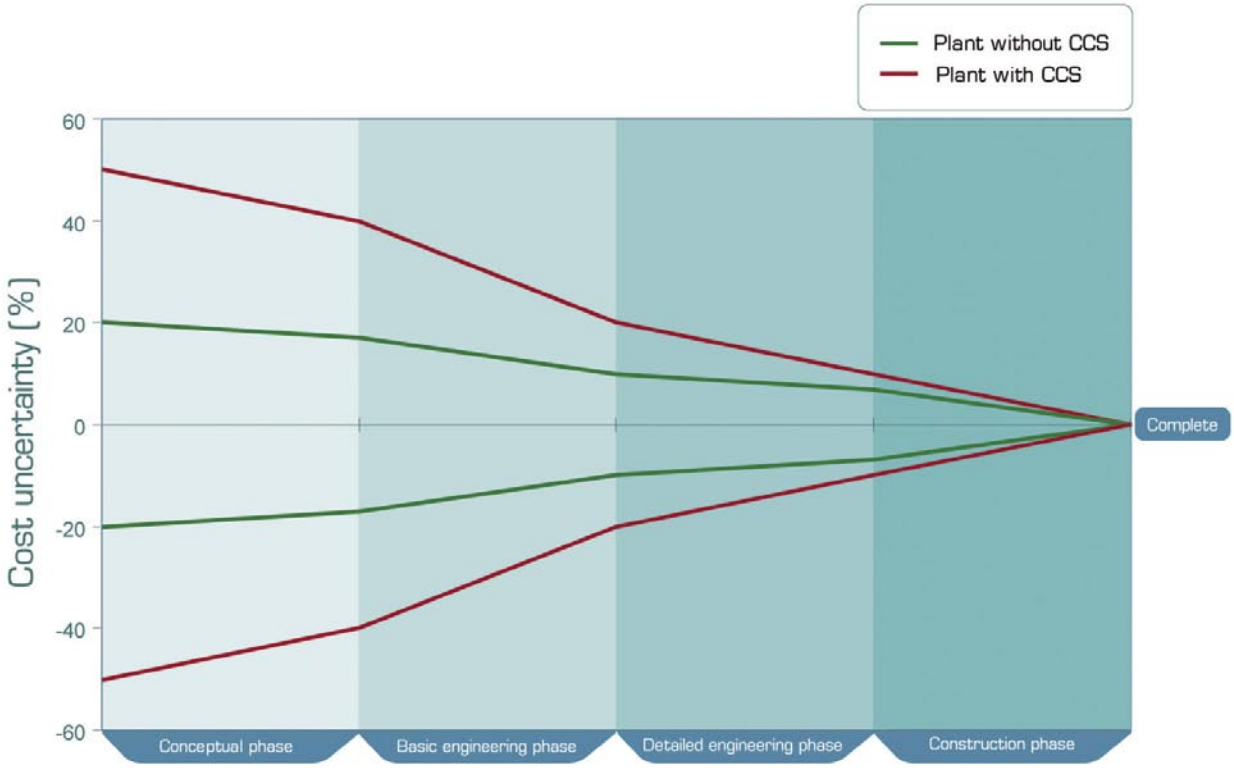
Accurate cost comparisons among technologies must also ensure that assumptions are consistent. For example, capital cost estimates may or may not include financing costs, which may be substantial. There are also regional differences, for example, in the cost of construction labor and commodities. Such assumptions may not always be explicitly stated.

These issues are not limited to CCS; they are typical of cost estimates of less mature technologies. These differences are compounded for a system as complex as CCS with the three very different stages of capture, transport and storage.

Table 3. Cutting CO_2 Emissions in Half: CCS Share of Investment and 2050 Emissions Reduction

Sector/Measure	Cumulative Investment (Trillion US$)	Share of Global Investment (%)	2050 Global Emissions Reduction ($GtCO_2$/Yr)	Share of Emissions Reduction (%)
Power Generation				
CCS	1.4	3.1	4.8	10.0
Other Power Generation Measures	2.2	4.9	13.5	28.1
Total	3.6	8.0	18.3	38.1
Industry/Fuel Transformation				
CCS	1.6	3.6	4.3	9.0
Increasing Efficiency/Fuel Switching	0.3	0.7	3.7	7.7
Total	1.9	4.2	8.0	16.7
Other Sectors				
All Measures	39.5	87.7	21.7	45.2
All Sectors				
CCS	3.0	6.7	9.1	19.0
Other Measures	42.0	93.3	38.9	81.0
Total	45.0	100.0	48.0	100.0

Source: Based on International Energy Agency, Energy Technology Perspectives, 2008, Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008. BLUE Map Scenario. Investment amounts are in constant 2007 US dollars.



Power plants with CCS have greater uncertainty in capital cost than plants without CCS at each phase of development. Most cost estimates of plant designs with CCS are conceptual in nature, whereas plant costs without CCS are based on experience. Uncertainty in capital cost goes to zero when a plant is built. The uncertainty bands shown in this graphic are illustrative and not indicative of any specific project.

Source: Bluewave Resources, LLC and CO2CRC.

The most widely-cited cost estimates for CCS with post-combustion capture in power generation tend to be extrapolations of the cost of the earliest option, amine separation. The original amine separation process, however, was not designed for CCS, but rather was adapted to CCS from other applications. Other options have now been proposed or are under development for CCS instead of amine separation. Some of these options have a good chance of improving on amine separation's cost and performance. Estimates based on amine separation or other early concepts may well overstate the cost of the post-combustion capture technology that will ultimately become commercial.

CCS Cost Trends

CCS costs are currently high due to the relatively early level of development, but are expected to come down as the technology matures. Cost uncertainty will also be reduced as experience is gained. Cost reduction is one of the primary goals of work on CCS, particularly for the capture stage. For example, the U.S. Department of Energy's goal is to develop CCS systems in which the cost of electricity generation would increase by less than 10 percent for pre-combustion capture and less than 35 percent for post-combustion capture. Similarly, the goal of the Castor project sponsored by the European

Commission is to reduce the cost of post-combustion capture from €50-60 down to €20-30 per tonne of CO_2.

Researchers are pursuing many options to reduce costs, including improvements to earlier concepts and new options for capture and storage. Much of the expected cost reduction will likely come not from the development of new technologies, but rather from a process of refinement and incremental improvement. CCS will be improved by building projects, learning what works well and what does not, identifying potential refinements, and making improvements to subsequent generations. This has been the experience with similar technologies.

Analogous technologies have experienced significant cost decreases as more were built, illustrated in Table 4. Capital and operating costs were reduced for these technologies as lessons learned in earlier installations were applied to later units, although sometimes after an initial increase. A doubling in production capacity reduced capital cost by 10 to 27 percent and the operating and maintenance costs by 6 to 27 percent.

CCS will also very likely experience such cost reduction. Much of the knowledge that will improve performance and reduce costs can only come from experience. The optimum design of components and the best way to integrate those components will be learned by building projects. The need for experience is a major reason why multiple commercial-scale demonstrations will be necessary to effectively bring costs down. Multiple projects will be required to address the diverse set of technologies and implement the lessons of learning-by-doing.

One current trend, however, is tending to increase the cost of CCS and its alternatives. Capital costs of major infrastructure projects throughout the world have been rising rapidly since about 2003, driven largely by increasing demand for construction materials in fast-growing developing countries such as China. This demand has affected the costs of proposed CCS projects as well as the costs of alternatives to CCS in power generation, such as renewables and nuclear energy.

Table 4. Cost Reductions Experienced by Technologies Similar to CCS

Technology	Percent Cost Reduction for each Doubling of Technology Capacity	
	Capital cost	Operating and Maintenance (O&M) Cost
Flue gas desulfurization	11	22
Selective catalytic reduction	12	13
Gas turbine combined cycle	10	6
Pulverized coal boilers	5	18
LNG production	14	12
Oxygen production	10	5
Hydrogen production	27	27

Source: Edward S. Rubin, Sonia Yeh, Matt Antes, Michael Berkenpas and John Davison, "Use of experience curves to estimate the future cost of power plants with CO_2 capture," International Journal of Greenhouse Gas Control, 1 (2007) 188–197, 26 February 2007.

Readiness of CCS

Given a substantial global commitment by government and industry, CCS can be ready in time to play a substantial role mitigating climate change. The first commercial CCS projects are now in operation in a few industrial facilities. CCS projects in the power sector will likely begin operation in the 2010s. Many will be demonstration projects. CCS can begin contributing a substantial portion of the required emissions reduction for power generation starting about 2020 and for more widespread industrial processes somewhat later. Like several other CO_2 reduction measures, transitional incentives will be required before CCS becomes commercially viable in most applications. Such incentives will no longer be required when the cost of CCS declines below the commercial value of CO_2 emissions reduction.

Many measures will be required to reduce CO_2 emissions. Some can start now; many others require new technologies not yet fully available, such as CCS. Those technologies can be developed.

As shown earlier, the potential "climate stabilization wedge" from CCS will grow to be large—9.1 $GtCO_2$ savings in 2050, which is about 19 percent of the emissions reduction needed in that year.

Given a strong commitment by government and industry to developing the technology and the institutional framework, CCS should be able to achieve those reductions. Power generation and other industrial sources constitute about 60 percent of CO_2 emissions produced by humans. Reducing these emissions is critical to achieving a stable climate.

Current Status of CCS Technology

The readiness of CCS is complex because CCS may be used for several types of CO_2 sources, each with different requirements. CCS is also a system that integrates three different and evolving stages (CO_2 capture, transport and geologic storage). Various technologies with different degrees of maturity compete for a role in each stage. Each of these technologies will be ready for different applications at different times.

Each of the stages of CCS is <u>technically ready</u> today for many applications. Existing technologies for those stages already work well in current applications. Each stage of CCS has been used commercially for many years, for some applications:

- ✓ <u>Capture technologies</u> have long been used commercially for high-concentration, high-pressure CO_2 sources. Over the last decade or so, as work on CCS has intensified, many new ideas for capture from lower-concentration, lower-pressure sources such as power plants have emerged. Technologies based on these ideas are at different levels of development. Some are still in the lab. For others, pilot plants have been operated and still others are ready for demonstration.

- ✓ <u>CO_2 transport</u> by pipeline, rail and truck has also long been safely used. CO_2 pipelines are in commercial use in several places. Ocean-going ships to transport CO_2 long distances have been proposed, but none have yet been built or operated.

- ✓ Geologic CO_2 storage has been conducted successfully in most types of reservoirs in which it is planned. More experience is needed to understand CO_2 behavior in diverse geologic formations, particularly deep saline formations and coal beds, and to refine methods to monitor and verify storage.

Success of the stages of CCS in their current applications, similarity of current to proposed applications, and the diverse technology options that are emerging, all give high confidence that CCS can be applied to more widespread sources such as power generation and types of storage reservoirs such as deep saline formations. Much

Current Commercial CCS Projects

Four fully-integrated, large scale CCS projects are in commercial operation today. Three—Sleipner, In Salah and Snøhvit—inject CO_2 from a natural gas production facility where it is separated from the natural gas sent to market. The fourth project captures CO_2 at the Great Plains Synfuels Plant and transports it to the Weyburn-Midale project. All four are contributing to the knowledge base needed for widespread CCS use.

Sleipner. The world's first commercial CCS project started in 1996 when Norway's state-owned oil company, Statoil, began injecting more than 1 million tonnes a year of CO_2 under the North Sea. This CO_2 was extracted with natural gas from the offshore Sleipner gas field. In order to avoid a government-imposed carbon tax equivalent to about US$50/tonne, Statoil built a special offshore platform to separate CO_2 from other gases. The CO_2 is re-injected about 1,000 meters below the sea floor into the Utsira saline formation located near the natural gas field. The formation is estimated to have a capacity of about 600 billion tonnes of CO_2, and is expected to continue receiving CO_2 long after natural gas extraction at Sleipner has ended.

In Salah. In August 2004, Sonatrach, the Algerian national oil and gas company, with partners BP and Statoil, began injecting about 1 million tonnes per year of CO_2 into the Krechba geologic formation near their natural gas extraction site in the Sahara desert. The Krechba formation lies 1,800 meters below ground and is expected to receive 17 million tonnes of CO_2 over the life of the project.

Snøhvit. Europe's first liquefied natural gas (LNG) plant also captures CO_2 for injection and storage. Statoil extracts natural gas and CO_2 from the offshore Snøhvit gas field in the Barents Sea. It pipes the mixture 160 kilometers to shore for processing at its LNG plant near Hammerfest, Europe's northernmost town. Separating the CO_2 is necessary to produce LNG and the Snøhvit project captures about 700,000 tonnes a year of CO_2. Starting in 2008, the captured CO_2 is piped back to the offshore platform and injected in the Tubåsen sandstone formation 2,600 meters under the seabed and below the geologic formation from which natural gas is produced.

Weyburn-Midale. About 2.8 million tonnes per year of CO_2 is captured at the Great Plains Synfuels Plant in the U.S. State of North Dakota, a coal gasification plant that produces synthetic natural gas and various chemicals. The CO_2 is transported by pipeline 320 km (200 miles) across the international border into Saskatchewan, Canada and injected into depleting oil fields where it is used for EOR. Although it is a commercial project, researchers from around the world have been monitoring the injected CO_2. The IEA Greenhouse Gas R&D Programme's Weyburn-Midale CO_2 Monitoring and Storage Project was the first project to scientifically study and monitor the underground behavior of CO_2. Canada's Petroleum Technologies Research Centre manages the monitoring effort. This effort is now in the second and final phase (2007-2011), to build the necessary framework to encourage global implementation of CO_2 geological storage. The project will produce a best-practices manual for carbon injection and storage.

work, however, remains to refine the technologies, reduce costs, select the best technologies and designs, and integrate all of the stages.

CCS and its stages are commercially viable today in several applications. CCS as an entire system is commercially viable in some projects. Individual stages are commercially viable on their own in some applications. The capture stage is commercially viable where capture costs are low due to high concentrations of CO_2 at high pressure or where a valuable end-product is produced after separation. The transport stage is commercially viable where CO_2 has an adequately high value at a distance from the source, typically for Enhanced Oil Recovery (EOR). The storage stage is commercially viable where CO_2 is injected into depleting oil fields for EOR. Most of the CO_2 for EOR is now extracted from natural underground formations. Ironically, CO_2 is in short supply and is considered highly valuable today in some of the oilfields where it could most be used.

CCS is not yet widely commercially viable as an integrated system in the applications where its use could be most widespread. These applications include power generation and many industrial processes. The question is: what will it take to make CCS commercially viable?

Phases of Technology Development

Large-scale, complex technologies such as capture or geologic storage require extensive development over a period of time. This development typically proceeds in several phases. Each phase increases in scale, complexity and cost and each builds upon what was learned in the prior stages. New ideas are first tried out in research and development programs, typically in laboratories or small-scale experiments. Technologies that prove successful in the lab may move on to pilot projects. These are facilities that do everything a full-scale, commercial installation would, but on a smaller scale and at a lower total cost. The demonstration phase of a new technology involves the operation of a full-scale facility that may still have many experimental aspects. Everything that is learned up to this point then goes into the first commercial projects, which is sometimes called the deployment phase. These early projects are often not fully commercially viable but form the basis for more efficient, effective and less-costly commercial phase projects.

In practice, these phases are not always distinct; projects may combine attributes of multiple stages. Various CCS technologies are currently in each development phase.

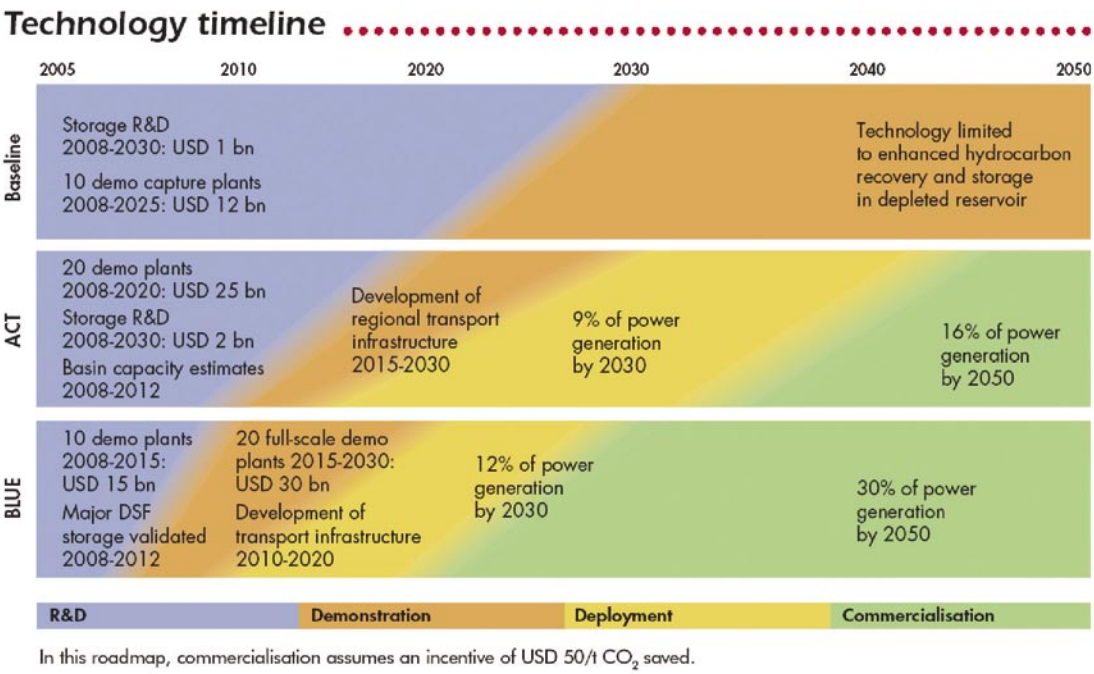
Making CCS Technically Ready and Commercially Viable

The speed with which CCS technology becomes technically ready and commercially viable in widespread applications will depend, in large part, on the resources devoted to developing it. As discussed earlier, the IEA Energy Technology Perspectives, 2008 study evaluated what it would take to make the full set of required technologies commercial on a timely basis to create necessary emissions reductions. Timelines to bring technologies into commercial use in each of the scenarios (Baseline, ACT Map, BLUE Map) were developed for each new technology, including CCS. The following page contains timelines for CCS in the power sector and the technology targets required to achieve those timelines. The timelines show how CCS can be moved through the phases of development (research and development, demonstration, deployment and commercialization) to achieve the scenario goals. Each path corresponds to a different level of global commitment to reach the technology targets.

A fundamental conclusion of the Energy Technology Perspectives, 2008 study is that

cutting emissions in half will require substantial efforts to develop and commercialize a wide range of technologies not available today. CCS for both power generation and industry is a vital part of that portfolio of technologies.

Other studies and roadmaps in Australia, Canada, China, Europe and the United States and by the CSLF confirm that, with adequate effort, CCS can be commercial by about 2020. While much needs to be done to develop and deploy



Technology targets

	ACT: Emissions Stabilisation	BLUE: 50% Emissions Reduction
RD&D		
Capture technologies for three main options (post-combustion, pre-combustion, and oxy-fuelling)	Technologies tested in small- and large-scale plants. Cost of CO_2 avoided around USD 50/t by 2020. Chemical looping tested	
Demonstration targets	20 large-scale demo plants with a range of CCS options, including fuel type (coal/gas/biomass) by 2020	30 large-scale demo plants with a range of CCS options, including fuel type (coal/gas/biomass) by 2020
New gas-separation technologies: membranes & solid adsorption	New capture concepts: next-generation processes, such as membranes, solid absorbers and new thermal processes	
Technology transfer	Technology transfer to China and India	Technology transfer to all transition and developing countries
Deployment		
Regional pipeline infrastructure for CO_2 transport	Major transportation pipeline networks developed and CO_2 maritime shipping	
Deployment targets	Early commercial large-scale plants by 2015 (ZEP, ZeroGen, GreenGen)	30% of electricity generated from CCS power plant by 2050

Technology timelines for CCS vary in the three IEA scenarios. Widespread commercial use of CCS for power generation is possible by about 2020, but this will require a substantial effort to advance the technology development and the operation of multiple demonstration projects.

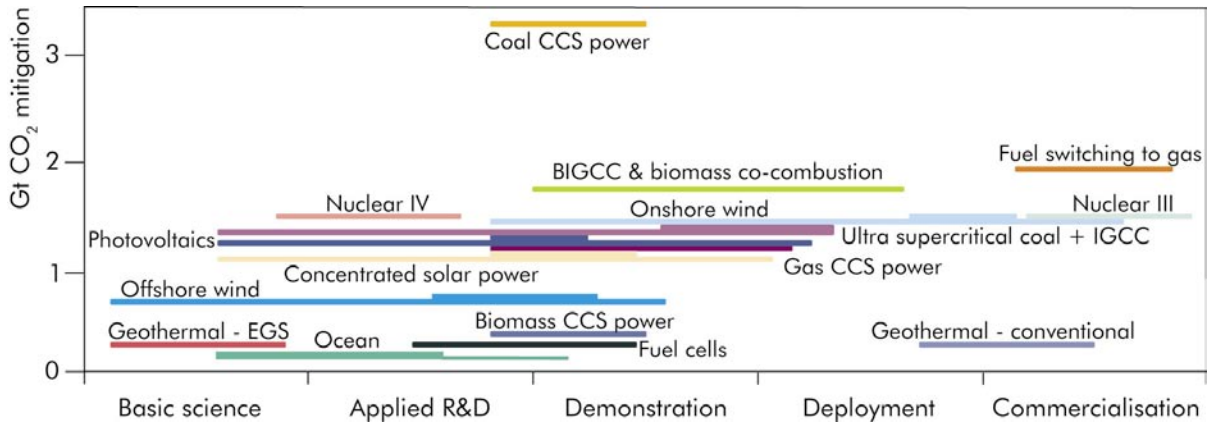
Image Source: International Energy Agency, Energy Technology Perspectives, 2008, Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008.

commercial CCS, it can be done. It requires mostly evolutionary progress and integration of existing technologies, not the development of entirely new ones. This is a lesser challenge than developing new technologies and there are many options.

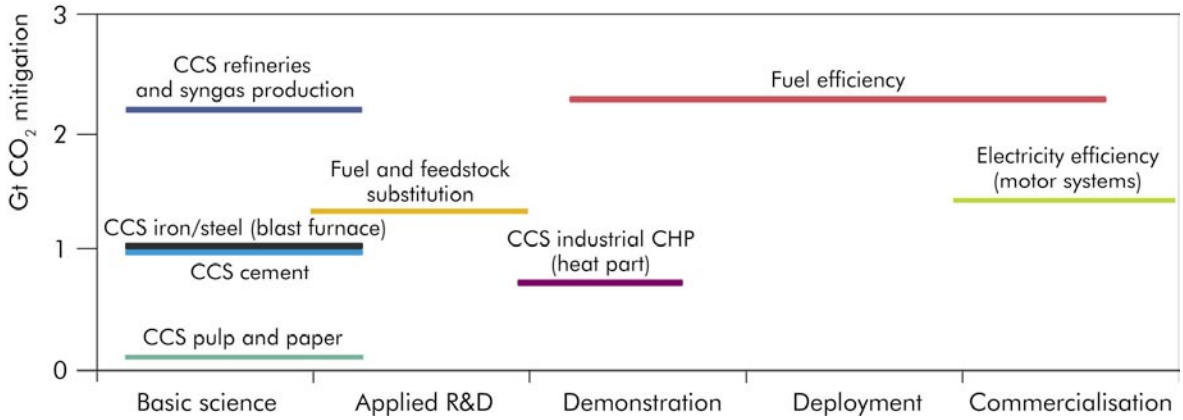
CCS Readiness Compared to Other Measures

The question of readiness is important and needs to be asked of all greenhouse gas mitigation measures under development. While CCS requires further development for many applications, many of the other technologies being considered to help reduce CO_2 emissions also require further development, often extensive. The commercial use of many of the other technologies proposed to mitigate CCS is probably further away and far more uncertain than CCS. (See figure below.) Given the inherent uncertainty of technology research and development, pursuing a broad and diverse portfolio of technology options is the approach with the highest likelihood of success in achieving adequate emissions reduction. CCS is one of the least uncertain options in the portfolio of new CO_2 emissions reduction technologies. This is especially true because each stage of CCS is really a family of many different technologies, each of which is advancing. CCS has many chances to succeed.

Power Generation Technologies



Industrial Technologies



This figure compares the development status of CCS and other new emissions reduction technologies in the power generation and industrial sectors. It also shows each measure's potential for CO_2 mitigation. In both sectors, CCS has the greatest mitigation potential. In the power sector, CCS is more advanced in development than many other options. In the industrial sector, fuel and electricity efficiency can reduce CO_2 emissions earlier, but CCS can eventually mitigate more CO_2 emissions. These technologies all require further development.

Image Source: International Energy Agency, Energy Technology Perspectives, 2008, Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008.

While many emissions reduction technologies may not be ready today, they are all still vitally needed to reduce CO_2 emissions adequately. The IEA Energy Technology Perspectives, 2008 study makes it clear that, while substantial emissions reduction must start soon with technologies currently at hand, today's technologies are not sufficient. New technologies, some of which will not be available for many years, are needed. Given its large potential for emissions reduction, CCS is probably the most important of these.

Capture-Ready Plants and Retrofits

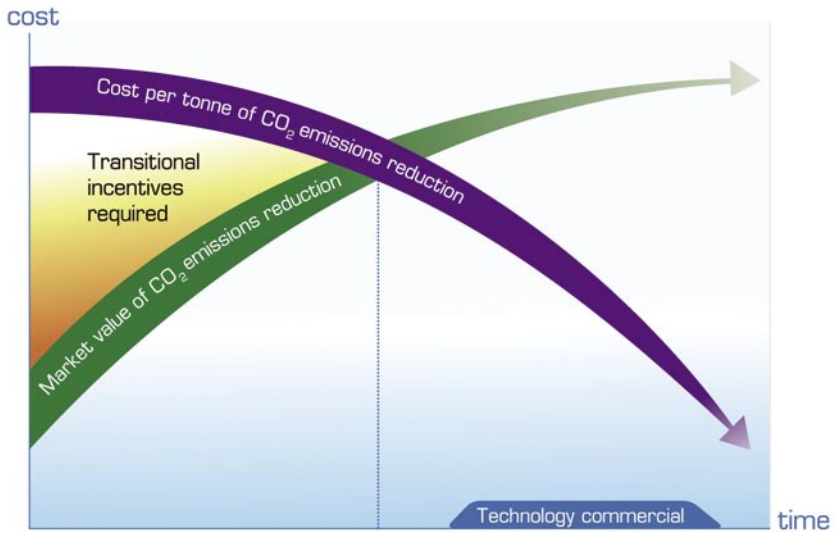
Many new large coal and natural gas power plants will be built to meet expected needs for electricity over the next decade or so before CCS is expected to be commercially viable for most power generation. A concept called "capture readiness" has been proposed for power plants built before CCS is fully commercial. A capture-ready plant would not initially have the capability to capture CO_2 but could be modified later to implement CCS when it is commercially viable. The design of a capture-ready power plant would depend on the plant and the type of capture. In general, capture readiness would require a location economically accessible to geologic storage with adequate capacity, space for the capture and compression equipment and the ability to integrate control systems.

This concept has generated considerable discussion as a measure to avoid "locking in" the emissions of power plants built before CCS is commercial for that application. From the perspective of a power plant developer, capture readiness would avoid plants being rendered obsolete by future CO_2 emissions limitations. First proposed for power plants in developing countries, it is also now being discussed for industrialized countries.

No definition of capture-ready plants is universally accepted. Perhaps the most widely-cited definition is that developed by the IEA Greenhouse Gas R&D Programme (IEAGHG):

> *A CO_2 capture-ready power plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture ready is to avoid the risk of "stranded assets" or "carbon lock in."*
>
> *Developers of capture-ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO_2 capture have been eliminated. These might include:*
>
> - *A study of options for CO_2 capture retrofit and potential pre-investments*
> - *Inclusion of sufficient space and access for the additional plant that would be required*
> - *Identification of a reasonable route to CO_2 storage*
>
> *Competent authorities involved in permitting power plants should be provided with sufficient information to judge whether the developer has met these criteria.*

This is a very broad definition, offered as a starting point for discussion. Over time, more specific definitions and regulatory requirements will likely emerge. Various proposals have been made for capture-ready power plants. The European Commission (EC), for example, has proposed that all new fossil power plants be capture ready, based on the IEAGHG definition. The United Kingdom is developing the details for its implementation of the EC proposal. Elsewhere, developers claim that their proposed power plants are capture ready. Ultimately, clear legislation or regulation based on adequate technical data must provide the definition of capture ready and its significance.



Like other emissions reduction measures, transitional incentives will be required before CCS becomes commercially viable in applications such as power generation. Such incentives will no longer be required when the cost of CCS declines below the value of CO_2 emissions reduction.

Image Source: Bluewave Resources, LLC and CO2CRC.

Retrofitting existing power plants would face many of the same issues as capture-ready plants. There is much less flexibility with retrofitting. Decisions on factors that determine feasibility of capture have already been made. Nonetheless, studies show that some existing power plants might be able to add CCS, provided they are relatively new and efficient, have adequate space, and are located directly above or very near to potential injection sites. Several pilot projects and major demonstration projects are planned as retrofits. Another option with older, inefficient plants might be to both replace the existing power generation equipment and add CCS. Retrofitting will be very site specific.

Time Frame for Commercial Viability of CCS

The economic value of CCS will be determined primarily by the value that society—through government—places on reducing CO_2 emissions. That value could be an explicit monetary value created through a carbon trading system or carbon taxes; it could be implicit through regulatory limitations on emissions from specific facilities; it could be mandated use or a portfolio standard; or it could be a combination of approaches. Different approaches are being considered in different places. Examples include the Norwegian offshore carbon tax, the European Trading System for CO_2, and the Kyoto Protocol's Clean Development Mechanism (which does not yet apply to CCS).

Implementation of long-term incentives is at an early phase. Probably the most common incentive is a "cap-and-trade" emissions trading system for CO_2. Under such a system, tradable "emission allowances" are allocated within a defined market up to a limit or "cap." This limit decreases over the years in most proposals. A market is created in CO_2 emissions which sets a monetary value for CO_2 emissions reduction. Its value depends on the overall supply and demand of emission allowances. Emission trading systems have already been established in the European Union, the Canadian province of Alberta, and the Australian state of New South Wales. National trading systems have also been proposed by the Australian and Canadian governments. In the United States, there is a voluntary CO_2 trading market; several states are working on trading systems; and proposals have been made in Congress for a national cap-and-trade system.

At current or projected emissions allowance prices in existing trading systems, such as the European Trading System (ETS), CCS would not be commercially viable over the next decade for power generation, its most widespread application. Even though the technology is technically ready for use, its cost is higher than the ETS price and

there are too many uncertainties for most firms to use the technology, unless transitional incentives are employed. While a few—mostly very large—industrial firms may be early movers (see box), the vast majority of firms are likely to wait until the cost and uncertainties come down, unless substantial offsetting incentives are provided. Even early movers will not proceed with projects that are not expected to be commercially viable.

Transitional incentives will be required for demonstration and early commercial CCS projects before projects become commercially viable. Such transitional incentives may include government cost-sharing on demonstration projects, portfolio generation standards, public investment, trust funds or various types of tax incentives such as investment tax credits. Similar transitional incentives are already widely used to advance emissions

Why Be an Early Mover on CCS?

Several power companies are deeply involved with CCS research and are implementing CCS at their power plants, long before it is required or economically viable. Why would they do that? They say that it is to gain experience to put them ahead of the game when the time comes.

Duke Energy, a large U.S. power generator, is planning an IGCC power plant at Edwardsport, Indiana at a cost of US$2 billion, considerably more than a conventional coal-burning power plant with the same capacity. "Duke believes IGCC and carbon capture and storage technology offer great promise in allowing us to continue using abundant, affordable coal in a world in which greenhouse gas emissions will be regulated," said John Stowell, Duke's vice president of environmental health and safety policy. "We are confident that the technology will work at commercial scale. Our Midwest power plants are located on favorable geologic ground where we have a real chance to prove and improve the technology," Stowell added.

Global diversified mining company Rio Tinto and the global energy company BP have formed a joint venture company called Hydrogen Energy to develop and operate low emissions power projects utilizing fossil fuels and CCS. Hydrogen Energy is developing two projects, one in California and one in Abu Dhabi. Both are progressing through feasibility studies with an objective of starting operation in the early to mid 2010s. Rio Tinto believes that CCS will make an important contribution to reducing emissions of greenhouse gases to the atmosphere. "The investment we are making in Hydrogen Energy will allow us to deliver decarbonised energy and carbon capture and storage.... Investing now means we will be well-placed to create value for shareholders from opportunities in the emerging clean power market," said Tom Albanese, CEO of Rio Tinto.

Another large U.S. power company, American Electric Power (AEP), is moving down all three capture paths—post-combustion, pre-combustion and oxyfiring—simultaneously. In addition to the post-combustion retrofits, AEP plans to build IGCC units in two U.S. states, West Virginia and Ohio. AEP is also working on a feasibility study on oxy-coal carbon capture and expects to have a commercial-scale installation of the technology on an AEP plant in the 2012 to 2015 timeframe. "Technology development needs are often cited as an excuse for inaction, but we see these needs as an opportunity for action," Nick Akins, AEP executive vice president, said.

The European electric utility Vattenfall is conducting several major CCS projects. These projects include an oxyfiring pilot plant now in operation at its Schwarze Pumpe plant, storage of the CO_2 captured at Schwartze Pumpe in the Altmark gas field, capture of CO_2 at its Nordjylland power plant in Denmark and participation in the European Test Centre Mongstad. According to Lars G. Josefsson, CEO of Vattenfall, "Alternative sources of energy are developing rapidly; nevertheless, the world will remain dependent on fossil fuels for a long time and CCS is an essential part of the solution. Vattenfall has taken a leading position in this field to get a first-mover advantage in the market. It is not only necessary from a climate perspective; it is good business, too."

reduction measures such as renewables and efficiency and, in some cases, for CCS projects. Transitional incentives are needed before, but not after, the value of emissions reduction exceeds the market value. As CCS develops, the costs and risks go down and, as emissions caps tighten, the value of such reductions increases, thus making transitional incentives unnecessary.

The economic value of CCS will also be determined, in part, by how level the incentives playing field is for CCS compared to other emissions reduction measures. A level playing field exists when the incentives—both transitional and permanent—are essentially the same for any measure of the same effectiveness. A playing field that is not level can result in the use of less cost-effective technologies to reduce CO_2 emissions.

With an adequate global commitment by government and industry, CCS can be ready to make a timely contribution to mitigating climate change. By about 2020, CCS can begin to contribute significantly to emissions reduction for power generation. Somewhat after 2020, CCS can begin to contribute to emissions reduction in widespread industrial processes.

What It Will Take

In order for CCS to enter timely, widespread commercial use, the capture and geologic storage stages of CCS require further technical development, as does the integration of the capture stage with host facilities. More experience in larger and more diverse projects is also necessary. Progress is being made in all these areas, but more work is required. Much of that work is ongoing.

Commercial CCS also requires the creation of enabling institutional frameworks that consist of:

- Effective expertise and institutions,
- Viable legal-regulatory frameworks,
- The ability to finance CCS, and
- Public understanding and support for CCS.

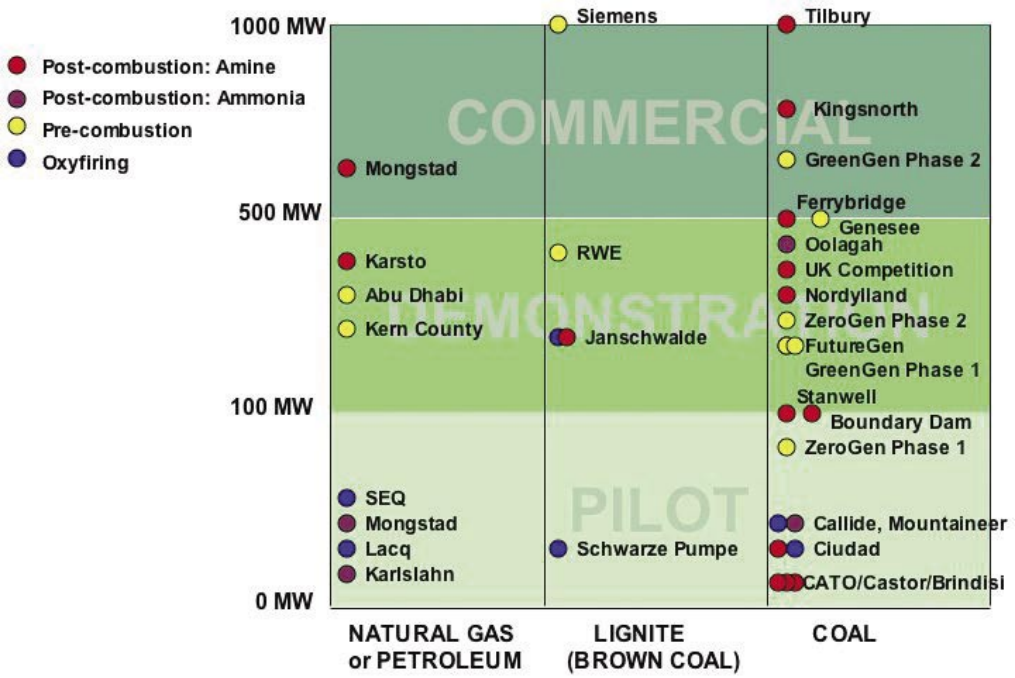
Developing the Technology

The major challenge associated with capture is its high cost for low-concentration, low-pressure, high-volume sources such as power plants. For power generation, three alternative approaches to capture—pre-combustion, post-combustion, and oxyfiring—are being developed. The objective of much of the work on each of these approaches is to substantially reduce cost. Each approach has strong advocates in the scientific and engineering community. It is not clear which approach will ultimately prove most cost-effective. It is still early in the development of CCS; much more work needs to be done; and new and innovative ideas are continuing to emerge. It is possible that different approaches may prove most attractive under different circumstances. Capture technologies for industrial processes such as steel and cement making must be specifically designed for those types of facilities.

Widespread implementation of geologic storage requires a more complete understanding of what happens to the CO_2 when large volumes of CO_2 are injected under diverse geologic conditions. A better understanding will facilitate development of storage practices tailored to a wide variety of geological conditions. Experience so far has been in a limited number of geologic settings.

CCS technologies must also be integrated with host facilities and experience must be gained building and operating these technologies on a larger scale. The Annex "Advancing CCS Technology" explains CCS technology in greater detail and describes some of the projects underway to develop that technology further.

Rapid progress is improving effectiveness, efficiency and cost, as well as applicability to different emission sources and geologic formations. Advances in capture technologies are continuing to take place as work proceeds. As further CCS experience is gained, more will be learned about how to implement CCS projects, and the cost and technical barriers will fall. More advanced and effective options for capture will become available over time. Similarly, testing of CO_2 storage in different geologic formations is building the knowledge required to store CO_2 in the wide range of geological conditions that will eventually be needed. Chemical and geologic engineering have a long history of advancement through refinement and incremental improvement. Such refinements and improvements will also



Many new capture projects for power generation are now planned throughout the world. They will use various fuels and capture technologies and are different sizes. A sample of the proposed projects is illustrated here. If a diverse set of these projects is ultimately implemented, they will provide much of the information necessary to make CCS widely commercially viable.

Image Source: Adapted from IEA Greenhouse Gas R&D Programme.

occur with CCS. Numerous projects are underway throughout the world. Progress to date has been substantial and more can be expected.

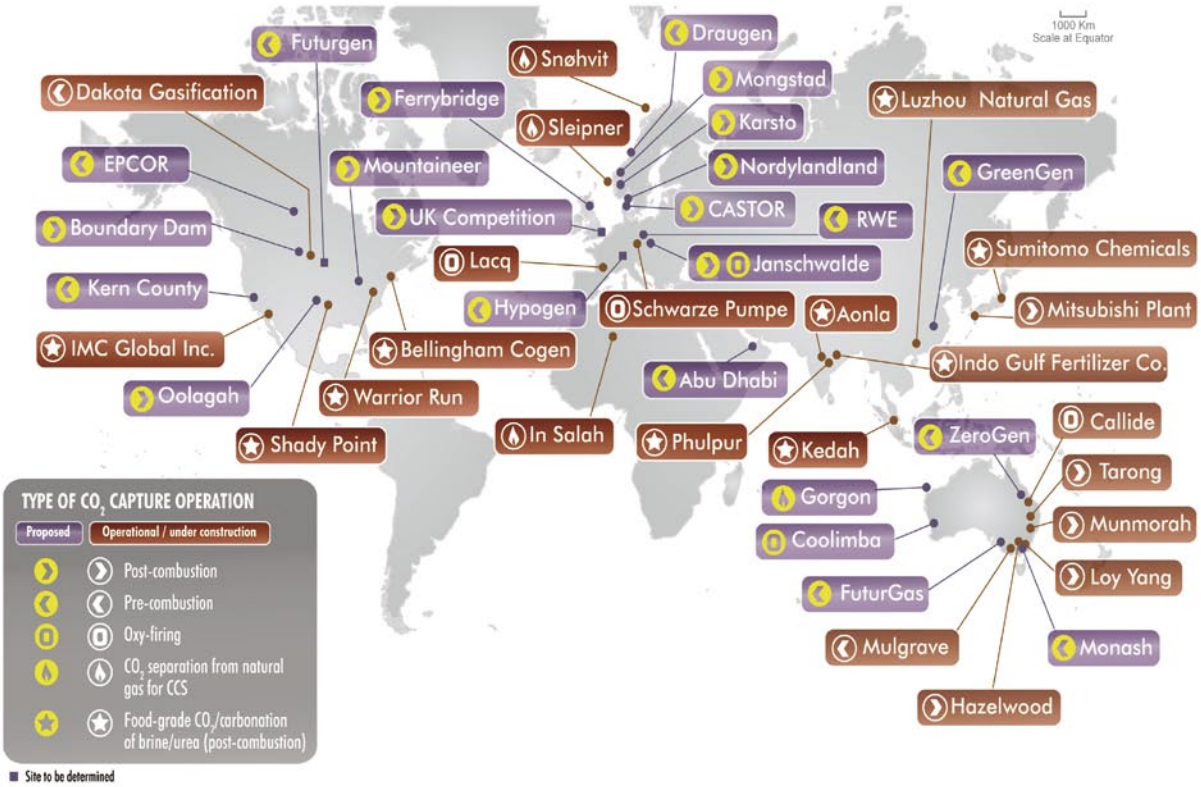
The challenges of integration and scale can be met through the experience of building and operating fully-integrated and commercial-scale CCS facilities. Many projects are in the pilot, demonstration and early commercial phases. Ultimately, not all will enter operation, but timely implementation of CCS will require that many of these projects succeed. Over the coming years, many commercial-scale fully-integrated projects will likely be built. Ideally, such facilities will be phased in different generations so that the lessons learned in one generation can be built into the next.

Considerable work on CCS is being conducted throughout the world and these efforts are growing rapidly. Many scientists, engineers and geologists are now devoting their efforts to all aspects of CCS. The number of these professionals is growing rapidly along with CCS-related budgets and the number of projects in both the public and private sectors.

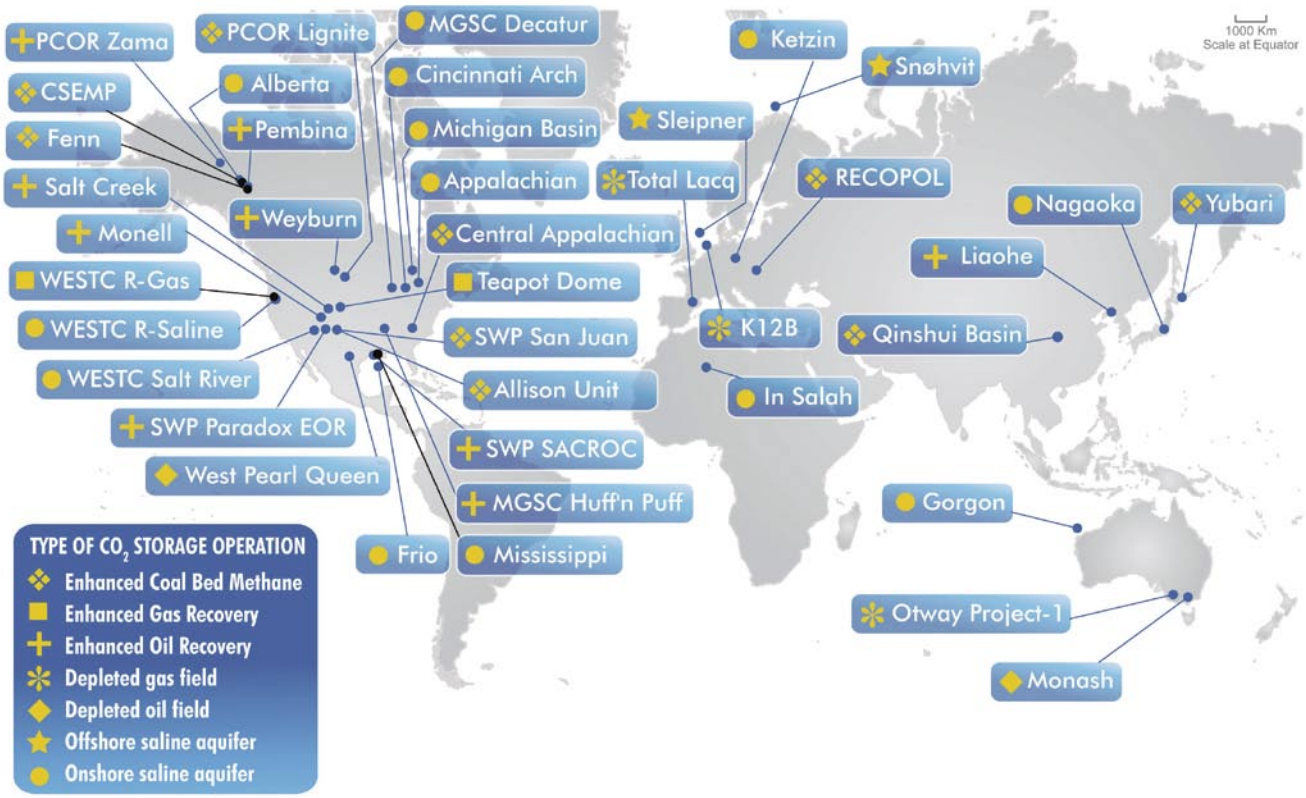
Government budgets devoted to CCS have been expanding rapidly from virtually nothing in the late 1990s, and the priority of CCS is rising. The U.S. Department of Energy's fiscal year 2008 CCS budget is US$283 million across several programs and is growing from year to year. In addition, US$6 billion in loan guarantees and US$1.65 billion in tax credits are targeted at CCS projects. The European Commission (EC) is spending approximately €32 million per year on CCS and several of its member states also have significant and growing budgets for CCS. The 2008 Canadian federal budget for CCS is C$250 million and provinces also contribute funding. The Canadian province of Alberta alone is planning to spend C$2 billion on new CCS projects. The Australian government has established its low-emissions coal initiative with funding of AU$500 million and has announced an international carbon capture institute funded at AU$100 million. Together, these and other countries are funding a diverse array of projects on every aspect of CCS and this funding is expected to grow. In addition, international collaboration among governments is taking place through the International Energy Agency (IEA) and the Carbon Sequestration Leadership Forum (CSLF), with 21 countries and the European Commission as members.

Private-sector investments in all aspects of CCS technology have also rapidly increased as equipment vendors and service providers seek a posi-

Capture Projects



Storage Projects



Increasing numbers of projects on all aspects of CCS are taking place throughout the world. As time goes on these projects are becoming more advanced and are moving toward commercial status.

Image Source: CO2CRC.

tion in what they see as a potentially large and fast-growing market and as the owners of large sources of CO_2 seek ways to reduce their emissions. Many companies are making investments.

Private collaborations are also taking place through various joint ventures and through joint projects such as the Carbon Capture Project, sponsored by eight of the world's leading energy companies and the EC's Zero Emissions Platform, comprised of over 30 companies, NGOs and other organizations. In the United States and parts of Canada, private companies and NGOs participate in seven Regional Carbon Sequestration Partnerships sponsored by the U.S. Department of Energy. These Partnerships are undertaking numerous projects, particularly in testing geologic storage in diverse geologic settings. The Australian Coal Association has established a voluntary fund that will raise AU$1 billion for low-emissions and demonstration projects over a ten-year period.

Building Expertise and Institutions

CCS projects must be planned, built, operated and closed, and all phases must be subject to appropriate regulation. Most private companies and government agencies that will conduct each of these functions have yet to fully develop the necessary capabilities and expertise. The people who are currently involved in CCS are, for the most part, experts who are involved in research and development activities.

Building the expertise and institutions will require the development of educational programs in universities and other training programs. Today, few such university courses or training programs exist, but they are beginning to emerge. One ex-

Career Opportunities in CCS

Consider a career in CCS. That is the advice from Dutch graduate student Michiel C. Carbo. Carbo is a Ph.D. candidate in the field of zero emissions power plants and works at the Energy Centre of the Netherlands (ECN). He is preparing for a career in CCS, an industry now in its infancy, but with tremendous growth potential.

Carbo was attracted to carbon mitigation and CCS not only because "it's a good cause," but because he finds CCS very challenging. "There are a lot of ins and outs and it is cutting edge research," he said. Carbo plans to earn his Ph.D. in chemical engineering in 2009 to prepare him to work on CCS. Toward that end, he also attended the first CCS Summer School of the International Energy Agency's Greenhouse Gas R&D Programme (IEAGHG). At the moment, very few specific academic courses are available for those looking to enter the new field of CCS, so IEAGHG attempts to fill the gap.

Since the field is young and research has only started in earnest relatively recently, "a lot of the studies involve learning-by-doing," he said. Chemical engineers like Carbo generally work on CO_2 capture. They look for ways to reduce costs and energy requirements. Those chemical engineers need to keep abreast of the work being done by geologists at the other end of the CCS process. Geologists are continually trying to improve CO_2 injection and storage. Both disciplines work to improve efficiencies and lower costs. In the Netherlands, the two disciplines work together at CACO, the Dutch national CCS program. Similar programs around the world unite disciplines to work on CCS.

Carbo sees interest in CCS growing rapidly. "There are more and more attendees [at conferences] and more and more publications as well," says Carbo. Many engineers working in CCS are employed by research institutions. As CCS takes off, enormous additional opportunities await engineers with the right skills and knowledge.

ample is a summer course on CCS operated by the IEA Greenhouse Gas R&D Programme. Both the CSLF and Asia Pacific Economic Cooperation (APEC) have CCS capacity-building initiatives that conduct training for developing countries.

Increasing numbers of organizations are now working on various aspects of CCS. Expertise and institutions will be built as private firms, governments, and research institutions engage in activities to develop and implement CCS, and as educational institutions and others begin to teach about CCS.

Creating Legal-Regulatory Frameworks

CCS is a new type of activity and complete legal-regulatory frameworks for CCS do not yet exist in most jurisdictions. Many legal-regulatory issues must be addressed: permitting, property rights, long-term liability, monitoring requirements, the classification of CO_2, and jurisdictional issues, to name a few.

Legal-regulatory frameworks are being created in many countries. In Australia, the federal government has proposed a framework for CCS regulation using the Offshore Petroleum Act of 2006 as a template. In Canada, legal frameworks that will apply to CCS are being created at both the federal and provincial level. On the Canadian federal level, proposed greenhouse gas emissions reduction targets are to be set by the Regulatory Framework for Industrial Greenhouse Gases, which is to go into effect in 2010. Under this Framework, new oil sands and coal-fired electricity plants entering operation in 2012 and later will have to meet a plant standard equivalent to CCS. Other regulatory activities are taking place at the provincial level, particularly in Alberta, the center of the Canadian energy industry. The EC in early 2008 proposed a directive to enable environmentally-safe capture and geologic storage of CO_2 as part of a major legislative package. In this package, the EC has proposed that all new fossil fuel plants be capture ready. In the United States, the existing framework of federal and state laws in areas such as oil and gas and underground injection is being adapted to CCS. The U.S. Environmental Protection Agency is proposing rules for underground injection of CO_2. Japan is developing a system of permits for sub-seabed storage. Injection under the seabed is covered by the London Convention and its 1996 Protocol, which were amended in 2007 to allow injection of CO_2 in sub-seabed geologic formations. The IEA has recently started a CCS Regulators' Network in which regulators from around the world can share their ideas and experiences.

One particularly important legal issue is financial responsibility for the long-term safety and reliability of geologic storage. The injection phase of geologic storage for a specific project will typically take place over 20 to 40 years. Injected CO_2 must stay in the ground for much longer, perhaps thousands of years. This is longer than the life span of any project and longer than commercial organizations last.

Project developers seek specific, well-defined limits on liability. Similarly, the public also seeks an understanding of risks and assurances that those conducting geologic storage take appropriate responsibility for the consequences of their actions.

Financing CCS

Ultimately, CCS projects will be financed entirely on a commercial basis. Commercial financing will depend on adequate returns on CCS investments and appropriate risk-sharing. Currently-commercial, large-scale projects (Sleipner, In Salah, and Snøhvit) were financed on the balance sheets of large multinational firms and are part of much larger portfolios and corporate strategies. In the case of Sleipner and Snøhvit,

CCS had high value as a means of avoiding a carbon tax. Eventually, CCS will need to create economic value on a stand-alone or retrofit basis for more firms' power or industrial facilities. As the price of CO_2 emissions rises and costs and risks decrease, more commercial financing will become available. Until then, CCS projects will require public financing for some share of capital costs. In addition, CCS will raise the operating cost for facilities. Commercial viability will require offsetting higher operating costs by giving value to CO_2 reduction.

Major projects are now being developed largely through various forms of public-private partnerships in which government and industry share costs and risks. Examples of such partnerships include the Cooperative Research Centre for Greenhouse Technologies (CO2CRC) in Australia, the ecoENERGY Technology Initiative in Canada, the Regional Carbon Sequestration Partnerships in the United States and Canada, the EC's Zero Emissions Platform and the CCS Demonstration Competition in the United Kingdom. The goals of these partnerships are often ambitious. For example, the goal of the ZEP is to enable European fossil fuel power plants to have zero CO_2 emissions by 2020.

CCS will not be a stand-alone technology. It will be part of larger projects that are the sources of the CO_2 that CCS abates. Those projects will have their own goals, for example, the production of electricity, natural gas, steel or cement. CCS will be commercially viable and financeable for its CO_2 source when the value of CCS exceeds its cost. CCS will be evaluated by potential users on the basis of how it affects total project economic performance, not just the costs of the CCS component. For example, CCS operating costs could affect how much electricity a power plant could economically generate within its electric system. Integration with the source facility is critical.

Project developers also need to understand the potential liabilities they face and ensure that those risks are acceptable to investors. Various methods of allocating risk and balancing these interests have been proposed, including private insurance, government assumption of long-term liabilities and various types of funds paid for by the operators. Discussions are underway about how to provide for liability sharing; it will eventually be the topic of legislation or regulation in many jurisdictions. Knowledge of geology and storage engineering developed over the next several years through geologic storage projects is fundamental. Early projects may require greater public assumptions of financial liability. As the risks of CCS are defined and reduced, it can be expected that treatment of financial liabilities will eventually follow normal commercial practices.

Public Understanding

Implementation of CCS will require public understanding and support. The public must understand why CCS is needed to mitigate climate change, how it will be conducted, why it will be safe and its role in the overall portfolio of climate mitigating measures. Surveys indicate that the public in most countries is generally unaware—or only recently becoming aware—of CCS. Efforts are underway in many countries to raise public understanding of CCS.

Expert Recommendations

At their 2005 Summit in Gleneagles, Scotland, the G8 Heads of State requested that the IEA and CSLF consider a number of issues relating to CCS, including how to accelerate near-term opportunities for CCS. In 2006 and 2007, the IEA and CSLF convened leading experts on CCS from around the world in a series of workshops to discuss near-term opportunities for CCS. These experts discussed the barriers to widespread commercial

use of CCS and developed 27 recommendations to advance near-term deployment of CCS.[2] The recommendations addressed both technical and institutional issues. To a large extent, these recommendations lay out what would be required to make CCS both technically ready and broadly commercially viable by about 2020. They were delivered to the G8 at its 2008 meetings in Japan. Some of the most important of these recommendations are listed below.

Recommendations Addressing Technical Issues

- Demonstrate CO_2 capture and storage through a diverse portfolio of least 20 fully integrated industrial-scale CCS demonstration projects;
- Undertake and fund work projects of CO_2 capture technologies with the objective of reducing costs and improving overall system efficiencies;
- Develop national storage capacity estimates; and
- Conduct further work to understand and define the concept of "capture and storage ready" and its value as a viable mitigation strategy.

Recommendations Addressing Institutional Issues

- Establish legal and regulatory frameworks for safe, large-scale geological storage;
- Utilize public-private partnerships and government-government collaboration to accelerate adoption of large-scale CCS projects;
- Raise public education and awareness;
- Address the financing gap facing early projects with higher costs and risks;
- Create a value for CO_2 reductions from CCS projects; and
- Take concerted international action on large-scale integrated CCS demonstration projects and near-term opportunities.

The G8 responded to these proposals at its 2008 meetings in Japan. The G8 Energy Ministers issued a statement at their June meeting stressing the critical role of CCS in tackling the global challenges of climate change and energy security. They also stated collective support for the recommendations developed by the IEA and the CSLF. In particular, they strongly supported the recommendation that 20 large-scale CCS demonstration projects be launched globally by 2010. The G8 Heads of State, meeting in July 2008, also supported actions to advance CCS, again specifically mentioning the 20 demonstration projects.

Implementation of these recommendations has already begun, but much more remains to be done. As discussed earlier, research and development is expanding around the world, particularly to reduce capture costs. Many large-scale demonstration projects have been proposed and legal and regulatory frameworks are being developed. Numerous new projects are now being conducted or planned and these projects build on the results of earlier projects. These projects are also becoming more sophisticated and are moving toward commercial status. They cover most of the varied approaches to both capture and storage.

Conclusion

CCS can be an important, cost-effective and timely part of the solution to climate change. Widespread commercial viability of CSS is feasible by about 2020 with sustained global cooperation by governments and industry. The results so far have been highly positive: a profusion of technologies have emerged; several commercial projects have begun operation, are under construction or are planned; and CCS has become a high priority for many governments and companies.

[2] The full discussions of these recommendations may be found on the websites of the International Energy Agency (www.iea.org) and the Carbon Sequestration Leadership Forum (www.cslforum.org).

Annex: Advancing CCS Technology

CCS has three basic stages: capture, transport and geologic storage. There are multiple options for each stage and all three must be combined into an integrated system. The technologies for all three stages are evolving rapidly.

How CO_2 Capture Works

CO_2 capture involves the separation of CO_2 from other exhaust gases emitted by a power generation or industrial facility and compression of that CO_2 into a supercritical fluid state for transport and storage. In power generation, CO_2 may be separated using one of three methods:

- Post-combustion,
- Pre-combustion, and
- Oxyfiring.

Other methods—membrane separation, chemical looping and cryogenic separation—are at an earlier phase of development. In industrial facilities, CO_2 may be emitted from multiple sources, including chemical reactions. The nature and complexity of industrial facilities varies widely and capture must be integrated into production processes.

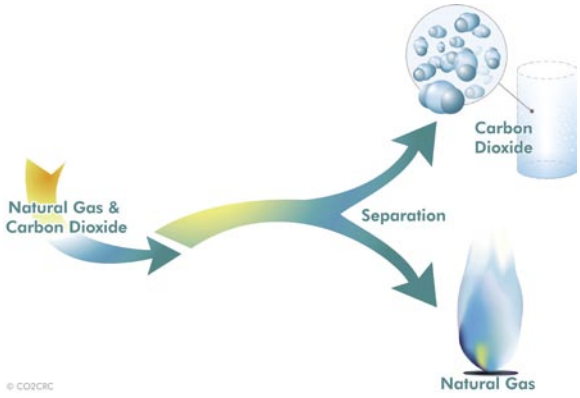
In post-combustion capture, CO_2 is separated from other exhaust gases after combustion of the fossil fuel. Post-combustion capture can be used to remove CO_2 from the exhaust gas streams of facilities such as power plants and industrial facilities. This system is analogous to systems that remove pollutants such as particulates, sulfur oxides and nitrogen oxides from many power plants. Post-combustion capture approaches use chemical or physical solvents to dissolve the CO_2, which is then released for compression at a later stage in the process. The original, and most developed, post-combustion capture concept is amine separation. This concept was derived from the process widely used for separating CO_2 from economically valuable components of natural gas such as methane. That process uses monoethanolamine (MEA) as the solvent. Natural gas from production wells often contains CO_2, and MEA separation is used to remove the CO_2 from those production streams.

Several potential solvents are being considered for post-combustion capture, including various types of amines, amino acid salts, ammonia, sodium carbonate solutions and solvent blends. Amines and ammonia are currently the two leading candidates for post-combustion capture solvents, but what will ultimately prove to be the best solvent has yet to be determined.

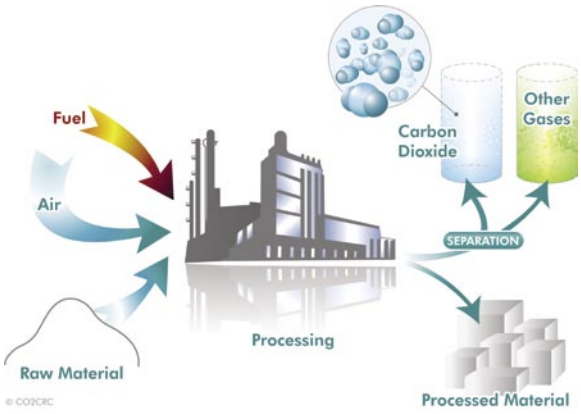
A variant of using solvents is a process called adsorption, in which the CO_2 adheres to the surface of a solid or liquid rather than being dissolved. Solids such as zeolites and activated carbon are being considered for adsorption-based processes.

Post-combustion capture is used today on a small scale in some power plants and industrial facilities. It is employed either to produce CO_2 for industrial uses such as carbonated beverages or in test facilities for CCS. In those power plants and industrial facilities, typically only part of the exhaust stream of the power plant is captured.

Capture from Natural Gas Processing

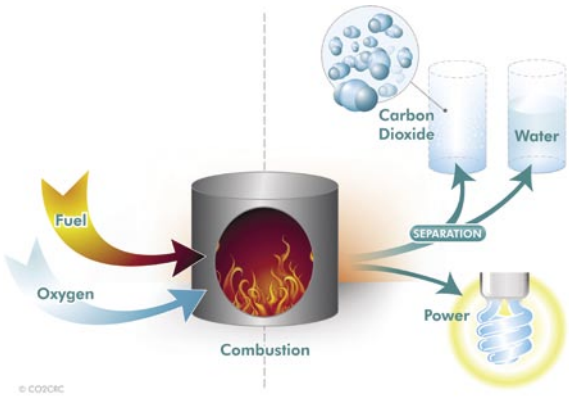


Capture from an Industrial Process

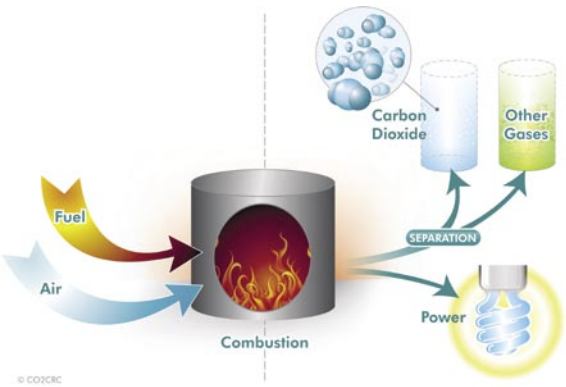


Capture from Power Generation

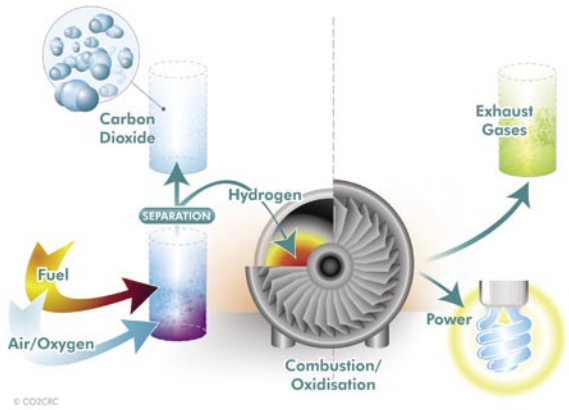
Oxyfiring



Post-combustion



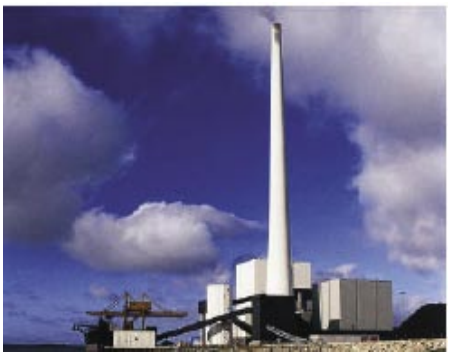
Pre-combustion



A number of options are available for CO_2 capture depending upon the type of source. Capture from natural gas processing and some industrial processes is now fully commercial and widely used. Capture from other industrial processes and power generation is under development.

Image Source: CO2CRC

CO_2 is captured commercially from the flue gas of a natural gas-fired combustion turbine operated by Suez Energy Generation in Bellingham, Massachusetts, U.S.A. The plant uses a proprietary MEA-based solvent.



As part of the Castor project sponsored by the European Commission, 25 tonnes per day of CO_2 were captured from the exhaust stream of the coal-fired Ejsberg Power Station in Denmark operated by Elsam. The project began operation in 2006 and was completed two years later.

Image Source: IEA Greenhouse Gas R&D Programme

The Quest for a Better Solvent

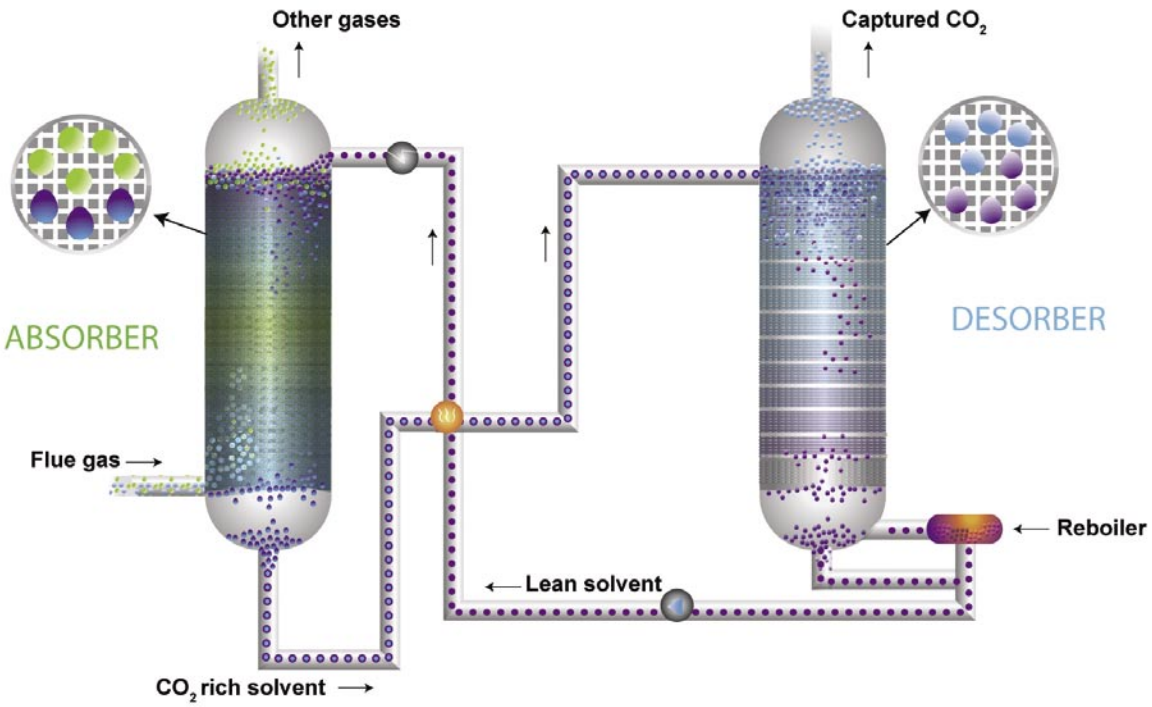
The race is on to find the best solvent for post-combustion CO_2 capture. Many companies believe that whoever finds the best solvent will be rewarded with a huge global market. Academic and government labs are also taking part in the search.

Engineers around the world are working to improve post-combustion capture, especially for coal-fired power plants. New capture systems must work with lower concentrations of CO_2 and the impurities that come with burning coal. No matter what is burned, the most critical component of post-combustion capture is the solvent.

The most common solvent used for CO_2 separation is monoethanolamine (MEA). MEA attaches to CO_2 relatively easily. Breaking apart the mixture and regenerating the pure solvent, however, substantially increases energy use. MEA degrades in the presence of CO_2, and has to be regularly supplemented, yielding a high rate of solvent consumption. MEA is also corrosive and therefore requires materials not prone to corrosion. These properties demand large, specialized equipment and increase capital and operating costs.

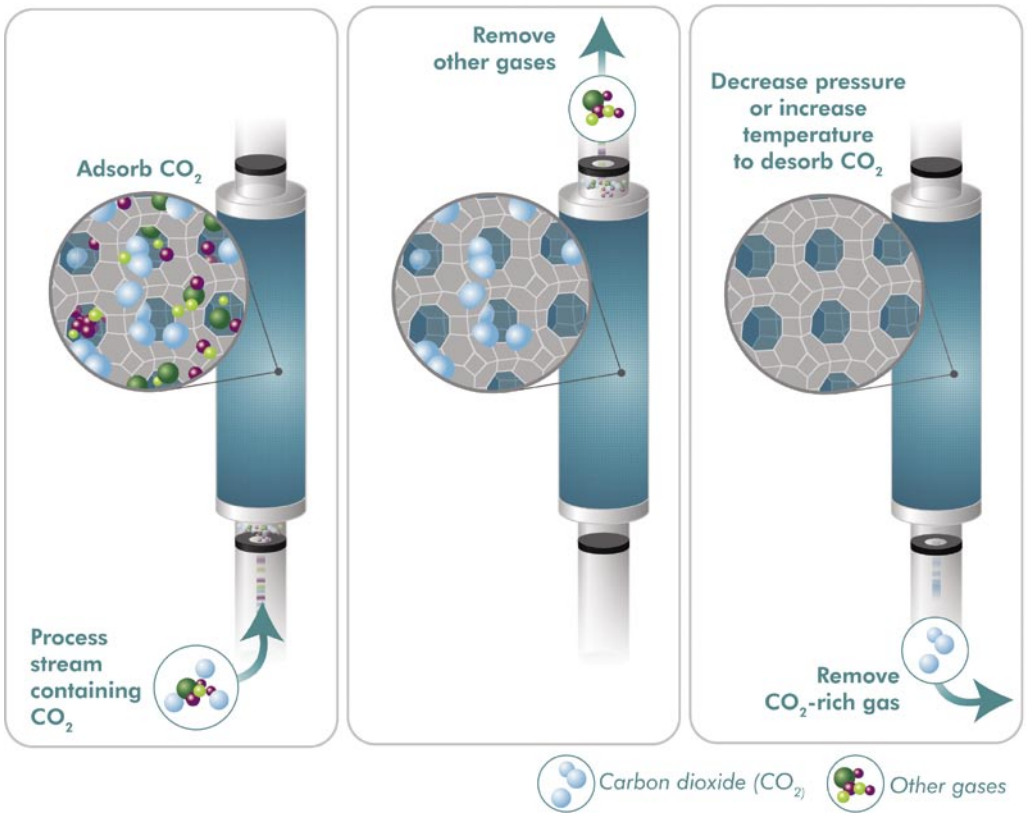
Engineers are looking for ways to improve upon MEA by finding a less degradable and/or corrosive solvent that attaches to and then easily lets go of CO_2. As Stuart Dalton of the U.S.-based Electric Power Research Institute (EPRI) put it, “Anything that likes to catch CO_2 doesn’t like to let it go, and anything that likes to let it go, doesn’t like to catch it. The kinds of compounds that like to bind with CO_2 bind to it pretty well, but to regenerate it typically take a lot of energy.”

Researchers around the world are working hard on developing new and improved solvents. Some are adding or subtracting ingredients from the traditional MEA solvent mix. Others are looking at possible ways to use different amines. Still others have abandoned amines altogether and are working with ammonia, amino acid and/or various different solvents. As of 2008, no improved solvent has been tested on a commercial scale at a coal-fired plant, but many tests, pilot projects and demonstrations are ongoing and planned.



Flue gas containing CO_2 and other gases (mostly nitrogen from the air) enters the chamber containing the solvent. The solvent with the dissolved CO_2 is then removed from the chamber. The other gases are released as they are not absorbed by the solvent. Recovery of CO_2 from the solvent is called desorption. Heat or pressure can be used to trigger the release of CO_2 from the solvent, which may require considerable energy.

Image Source: CO2CRC



Adsorption occurs when a gas accumulates on the surface of a solid or a liquid, known as the adsorbent. Possible adsorbents include metal organic frameworks, zeolites and porous carbons. The gas mixture enters the adsorbent chamber and the CO_2 is trapped in the chamber, while the other gases pass through. The adsorbent with trapped CO_2 is then triggered to release the CO_2 by pressure or temperature, depending on the process.

Image Source: CO2CRC

In pre-combustion capture, CO_2 is separated from a hydrocarbon fuel before the fuel is burned. Solid or liquid fuels such as coal, biomass or petroleum products are first gasified in a chemical reaction at very high temperatures with a controlled amount of oxygen. Gasification produces two gases, hydrogen and carbon monoxide (CO). These same two gases are produced from natural gas through a process called reforming. In reforming, the methane in the natural gas chemically reacts with steam to produce hydrogen and CO. After production by either gasification or reforming, the CO is converted to CO_2 and then removed, leaving pure hydrogen to be burned to produce electricity or used for another purpose. The CO_2 is then compressed into a supercritical fluid for transport and injection.

Gasification has been in use since the 1800s, when it was originally developed to produce town gas for lighting and cooking. Since then, it has been widely used to produce synthetic fuels, chemicals and, recently, electricity. Reforming of natural gas is widely used throughout the world to produce hydrogen and is a well-established commercial practice.

Over 100 gasifiers currently operate worldwide, most of which gasify petroleum products for chemical production. Four coal-fired power plants and about 20 power generation facilities in oil refineries now use a gasification-based system called Integrated Gasification Combined Cycle (IGCC). Considerable experience has already been gained separating CO_2 as a by-product of gasification. This CO_2 is used for various commercial purposes ranging from beverage carbonation to urea production and Enhanced Oil Recovery (EOR). Perhaps the best known gasification plant that captures CO_2 is the Great Plains Synfuels Plant in North Dakota. Other gasification plants have captured CO_2 for industrial purposes. These include:

- Tennessee Eastman, Kingsport, Tennessee, U.S.A.—for the food and beverage industry;
- Texaco Refinery, Los Angeles, California, U.S.A.—for enhanced oil recovery (EOR);
- Eight gasification plants in China—for urea production; and
- Coffeyville, Kansas, U.S.A.—for urea production.

Oxyfiring (sometimes called oxy-combustion, oxyfuel or oxy-coal) is the combustion of fuel in an oxygen-rich environment. Oxyfiring has been used on a small scale for high-temperature industrial processes since the 1940s. Large-scale oxyfiring of coal to increase CO_2 concentrations for CCS has been studied since the late 1980s. When fuel is burned in air, CO_2 concentrations are relatively low since most of the air consists of nitrogen. Higher CO_2 concentrations are expected to make separation less expensive. Burning fuel in pure oxygen creates temperatures well beyond what the steel used in a boiler could tolerate. To avoid that, flue gas containing CO_2 is recycled into the boiler (in place of the nitrogen

The Great Plains Synfuels Plant gasifies coal to produce synthetic natural gas and various chemicals. The plant captures 2.8 million tonnes of CO_2 per year, which is transported by pipeline to Saskatchewan, Canada for use in Enhanced Oil Recovery (EOR). This facility has been capturing CO_2 since 2000.

Image Source: Dakota Gasification Company

present during combustion in air). Pollutants are removed, the flue gas is cooled and then CO_2 is extracted and compressed. Oxyfiring has been proposed for both new and retrofit applications.

Oxyfiring has been tested in a number of small experimental facilities for many years. For example, the CANMET Energy Technology Center, a division of Natural Resources Canada, has operated a pilot scale oxyfiring facility in Ottawa, Ontario, Canada since 1994. That and other facilities have provided much of the data required to ready oxyfiring for use on a somewhat larger scale in actual power plants. The first coal-fired power plant with oxyfiring went on line in Germany in 2008.

Oxygen production: a key enabling technology. Both gasification (used in pre-combustion capture) and oxyfiring require large amounts of oxygen. Currently this oxygen is produced by cryogenic air separation. Cryogenic air separation adds to capital costs. It typically constitutes about 10 percent of the capital cost of a coal gasification plant and adds to its complexity. Cryogenic oxygen production also consumes considerable energy—about 15 percent of fuel consumption for oxyfiring. Reducing oxygen production costs and energy use would benefit both oxyfiring and pre-combustion capture.

Emerging capture processes. Several other capture methods are in early development:

- Membrane separation is a post-combustion method which uses a semi-permeable barrier (the membrane) through which one or more of the gases in a mixture of gases moves faster than the others, thus separating the components. Membrane separation methods for oxygen production are also being developed that would enhance both oxyfiring and pre-combustion capture. They have the potential to be more efficient and less capital intensive than solvent-based systems.
- Chemical looping combustion uses metal oxide particles to react with a solid, liquid or gaseous fuel, producing solid metal particles and a mixture of carbon dioxide and water vapor. The water vapor is condensed, leaving pure carbon dioxide.
- Cryogenic separation and distillation takes advantage of different temperatures at which CO_2 and other components of an exhaust stream change from a gas to a liquid or vice versa.
- Advanced compression processes utilize new principles such as ramjet compression, which have the potential to be more efficient and less costly than turbine-driven compressors currently in use.

Capture from industry. Several types of industrial manufacturing facilities could potentially capture CO_2. CO_2 is now commercially separated from natural gas production streams and in plants that produce ammonia or hydrogen. CO_2 could also be captured from other industries including integrated steel mills, cement plants, oil refining, petrochemicals, cement plants, pulp and paper production, processing of heavy oils such as tar sands, and synthetic fuels production. Methods to capture CO_2 at each of these types of facilities depend on their specific production processes, which can be quite complex. Some facilities such as oil refineries and petrochemical plants may emit large amounts of CO_2 in total, but the CO_2 may actually be emitted from many different individual sources within the facility. Each source may emit a different quantity of CO_2 at a different pressure and purity. The CO_2 emitted from some types of operations—cement kilns and iron reduction, for example—may come from chemical reactions involving the raw materials. In each case, the capture methods must be tailored to the specifics of the production process. Adaptations of post-combustion, pre-combustion and oxyfiring approaches have been proposed for various types of industrial facilities.

Improving Capture Technologies

The major challenge associated with capture is to reduce costs for low-concentration, low-pressure, high-volume sources such as power plants. For power generation, several alternative technology approaches potentially offer substantial cost reductions. Each approach has strong advocates in the scientific and engineering community. It is not clear which approach will ultimately prove most cost-effective. It is still early in the development of CCS and new and innovative ideas continue to emerge. It is possible that different approaches may prove most attractive under different circumstances.

Post-combustion capture faces three challenges in power generation facilities compared to its use in currently-commercial industrial processes. In power generation:

- The CO_2 concentration is lower (typically 10-20 percent versus 27-33 percent);
- CO_2 is emitted at atmospheric pressure, requiring considerable compression;
- The scale is larger—up to several million tonnes (metric tons) per year.

Larger and more-expensive equipment and more energy are required to separate and compress the CO_2 in power generation. Currently-commercial capture facilities also produce CO_2 for an end-use (such as EOR or food production) where the CO_2 has a higher financial value than simply avoiding CO_2 emissions.

Considerable work is taking place to develop improved post-combustion systems for CCS in power generation applications. This work has several basic improvements as goals:

- Improving capture using MEA,
- Finding solvents that require less energy to release the CO_2,
- Extending the life of expensive solvents,
- Advancing designs and materials for greater

Large-Scale Post-Combustion Projects

Pilot projects that capture CO_2 from a portion of power plant exhaust gases provided the information necessary for some post-combustion approaches to removing CO_2 from power plants on a larger, commercial scale.

- **Mountaineer and Oolagah.** The U.S. power company American Electric Power (AEP) plans to install a chilled ammonia post-combustion capture system developed by Alstom at its Mountaineer power plant in West Virginia in 2009. The unit will capture 200,000 tonnes of CO_2 per year from a 30 Megawatt installation and inject it into saline formations under the site. AEP will use the information gathered at Mountaineer to design and install the same technology on a 450 Megawatt coal-fired generation unit at Oolagah, Oklahoma in 2012. It will capture about 1.5 million tonnes of CO_2 per year for use in EOR.

- **U.K. Competition.** The United Kingdom government has solicited bids for a commercial-scale post-combustion power demonstration project at a coal-fired power station, with CO_2 stored offshore. The U.K. government will pay for the full cost of capture and storage. CCS is to be demonstrated by 2014 in a project of at least 300 Megawatts.

- **Norwegian natural gas power plants.** Two Natural Gas Combined Cycle (NGCC) power plants in Norway are planned with post-combustion capture. An NGCC plant at the Mongstad Refinery will capture 100,000 tonnes of CO_2 in 2010 and 1.1 to 2.1 million tonnes by 2014. This plant will become the European Test Centre Mongstad. Capture will also be implemented at the existing Kårstø NGCC plant.

Several other large-scale post-combustion projects are also planned.

removal efficiencies and larger scale, and
- Improving compression technologies.

Pre-combustion capture may be used for IGCC power plants, gasification plants that produce synthetic fuels or chemicals (like the Great Plains Synfuels Plant), or for power generation using natural gas. Gasification coupled with pre-combustion capture is a well-established technology. IGCC technology has been widely used in oil refineries to produce electricity using low value byproducts for many years. The IGCC used at refineries, however, is somewhat simpler than the power industry needs and uses less-expensive refinery byproducts as fuel.

IGCC has the potential to generate power and capture CO_2 with relatively high efficiency at a competitive cost. Capturing CO_2 from IGCC is not a major challenge—several commercial processes are available. Moreover, IGCC produces CO_2 at a higher pressure, so compression costs are reduced compared to other capture methods. The challenge is to reduce the cost of building and operating the entire IGCC plant to make it commercially feasible for the power industry. The best ways to do so are being worked out now.

Even without CO_2 capture, IGCC is a highly complex system with several major components. Those components must be integrated to be efficient, reliable and cost-effective. Those components are the gasifier; combined cycle power generation equipment; oxygen plant (in most designs); and, if incorporated, CO_2 capture equipment. Several different gasifiers and types of capture equipment can be used, each of which performs differently. Alternative gasifiers have varying abilities to gasify different fuels and the components can be tied together in many different ways. A critical piece of equipment for an IGCC or natural gas plant with capture is a combustion turbine that runs on hydrogen. That type of turbine is still under development.

Large-Scale Pre-Combustion CCS Projects

IGCC with CCS under construction. The Dutch utility Nuon is retrofitting its Buggenum IGCC plant to capture 30,000 tonnes per year of CO_2 starting in December 2008. That plant gasifies both coal and biomass. The first 250 Megawatt phase of the GreenGen IGCC project in Tainjin, China is planned to capture CO_2 at pilot scale in 2009. Later phases will expand the plant to 650 Megawatts and capture CO_2 at commercial scale. China Huaneng, China's largest power generator, is building GreenGen with the support of the Chinese government and several partners.

Planned IGCC with CCS. In the U.S., the Department of Energy's FutureGen project was restructured in 2008 from one advanced research facility to multiple commercial projects. A solicitation with multiple awards is underway. BP and Rio Tinto are planning an IGCC project that will use refinery byproducts as fuel and capture CO_2 for enhanced oil recovery in Kern County, California. The European Commission is planning to build CCS into an advanced IGCC unit known as Hypogen starting around 2012. Meanwhile, European utility RWE also plans a 450 Megawatt lignite IGCC with CCS for 2014 in Germany. Additionally, U.K. power producer Powerfuel Power Ltd expects the 900 Megawatt IGCC plant it plans to build in Hatfield will start capturing CO_2 in 2013. ZeroGen is a planned IGCC plant with CCS in Australia. ZeroGen is to be built in two stages. An 80 Megawatt demonstration plant will capture 75 percent of the CO_2 emissions by 2012. Next, a 300 Megawatt full-scale commercial plant will capture 90 percent of the CO_2 emissions by 2017.

Several other IGCC plants with CCS have been announced, but are not as far along in planning or have not definitively committed to incorporating CCS.

Several major equipment manufacturers and engineering companies have formed teams to commercialize IGCC. They have invested heavily in developing the technology. IGCC without capture is now offered commercially to power generators and the first orders for these plants have been placed. Even without capture, IGCC is unfamiliar to the power industry and costlier than conventional steam boiler coal plants. Integrating capture will take further time and investment. When the challenge of integration is overcome, IGCC with capture has the potential to perform with higher efficiency and lower cost than the alternatives.

Oxyfiring is the least advanced of the three major capture options for power generation. It faces three technical challenges:

- The high cost of oxygen production (a challenge shared with pre-combustion capture),
- Overall design of the boiler and burners, and
- Removal of impurities from the CO_2 stream.

Several small facilities are exploring methods to overcome these challenges. Several oxyfiring pilot projects are planned and one is now in operation.

Capture from most large industrial facilities and other sources of CO_2 faces greater challenges. Capture technologies for industrial processes such as steel- and cement-making must be specifically designed for those types of facilities. Industrial facilities can be very complex and have many individual sources of CO_2 embedded within them, sometimes with large individual emissions. In addition, much

Power Plants with Oxyfiring

The first coal-fired power plant with oxyfiring went on line at the Schwarze Pumpe power station owned by Vattenfall in eastern Germany in September 2008. This 30 Megawatt pilot plant burns both brown (lignite) and hard (bituminous) coal and captures CO_2. The CO_2 is carried by truck 320 km (200 miles) for injection into an onshore depleted gas field. According to Vattenfall, the plant is to validate engineering work, learn and better understand the dynamics of oxyfiring and demonstrate capture technology. Learning from Schwarze Pumpe, Vattenfall plans to demonstrate oxyfiring at a 250 Megawatt boiler at its Janschwalde plant in 2013. Another boiler of the same size at Janschwalde will also demonstrate post-combustion capture.

Australian power generator CS Energy and several partners are planning to retrofit the Callide A power station in Queensland with oxyfiring technology in a project partly funded by the Australian and Japanese governments. The project will demonstrate a completely integrated oxyfiring process at a coal-fired power plant. It will obtain design and operational experience with oxyfiring for future oxyfiring plants. Retrofitting involves refurbishment of a 30 Megawatt coal-fired boiler for oxyfiring operation and the addition of both a cryogenic air separation unit to produce oxygen and a CO_2 capture and purification unit. The plant will capture about 75 tonnes of CO_2 per day. The project is in the pre-construction phase with funding and final agreements approved. The storage site will be selected in 2009. Capture and storage will begin in 2011.

The French oil company Total is planning to begin operation in late 2008 of a pilot oxyfiring plant at the Lacq gas processing plant in southern France. A boiler at that plant is being converted into an oxyfiring combustion unit. Captured CO_2 will be transported through a 27-kilometer pipeline for injection into the nearly-depleted Rousse natural gas reservoir at a depth of 4,500 meters. The pilot plant will emit up to 150,000 tonnes of CO_2 over a two-year period. The pilot will also contribute to the goal of CO_2 emissions-free power generation defined by the European Technology Platform, in which Total is a partner.

of the CO_2 in many industrial processes—steel production, chemicals, cement—comes from chemical reactions inherent in their operation, not from the burning of fuel. Capturing CO_2 from these processes will require modifications to long-established production methods and integration with those processes. Much of the growth in these industries will be in developing countries such as China. Compared to power generation, relatively little effort so far has gone into capture from these processes.

One industrial process for which capture is now being extensively worked on is the production of synthetic crude oil from oil sands in western Canada. CO_2 is produced in this process in two ways. Boilers produce steam for injection underground and emit CO_2 and hydrogen is produced by reforming natural gas for upgrading heavy oil, which also emits CO_2.

The extreme edge of difficulty would be to capture CO_2 from the atmosphere itself. CO_2 is only about 0.04 percent of the atmosphere and it is obviously at atmospheric pressure, requiring extensive compression. Even so, a number of research teams are working on air capture. Success and cost-effectiveness are not guaranteed, but Sir Richard Branson has offered the $25 million Virgin Earth Challenge prize for a commercially viable air capture design.

Reducing Energy Use of Capture

All three capture options for power generation have higher capital and operating costs as well as lower efficiencies than conventional power plants without capture. Costs are higher than for plants without CCS because more equipment must be built and operated. Ten to 40 percent more energy is required with CCS than without. Energy is required mostly to separate the CO_2 from other gases and to compress it, but some is also used to transport the CO_2 to the injection site and inject it underground.

As CCS and power generation technology become more efficient and better integrated, the increased energy use is likely to fall well below early levels. Much of the work on capture is focused on lowering costs and improving efficiency as well as improving the integration of the capture and power generation components. These improvements will reduce energy requirements. At the same time, work is underway to increase the overall efficiency of power generation. More efficient combustion turbines, ultrasupercritical steam power plants and IGCC plants are being developed. Advanced power plants with CCS may eventually be as efficient as today's power plants without CCS.

CO_2 Transport

The best way to have CO_2 in supercritical fluid form reach the injection site is to build the capture facility directly over the site, eliminating the need for transport. Otherwise, CO_2 transport is needed. Small amounts of CO_2 are now transported by truck for use in the beverage, dry cleaning and dry ice industries. In contrast, the large quantities of CO_2 to be transported from power plants or industrial facilities would generally necessitate pipeline transport. Ocean-going ships have also been suggested for very long-distance transport, but none has yet been built.

CO_2 pipelines have operated for many years and are well established. The United States has an extensive pipeline network that has been in operation for many years that carries CO_2 from naturally-occurring fields and capture plants to depleting oil and gas fields. There it is used to increase production in Enhanced Oil Recovery (EOR). CO_2 is also transported 320 km (200 miles) from a gasification plant in North Dakota to two mature oil fields in Saskatchewan, Canada for EOR. Another pipeline network carries CO_2 between capture facilities and large greenhouses in the Netherlands where it is used to stimulate plant growth. In the Snøhvit CCS project, CO_2

A network of commercial pipelines safely brings CO_2 from natural sources and capture facilities to EOR operations in the United States and Canada.

Source: United States Department of Transportation

is transported in an undersea pipeline from a capture facility on the Norwegian coast to an offshore storage reservoir.

How Geologic Storage Works

In CCS, CO_2 is injected into deep geologic formations that can securely contain it. Potential sites for geologic storage include depleted oil and gas fields, deep saline formations and deep unmineable coal beds. Each of these types of geologic formations holds or has held large quantities of fluids for long periods—often millions of years—using various natural trapping mechanisms. Geologic storage uses the same trapping mechanisms. (See box.) The security of geologic storage is covered in detail in a companion booklet published by the IEA Greenhouse Gas R&D Programme, "Geologic Storage of Carbon Dioxide: Staying Safely Underground." In addition, basalt and shale formations have also been suggested for geologic storage, but much more research must be done before they can be used as CO_2 storage reservoirs.

For more than 30 years, oil and natural gas producers have injected CO_2 to force out stubborn pockets of oil from maturing fields, a process known as Enhanced Oil Recovery (EOR). Once underground injection of CO_2 is finished, the injection well can be capped and the CO_2 stored underground. Increased oil production can help offset the costs of CCS, but EOR opportunities are limited compared to the vast amounts of CO_2 that must be disposed of. Similar processes are being developed for Enhanced Gas Recovery (EGR) and Enhanced Coal Bed Methane (ECBM).

Geologic storage activities are conducted in three phases: planning and construction, injection, and post-injection. In the planning and construction phase, sites are first identified and characterized and then wells for injection and monitoring are drilled based on the geologic data. During the injection phase, which may last 20-40 years, CO_2 from the source is injected into the selected reservoir formation and is monitored to ensure that the CO_2 stays safely in place. Monitoring may continue for some time in the post-injection phase.

Geologic storage of CO_2 has already been conducted on a commercial or test basis at several sites throughout the world. These sites include depleted oil and gas fields, saline formations and coal beds. Many further projects are planned over the next several years. Four integrated CCS projects involving geologic storage are now commercial: Sleipner and Snøhvit offshore from Norway, In Salah in Algeria and Weyburn-Midale in Canada. Weyburn-Midale also hosts a major research project conducted by the IEA Greenhouse Gas R&D Programme. Much useful information has been produced by these projects.

CCS has already been used in several commercial projects and experimentally in a number of others. Several technical challenges must be overcome, however, for widespread use of CCS in large-scale integrated projects. Extensive work is being conducted throughout the world to meet these challenges.

Improving Geologic Storage

Widespread implementation of geologic storage requires a more complete understanding of what happens when large volumes of CO_2 are injected under diverse geologic conditions. This will facilitate the developing storage practices that can be tailored to the wide variety of geological conditions likely to be encountered. Experience so far has been in a limited number of

What Keeps the CO_2 Underground?

CO_2 is injected under extremely high pressure as a supercritical fluid into tiny pores within deep rock formations which have already trapped liquids such as oil, natural gas or highly salty and unusable water for millions of years. Supercritical CO_2 takes up as little as 0.27 percent of the space of gaseous CO_2 and diffuses readily through the pore spaces of solids. Supercritical CO_2 compresses more the deeper it is injected, increasing the amount that can be stored in the same volume of rock. High pressure and sufficient depth (2,600 feet or 800 meters) maintains the supercritical fluid state. Once in an appropriate geologic storage space, CO_2 is held in place by one or more of five trapping mechanisms, depending upon geology:

- Stratigraphic trapping uses cap rock, a dense layer of impermeable rock that overlies the CO_2 deposit forming a closed container.
- Structural trapping occurs when impermeable rocks overlie a fault or fold in the geologic strata, holding the CO_2 in place. The CO_2 is also generally separated from the surface by other thick layers of impermeable rock called seals.
- Residual trapping takes place when the CO_2 is trapped in the tiny pores between rocks by the capillary pressure of water.
- Solubility trapping occurs when CO_2 dissolves in the saline water in the rock formation, forming a denser fluid which may then sink to the bottom of the storage reservoir.
- Mineral trapping occurs when CO_2 chemically combines with the surrounding rocks to form minerals.

The security of geologic storage is discussed in more detail in a companion booklet from the IEA Greenhouse R&D Gas Programme—"Geologic Storage: Staying Safely Underground."

geologic settings. The behavior of trapping mechanisms, the migration of displaced fluids (such as saline water), potential leakage mechanisms, and the mechanical impacts on geologic structures all need to be better understood for different types of reservoirs. To a large extent, geologic storage builds on decades of experience in oil and gas production and the underground injection of other fluids. Yet, there are differences due to the large volumes of CO_2 that will be injected and CO_2's physical and chemical properties. Site characterization and selection, storage planning and operational practices must be further developed so that they can be widely and safely conducted for different geological conditions in each type of reservoir. Methods for monitoring CO_2 storage and, if necessary, remediation, must be tested and validated. Much of this work is already underway.

Geologic storage challenges can be overcome by gaining experience injecting CO_2 in a diverse set of storage reservoirs and sharing the information. So far, however, CO_2 has been injected at a small number of sites, mostly in relatively small amounts. Much of this work has been done by leading experts and the results so far are encouraging, but geological conditions are extremely diverse. Many future projects will be undertaken by commercial organizations in geologies different from those where experience has been gained so far. Large quantities, on the order of several million tonnes of CO_2, must be

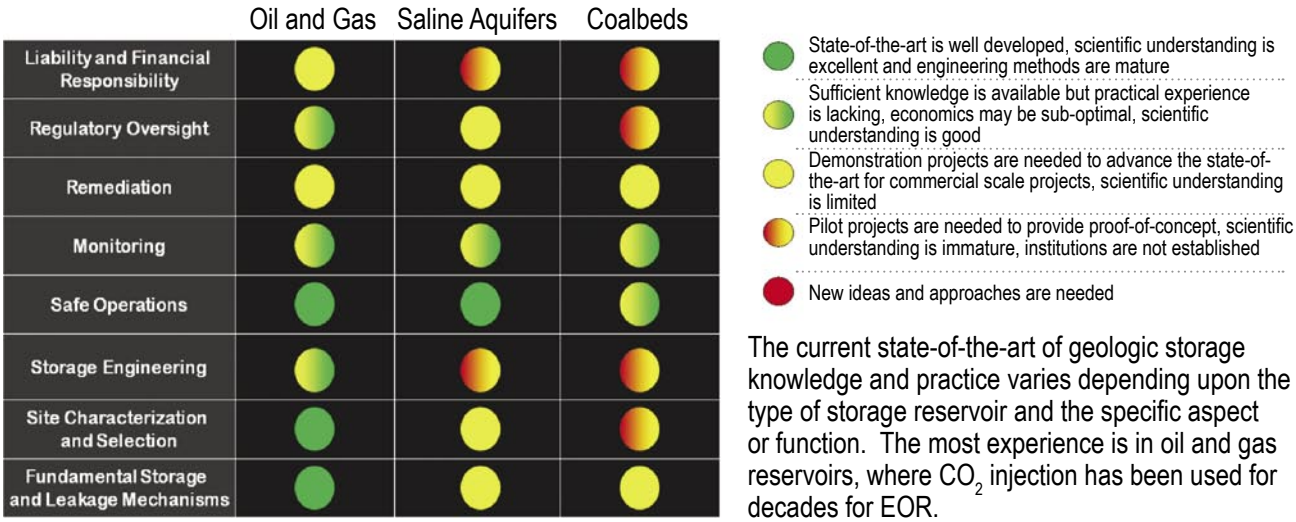


Image Source: Sally Benson, Stanford University

The current state-of-the-art of geologic storage knowledge and practice varies depending upon the type of storage reservoir and the specific aspect or function. The most experience is in oil and gas reservoirs, where CO_2 injection has been used for decades for EOR.

The Otway Project

In April 2008, Australia's Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) started injecting CO_2 into a depleted natural gas field as part of the first underground carbon storage project in the southern hemisphere—the Otway Basin Pilot Project. The injection site in southwestern Victoria is expected to eventually hold 100,000 tonnes of CO_2. Most importantly, it will yield detailed technical information on storage processes, injection technologies and comprehensive monitoring techniques as well as verification procedures. As of September 2008, more than 21,000 tonnes of compressed, naturally occurring CO_2 had been safely injected. The injection process will last two years, but monitoring and modeling activities will go on for several years after injection ceases.

Otway and similar projects around the world are developing the broad base of information that will enable geologic storage in diverse geologic settings.

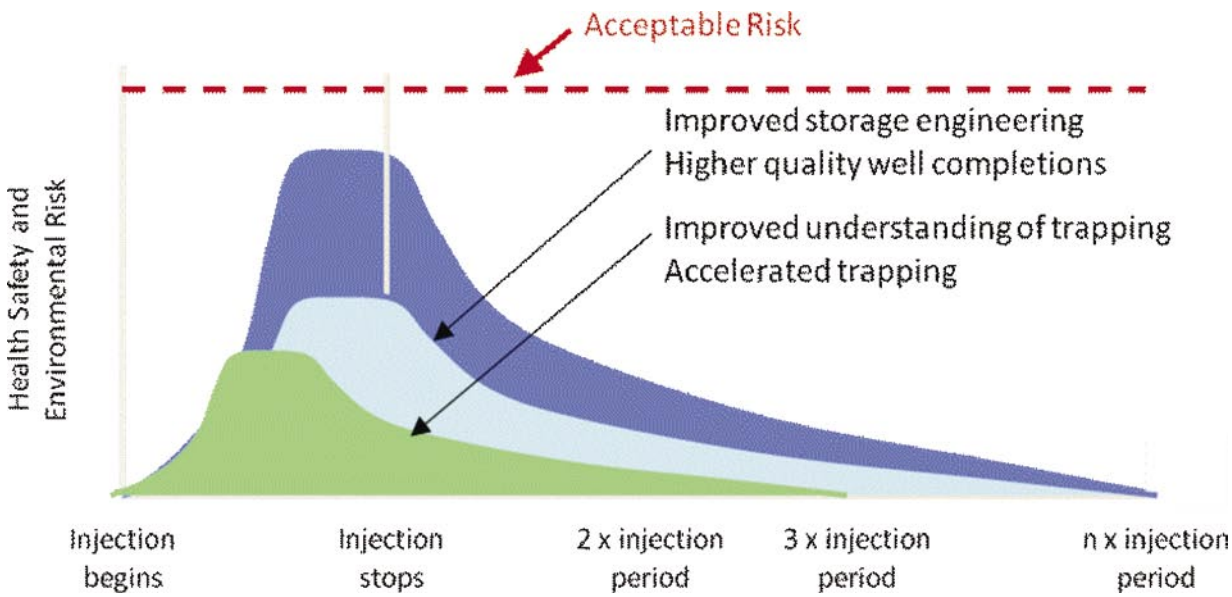
injected into a greater number of sites. This will enable geologists and engineers to more fully understand what happens underground and to develop commercial practices for all aspects of geologic storage. Based on the information gained from this further work, effective practices must be developed for commercial operations in a wide range of geological settings.

Research so far indicates that risks such as movement of CO_2 out of the storage formation are extremely unlikely if the storage is conducted properly. Further research is necessary to fully quantify risks in different geological circumstances and to develop methods for avoiding them. Researchers are conducting experiments and analyses to better understand potential risks. This work involves studying how CO_2 behaves in underground geologic formations and how it is affected by each of the trapping mechanisms. Such an understanding must be gained for the wide range of geological conditions under which storage may eventually take place. The goal is to ensure that planning can be conducted with confidence and that operations and closure are safe and secure. Criteria are being developed, for example, to ensure that commercial projects are below an acceptable level of risk. In addition, work is being conducted to enhance and further develop equipment and protocols for measurement, monitoring and verification and for practices to remediate any leaks that might occur. Experimental work currently being conducted and planned over the next few years is likely to generate much of the needed information.

Analyses indicate that the overall risk is highest toward the end of the injection period and then decreases to become virtually nonexistent over time. Improved storage engineering and greater understanding of trapping mechanisms will lower the risks. The pattern of risks over time also has significant implications to the financing and regulation of geologic storage.

Integration and Scale Challenges

Integration of capture equipment with the CO_2 source facility is a significant challenge. Source facilities exist to produce a useful output, whether electricity, natural gas, steel, cement, chemicals or other products. They burn fuel, generate steam and may operate various other chemical process-



Methods are being developed to estimate potential risks and how they change over time. Only projects for which the risks are sufficiently low will be undertaken. Improved geologic knowledge and storage engineering practices would reduce risks of geologic projects.

Image Source: Sally Benson, Stanford University

es. All facilities must be carefully integrated in terms of process flows, pressures, volumes and heat transfers to be efficient and cost effective. Integration is both a design and an operational issue. CO_2 capture adds a new and potentially significant process that could change how the entire plant is integrated. On the other hand, integrating the capture, transport and storage stages with one another mostly just involves matching the capacities of each stage and coordinating operations.

Integration is particularly a challenge for pre-combustion capture in IGCC power plants. IGCC plants are very complex chemical process facilities that are only now reaching technical maturity. One additional challenge for pre-com-

An Integrated CCS Network in Canada

A group of Canada's largest industrial companies is working out a way to capture CO_2 from a number of different sources and transport it via pipeline to a common storage area. The Integrated CO_2 Network (ICO2N) initiative is focused on developing an integrated infrastructure to reduce the costs and risks of CCS and to accelerate its deployment.

ICO2N is planning an integrated CO_2 transport, EOR and direct storage infrastructure. This infrastructure will move CO_2 produced in Alberta's industrial areas to the Western Canada Sedimentary Basin (WCSB) for EOR and direct storage. The WCSB is a vast sedimentary basin underlying 1.4 million square kilometres (540,000 square miles) of western Canada including southwestern Manitoba, southern Saskatchewan, Alberta, northeastern British Columbia and the southwest corner of the Northwest Territories. Not only is the CO_2 storage potential huge, the WCSB also offers the prospect of reducing the overall cost of the project by using the CO_2 for Enhanced Oil Recovery (EOR).

ICO2N's CO_2 sources in Alberta will be coal-fired power plants near Edmonton, oil sands facilities near Fort McMurray, oil upgrading and refining facilities in and around Fort Saskatchewan and a number of chemical and agricultural industrial facilities near Red Deer.

Linking the CO_2 sources with the injection and/or EOR sites requires building a high-pressure CO_2 pipeline network. That pipeline would consist of a large main line connecting CO_2 capture facilities with the main EOR market and storage locations across the WCSB. ICO2N says the pipeline would likely be built to accommodate the needs of early adopters of carbon capture and then could be expanded in phases. According to ICO2N, its studies indicate that the project has the potential to reduce CO_2 emissions by more than 20 million tonnes per year over the next decade, the equivalent of taking four million cars off the road.

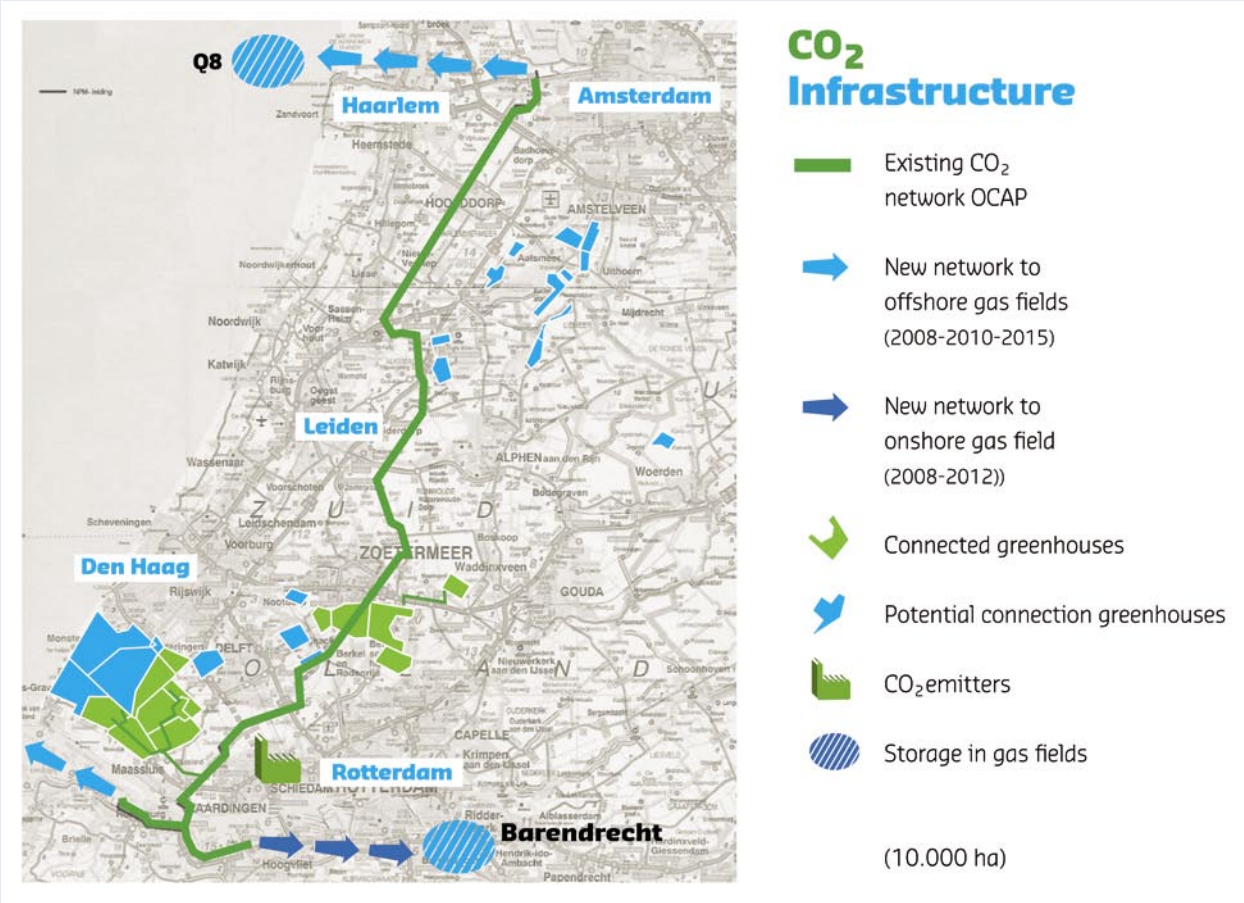
The proposed Canadian network, ICO2N, would connect multiple energy facilities in northern Alberta with a variety of CO_2 reservoirs further south. This map represents one of several possible routings.

Image Source: ICO2N

Rotterdam Climate Initiative

Rotterdam in the Netherlands set out to cut greenhouse gas emissions 50 percent from 1990 levels by 2025, while promoting the economy of the entire Rotterdam region. The Rotterdam Climate Initiative (RCI) is a program that involves government, environmentalists and industry as well as the Port of Rotterdam Authority. Since Rotterdam is the largest port in Europe, the city of Rotterdam and the surrounding area grew to be an industrial powerhouse that now emits enormous amounts of CO_2.

The RCI is a comprehensive plan to reduce CO_2 emissions by combining increased energy efficiency, reuse of waste heat, large scale use of biomass and CCS. One of the main ways RCI plans to cut CO_2 emissions is through the use of a CCS network. The Port of Rotterdam has a concentration of large, energy-intensive industrial facilities. Several oil refineries already capture CO_2, which is piped through an already-existing pipeline network to large industrial greenhouses. Plans are for more of Rotterdam's industries—including several new power plants—to add carbon capture capability. More CO_2 will be captured than the greenhouses will use and this CO_2 will be stored underground. The existing pipeline network will be expanded short distances to deep saline formations for CO_2 storage both onshore and offshore under the North Sea.



The Rotterdam Climate Initiative is developing a CCS network that will capture CO_2 from several industries, expand an existing CO_2 pipeline network, and inject CO_2 into both onshore and offshore storage. Combined with other measures, this Initiative is projected to cut the region's industrial CO_2 emissions in half by 2025.

Image Source: Rotterdam Climate Initiative

bustion capture is the development and testing of combustion turbines that operate on pure hydrogen. As with pre-combustion, capture is inherently a part of the oxyfiring production process. Post-combustion capture probably requires less integration, but still affects the flow and constituents of exhaust gases and this impacts the overall balance of pressures in a power plant and the treatment of exhaust gases.

Integration challenges are all solvable. Process engineers have been solving such problems for decades. Typically, many alternative solutions are possible early on. Finding the most cost-effective solutions requires experience and usually some trial and error. Individual components may already be mature in some applications, but experience with integration is needed, especially at large scale.

Scale presents several challenges. The size of many future commercial CCS projects will be larger than previous projects. Many hundreds of CCS projects will eventually be built. Equipment originally designed for smaller projects will need to be scaled up to commercial sizes. This type of challenge is frequently addressed by engineers, but it requires time, effort and learning. Many other greenhouse gas abatement options also face the same challenge of scale.

As CCS becomes more widespread, multiple CO_2 sources and reservoirs will be joined into networks tied together by a web of pipelines. Building common facilities and using them as a system could potentially bring substantial savings. Several such networks are under consideration. One such regional network is currently being planned for western Canada by the ICO2N project. Others have been proposed, notably in Europe. Networks could also tie together industrial facilities that would otherwise be too small for CCS individually into a network that would be economically viable as a group. The Rotterdam Climate Initiative in the Netherlands is planning such a grouping.

Notes

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