I

Report of the Panel on DOE's Carbon Sequestration Program

INTRODUCTION AND OBJECTIVE OF THE STUDY

The panel on DOE's Carbon Sequestration Program was formed by the National Research Council to examine the benefits of the U.S. Department of Energy's (DOE's) program on carbon sequestration as part of the activities of the Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, Phase Two. The panel was charged with applying the method that the committee had developed for estimating the benefits of DOE's R&D. Although the panel was charged with estimating the likelihood that the program goals would be achieved within the budget and specified time period, the panel was not given detailed materials that would allow it to review individual projects to judge whether they would achieve their goals. Rather, it conducted a high-level program review, relying on members' knowledge of each area and the difficulties of achieving specific R&D goals.

The method developed by the committee asked the panel to come to a judgment concerning the likelihood that the DOE program as currently funded would achieve the goals within the specified time period. The panel was also asked to come to a judgment concerning the extent to which the technology would be deployed in the market. The committee's method outlined three scenarios for the panel and allowed the panel to add a fourth, which the panel believed would be of particular interest for this program.

The first scenario, the Reference Case, from the *Annual Energy Outlook (2005)*, assumed business as usual, the second assumed high oil and gas prices, and the third assumed that carbon emissions would be curtailed—namely, that a carbon tax would be imposed on emissions at $100 per ton of carbon.[1] The panel decided to evaluate another scenario wherein the carbon tax was assumed to be $300 per ton.

Since the panel did not think that a technology that separated and sequestered the carbon would be as inexpensive per megawatt-hour of generated electricity as a technology that did not, it concluded that carbon sequestration would not be implemented unless there were restrictions on carbon emissions. Thus, the panel concluded that the sequestration technology would not be implemented in the first two scenarios, even if DOE achieved its R&D goals. Thus, the panel focused its analysis on the scenarios with carbon taxes of $100 or $300 per ton of carbon emitted.

In evaluating the benefits of each scenario, the panel utilized the DOE NEMS model runs to provide baseline estimates of fuel costs and capacity additions in each scenario. Unfortunately, DOE was not able to make additional model runs for these two carbon tax scenarios within the time available, so previous NEMS runs for a carbon constrained scenario were adapted to provide the necessary estimates. The panel believes that the quantitative results are reasonable approximations to what new NEMS model runs would have given in these scenarios.

During Phase One of the prospective benefits study, the earlier panel estimated the benefits of the same DOE carbon sequestration program. Owing to differences in the extent to which two factors were considered, the Phase One panel calculated an expected economic benefit of $35 billion, whereas the current panel calculated benefits of $3.5 billion. The difference in results is primarily due to the current panel's more complete and rigorous application of the methodology outlined in Phase One. In particular, the current panel focused on what would happen without effort by DOE and the impacts of competing technologies. The earlier (Phase One) evaluation of the carbon sequestration program was done as part of the task of developing the methodology and consequently did not adequately consider these two factors.

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[1]The tax is assumed to be imposed in 2012 and to increase at 3 percent per year thereafter.

SUMMARY OF DOE'S CARBON SEQUESTRATION PROGRAM

Carbon sequestration is the separation and storage of carbon dioxide CO_2 and other greenhouse gases (GHGs) that would otherwise be emitted to the atmosphere. GHGs can be captured at the point of emission or they can be removed from the air. The captured gases can be used, stored in underground reservoirs or possibly the deep oceans, or converted to rocklike mineral carbonates and other products. There is a wide range of sequestration possibilities to be explored, but a clear priority for near-term deployment is to capture a stream of CO_2 from a large, stationary emission point source and sequester it in an underground formation. Carbon sequestration holds the potential to provide deep reductions in greenhouse gas emissions since a little less than half of total U.S. GHG emissions are from large point sources of CO_2. Research is ongoing to develop a clearer picture of domestic geologic sequestration storage capacity, but it is likely that domestic formations have at least enough capacity to store several centuries' worth of point source emissions. Technologies aimed at capturing and utilizing methane emissions from energy production and conversion systems can be applied to carbon sequestration and will reduce an important GHG emission. Mobile and dispersed GHG emissions can be offset by enhanced carbon uptake in terrestrial ecosystems, and research into CO_2 conversion and other advanced sequestration concepts will expand the range of sequestration.

Program Goals

DOE established the carbon sequestration program in 1997.[2] The program, which is administered within the Office of Fossil Energy (FE) by the National Energy Technology Laboratory (NETL), seeks to move sequestration technologies forward so that their potential can be realized and they can play a major role in meeting any future needs for the reduction of GHG emissions. This program utilizes an annual Carbon Sequestration Technology Roadmap and Program Plan to identify research pathways that are expected to lead to commercially viable sequestration systems and sets forth a plan of action for sequestration research. Table I-1 is a top-level roadmap for core R&D and infrastructure development. The overarching program goal is 90 percent CO_2 capture with 99 percent storage permanence at no more than a 10 percent increase in the cost of energy services by 2012.

Core R&D

The goal of the core R&D program is to advance sequestration science and develop new sequestration technologies and approaches to the point of precommercial deployment.

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[2]Carbon Sequestration Technology Roadmap and Program Plan, U.S. Department of Energy, National Energy Technology Laboratory, May 2005.

The core program is a portfolio of work including cost-shared, industry-led technology development projects, research grants, and research conducted in-house at NETL. The core program is divided into the following six areas.

- *CO_2 capture.* CO_2 exhausted from fossil-fuel-fired energy systems is typically too dilute, at too low a pressure, or too contaminated with impurities to be directly stored or converted to a stable, carbon-based product. The aim of CO_2 capture research is to produce a CO_2-rich stream at high pressure. The research is categorized into three pathways: postcombustion, precombustion, and oxyfuels.
- *Carbon storage.* Carbon storage is defined as the placement of CO_2 into a repository in such a way that it will remain stored (or sequestered) permanently. It includes three distinct subareas: geologic sequestration, terrestrial sequestration, and ocean sequestration.
  —Trapping within a geologic formation is the primary method for storing CO_2. A layer, or cap, of impermeable rock overlies the porous rock into which the CO_2 is injected and prevents upward flow of CO_2.
  —Because the surface of sandstone and other rocks preferentially adheres to saline water in preference to CO_2, if there is enough saline water within a pore (75-90 percent of the pore volume), the water will form a capillary plug that traps the residual CO_2 within the pore space.
  —When CO_2 comes in contact with the saline water it dissolves into solution.
  —Over longer periods of time (thousands of years), dissolved CO_2 reacts with minerals to form solid carbonates. This process is known as mineralization.
  —Preferential adsorption of CO_2 onto coal and other organic-rich reservoirs takes place as a function of reservoir pressure.

Monitoring, Mitigation, and Verification (MM&V). Monitoring and verification for geologic sequestration has three components: (1) modeling, which facilitates the understanding of the forces that influence the behavior of CO_2 in a reservoir; (2) plume tracking, the ability to see the injected CO_2 and its behavior; and (3) leak detection systems, which serve as a backstop for modeling and plume tracking. MM&V for terrestrial ecosystems also has three components: organic matter measurement, soil carbon measurement, and modeling.

Non-CO_2 GHG Control. Because some non-CO_2 GHGs (e.g., methane, N_2O, and gases having high global warming potential) have significant economic value, they can often be captured or avoided at relatively low net cost. This area of the core sequestration program is focused on fugitive methane emissions, whereby non-CO_2 GHG abatement is integrated with energy production, conversion, and use. Landfill gas and coal mine methane are two top-priority opportunities.

Breakthrough Concepts. R&D on breakthrough concepts is

TABLE I-1 Top-Level Carbon Sequestration Roadmap

	Pathways	Metrics for Success	
		2007	2012
CO_2 capture	Postcombustion Precombustion Oxy-fuel	Develop at least two capture technologies that each result in less than a 20% increase in cost of energy services.	Develop at least two capture technologies that each result in less than a 10% increase in cost of energy services.
Sequestration storage	Hydrocarbon-bearing geologic formations Saline formations Tree plantings, silvicultural practices, and soil reclamation Increased ocean uptake	Field tests provide improved understanding of the factors affecting permanence and capacity in a broad range of CO_2 storage reservoirs.	Demonstrate ability to predict CO_2 storage capacity with +/– 30% accuracy. Demonstrate enhanced CO_2 trapping at precommercial scale.
Monitoring, mitigation, and verification (MM&V)	Advanced soil carbon measurement Remote sensing of above-ground CO_2 storage and leaks Detection and measurement of CO_2 in geologic formations Fate and transport models for CO_2 in geologic formations	Demonstrate advanced CO_2 measurement and detection technologies at sequestration field tests and commercial deployments.	CO_2 material balance greater than 99%. MM&V protocols enable 95% of stored CO_2 to be credited as net emissions reduction.
Breakthrough concepts	Advanced CO_2 capture Advanced subsurface technologies Advanced geochemical sequestration Novel niches	Laboratory scale results from one or two of the current breakthrough concepts show promise to reach the goal of an increase of 10% or less in the cost of energy and are advanced to the pilot scale.	Technology from the program's portfolio revolutionizes the possibilities for CO_2 capture, storage, or conversion.
Non-CO_2 GHGs	Minemouth methane capture/ combustion Landfill gas recovery	Deployment of cost-effective methane capture systems.	Commercial deployment of at least two technologies from the R&D program.
Infrastructure development	Sequestration atlases Project implementation plans Regulatory compliance Outreach and education	Phase II partnerships have pursued priority sequestration opportunities identified in Phase I and have conducted successful field tests.	Projects pursued by the Regional Partnerships contribute to the 2012 assessment under GCCI.

pursuing revolutionary and transformational sequestration approaches with potential for low cost, permanence, and large global capacity. These concepts are speculative but could offer performance and cost improvements that let them leapfrog existing technologies.

Field Projects. Because conditions in both terrestrial ecosystems and geologic formations are difficult to simulate, testing ideas in the field often enables significant learning and insight. Sequestration field tests serve as a test bed for CO_2 detection and measurement technologies and also present an opportunity to validate models.

Infrastructure Development

DOE initiated seven regional carbon sequestration partnerships (RCSPs) in 2003 with the goal of developing an infrastructure to support and enable future carbon sequestration field tests and deployments. The first stage of the RCSPs ended in June of 2005. The partnerships have established a national network of companies and professionals working to support sequestration deployments, created a carbon sequestration atlas for the United States, and identified and vetted priority opportunities for sequestration field tests. The primary and overarching objective of the second stage will be to move forward with the high-priority tests to validate sequestration technology that were identified in the first stage of the effort. In support of this primary objective will be the refining and implementing of MM&V protocols, improving the understanding of environmental and safety regulations; establishing protocols for project implementation, accounting, and contracts; and conducting public outreach and education. Also in the second stage, partnerships will seek to continue the characterization of the regions and to refine a

national atlas of carbon sources and sinks. In FY 2009 DOE will consider an optional third stage effort for the RCSPs. A third stage, which would run through 2013, would be contingent on the continued importance of and synergies with the FutureGen initiative (partially funded by DOE), the need for validation of additional sequestration sites throughout the United States, and funding availability.

Program Budgets

The base sequestration program funding is roughly $55 million per year. DOE will provide approximately $100 million to support the RCSPs over the next 4 years. Each partnership will receive between $2 million and $4 million per year in DOE funding. At least 20 percent of project costs are covered by non-DOE funding. The total value of the projects exceeds $145 million over the next 4 years. The RCSPs are structured to become self-sustaining by 2013. The approximate actual and projected funding levels from 2001 to 2020 are shown in Figure I-1. Program costs through 2020 are expected to be $875 million.

TECHNICAL RISKS

While DOE has taken a portfolio approach for its CO_2 sequestration program, it has focused on developing components suitable for advanced integrated gasification combined cycle (IGCC) technology, with sequestration based on deep well injection. DOE sees advanced IGCC as the technology of choice to achieve the goal of 10 percent incremental COE

for CO_2 sequestration beyond that achieved by IGCC units. (There is a goal of 20 percent increase in the COE for combustion-based systems. The cost of electricity generated from such systems, including carbon capture and storage (CCS), has been estimated to be about 10 percent greater than the cost of IGCC. A review of cost studies found that the cost of electricity generated using supercritical pulverized coal (SC-PC) technology with (post-combustion) amine-based CO_2 capture would be $77/MWh and, if using IGCC with a Selexol unit for carbon capture, $65/MWh. Both the cost estimates include $5 per ton CO_2 for geologic storage (Rao et al., 2005).

The carbon sequestration program is taking on a relatively high overall risk to create technologies for commercial demonstration by 2012 in that it relies heavily on the successful deployment of full-scale IGCC plants (more than 200-500 MW) in parallel with the sequestration program schedule. There are only a few IGCC plants operating worldwide, and advanced, commercial-scale IGCC units are only in the design stage and have no CO_2 sequestration. An end-to-end, full-sized plant demonstration of IGCC technology with sequestration will take longer.

The recent DOE systems analysis of the developments from the CO_2 capture program is framed in terms of four main components: (1) sorbent improvement associated with the Selexol process, (2) oxygen membrane separation to replace cryogenic separation, (3) membrane technology to facilitate the water gas shift reaction to produce hydrogen, and (4) storage of the CO_2 in deep geological formations. The storage component is said to be advanced, and based on
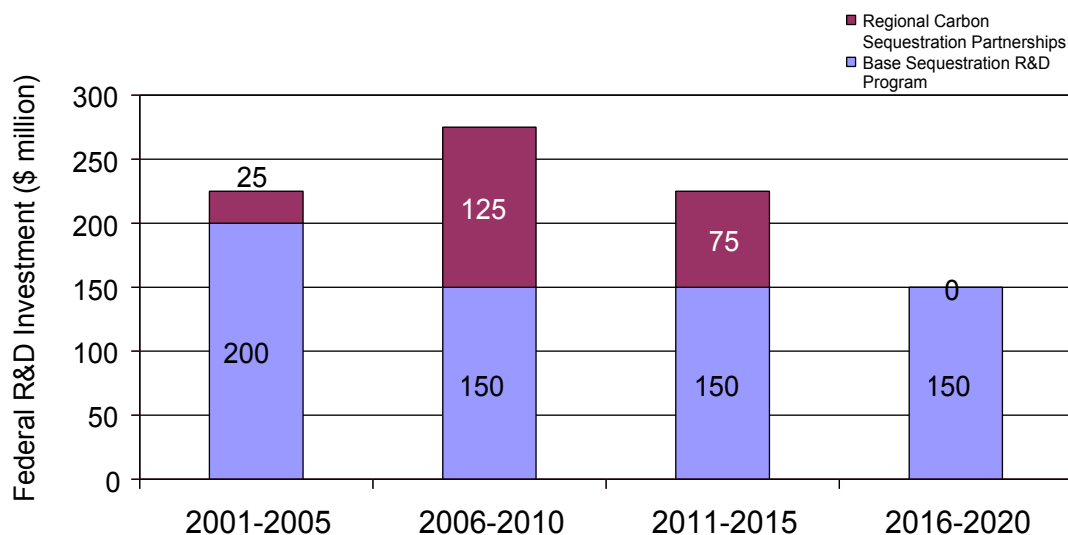

FIGURE I-1 Funding requirements for DOE's carbon sequestration program. RCSP, regional carbon sequestration partnerships.

the extensive commercial CO_2-enhanced oil recovery effort in place today. While this experience has shown the process to be viable and there have been no serious accidents, the storage time frame has been a few decades, compared with the centuries-long time frame needed for CO_2 storage. The cost reductions for electricity production with sequestration are more sensitive to increases in the efficiency of the IGCC system than to advances in CO_2 capture.

The results from new sorbent technologies are expected to improve the performance of CO_2 scrubbers greatly by increasing capture efficiency at higher temperature and pressure (DOE, 2005d). While sorbent research has shown a number of options for improved systems,[3] none of these have been tested in pilot or larger combustion systems relevant to power plant operations. The technologies need to be tested thoroughly for sorbent stability, operational reliability, and integrated performance to establish a cost-effective design basis. This is an ambitious task to be completed by the target date of 2012.

The second component envisaged for reducing IGCC power production costs, specific oxygen separation based on ion transport membranes (ITMs) for oxyfuels, is funded not within the DOE carbon sequestration program but within its advanced gasification research program. The technical risk of achieving the sequestration program's goals is increased by having this critical component controlled elsewhere. More important, this membrane technology is predicated on successful operation with temperatures of about 1000°C or even higher. While membrane materials for operation in this temperature range are well developed, the supporting equipment for operating a membrane-based system is problematic. Failure of this equipment could slow down practical applications and increase costs for the technology. Since none of the membrane technology has been tested beyond small pilot scale, the reliability and expected performance of these systems at larger scale for design engineering and costing remain an open question.

The water gas shift membrane technology is jointly funded by the DOE carbon sequestration and IGCC programs. While this technology appears to have a favorable future in the laboratory, the use of polymer membranes here depends on achieving the flux and membrane stability at ~300°C. This temperature is an ambitious goal for any polymer membrane; good membrane stability and performance at this temperature are yet to be demonstrated. The performance of this technology at the pilot scale and larger remains to be demonstrated at an aggressive pace, to provide an informed and confident basis for large-scale design and integration into IGCC technology, as planned.

The panel's perception, taken in toto, is that the DOE carbon sequestration program, which depends heavily on complementary work in fossil fuel technology, demands a

highly ambitious, relatively high-risk effort to achieve its technical goals by 2012.

DOE is using systems analysis tools in a constructive way to evaluate past progress and future objectives. These tools have the potential to strengthen the program by guiding the choices of technologies to pursue most vigorously as well as the down-selection process. However, in the briefings the panel received about the DOE program, it observed the distorting effect of the program's "aspirational goals" on the systems analysis effort. The leadership of the program has set cost increment goals—sometimes 10 percent, sometimes 0 percent—for CCS. The systems analysis effort has been unduly influenced by an apparent need to show strategies that meet these goals. First, the difficulty of meeting them is hidden by comparing future (lower cost) IGCC systems with CCS to present systems without CCS, making it appear that the cost savings for advanced IGCC can be attributed to sequestration savings. (The savings, presumably, is that the COE from IGCC with carbon sequestration would be less than the cost of electricity from IGCC with venting and paying the tax.) The DOE goal is an increase of no more than 10 percent for IGCC with sequestration compared with IGCC without sequestration. The analysis thus makes a misleading comparison to arrive at a small increase (or no increase) due to sequestration. Second, in an effort to drive downward the apparent incremental cost of CCS for electricity production, systems analyses have built in large credits, sometimes for the sale of by-products of the carbon sequestration process (hydrogen or chemicals), sometimes for the sale of CO_2, and sometimes for the avoidance of sulfur management above ground via co-storage of sulfur (as H_2S or SO_2) with CO_2. All of these credits can be real in some situations but are zero in others. DOE should consider the ancillary benefits in scenarios whose assumptions are clear. Fortunately, the panel finds that the program as a whole has not been distorted to emphasize these secondary concerns. However, the value of the systems analysis effort to the program is considerably reduced by a focus on such credits. The panel recommends that the leadership of the program work harder to insulate the systems analysis group from pressure to produce results that conform to the program's aspirational goals, so as to get greater value from the expertise of the group.

The CO_2 storage component is smaller than the capture component as it currently relies on existing technologies needing relatively little innovation. The program emphasis is on small-scale demonstration in the field and partnership in one large project (Weyburn).

Once CO_2 is injected into the subsurface, there are two primary routes for leakage: through or around the reservoir seal (caprock) or through well bores that could be created for this purpose or that might have been drilled in the past for oil or gas exploration. The reservoir seal could be compromised by tectonic activity or by overfilling the reservoir, while the well bores could be attacked by carbonic acid formed when CO_2 dissolves in the formation water.

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[3]See, for example, DOE (2005d) and Rao et al. (2005).

Industry has over 30 years experience with CO_2 injection for enhanced oil recovery, with no mishaps that would indicate the process has serious flaws. However, carbonic acid reacts with the Portland cement that is used in the construction of wells as well as with the tubular bores that communicate to the surface. These reactions can be evaluated in the laboratory over relatively short time spans, but there is no known way in the laboratory to evaluate the reactions that might degrade the well bore seals over hundreds to thousands of years. There may have to be some sort of protocol to monitor the wells periodically and make repairs as needed. The DOE program devotes little effort to remediation, assuming that the technology available in the industry is, or will be, adequate. The other major forms of carbon storage envisioned in this program are ocean and terrestrial. For ocean sequestration, environmental impacts may be more significant than concerns about safety, whereas the reverse is true of terrestrial sequestration in geologic formations (Herzog, 2001; Brewer, 2003; Orr, 2003).

While success of the capture program depends almost entirely on the ability to reduce the cost of the operation by technical means, the storage program cannot be successful if a significant fraction of the public views it as dangerous or unacceptable. Thus, the technologies must not only be safe and effective, they must be explainable to the public and the regulatory community in such a way as to instill confidence that they are in fact safe and effective. The federal government in general and the DOE in particular have not had a good track record in accomplishing this task in other programs, such as the Yucca Mountain nuclear waste repository, and the siting of terminals for unloading liquefied natural gas.

The cornerstone of the DOE program is the RCSPs, a collection of seven organizations run by respected entities and with a wide base of participation. These partnerships are in the second stage of their development and have developed work plans that include not only technical development and demonstration but also outreach. DOE holds meetings routinely to coordinate the efforts of the RCSPs and share results.

The RCSPs were told to develop demonstration projects relevant to their regions, and they hold storage field trials with significant monitoring and evaluation components. These projects, which will be completed over the next few years, will familiarize interested parties with the process. However, the RCSP program may not resolve uncertainties in extrapolating the volume scale and the time frame over which the demonstrations can operate.

MARKET RISKS

Both competing technologies and political factors will have an effect on the deployment of carbon sequestration technologies in the market. The primary driver for deployment is an incentive for reducing carbon emissions. The panel believes that only in a carbon-constrained scenario will any carbon sequestration technologies be implemented; accordingly, the benefits of DOE's carbon sequestration program were evaluated only for scenarios where a carbon tax exists.

Competing Technologies

A high carbon tax will make zero-emissions or very low carbon emissions electricity generating technologies more attractive. The panel believes IGCC with CCS is a promising technology. Other technologies that could potentially compete against IGCC with CCS are natural-gas-fired electricity generation technologies; technologies that transform coal into a noncarbon fuel, such as hydrogen, with carbon storage; high-efficiency combustion cycles with backend CCS; oxygen combustion with CCS; nuclear power systems; and renewables.

If only a modest reduction in carbon emissions is required, substituting natural gas (CH_4) for coal in a high-efficiency combined cycle generator can accomplish that reduction. However, natural gas prices have increased rapidly in recent years owing to high demand and static supply. At current prices, switching to natural gas would be a costly strategy with considerable doubt that the supply of natural gas would be sufficient through 2017.

Coal gasification can lead to a pure hydrogen stream with separation and sequestration of the CO_2. The resulting hydrogen could be burned in a turbine or used in fuel cells. This approach is a variant of IGCC and is attractive only if carbon separation and sequestration is an attractive, low-cost technology that effectively sequesters the carbon. If the DOE program were successful in creating an attractive IGCC technology with carbon sequestration, the hydrogen stream would be available for other applications.

Both higher efficiency combustion cycles (supercritical and ultrasupercritical) with backend CCS and oxycombustion systems are more expensive today than gasification with CCS,[4] and oxycombustion is in its early stages of development (Rao et al., 2005; Anderson et al., 2004). Whether these systems, which are being addressed in the DOE sequestration program, can provide a viable alternative remains to be seen. An as-yet- unresolved issue surrounding viable alternatives for coal remains the performance and cost of combustion or gasification with different types of coal. For example, lower rank coals such as lignite, when slurry-fed to the gasifier, bring in lower system efficiencies and net power outputs (Maurstad et al., 2006).

Several panel members believe that nuclear generation has significant market potential in the long run in a carbon-

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[4]Based on an extensive literature review, Rubin (2006) has determined that a representative estimate of the cost of electricity, if generated using supercritical pulverized coal technology with CCS, would be $77/MWh and, if using IGCC with CCS, $65/MWh.

constrained scenario and could be a strong competitor for IGCC with sequestration. The relative attractiveness of the two technologies will depend on public acceptance and the cost of each technology, which will be influenced by DOE's fossil energy R&D program.

Political Risks and Other Market Factors

The panel identified several other potential barriers to the deployment of IGCC with carbon sequestration. Each of these barriers would make successful deployment of sequestration less likely and would tend to favor some of the competing technologies as a way to meet carbon constraints:

• *Public opposition based on the risk of sequestration.* It is not yet apparent whether the public would be receptive to carbon sequestration, and it is possible that people living near sequestration sites would have significant concerns that might lead them to oppose proposals to sequester CO_2 in their local environment. Strong public opposition could delay or even prevent the deployment of an IGCC plant with CCS. Some preliminary studies suggest that the public is not favorably disposed to carbon storage in the oceans or deep underground (Palmgren et al., 2004). To the panel's knowledge, there has not been a full risk assessment of carbon storage; such an assessment, could alleviate some public concerns.

• *Regulatory issues.* A variety of siting and permitting issues associated with carbon sequestration remains to be worked out, including jurisdictional issues that accompany the permitting process. Delays or problems in resolving these issues could significantly delay the deployment of sequestration technologies.

• *Physical siting requirements.* Storage in geological formations calls for sites having adequate capacity and injectivity, a confining unit (e.g., a caprock), and a geologically stable environment (IPCC, 2005). These requirements, along with regulatory requirements and public concern, could further limit potential sites and the penetration of IGCC with CCS. The location of generation away from load centers might raise costs to the consumer.

• *Competition from energy conservation and alternative energy sources.* In addition to public views and regulatory requirements, the competition will depend on the cost of electricity from each technology. This cost will be influenced by the regulatory requirements for each technology. For example, if regulators insisted that CO_2 had to be placed in areas where no oil or gas wells have been drilled, or below the depth to which wells have been drilled, IGCC with CCS could become less cost-competitive.

DECISION TREE MODEL AND PROBABILITY ASSESSMENT RESULTS

Rather than attempting to assess probabilities at a project level and somehow aggregate them, the panel decided to focus on an overall assessment of the effectiveness of the research program. The process and calculation methodology for this assessment[5] followed the recommended guidelines of the Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, Phase Two. The impact of government support can be captured by considering the probabilities of various technical and market outcomes with and without government support. The decision tree developed by the panel is summarized in Figure I-2.

The main technological uncertainty considered was the increase in the COE associated with the capture and storage of carbon emissions from coal-fired power plants, specifically from advanced IGCC plants. DOE's R&D program assumes that IGCC plants without CCS will be the cheapest coal-based generation plants and that these plants will meet all EPA emissions requirements (aside from CO_2 emissions). Thus, the only significant difference between the two technologies is the COE and whether the carbon is sequestered. The panel considered COE in three time periods (2012, 2017, and 2022) and at four different levels of cost increase at each point in time. The probability assessments for costs in 2012 were conditional on the currently expected level of DOE funding for research on sequestration. The assessments for 2017 were made conditional on the 2012 results and the 2022 assessments were conditional on the 2012 and 2017 results as well as on the presence or absence of DOE support. Specifically, panelists were asked to assign probabilities that the COE increase associated with sequestration in 2012 would be 0 to 10 percent; 10 to 20 percent; 20 to 30 percent and more than 30 percent; four probabilities in total. For 2017, panelists were asked to assign conditional probabilities for the same ranges that depend on the cost increase in 2012. For example, if the cost increase in 2012 were in the 20-30 percent range, panelists were asked to specify probabilities that the costs in 2017 would 0-10 percent; 10 to 20 percent; 20-30 percent and more than 30 percent. In principal, there are four conditional probabilities for each of the four scenarios (16 in total), but many of these scenarios were judged to have zero probability: For example, panelists thought that there was no chance that the cost increases associated with sequestration would increase from 2012 and 2017. Thus, if the cost increase in 2012 were in the 20-30 percent range, there was no chance that the cost in 2017 would be more than 30 percent. The assessments for 2022 similarly depended on the outcomes in both 2012 and 2017; in principle there are a total of 16 scenarios requiring four probabilities each, but many of these scenarios were judged to have zero probability. To calculate expected costs and benefits, the 0-10 percent, 10-20 percent and 20-30 percent ranges were represented by their midpoints (5, 15, and 25 percent, respectively) and the over 30 percent range was represented by 40 percent. All of these probabilities were assessed assuming there would be

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[5]A complete discussion of the methodology and process can be found in Chapters 3 and 4, respectively.

Cost of Electricity with Carbon Capture and Storage

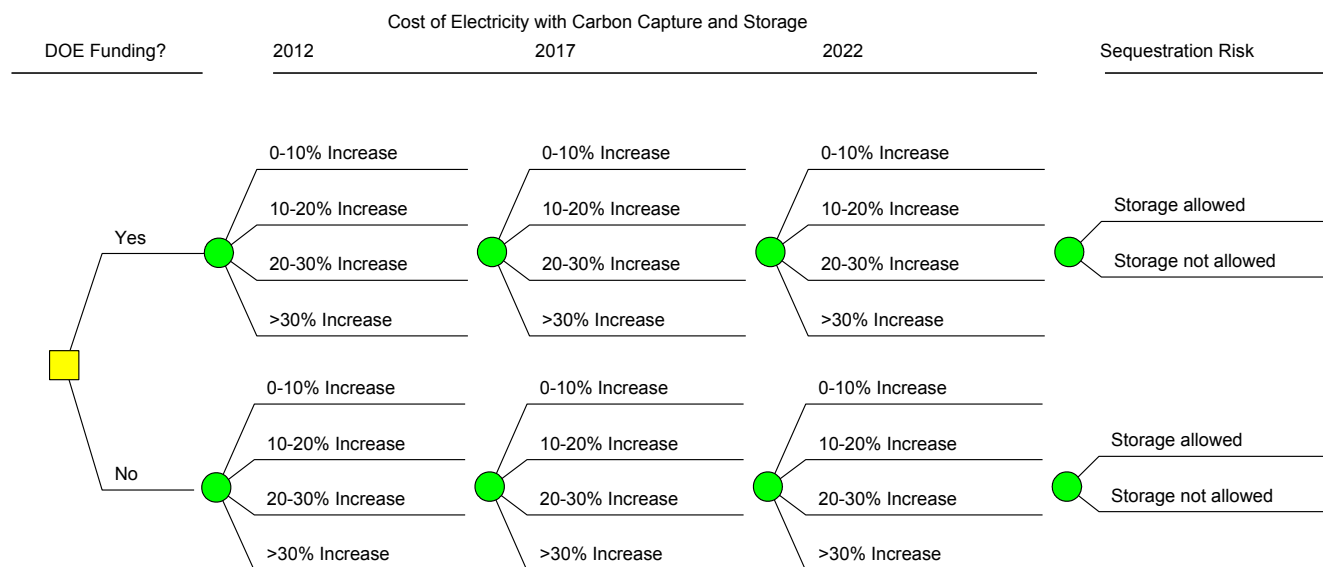| DOE Funding? | 2012 | 2017 | 2022 | Sequestration Risk |

FIGURE I-2 Decision tree used by carbon sequestration panel.

a $100 per ton carbon tax beginning in 2012 with industry participants knowing well in advance of this impending tax. The same assessments were repeated assuming a $300 tax.

In the discussion of benefits below, the panel assumes that decisions about which technology to deploy are made with knowledge of the carbon tax level—$100 or $300 per ton carbon tax. However, when the panel discusses the COE for IGCC with or without carbon sequestration, it assumes the carbon tax is zero. In particular, if the COE of IGCC with carbon sequestration were 30-35 percent more expensive than for IGCC without sequestration, a $100 per ton carbon tax would make the COE about equal for the two plants. A $300 per ton carbon tax would make the COE for an IGCC plant with sequestration much cheaper than the COE for a plant without.

The results of these assessments are summarized in Figure I-3. Here are shown the expected costs by year, with and without DOE support, for the two different carbon taxes. The effect of a higher carbon tax is to induce greater near-term R&D efforts sooner to bring down the cost of IGCC with carbon sequestration. These expected COE increases are probability-weighted averages and were calculated from the probabilities the panelists provided. The costs expected by individual panelists are indicated by small crosses and the panel average is indicated by the larger diamonds. Reviewing these assessments, varying degrees of consensus among the panelists can be seen in the different scenarios. In the 2012 assessment with the $100 tax and no DOE support (the left-most series shown in the figure), the panelists' expected cost increases average 35 percent and range from 32 percent to 39 percent. Estimates span a wider range for 2017 and 2022.

The panel's view of the effect of the DOE research support can be seen by comparing the expected COE increases with and without DOE research. For example in 2017 with the $100 tax, the panel's average expected cost increase without DOE support is 28 percent versus 24 percent with DOE support. These differences vary by year, with the impact of DOE research being smaller in 2012 and 2022 (by about 2 percent) than in 2017 (by about 4 percent). These results suggest that the panel believes that the impact of the DOE support is greatest in the medium-term. Comparing the low- and high-tax scenarios, it can be seen that the higher tax leads to lower expected costs both with and without DOE support, because higher tax would provide a greater incentive for the private sector to develop cost-effective CCS technologies. The estimated incremental effect of DOE support is approximately the same in the two tax scenarios.

These estimates are not compatible with the assumptions that DOE makes in its own benefit calculations. DOE assumes that it will succeed in developing a commercial design with only a 10 percent increase in the COE that will be available for demonstration by 2012 and for commercial deployment after 2016. The panel viewed this goal as very optimistic. In contrast, DOE's assumptions about the increased COE without DOE research funding were viewed as quite pessimistic: DOE's benefits calculations assume that without their sequestration research, there would be a 57 percent increase in the COE associated with carbon capture and storage in 2017 and a 50 percent increase in COE in 2022.[6]

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[6]Julianne M. Klara, NETL, "NEMS-Based Benefits of FE Sequestration R&D," Presentation to the panel on September 29, 2005.
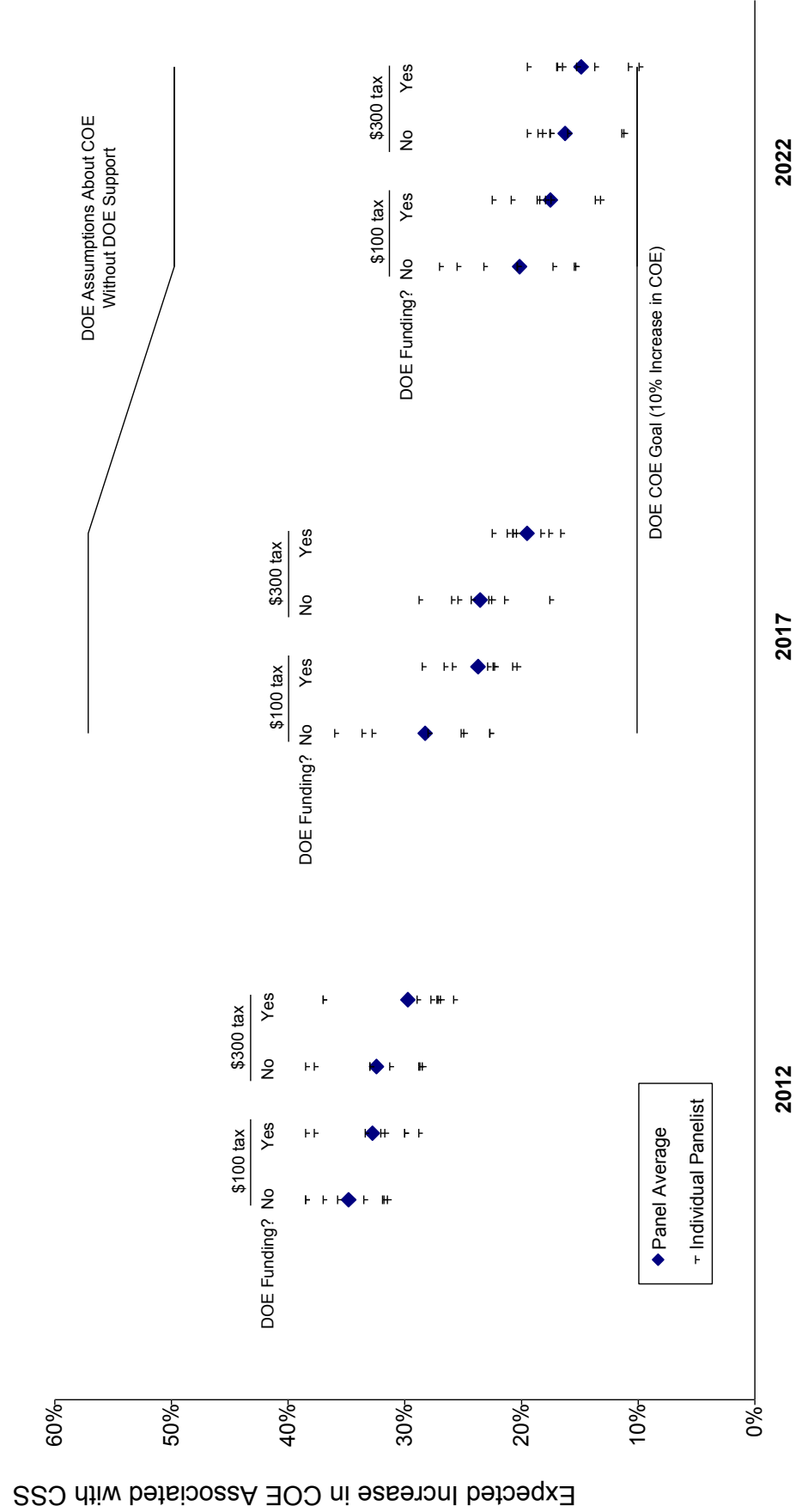
FIGURE I-3 Summary of probability assessment results.

The panel felt that the existence (or even the anticipation) of carbon taxes would lead to extensive private sector R&D that would reduce costs below these levels, even without DOE's research support. R&D activities overseas would probably increase as well if there were a U.S. commitment to reducing emissions. This combination of optimistic assumptions with DOE support and pessimistic assumptions without DOE support leads DOE to arrive at a much higher estimate of the benefits of its support than arrived at by the panel, although to be sure the panel assessments still show a high net payback.

In addition to the uncertainty about costs, the panel also considered a market acceptance uncertainty that focused on whether the public (and regulators) would allow large-scale underground storage of carbon. Without such acceptance, CCS technologies would not deployed. The panel's assessments of this uncertainty are summarized in Figure I-4. The average panel probability that the large-scale sequestration would be allowed is .66 without DOE's research support and increases to .77 with DOE's support. There was also a fair amount of disagreement about these probabilities, though the probabilities were all .5 or higher.

The panel considered competing technologies (e.g., nuclear power, natural gas with or without sequestration) in the benefits calculation, although without explicit modeling of the uncertainty about the costs of these competing technologies. If DOE's R&D programs in these competitive

technologies progress rapidly, they could vitiate the benefits of IGCC with carbon sequestration.

QUANTIFYING THE BENEFITS OF THE DOE PROGRAM

The economic, environmental, and security benefits of improvements in carbon sequestration technologies depend on the degree of technical improvement, the amount of IGCC with carbon sequestration that is deployed, the technologies that would have been implemented absent carbon sequestration, and the COEs for IGCC with CCS and for the next-best alternative technology.

In assessing the benefits of DOE's carbon sequestration research program, the panel focused on the COE for IGCC plants with CCS, the COE from other technologies for generating electricity, and the COE for nonsequestering plants given either a $100 per ton or $300 per ton carbon tax. The panel concluded that carbon sequestration would add to the cost of IGCC within the time frame and that no carbon sequestration would be implemented absent some sort of limitation on carbon emissions.

The economic benefit of carbon sequestration improvements in any one year is the product of the amount of electricity produced by IGCC with sequestration and the difference between the costs of the IGCC with sequestration and the costs of the cheapest alternative technology. Since a generating plant lasts 30 or more years, a rational plant owner would
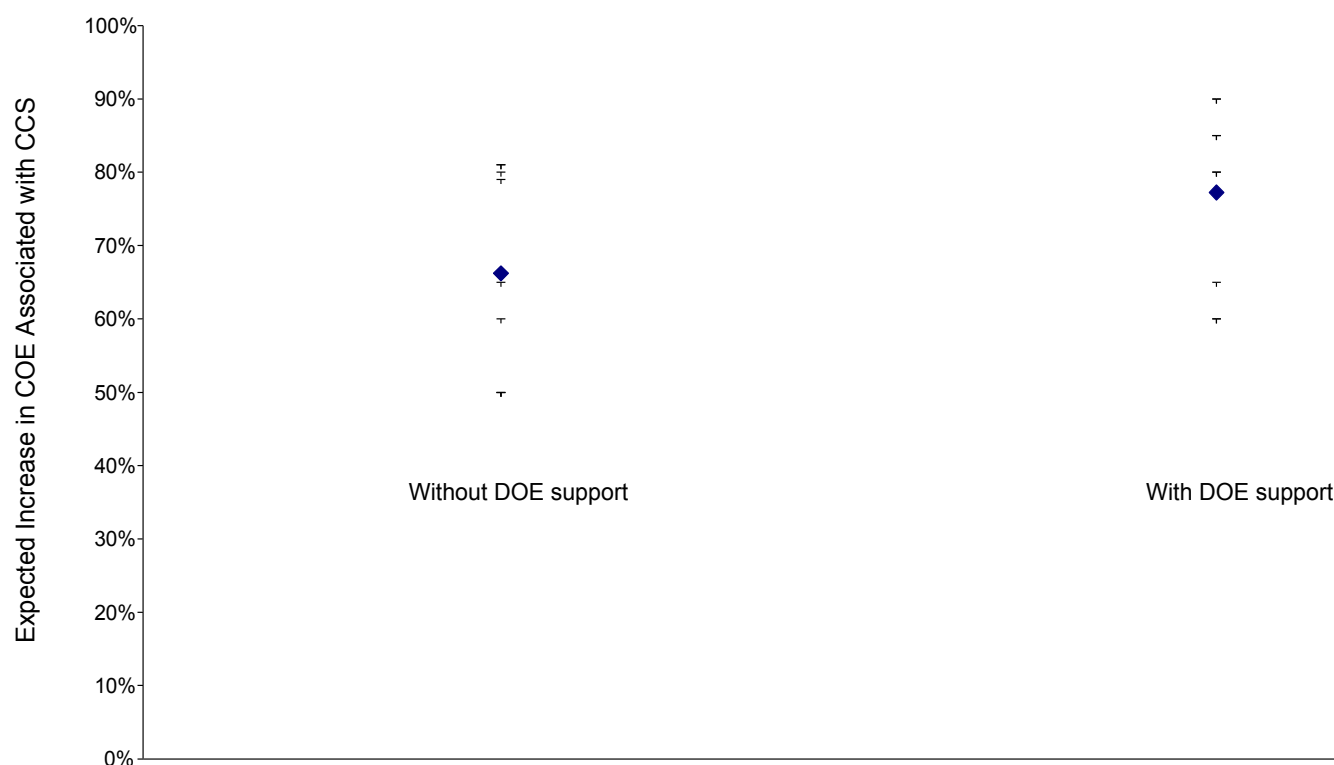

FIGURE I-4 Panel assessment of sequestration risks.

select the technology that is expected to be cheapest over the life of the plant. The total benefits can be calculated as the net present value (NPV) of the annual benefits stream. The carbon taxes affect the amount of sequestered IGCC capacity that is installed: Producers make their choices taking into account the taxes paid, as discussed below. However taxes are not considered in the COE calculations since the taxes net out from a societal perspective: Any carbon taxes paid by producers are receipts for the government. Thus, when comparing the COE for IGCC with sequestration and the COE for the cheapest alternative technology, the panel did not consider the taxes in either case. First, the panel developed a simple model for estimating COE with different generation technologies and next it estimated the amount of IGCC that would be built.

Estimating the COE for IGCC with Carbon Sequestration

The COE (busbar costs) for all electricity-generating technologies considered in the evaluation is based on capital costs, plant efficiencies, operating and maintenance costs, and fuel costs using plant characteristics taken directly from the Energy Information Administration's *Annual Energy Outlook 2005* (EIA, 2005b).[7] Fuel costs were taken to be the fuel cost projections in the AEO 2005 Reference Case, as suggested by the parent committee. Technologies considered explicitly included IGCC with and without sequestration, NGCC, nuclear, and several renewable sources (wind, biomass, and solar).

Baseline costs for IGCC without sequestration play an important role in estimating benefits. A separate panel, the NRC's Panel on DOE's Integrated Gasification Combined Cycle Program, evaluated the effect of DOE's R&D on IGCC technologies (Appendix H), and this panel (the "carbon sequestration" panel) used the results that panel's assessment of the future costs of IGCC as its baseline IGCC costs.

To estimate the COE for IGCC with carbon sequestration, the panel defined a range of possible technical outcomes of carbon sequestration research in 2012, 2017, and 2022, as described in the section on the decision tree model and probability assessment results. For each set of technical outcomes, a COE for IGCC with carbon sequestration can be calculated. Figure I-5 shows the estimated COE (including tax) over time using the baseline costs for IGCC as described above and the expected technical outcome of DOE's carbon sequestration research from the panel's probability assessments. The line with diamond markers corresponds to the expected increase in COE calculated from the probability-weighted averages shown in Figure I-3 for the $100 per ton carbon tax and assuming DOE funding of the research. Figure I-5 also shows the estimated COE for an IGCC plant without sequestration, with and without a $100 per ton carbon tax.

The abrupt rise in cost for IGCC without CCS reflects the tax being implemented in 2012. Thereafter, the change in COE is the sum of two contrary effects: a three percent per year rise in the carbon tax and a linear decrease in the capital cost that levels off in 2020. Finally, the smooth solid lines bound the range of estimates by panel members of the COE for IGCC with carbon sequestration. Thus, for a $100 per ton (or higher) carbon tax, under any cost scenario considered by the panel, the COE for IGCC with carbon sequestration is always less than the COE for IGCC with venting and the tax.

Estimating the Amount of IGCC with Carbon Sequestration That Will Be Built

To estimate the benefits of DOE's carbon sequestration research, we also need to know the amount of IGCC with sequestration that will be built. That amount is assumed to depend on the cost of IGCC with carbon sequestration and the costs of competing low- or zero-emissions technologies.

DOE has evaluated a global scenario with a carbon constraint that provides a starting basis for estimating how much IGCC with carbon sequestration will be built. In its analyses, DOE assumes a carbon cap (rather than a tax), and it assumes that the COE for IGCC with carbon sequestration will be 10 percent higher than for IGCC without sequestration. Under that scenario, about 70,000 MW of IGCC with sequestration is projected to be built by 2025. The panel took this as a reasonable upper bound estimate for the quantity that would be built under DOE's optimistic cost assumptions.

DOE's quantitative modeling is done with a U.S. energy model, perhaps because it would be so difficult to develop and implement a world energy model that would quantify the value of any energy technology. Such a model would have to account for the decisions of other governments regarding carbon emissions and the R&D in other nations.

To estimate the quantity of IGCC with carbon sequestration that would be built in each year under the cost scenarios identified by the panel, a simple cost comparison was made to determine which technology would be least costly for a utility making a decision about what to build. Whichever technology was least expensive was assumed to capture all of the possible low-emissions capacity added in that year.[8] The technologies are, in addition to those shown in Figure I-5, the following:

• NGCC with venting and paying the tax and
• Zero-emissions technologies: nuclear, wind, biomass, and solar.

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[7]Assumptions to the *Annual Energy Outlook 2005* (EIA, 2005a), Electricity Market Module, especially Tables 38 and 48.

[8]This obviously is not a realistic assumption. Most years will see a combination of technologies built, and the relative costs will change with factors such as fuel resources, site availability, industrial supply capability, and many others. In the absence of detailed simulation, such as with the NEMS model, this approach still gives useful approximate results, which should be viewed as illustrative rather than as forecasts.
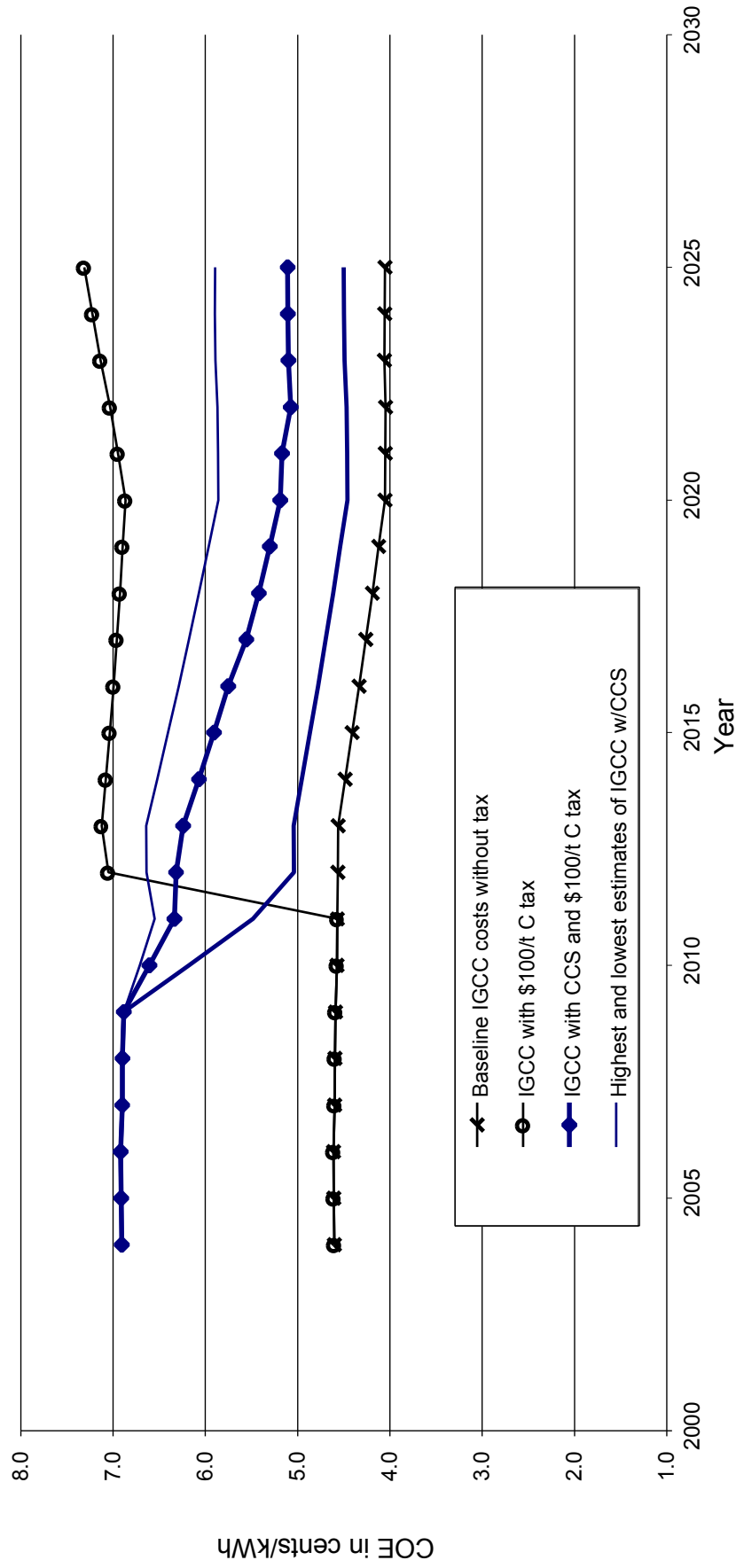
FIGURE I-5 Effect of carbon tax and incremental cost of CCS on COE for IGCC. The incremental cost of adding CCS was taken as the average of each panel members' individual estimates; the incremental cost was added to the baseline cost to determine COE for IGCC with CCS. Two additional lines are shown corresponding to the highest and lowest estimates made by individual panelists. The COE for baseline IGCC was taken from Appendix H, the report of the Panel on DOE's IGCC Technology R&D. C, carbon; CCS, carbon capture and storage; COE, cost of electricity; /t, per ton.

Costs are compared in Figure I-6 based on the net present value of the expected total costs over a 20-year life discounted at 14 percent.[9]

Assuming a winner-take-all competition among technologies, the panel estimated the amount of IGCC with CCS that would be built in each technology scenario. Figure I-7 shows the cumulative IGCC with carbon sequestration added, with and without the DOE program, based on the average probability assigned to each COE increase scenario identified by the panel. The figure also shows the maximum and the minimum IGCC with carbon sequestration added under any of the COE scenarios. The actual amount deployed varies by scenario. For example, the maximum amount will be deployed if there is a 0-10 percent or a 10-20 percent COE increase for carbon sequestration in 2012. However, no IGCC with sequestration will be deployed if the COE increase is always 20-30 percent or more. With intermediate costs, varying amounts of IGCC with carbon sequestration will be built.

Results of Expected Benefits Analysis

Using the approach described above, the panel estimated the benefits of carbon sequestration associated with each of the possible cost estimates defined by the panel (see Figure I-2). For the lowest level of technical success, the benefits are zero, and no IGCC with carbon sequestration is built because the technology is not cost-competitive. For the highest level of technical success considered, where the cost of IGCC with carbon sequestration is just 5 percent more than the cost without sequestration (starting in 2012), the net present value of the benefit is about $36 billion, assuming that large-scale carbon sequestration is allowed.

Each of those carbon sequestration cost scenarios has two probabilities assigned to it by the panel: the probability of achieving that level of technical success without the DOE research program, and the probability of achieving that level of success with it. The expected value of the carbon sequestration research with or without the DOE program is simply the probability-weighted average of the NPV for each technical success scenario using the appropriate probabilities, multiplied by the risk discussed in "Political Risk and Other Market Factors"—namely, that large-scale sequestration may not be allowed. The value of the DOE research program is the difference between the expected value of carbon sequestration research with the program and the expected value without the program.

Figure I-8 illustrates the expected economic benefits of carbon sequestration R&D, as well as the uncertainty surrounding those benefits. It shows a cumulative distribution on net economic benefits with and without DOE support.

The net benefit of zero represents the panel's assessment of market acceptance in the case that large-scale carbon sequestration is not allowed by either the public or regulators. The vertical lines represent the expected value of the distribution of benefits: The expected value is calculated as the probability-weighted average of the benefits calculated for possible outcomes identified by the decision trees. The expected value of DOE's carbon sequestration research program is $3.5 billion, the difference between the expected value with the program and the expected value without the program (see Figure I-9).

With the carbon tax, the COE for IGCC with sequestration or for advanced nuclear or wind,[10] which release no carbon-dioxide to the atmosphere, is lower than for fossil fuel technologies without sequestration (either IGCC or NGCC), so none of the latter are built after 2015. Thus, it makes no difference to the environment from the standpoint of carbon emissions between IGCC with carbon sequestration and the viable alternatives, given a $100 per ton carbon tax, and the benefit of the DOE R&D program is simply the reduced cost of producing electricity.

The analysis illustrates that IGCC with carbon sequestration is likely to be such an important technology for generating electricity starting in 2012 that even a small reduction in the time required for the technology to become available, coupled with a small reduction in cost, would lead to a large benefit. The panel emphasizes that a DOE R&D project need not have a 100 percent chance of success or be focused on accomplishing something that could not have been achieved without DOE funding to make an important contribution. In an age of growing concern about GHG emissions, even a small contribution to the reduction of CO_2 emissions from fossil-fuel-based generation technology can be important. In the judgment of the current panel, DOE's R&D program is likely to attain these results only a few years ahead of when the private sector would have achieved the results without DOE funding. Thus, private sector R&D is effective here, and DOE should encourage it. Society would lose if DOE's actions discouraged private R&D or if DOE did not disseminate the results of its R&D to help make private R&D effective.

COMPARISON WITH THE PHASE ONE EVALUATION OF THE CARBON SEQUESTRATION PROGRAM

Although higher than government R&D expenditures, the expected economic benefit of $3.5 billion given by this analysis is substantially less than the expected benefit of $35 billion arrived at by the evaluation carried out in Phase One.[11] The difference in results is primarily due to the much

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[9]This value was selected to represent what might be used by a utility or merchant generator. This is distinct from the discount rates of 3 and 7 percent that were applied to the benefits stream.

[10]Wind is not directly comparable with IGCC since it is an intermittent energy source while IGCC can run continuously. However, electric systems could utilize a much higher fraction of wind than they do now, and with improved storage and control, that fraction will increase.

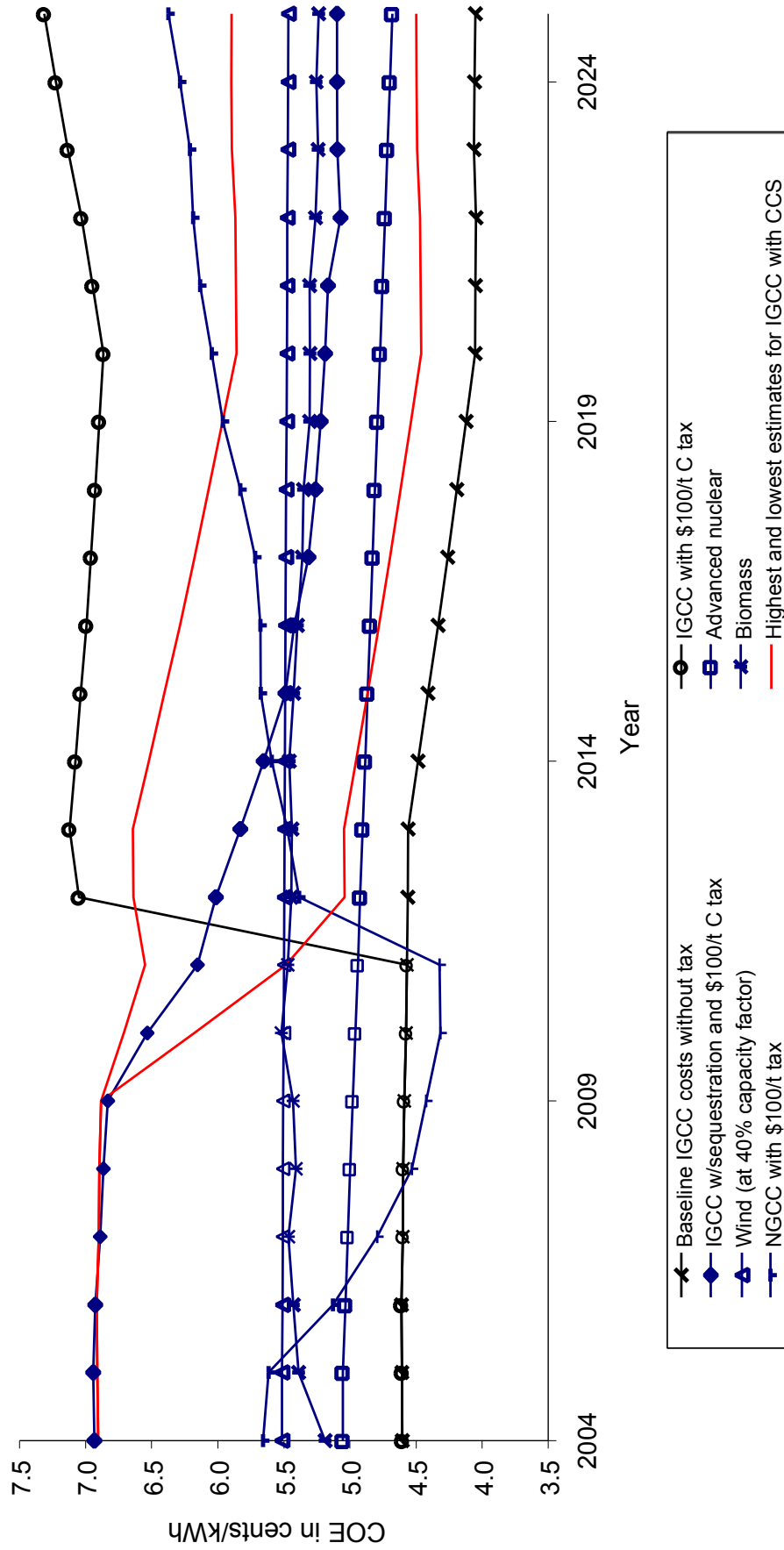[11]See Appendix G of the Phase One report, p. 97.

FIGURE I-6 Comparison of COE with competing technologies. COE for IGCC are as shown in Figure I-5. COE for other technologies is based on AEO technology forecasts. Carbon tax is assumed to be $100 per ton, increasing at 3 percent per year after 2012. C, carbon; CCS, carbon capture and storage; COE, cost of electricity; /t, per ton; IGCC, integrated gasification combined cycle.
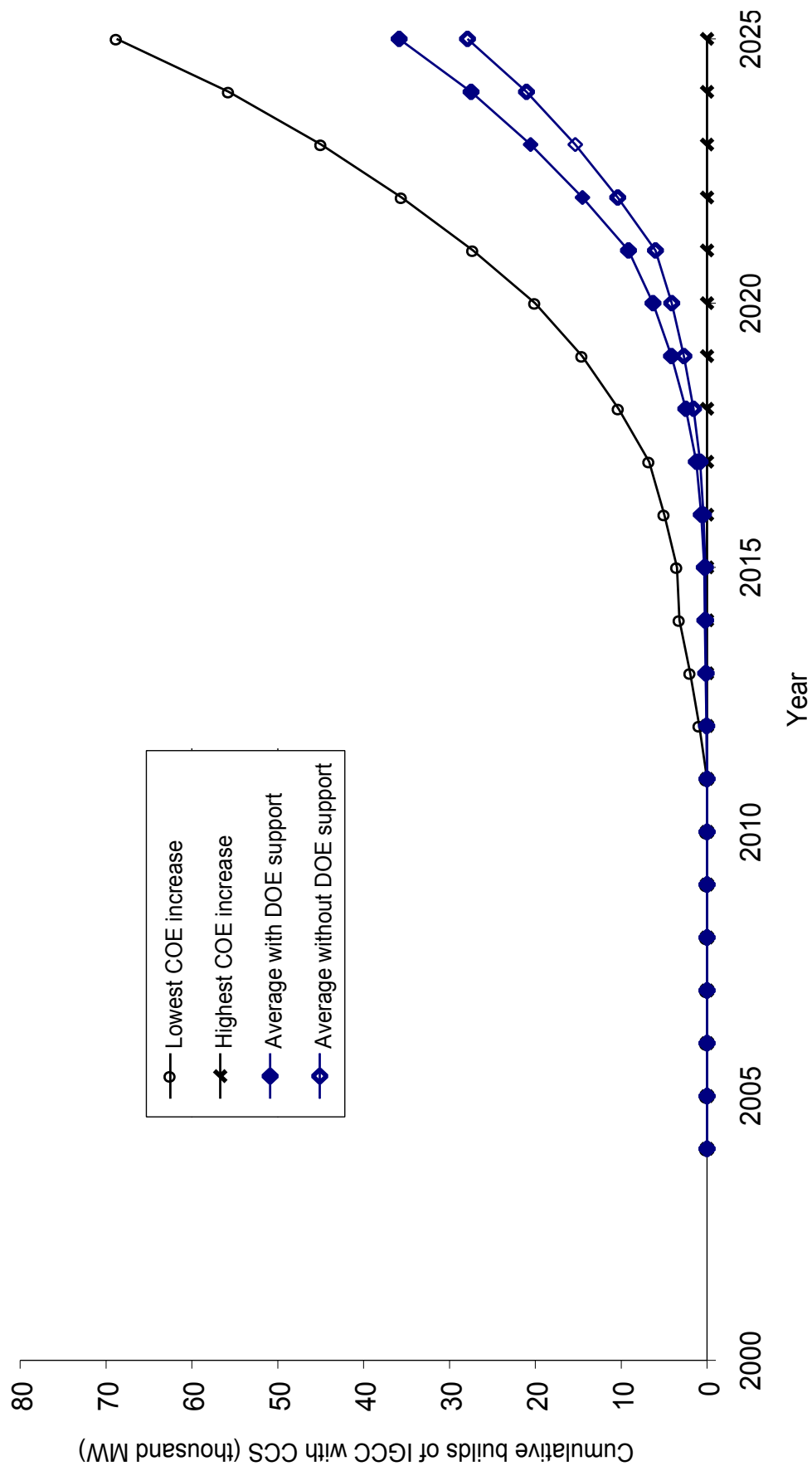
FIGURE I-7 Impact of DOE program funding on cumulative builds of IGCC with CCS, through 2025. The two lines, "with DOE support" and "without DOE support," were calculated by determining the number of builds for each scenario given in Figure I-2 and taking the probability-weighted average. Additional lines are shown corresponding to the number of builds estimated assuming the highest and lowest COE estimates from Figure I-5.
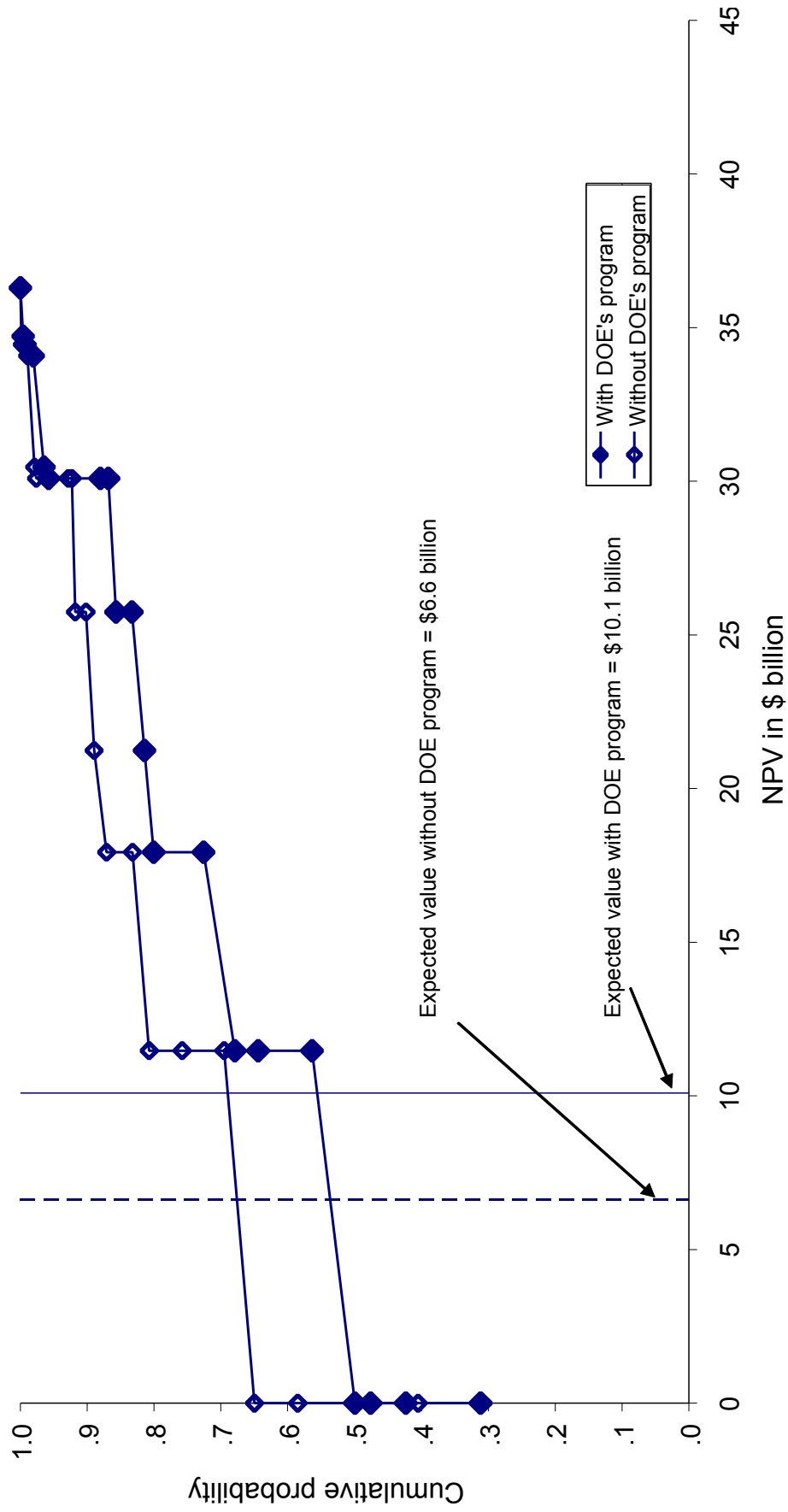
FIGURE I-8 Cumulative distribution on the NPV of the economic benefits of carbon sequestration research, with and without the DOE program. Expected values, with or without DOE research funding, were calculated as the probability-weighted average of the net present value of benefits in each cost scenario.

		Global Scenario[a]						
		Carbon Constrained						
		$100/ton Carbon Tax			$300/ton Carbon Tax			
Program Risks	Technical Risks	Estimated as the probability of achieving specified impacts on the cost of electricity for IGCC plants with sequestration over those same plants without sequestration. Average of the panel assessments for the increase in cost of electricity (COE) for sequestration at three different times were as follows:						
			2012	2017	2022		2012	2017	2022
		w/DOE program	33%	24%	18%	w/DOE program	30%	20%	15%
		w/o program	35%	28%	20%	w/o program	32%	24%	16%
	Market Risks	Estimated as the probability large-scale carbon sequestration would be allowed by both the regulators and the public. Probabilities were assigned for the "with DOE program" case and the "without program" case and were assumed to be the same in the two global scenarios considered: with DOE program, 77%; without program, 66%.						
Program Benefits	Expected Economic Benefits[b]	$3.5 billion at 3% Range: $0-$36 billion			$3.9 billion at 3% Range: $0-$36 billion			
		$1.3 billion at 7% Range: $0-$13 billion			$1.5 billion at 7% Range: $0-$13 billion			
	Environmental Benefits	The environmental benefit of carbon sequestration is reduced greenhouse gas emissions. The environmental benefit of DOE's carbon sequestration program depends on what technologies would be implemented if IGCC with sequestration does not become cost-competitive. Given the level of carbon tax in the scenarios evaluated, the least-cost alternatives to carbon sequestration are other zero-emissions technologies. Thus there is no quantifiable environmental benefit of the research program that is separate from the economic benefit of the reduced costs for very-low emissions generation. Under other assumptions, emissions would be reduced.						
	Security Benefits	The security benefit of carbon sequestration is the ability to continue to build electric generation plants that use coal, a domestic resource, minimizing our dependence on imported fuel resources. Given the level of carbon tax in the scenarios evaluated, however, the least-cost alternatives to carbon sequestration are a combination of nuclear generation and renewables; thus there are no quantifiable security benefits associated with the research program separate from the economic benefits. It is possible, however, that absent carbon sequestration, natural gas will be used instead. In such a case U.S. energy security would be decreased.						

[a]The panel judged that carbon sequestration technologies would not be implemented in global scenarios without a carbon constraint. They did not evaluate the program under the Reference Case or the High Oil and Gas Prices scenarios but evaluated it instead under the Carbon Constrained scenario and a fourth scenario defined by the panel to have a higher carbon tax than the Carbon Constrained scenario.

[b]Net economic benefits are calculated as the expected net present value (at 3% and 7% annual discount rates) of the reduction in the cost of electricity for zero- or very-low emissions generation over a 20-year plant life for all IGCC plants with carbon sequestration built between 2006 and 2025.

FIGURE I-9 Results matrix of the Panel on DOE's Carbon Sequestration Program.

more extensive analysis of during Phase Two what would happen without DOE. Two issues that had largely been neglected in Phase One were considered: the degree to which industry would develop sequestration technologies given adequate notice that they would be needed, and the impact of competing technologies. During Phase One, the methodology was still in an early stage of development, and the importance of examining the full range of options without DOE was not fully appreciated.

More specifically, in the Phase One evaluation of the carbon sequestration program, the panel assessed the likelihood of obtaining various costs of electricity with sequestration by various dates assuming DOE support. Although the assessments were framed differently (in Phase One they were stated in terms of costs; here, they are stated in terms of percentage increases in costs without sequestration), the structure of the earlier assessment was similar to the top branch of Figure I-2. The resulting forecasts for the COE with DOE

support were similar. However the assessments without DOE support are quite different in the Phase One report and the current report. In the Phase One analysis, the panel adopted DOE's forecasts of costs without DOE support, which called for relatively modest decreases in the costs of electricity with sequestration. In the current study, panel explicitly considers the probabilities of achieving various cost levels without DOE support, as shown in the bottom branch of Figure I-2. The panel assumes that a CO_2 reduction program will be announced soon, giving 5 years to do R&D and commercialize the new technologies before the CO_2 emissions reductions are required. As shown in Figure I-3, the panel considers what the private sector is likely to do if a firm timetable is set for future abatement of CO_2 emissions. It concludes that private R&D will be increased greatly, thus coming closer to realizing the costs that DOE projects. Because the benefit of the DOE research program is taken as the difference between expected benefits with and without DOE support, improving the expected benefits of the technology without DOE support will decrease the estimated benefits of the program.

The second major difference in the two studies concerns the treatment of competing technologies. The panel that produced the Phase One report assumed that a fixed amount of carbon sequestration technology would be deployed regardless of its costs. The expected economic benefit of the program was then given by difference in expected costs with and without DOE support, multiplied by the fixed capacity that is deployed. The panel writing this report explicitly considers competition with other technologies, such as NGCC with venting and paying the tax as well as competition with other zero-emissions technologies such as nuclear, wind, and biomass. In scenarios with high costs of carbon sequestration, these competing technologies are cheaper than carbon sequestration; if they are cheaper, the carbon sequestration technology will not be deployed and hence would provide no benefit. Even when CCS technology is deployed, its economic benefits are measured relative to the costs of the competing technologies rather than to an assumed high-cost CCS technology. Recognizing competing technologies in this way reduces the benefits relative to those estimated by the Phase One study, which assumed a fixed capacity would be deployed and that benefits would be measured relative to an assumed high-cost alternative.

Although the models used in this study are still approximations, the difference in results between the Phase One evaluation and this Phase Two evaluation of the carbon sequestration program highlights the importance of thinking carefully through the "without DOE support" scenario and capturing, at least in a rough way, the impact of competing technologies.

CONCLUSIONS AND RECOMMENDATIONS

This panel found that the method developed by the parent committee for estimating the benefits of DOE R&D worked satisfactorily in this case. It was frustrated, however, by not having been charged with examining the R&D and not having been given the data to do that. Members thought that they could have given somewhat better estimates of the likelihood of the R&D projects achieving their goals had they had the detailed data. Nonetheless, they found that they were able to implement the method proposed by the parent committee. While individual members had different judgments about the likelihood of achieving the R&D goals and the extent of market penetration for the resulting technology, there was general agreement on these conclusions:

• Carbon sequestration technology will not be implemented commercially without carbon emissions constraints.
• A carbon tax of $100 per ton is sufficient to make carbon sequestration competitive with IGCC plants that vent their carbon.
• DOE's R&D program will speed the attainment of the carbon sequestration program's R&D goals by about 3 years because there is so much private sector interest and R&D in these technologies.
• If the technology is demonstrated to be reliable and cost-effective, IGCC with carbon sequestration could be widely deployed following the implementation of carbon emissions constraints.
• The expected benefit of the DOE program is large, roughly four times the R&D costs incurred by the federal government.
• DOE's CCS R&D can make a contribution to society of about $3.5 billion in spite of the panel's view that it will accelerate the attainment of the program goals by only a few years. Setting aside DOE's overly optimistic assumptions about the contribution of its R&D program and recognizing the private sector R&D the panel finds that even attaining the national goals only a few years sooner is important and would amply repay the R&D investment.

Recommendation: DOE should encourage private sector R&D in conducting its program. The DOE R&D results should be made available quickly to the private sector.

Recommendation: The panel recommends that the leadership of the DOE sequestration program work harder to insulate its systems analysis group from pressure to produce results that conform to the program's aspirational goals, so as to get greater value from the expertise of the group.

ATTACHMENT A
PANEL MEMBERS' BIOGRAPHIES

Lester B. Lave (IOM), *Chair*, is the Harry B. and James H. Higgins Professor of Economics and University Professor; Director, Carnegie Mellon Green Design Initiative; and Co-Director, Carnegie Mellon Electricity Industry Center. His teaching and research interests include applied economics,

political economy, quantitative risk assessment, safety standards, modeling the effects of global climate change, public policy concerning greenhouse gas emissions, and understanding the issues surrounding the electric transmission and distribution system. He is a member of the National Academies' Institute of Medicine and a recipient of the Distinguished Achievement Award of the Society for Risk Analysis. He has a B.S. in economics, Reed College, and a Ph.D. in economics, Harvard University.

Charles Christopher is a project manager in the Exploration and Production Technology Group of BP Americas in Houston. He is an internationally recognized expert in improved oil recovery and greenhouse gas issues. He is the co-lead of the storage, monitoring and verification team of the CO_2 Capture Project, a $25 million joint industry project sponsored by 8 energy companies and three governments. The purpose of the project is to identify and develop technologies to allow CO_2 to be effectively and economically captured and stored in the subsurface. Mr. Christopher is also the subsurface technical liaison for BP to the Princeton Carbon Mitigation Initiative, and principal BP representative for the Weyburn Joint Industry Project, the Mt. Simon project, and the Frio CO_2 Injection Demonstration. He helped organize several DOE-funded regional CO_2 sequestration centers and is BP's North American representative for greenhouse gas technology issues.

George M. Hidy is retired Alabama Industries Professor of Environmental Engineering at the University of Alabama, where he was also professor of environmental health science in the School of Public Health. From 1987 to 1994, he was technical vice president of the Electric Power Research Institute (EPRI), where he managed the Environmental Division and was a member of the Management Council. From 1984 to 1987, he was president of the Desert Research Institute of the University of Nevada. He has held a variety of other scientific positions in universities and industry and has made significant contributions to research on the environmental impacts of energy use, including atmospheric diffusion and mass transfer, aerosol dynamics, and chemistry. He is the author of many articles and books on these and related topics. Dr. Hidy received a B.S. in chemistry and chemical engineering from Columbia University; an M.S.E. in chemical engineering from Princeton University; and a D.Eng. in chemical engineering from the Johns Hopkins University.

W.S. Winston Ho (NAE) is a University Scholar Professor in the Department of Chemical and Biomolecular Engineering at the Ohio State University. His research interests include molecularly based membrane separations, fuel-cell and fuel processing and membranes, transport phenomena in membranes, and separations with chemical reaction. Dr. Ho holds a B.S. from Taiwan National University

and an M.S. and a Ph.D. from the University of Illinois at Urbana-Champaign.

David Keith is an assistant professor in the Department of Engineering and Public Policy, Carnegie Mellon University. Dr. Keith's policy work addresses the uncertainty in climate change predictions, geoengineering, and carbon management. He has been a collaborator in research on climate-related public policy at Carnegie Mellon since 1991 and an investigator in the Center for the Integrated Study of the Human Dimensions of Global Change since its inception. His current research involves an analysis of the use of fossil fuels without atmospheric emissions of carbon dioxide by means of carbon sequestration. This research aims to understand the economic and regulatory implications of this rapidly evolving technology. Questions range from near-term technology-based cost estimation to attempts to understand the path dependency of technical evolution; for example, how would entry of carbon management into the electric sector change prospects for hydrogen as a secondary energy carrier? In addition, Dr. Keith is working on a study of geoengineering that explores its historical roots and its ethical implications. As an atmospheric scientist, he collaborates with Professor James Anderson's group at Harvard on observations of water vapor, cirrus clouds, and stratosphere-troposphere exchange. He was the senior scientist for INTESA, a new Fourier-transform spectrometer that flies on the NASA U-2, and he worked as project scientist on Arrhenius, a proposed satellite aimed at establishing an accurate benchmark of infrared radiance observations for the purpose of detecting climate change. He has a B.Sc. in physics from the University of Toronto and a Ph.D. in experimental physics from MIT.

Larry W. Lake (NAE) is a professional engineer (Texas) and the W.A. "Monty" Moncrief Centennial Endowed Chair for the Department of Petroleum and Geosystems Engineering at the University of Texas, Austin, where he has served on the faculty since 1978. He has 5 years of industrial experience and has authored one book and more than 50 technical articles and reports. His research interests are in the areas of enhanced oil recovery, geochemical flow processes, and petrophysics, all of which involve numerical simulation in one form or another, and flow through permeable media. In addition, Dr. Lake has been most involved in finding ways to model geologically realistic reservoir properties—primarily permeability quantitatively—with the hopes of improving the ability to predict hydrocarbon recovery better. This has led to efforts that seek to merge sedimentary concepts with the discipline of geostatistics. Dr. Lake holds a Ph.D. in chemical engineering from Rice University and was elected to the National Academy of Engineering in 1997.

Michael E. Q. Pilson is professor emeritus of Oceanography at the University of Rhode Island (URI). He was director

of the Marine Ecosystems Research Laboratory at URI for 20 years. His current research interests include the chemistry of seawater, biochemistry and physiology of marine organisms, and nutrient cycling. He received a B.Sc. in chemistry-biology from Bishop's University, in Canada, an M.Sc in Agricultural Biochemistry from McGill University, and a Ph.D in marine biology from the University of California, San Diego. He is a member of the American Association for the Advancement of Science; Sigma Xi; the American Geophysical Union; the American Society of Mammalogists; the American Society of Limnology and Oceanography; and the Oceanography Society. He has published extensively, including the text book *An Introduction to the Chemistry of the Sea.*

Jeffrey J. Siirola (NAE) is a research fellow in the Chemical Process Research Laboratory at Eastman Chemical Company in Kingsport, Tenn. He received his B.S. degree in chemical engineering from the University of Utah in 1967 and his Ph.D. in chemical engineering from the University of Wisconsin-Madison in 1970. His research centers on chemical processing, including chemical process synthesis, computer-aided conceptual process engineering, engineering design theory and methodology, chemical technology, assessment, resource conservation and recovery, artificial intelligence, nonnumeric (symbolic) computer programming, and chemical engineering education. He is a member of the National Academy of Engineering.

James E. Smith is professor of decision sciences at the Fuqua School of Business at Duke University. He teaches courses in probability and statistics and decision modeling. Dr. Smith's research interests lie primarily in the areas of decision analysis and real options, focusing on developing methods for formulating and solving dynamic decision problems and valuing risky investments. His research has been supported by grants from the National Science Foundation, Chevron, and the Eli Lilly Foundation. Dr. Smith received B.S. and M.S. degrees in electrical engineering from Stanford University (in 1984 and 1986) and worked as a management consultant prior to earning his Ph.D. in engineering-economic systems at Stanford in 1990. He has been at Fuqua since the fall of 1990 and received the Outstanding Faculty Award from the daytime MBA students in 1993 and 2000. He served as associate dean for the Duke MBA Program from 2000-2003. He has been a member of the Advisory Panel for the National Science Foundation's Decision Risk and Management Science program and has been departmental editor for decision analysis at the journal *Management Science*.

Robert H. Socolow is a professor of mechanical and aerospace engineering at Princeton University, where he has been on the faculty since 1971. He was previously an assistant professor of physics at Yale University. Professor Socolow is a fellow of the American Physical Society and the American Association for the Advancement of Science. He currently codirects Princeton University's Carbon Mitigation Initiative, a multidisciplinary investigation of fossil fuels in a future carbon-constrained world. From 1979 to 1997, Professor Socolow directed Princeton University's Center for Energy and Environmental Studies. He has served on many NRC boards and committees, including the Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes, the Committee on Review of DOE's Vision 21 R&D Program, and the Board on Energy and Environmental Systems. He has a B.A., an M.A., and a Ph.D. in physics from Harvard University.

John M. Wootten is retired vice president, Environment and Technology, Peabody Energy. He spent most of his professional career with Peabody Holding Company, Inc., the largest producer and marketer of coal in the United States. His positions at Peabody and its subsidiaries included that of director of environmental services, director of research and technology, vice president for engineering and operations services, and president of Coal Services Corporation (COALSERV). His areas of expertise include the environmental and combustion aspects of coal utilization, clean coal technologies, and environmental control technologies for coal combustion. He has served on a number of NRC committees, including the Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes and the Committee to Review DOE's Vision 21 R&D Program. He received a B.S. (mechanical engineering) from the University of Missouri-Columbia and an M.S. (civil engineering, environmental and sanitary engineering curriculum) from the University of Missouri-Rolla.

Attachment A

Statement of Task

PROSPECTIVE BENEFITS OF DOE'S ENERGY EFFICIENCY AND FOSSIL ENERGY R&D PROGRAMS—PHASE 2

Project Scope:

The Phase 2 activity follows the completion of Phase 1, which resulted in the issuance of two reports on methodology for estimating prospective benefits and evaluating energy R&D programs at DOE. These reports [*Energy Research at DOE: Was It Worth It?,* and *Prospective Evaluation of Applied Energy Research and Development at DOE: A First Look Forward*] are posted in the project record with project identification number BEES-J-03-01-A in the Current Projects System.

At least three issues will require attention as part of the Phase 2 Task. These issues include: (a) further improving the estimation of the value of environmental benefits (e.g., reduced emissions), (b) further improving the estimation of the value of security benefits (e.g., reducing oil imports or ensuring more reliable electricity supplies), and (c) determining how to estimate the overall benefits of the options under a variety of scenarios. The first two issues involve the public good rather than direct economic benefits. The committee will build on the foundation of work from Phase 1 and the body of literature that exists to determine appropriate values for these factors. The committee might commission white papers defining the state of knowledge and suggesting how the methodology could incorporate these estimates. For (c), options evaluation, the committee will consider the extent to which an analytical foundation is appropriate, building on the Phase 1 work and incorporating the full range of benefits for representative scenarios. In addition, the committee will consider mechanisms for quantifying knowledge benefits and include them as appropriate in the overall evaluation. The committee will also provide a peer review of how DOE is evaluating prospective benefits of various Energy Efficiency (EE) and Fossil Energy (FE) programs/projects. As in Phase 1, several panels will be separately appointed to assist the committee in Phase 2.

A workshop will be held early in Phase 2 to discuss the Phase 1 reports and methodology, following which the committee will write a letter report that will set the stage for the work to be accomplished in Phase 2. A final report will be issued at the conclusion of Phase 2, about the end of April 2006. The panels will write panel reports documenting the results of the analyses of the prospective benefits of the various programs/projects in EE and FE chosen by the committee to evaluate. These panel reports may be issued separately or incorporated into the Phase 2 final report.

The project is sponsored by the U.S. Department of Energy.

The approximate starting date for this project is March 15, 2005.

Project Duration: 14 months