Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Capture and Separation of Carbon Dioxide from Combustion Sources

Edited by

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Chapter 2

REVIEW AND EVALUATION OF THE CO_2 CAPTURE PROJECT BY THE TECHNOLOGY ADVISORY BOARD

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ABSTRACT

As part of its responsibilities and charter, the Technology Advisory Board (TAB) provides technical oversight, performance evaluation and peer review for the CO_2 Capture Project (CCP). The TAB is an international panel of technology experts and funding agency representatives that provides a portion of the overall "quality control and assurance" function to the project.

This chapter summarizes the TAB's assessment of the CCP's accomplishments in reducing the costs and energy penalty of CO_2 capture and for improving the safety and reliability of its geologic storage. It concludes with a set of priorities and recommendations for future activities.

INTRODUCTION

The initial meeting of the CO_2 Capture Project's (CCP) Technology Advisory Board (TAB, named in Table 1) was in March 2001. This meeting helped identify the relevant CO_2 capture technologies and select the technologies that would benefit most from future investment by the CCP. The five questions posed for TAB consideration were:

1. Have the Technical Teams reviewed all relevant technology?
2. Have we followed a reasonable process to select technologies for investment?
3. Do we have the correct mix of technologies to meet our goals (short/long term, high/low risk)?
4. Are our cost-reduction and commercial readiness goals for these technologies appropriate?
5. Are we spending the correct proportion of funds in each of the project areas?

Overall, the TAB concluded that the CCP Technology Teams had conducted a very thorough technology selection process. The TAB commended the Technology Teams for establishing a strong, robust portfolio of CO_2 capture technologies, appropriate to each "scenario" set forth by the CCP. The TAB recommended: (1) placing additional emphasis on advanced amine and solvent systems as well as on innovative design and integration for post-combustion CO_2 capture technology; (2) investing in the promising membrane technologies, even though the required research may entail longer lead times than initially expected by the CCP; (3) undertaking "breakthrough" technologies for oxyfuels, particularly for air separation, as evolutionary improvements would not be sufficient to make this process competitive; and, (4) if possible, expanding the CCP's efforts in geologic storage of CO_2.

The second meeting of the TAB, in January 2002, focused primarily on the Common Economic Model (CEM), on "new and novel" ideas for CO_2 capture technology, and on the proposed work plan for storage, monitoring and verification (SMV). During this meeting and in subsequent communications with the CCP, the TAB: (1) strongly supported efforts on building the CEM, giving priority to model transparency and consistency (in output measures) and to benchmarking the model against other public models; (2) recommended giving higher priority to pursuing new and novel technologies, including funding the more promising of these ideas and concepts; and (3) continuing to give high priority and appropriate public access to the work by the SMV Team.

TABLE 1
CCP TECHNOLOGY ADVISORY BOARD (TAB)

Vello Kuuskraa	TAB Chairman, Advanced Resources International
David Beecy	US Department of Energy (HQ)
Sally Benson	Lawrence Berkeley National Laboratory
Jay Braitch	US Department of Energy (HQ)
Pierpaolo Garibaldi	Independent Consultant
Arnie Godin	Arnie Godin Consulting Ltd
David Hyman	US DOE/NETL
Scott Klara	US DOE/NETL
Vassilios Kougionas	European Union, DG Energy and Transport
Denis O'Brien	European Union, DG Research
Dale Simbeck	SFA Pacific
Hans-Roar Sorheim	KLIMATEK—Christian Michelsen Research AS
Maarten van der Burgt	Independent Consultant

The third meeting of the TAB, in December, 2002, took place at an important milestone for the CCP. The Technology Teams had just completed their detailed evaluations of the promising CO_2 capture technology candidates and were prepared to recommend the set of "favored technology options" that would proceed to proof of feasibility. The TAB was asked to review the selection process and to address a series of key questions:

1. Is the CCP focusing on the "best" set of capture technologies for meeting its time frame and cost reduction objectives?
2. Are the performance goals and cost reduction targets established for the favored technology options reasonable and achievable?
3. To what extent will the 2003 CCP Program, as proposed, provide the required proof of feasibility for the favored technology options?
4. Are there any key gaps or omissions in the set of capture technologies that have been assessed and selected? Are the priority gaps identified by the SMV Team being addressed?
5. Is the structure and output of the CEM sufficiently transparent to provide a common evaluation tool for technology evaluators? Is the process proposed for sharing the CEM adequate?
6. Do the four CCP "scenarios"—CO_2 capture from an oil refinery, a natural gas power plant, a frontier oil field, and a synthetic crude facility—sufficiently cover the major emissions sources of the petroleum industry?
7. Are the technology transfer plans of the CCP sufficient to assure a broad sharing of publicly transferable results?

The TAB found that a careful sorting of favorable and less favorable CO_2 capture technologies had been accomplished, particularly in pre-combustion. In addition, the TAB agreed with the "breakthrough" technologies selected for cost-effective use of oxyfuels as part of CO_2 capture. Finally, the TAB continued to encourage engineering-based design and optimization studies to identify realistic cost-savings in post-combustion CO_2 capture technology. In addition, the TAB recommended:

- continued pursuit of promising technologies, such as the hydrogen membrane for CO_2/hydrogen separation and the ionic transport membrane (ITM) for air separation, even though they may miss the rigorous year 2003 "stage gate" review requirements;
- move the technology transfer phase of the project to 2004, to provide additional time to complete the technical work and to give proper emphasis to the full set of valuable technology transfer activities; and
- give additional priority and funding emphasis to technologies that are consistent with a future where hydrogen becomes a more significant part of the energy mix.

The primary purpose of the fourth TAB meeting, in May 2003, was to review the CCP work on the CEM, to help select the technology options for detailed cost studies, and to review (in-depth) the chemical looping combustion technology. The TAB found that:

- the structure and design of the CEM was appropriate and, would provide an excellent tool for technology evaluators and R&D planners. The TAB also recommended adding two output measures to the CEM: (1) cost of CO_2 capture per unit of output (e.g. \$/kW h) and (2) net CO_2 emitted per unit of output (e.g. tons CO_2/kW h);
- the research and progress to date on chemical looping combustion was most promising. To properly evaluate this technology, the TAB asked the CCP Technology Team to address a series of technical questions (e.g. heat duty per ton of materials circulated and per ton of CO_2 captured) during the upcoming stage gate review.

The final meeting of the TAB occurred in January, 2004. The purpose of the meeting was to review the accomplishments and recommend next steps for the CCP. The remainder of this chapter transmits the TAB's evaluation of the CCP's accomplishments and recommendations for future work.

EVALUATION OF ACCOMPLISHMENTS

Overview

The CCP has made a major contribution toward lower cost, safe options for reducing greenhouse gas emissions from energy industries. As so well summarized by one of the TAB members, "The CCP has met its promises." Specifically:

- the CCP has identified and developed a suite of advanced technologies that have the potential to reduce the costs of CO_2 capture by a third to over a half, with further work offering promise of additional cost reductions. These technologies are as applicable to the natural gas and coal-fired electric power sector as they are to oil refineries, to coal gasification plants and to remote Arctic oil and gas field operations. Importantly, the suite of CCP CO_2 capture technologies are applicable as retrofits to existing plants as well as integrated components of new plants;
- it has made major contributions to the knowledge base and technology for assuring safe, reliable geologic storage of CO_2. These contributions are enabling the geologic storage option to become one of the main greenhouse gas mitigation strategies available to the entire energy and power sector;
- it has developed a CEM that is usable by a wide variety of policy, research and technology managers. This model provides a consistent and transparent means for establishing the costs of alternative CO_2 capture technologies. The CEM also provides a valuable tool for projecting the benefits of research and technology progress in CO_2 sequestration;
- finally, the CCP has provided a significantly lower cost, zero-emissions pathway toward introducing hydrogen as the "fuel of the future."

The advanced CO_2 capture technologies pursued by the CCP were applied (using detailed process engineering and costing studies) to four geographically specific settings or scenarios—a United Kingdom oil refinery; a Norwegian natural gas-fired power plant; a North Slope of Alaska oil and gas field; and a Canadian oil sand/synthetic crude facility. This helped identify which of the advanced technologies offered the greatest cost savings over the "baseline" CO_2 capture technologies available today. This site-specific scenarios approach helped provide "real world" information and potential for cost savings to the CCP participants. However, the scenarios are sufficiently representative to enable the results to have value for a broad set of industries and plant operators, including coal-fired power plants, hydrogen production facilities and new coal gasification installations, as further discussed below.

Table 2 provides a summary for a small set ("the most promising") of the advanced CO_2 capture technologies identified and developed by the CCP. The table tabulates the extent of cost reductions these technologies offer for each of the four CCP scenarios. The timing of commercial readiness and certainty of cost reduction offered by each technology varies considerably. For example, the cost savings offered by the advanced post-combustion technologies and sorption enhanced water-gas shift (WGS)

TABLE 2
REDUCTIONS IN CO_2 CAPTURE COSTS FROM CCP TECHNOLOGIES[a]

	CCP scenarios			
	UK refinery (heaters and boilers)	**Norway natural gas power plant**	**Canada oil sands (coke gasification)**	**Alaska oil field (compressor operations)**
I. "Normalized" cost of baseline CO_2 capture technology[a]	1.00	1.00	1.00[b]	1.00
II. Selected advanced CO_2 capture technologies				
A. Pre-combustion technologies				
Membrane water-gas shift (WGS)	(38%)			
Sorption enhanced WGS/ Air ATR		(44%)		(19%)
Hydrogen membrane reformer		(60%)		
CO_2 LDSEP (Fluor)			(16%)	
B. Oxyfuels technologies				
Flue gas recycle w/ionic transport membrane	(48%)[c]			
Integration of air separation membranes in gas turbines/ boilers (TBD)				
Chemical looping (TBD)				
C. Post-combustion technologies				
MHI-Kverner (non-integrated)		(23%)		
MHI-Kverner/CCP integrated post-combustion technology		(54%)		

[a] All scenarios and capture technologies were evaluated using generic fuel and power prices and Gulf Coast construction costs; cost reductions are on a CO_2 avoided basis.
[b] Baseline technology already represents a relatively advanced technology case involving production of multiple products, such as hydrogen, steam and power.
[c] Cost reductions are −29% under the actual higher natural gas and lower electricity sales prices in the UK.

technology could be available in the near-term. In contrast, the cost-reductions and commercial availability of the oxyfuels technologies and the hydrogen membrane reformer that still depend on further bench scale and pilot testing face a decade or so of further work.

Participating Entities

Three governments, eight industrial firms and several dozen technology providers have combined their world class expertise and efforts through the CCP, providing a success model of a joint industry–government partnership and of international cooperation.

First to be acknowledged are the sponsors and funders of the CCP—the US Department of Energy—Office of Fossil Energy/National Energy Technology Laboratory's (DOE-FE/NETL) Carbon Sequestration Program, the European Union's Director Generals for Research and for Energy and Transport, and Norway's Klimatek Program. These government organizations and their staff had a vision of what could be

accomplished, allocated significant portions of their scarce resources to the effort, and provided direction to the CCP through their participation on the TAB and their project management. Of particular value was the guidance that the representatives of the funding agencies provided on technology priorities and on integration of the CCP's efforts with other ongoing research.

Equally to be acknowledged are the eight participating companies, led by BP, who initiated the effort, provided the matching funds and allocated significant amounts of in-kind time and effort by their most capable technical and management staff. Also to be recognized are the technology providers—the companies, laboratories and contractors that conducted much of the technical assessments, research investigations and cost studies.

As such, this is a unique example of multi-company and multi-national cooperation in addressing issues and technologies of global interest.

While BP provided the overall management and leadership for this joint industry project (JIP), each of the eight participating companies made significant contributions.

- ChevronTexaco took the primary lead on the CO_2 "Storage, Monitoring and Verification" and the "Policies and Regulations" teams.
- Norsk Hydro served as the team leader for "Pre-Combustion" capture of CO_2 and, in partnership with BP, managed the development of the "Common Economic Model."
- ENI and BP served as the team leaders for "Oxyfuels Technology" and led the very valuable "Technology Screening Task Force."
- Statoil and BP provided the team leads for "Post-Combustion" capture of CO_2.
- Shell provided valuable process engineering and cost estimation support, while Encana and Suncor (along with Shell) provided expert scientists to the various Technology Teams, specifically on pre-combustion capture of CO_2 from gasification of coke and residual hydrocarbons.

The Portfolio of CO_2 Capture and Storage Technology Advances

The CO_2 capture and storage technology cost savings identified and further developed by the CCP cover a broad range of options:

Post-combustion technologies

By combining innovative design engineering with a new sorbent material and an innovative CO_2 contact process, work by the CCP identified potential capital cost reductions for CO_2 post-combustion capture of over 50% and defined overall reduction in the CO_2 post-combustion capture process by nearly 54% (on a CO_2 avoided basis), compared to currently available technology for the Norway gas-fired power plant scenario. Significantly, this advanced, lower cost technology could be commercially introduced for large-scale application before the end of this decade, if aggressively pursued through further public–private collaboration. The TAB encouraged and strongly supported the examination of cost-efficient design and energy integration as a means for reducing costs in this previously classified as "mature" post-combustion CO_2 capture technology. One logical step next would be to provide a modified design that is optimized for an NGCC facility as well as for an existing coal-fired boiler power plant with supercritical steam rebuilds and amine stripper heat integration.

Oxyfuel technologies

Advances in air separation and combustion technologies developed and bench-scale tested by the CCP would enable existing power plants to consider retrofit options for CO_2 capture without the high-energy penalties and costs associated with today's technologies. Assuming continued R&D in this area, the combined application of ITMs with flue-gas recycle could provide a 48% reduction in CO_2 capture costs (on a CO_2 avoided basis) for the UK oil refinery scenario, assuming that the excess power from this process can be sold at market rates. The TAB believes that additional significant technology advances are achievable for oxyfuel technologies. The application of ITM for air separation in new-built gas turbine systems or novel boilers shows promise for further reducing the costs of CO_2 capture. For example, integrating the Hydro MCM membrane in a gas turbine (Alaska scenario) shows potential for cost reductions of over 50%, assuming technical uncertainties are resolved and unproven equipment performs to specifications.

The integrated application of the OTM membrane inside a novel boiler could lead to similar cost savings. Finally, the TAB agrees that the proof-of-feasibility testing of the "breakthrough" chemical looping combustion technology, if and when successfully demonstrated at commercial scale, could further be improved on these results.

Pre-combustion technologies

Of all of the options pursued by the CCP, the pre-combustion removal of CO_2 appears to be the most promising for breakthroughs. These technologies, particularly involving advanced membranes, can reduce the capital costs of CO_2 capture by 50% and reduce the energy efficiency penalty by up to 75%. Not only are these technologies critical for carbon sequestration, but they also become essential components of a zero-emissions pathway to hydrogen. Importantly, these technologies may offer even more promise and cost savings for producing hydrogen from coal and other heavy hydrocarbons (such as oil sands and refinery residues) than for hydrogen from natural gas. Three key CO_2 capture technology options have been developed for gas-fired power generation and production of hydrogen from natural gas or clean refinery off-gas. Two of the lower risk technologies, sorption enhanced WGS and membrane WGS, offer cost reductions of 19–44%, depending on the scenario, compared to today's baseline cost for post-combustion capture of CO_2. The third technology, the advanced hydrogen membrane reformer, offers a cost reduction of 60% (CO_2 avoided cost basis), although it still requires considerable additional pilot testing and is a decade or so from being commercially available. The work by the CCP on CO_2 capture from petroleum and oil sands-based coke gasification, the Canadian scenario, showed relatively low costs of about $15 per ton of CO_2 (CO_2 avoided basis). The one advanced technology examined for this scenario provided only a modest 16% cost savings (CO_2 avoided basis). The assumptions were that the primary products from the gasification plant would be steam, power, and hydrogen. As such, many of the facilities and processes for CO_2 capture were already assumed to be in place, requiring primarily the addition of facilities and energy for compressing the already separated CO_2. In oil sands and synthetic crude operations, where power, hydrogen, heat and natural gas requirements are high, the gasification of petroleum coke offers a very valuable option, especially when it is integrated with CO_2 capture. Even so, because the CO_2 volumes are high, the capture and compression of CO_2 adds considerably to the costs of the salable products. The TAB believes that significant additional cost savings may be achievable in coke and coal gasification by incorporating a number of the advanced technologies, such as advanced air separation (ITMs), the enhanced CO WGS systems, and the hydrogen membrane reactor. The TAB recommends that the CCP focus additional efforts on sulfur-tolerant membranes, as this area was one of the few "shortfalls" or "failures" of the CCP, and further pursue integrated design and optimization studies for CO_2 capture from coke, petroleum residues and coal gasification during its next phase.

Storage, monitoring and verification

The CCP's SMV program emphasized four areas of priority, namely: (1) integrity of geological storage systems; (2) monitoring technology for CO_2 confinement, movement and leakage; (3) risk assessment methodology for geologic storage; and, (4) optimizing the storage capacity of alternative geologic CO_2 storage systems. The CCP sponsored over 40 individual geological, engineering and systems studies addressing these four topics that had been identified as knowledge and technology gaps. The TAB recognizes that the SMV topic is complex, ultimately requiring a broad set of CO_2 storage assessment and monitoring technologies as well as significant changes in current formation evaluation methods, well design, and CO_2 injection and tracking. Continued work in this area will be essential for building a sound base of scientific knowledge and data. Equally important will be testing this knowledge and technology in actual field settings to further understand the challenges of long-term CO_2 storage. These steps will be essential for building public understanding and acceptance for geologic storage of CO_2. Application and testing of these SMV technologies as part of a large-scale, integrated CO_2-enhanced oil recovery (EOR) and CO_2 storage field test demonstration could be a most valuable next step. The TAB finds that the CCP has significantly advanced the understanding and technology of CO_2 storage in geologic formations. In addition, the TAB supports the CCP's building of linkages with other international organizations such as GEODISC (Australia), GEUS (European Union), COAL-SEQ (US) and Weyburn (Canada) that are also addressing geologic storage of CO_2.

APPLICABILITY OF CCP TECHNOLOGIES TO COAL-FIRED POWER

CO_2 Emission Mitigation Options for Coal-Fired Power

Currently, there is over 300,000 MWe of existing coal-fired power plant capacity in the US, accounting for nearly 40% of domestic and nearly 10% of worldwide industrial CO_2 emissions. Should constraints on CO_2 emissions emerge, these plants will need to decide whether to:

- shut down;
- add a post-combustion or oxyfuels combustion retrofit;
- re-power the plant by converting it to natural gas (NGCC) or an integrated coal gasification (IGCC) unit; or
- purchase (or create) emission allowances from other sources.

In addition, should the choice be CO_2 capture, the plant operator will need to develop and gain approval for storing the CO_2, most likely in a geological formation.

Given the state of today's CO_2 capture technology, each of these choices entails high costs, risks and inefficiencies for the power plant operator:

- obviously, shutting down the facility or purchasing CO_2 emission allowances will make a significant negative financial impact on the plant owner and operator;
- adding a conventional retrofit flue gas amine CO_2 scrubber to an existing power plant, besides being costly, will lead to capacity and energy efficiency losses of 25–30%, due to the large steam requirements for amine stripping; and
- re-powering the power plant with a conventional NGCC or IGCC unit is costly and considered risky by power plant operators.

In addition, as set forth in the recent EIA Annual Energy Outlook 2004, over 100,000 MW of new coal-fired power plant capacity is expected between now and 2025, with the bulk of these coming online after 2015. Prolonged periods of higher than forecasted natural gas prices, as is the case today, would significantly increase and move forward the expectations for new coal-fired power. Significant cost savings would accrue to the owners and operators of these new coal-fired power plants if low-cost and energy-efficient CO_2 capture systems would become commercially available and be integrated with a new plant design, as opposed to being added-on as part of future re-powering or retrofit where there has been no prior design consideration for this option. As such, integrated lower cost CO_2 capture technology would provide tremendous economic benefits for both the coal-fired and the gas-fired electric power industry.

CO_2 Capture Technology Options for Coal-Fired Power

The CO_2 capture and storage technologies developed by the CCP could provide significant benefits to the coal-fired power sector, as set forth below.

Post-combustion CO_2 capture technology

The improved amine scrubber design of the CCP offers major cost and efficiency improvements for post-combustion capture of CO_2. This result is in sharp contrast to prior work that had labeled this technology "mature" and had not fully exploited the potential of heat and pressure integration. Although the CCP study was for a new NGCC, the results could be even more significant for coal-fired power. This is especially true for existing coal power plants assuming a rebuild of the steam cycle for effective heat integration for the critical amine CO_2 stripper energy needs. The CCP identified MHI amine/CO_2 scrubber technology has much lower capital and heat requirements than today's baseline technology. This suggests much less derating for existing coal power plants that are considering flue gas CO_2 scrubber retrofits. When the improved amine/CO_2 scrubber design is combined with boiler and supercritical steam cycle rebuilds at existing coal power plants, the plants could avoid any capacity or efficiency derating due to CO_2 capture. This technology could be particularly attractive to coal-fired power due to the higher concentrations of CO_2 in the flue gas. The next logical step for this technology would be for the CCP to provide a modified design that is optimized for existing coal boiler power plants with supercritical steam rebuilds and amine stripper heat integration. This could be just what the existing coal-fired electric utilities need to stay competitive if a carbon-constrained world develops. This would also allow effective conversion of older and less efficient subcritical boiler-fired plants into modern, efficient and clean supercritical plants with effective CO_2 capture. Many of the older coal units with greater than 500 MWe plant capacity, accounting for nearly half (over 160,000 MWe) of total US power capacity, are good candidates for retrofit with the improved amine/flue gas CO_2 scrubber technology.

Oxygen combustion CO_2 capture technology
CCP work on oxygen combustion could have major advantages for both new and retrofit coal-based power generation. For example, the CCP fluidized bed chemical looping combustion technology for natural gas has already led to a follow-on DOE project applying this innovative system to coal. A major problem with oxygen combustion retrofit of existing coal-fired boiler power plants is the net capacity and efficiency losses of 30–35%. This is mostly due to the large electric power requirements of traditional cryogenic air separation. The ITM oxygen system (using natural gas to make the oxygen) avoids essentially all capacity and energy efficiency derating. Many of the newer supercritical coal units (accounting for about 50,000 MWe of US power capacity) would be good candidates for the option of oxygen combustion via a natural gas-based ITM oxygen generator. As such, the CCP work on incorporating oxygen combustion in refinery heaters and boilers is also applicable to existing coal-fired power plants. The key innovation in this area by CCP is the use of the integrated ITM or a ceramic membrane to generate hot oxygen. Further design work, however, is still required to better match the increased power generation output with power needs.

Pre-combustion CO_2 capture technology
Many of the pre-combustion technologies pursued by CCP, particularly the membrane technologies, apply directly to lowering the cost of CO_2 capture from IGCC power generation, as this involves generation of hydrogen (H_2) and its combustion in gas turbines. Independent analysis of H_2 for fuel cell vehicles (FCV) shows that H_2 and IGCC co-production could enable the capital-intensive gasification plants to maintain high annual load factors with a gradual shift to more H_2 and less electricity each year as demand emerges. The CCP work on converting gas turbines from natural gas to H_2 firing is essential for all gas turbines considering the challenges of effective H_2 use. The CCP work on petroleum coke gasification polygeneration of H_2, electricity, hydrogen and steam shows low incremental CO_2 capture costs, although the overall cost penalty is still much too high. Here, the CCP works to enhance the CO WGS reaction using sorption enhanced WGS and membrane WGS technology is most applicable. This work will likely benefit coal and petroleum coke gasification more that natural gas reforming due to the significantly higher amounts of CO generated by gasification. Coal gasification-based repowering with H_2-fired gas turbines and CO_2 capture, when the existing steam cycle is matched to the bottoming cycle of the new IGCC, could be attractive for many of the older and smaller coal-based power plants that account for about 120,000 MWe of US power capacity. A good example of coal gasification repowering is the highly successful Wabash River Clean Coal Technology project. Adding CO_2 capture to this repowered IGCC plant would demonstrate how CO_2 capture technology could be cost-effectively added during a second stage, when properly planned.

Because the cost-reductions for new CO_2 capture technology studied to date have been for natural gas, oil and petroleum coke-based feedstocks, considerable uncertainty still exists as to how much the CCP technologies could reduce the cost of CO_2 capture from coal-fired plants. However, the levels of cost savings, identified by the CCP for these other energy fuels, provide one valuable point of reference. Future work by the CCP on lower cost CO_2 capture technologies for coal-fired power generation would be a logical next step.

OVERVIEW OF THE CCP APPROACH

Technology Screening and Evaluation
To achieve the technology advances discussed above, the CCP conducted in-depth reviews of nearly a 100 technologies, ideas and concepts for improving on the state-of-the-art of CO_2 capture and storage. A number of these failed to deliver on their postulated costs savings, some were found to be scientifically flawed, while others were found to still be ideas requiring more rigorous definition and process design. From this mix, the CCP identified, sponsored and itself developed a handful of technologies (including combinations of technologies) that offered the most significant cost savings and promise of commercial readiness.

The final set of lower cost, advanced technologies (summarized above and in Table 2) were rigorously evaluated by outside engineering firms, by expert cost analysts within the participating companies, and finally by using the "Common Economic Model."

The TAB recommends that the insights from the technology evaluation process and the CEM itself become CCP products that will be available not only just to the project sponsors and participants but also to the broader scientific and research management community.

Impact and Benefits

The domestic and international economic benefits of the knowledge and technology on CO_2 capture and storage developed by the CCP will be measured in the hundreds of billions of dollars, particularly should the US pursue a pathway toward atmospheric stabilization of greenhouse gas concentrations. For the European Union and Norway, the other two governmental sponsors of the CCP, the economic benefits could be comparable, although additional work is required to establish the economic and environmental benefits.

To date, the impact and benefits of the CCP technologies have been assessed in terms of reduced costs of CO_2 capture (on a CO_2 avoided basis). While reduced CO_2 capture costs are one useful measure. Understanding the impact that CO_2 capture and storage will have on the cost of the primary product, be it electricity, a refined product, or hydrogen is as valuable. The TAB strongly recommends that this second valuable impact measure be incorporated into future CCP and CEM work.

Meeting its Promises

When the CCP was first formed and selected for funding by the US DOE/FE's National Energy Technology Laboratory, by the European Union's DGs for Research and for Energy/Transport, and by Norway's Klimatek Program, it set forth ambitious (some would say most ambitious) goals. The goals were to reduce the cost of CO_2 capture (on a CO_2 avoided basis) by 50% for retrofit technology and by 75% for new plants. The goals also were to advance the use of geological storage of CO_2 as a safe and reliable option. The results and accomplishments to date by the CCP offer promise that these ambitious goals can and will be met.

Summary of TAB and CCP Interactions

The TAB has been most pleased with its role and interaction with the board, management and staff of the CCP. The TAB was provided "pre-read" information prior to its formal review meetings, it received detailed presentations from the Technology Team leaders and key team members, and it was provided considerable time for in-depth and frank questioning by the members of the TAB.

Most importantly, the TAB finds that its comments and recommendations were seriously considered and incorporated into the priorities, work plans and technical pathways of the CCP. As such, the TAB believes it was given the opportunity to provide valuable technical advise to the project as opposed to merely serving as "window dressing", as is often the case with advisory boards.

NEXT STEPS

Importantly, the work is not yet finished. The CO_2 capture technologies identified and developed by the CCP need to be pilot tested and demonstrated to assure their commercial availability in the next 10 years. In parallel, there is need for further research and large-scale demonstrations to provide public confidence that CO_2 can be reliably and safely stored for thousands of years.

Still, the costs of CO_2 capture are too high. Further research, process optimization and innovative engineering by the CCP, its participating companies and its technology providers offer promise that additional cost reductions and technology advances can be expected. And, full public understanding and acceptance of CO_2 storage is yet to be achieved, placing a high priority on this essential aspect of CO_2 sequestration.

Going forward, the TAB recommends the following paths and priorities for the next phase of the CCP:

1. *Maintain the vision and organization structure*. The CCP is a unique and successful example of a joint multi-industry and government partnership and of international cooperation. By adopting broad and bold

goals and working closely with the government project managers, this type of organization and participation is essential for the cost-effective pursuit of the most promising options for CO_2 capture and storage.

2. *Expand the membership, particularly to include traditional electric power companies*. While the CCP sought to recruit electric power companies (with unsuccessful results) when it was first formed, the landscape has changed. Several US power companies have made voluntary commitments to reduce their CO_2 emissions toward the President's year 2012 goals for carbon intensity. These companies may now be considerably more interested in participating in this technology development effort, assuming that the terms for participation are acceptable.
3. *Further develop, test and optimize the most promising CO_2capture technologies*. Detailed engineering-based energy and pressure integration and optimization studies, the classic "learning by learning" approach, has enabled the CCP to significantly lower the costs of the post-combustion CO_2 capture and pre-combustion membrane WGS technologies. Similar optimization-based gains may be possible in the remaining set of promising CO_2 capture technologies. Having pushed the envelope of integration and optimization, the final steps would be to take the proof-of-concept technologies into pilot and demonstration testing and on the path toward commercial availability.
4. *Address the technologies and benefits of joint capture and storage of CO_2, SOX*, NO_X emissions from power and industrial plants, including refineries and sour gas processing units. Many of the CCP technologies offer lower volumes of NO_X, as well as the joint capture of CO_2, SO_X and other emissions. The optimum pathway for capturing the multi-pollutants, their impact on risks of storage, and their economic benefits (or penalties) have yet to be rigorously established and evaluated. The CCP is in a unique position to undertake this important issue.
5. *Examine and demonstrate the potential of using CO_2-based enhanced oil and gas recovery as a transition step toward "permanent" storage of CO_2*. New CO_2-based EOR and enhanced gas and coalbed methane recovery (EGR/ECBM) projects can provide a platform for testing advanced SMV technology and practices, while providing additional oil and gas production and near-term reductions of CO_2 emissions.
6. *Sponsor a series of world class, transparent demonstrations of the safety and reliability of geologic storage of CO_2*. Important steps have been taken by the CCP that further the understanding and technology for geologic storage of CO_2. These will be described more fully in the upcoming CCP publications. These technologies, plus the development of advanced "early warning" and mitigation technologies, need to be tested and shown to be reliable, safe and verifiable, helping build the essential public trust for this important greenhouse gas management option.