Chapter 6 — Analysis, Research, Development and Demonstration

In the United States, most of the energy supply and distribution activity, for example oil and gas production, coal mining, electricity generation, is performed by private sector firms. These firms make the massive investments required to sustain the energy system of the country and to develop and introduce new technology to the market.

Government support for this industry innovation occurs in four ways: (1) setting the rules for private sector innovation and technology deployment incentives, e.g., intellectual property protection and R&D tax credits; (2) support for basic scientific research; (3) support for pre-commercial technology and engineering development, and (4) support for demonstration projects that inform industry about the technical performance, cost, and environmental risks of a new technology. Support of pre-competitive research by government offers new technology options because private firms generally will not make investments whose benefits are not easily captured by individual firms. The rationale for later stage government support turns on other market failures or imperfections. These rationales are sometimes distorted in the political process so as to provide inappropriate subsidies, but significant learning-by-doing economies and social insurance considerations can be, under the right circumstances, sound rationales, along with other features like cost sharing.

The DOE is the primary federal sponsor of energy technology RD&D in the U.S. Because of the enormous coal resource base in the United States and the environmental challenges associated with its large-scale use, coal has been a major focus of the DOE RD&D program for more than thirty years. We comment on the extent to which the ongoing DOE RD&D effort is providing important options for meeting the principal challenges facing large-scale coal use in the coming years and decades. We also suggest the RD&D priorities we consider to be most critical and provide a rough estimate of the needed resource commitments.

The United States and other countries will want to use coal in the future because it is cheap and plentiful. But, in order to do that, technology must be available to control carbon dioxide emissions. The challenge applies both to new power plants and to improvement or retrofit of the large installed base of PC power plants.

The United Sates also has an interest in coal technology deployment in the large emerging economies such as China and India, principally because these countries are major emitters of greenhouse gases. A secondary interest is the potential commercial opportunity for U.S. firms to participate in the CO_2 emission control programs these large developing economies may offer. For some time, developing countries will be primarily interested in coal technologies that reduce emission of pollution that affects human health and the local and regional environment. The possible synergy between control of criteria pollutants and mercury, and the control of CO_2 emissions is an important factor in assessing the effectiveness and balance of the RD&D portfolio.

The critical technology options for meeting the challenge of CO_2 emission reduction are:

- ultra-high efficiency coal combustion plants
- gasification technologies, including gas treatment
- long-term carbon dioxide sequestration
- improved methods for CO_2 capture and for oxygen production
- syngas technologies, such as improved hydrogen-rich turbine generators and technologies to convert syngas to chemicals and fuels
- technologies that tolerate variable coal qualities
- integrated systems with CO_2 capture and storage (CCS)
- novel concepts, such as chemical looping, the transport gasifier, the plug flow gasifier, membrane separation of CO_2, and others
- large-scale transport of CO_2, captured and pressurized at coal combustion and conversion plants, to injection at storage sites.

In addition, some large-scale demonstration is needed in the near term:

- large-scale sequestration with appropriate site characterization, simulation, measurement, and monitoring;
- integrated coal combustion and conversion systems with CCS.

THE CURRENT DOE RD&D PROGRAM

A key question is the success the DOE RD&D program has had in providing these needed technologies in the past and its likelihood of success going forward. Our conclusion is that the DOE coal RD&D program has had some important successes over the last thirty years, but it has had some significant gaps and needs considerable strengthening and restructuring to meet the current challenges facing coal use.

Since 1978 the DOE has supported a broad effort of RD&D on advanced coal technologies for: (a) coal processing, (b) environmental control, (c) advanced power generation, (d) CO_2 capture and sequestration, and (e) industrial coal applications. A number of these activities have been undertaken in cooperation with industry and other organizations such as EPRI.

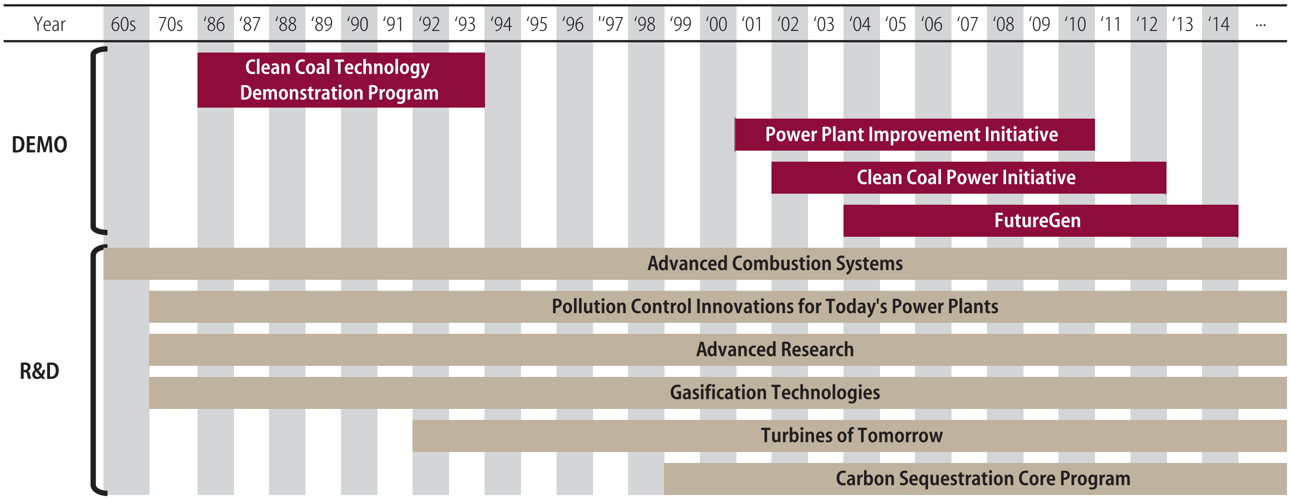
Figure 6.1 presents a timeline of the major RD&D program components. Since 1978 DOE has spent about $10 billion (2003 $) on these activities. The **Clean Coal Technology Demonstration Program** focused on commercial scale demonstration of technologies to improve the efficiency and reduce the environmental impact of coal-fired power generation. The **Power Plant Improvement Initiative** focused on demonstrating near-term technologies for improving environmental and operational performance of the PC fleet. The current **Clean Coal Power Initiative** is directed toward demonstrating innovative technologies to help meet the Clear Sky Initiative, the Global Climate Change Initiative, FutureGen, and the Hydrogen Initiative. **FutureGen** is intended to demonstrate the first commercial-scale, near-zero-emissions, integrated sequestration and hydrogen production power plant. The Advanced Research program is designed to develop the underlying basic science and innovative technologies to support the demonstration programs.

A summary of the FY07 Administration budget request for coal RD&D is presented, along with FY06 funding, in Table 6.1. The central role projected for FutureGen is evident. The table provides a reference point for our discussion of the principal ARD&D needs. We do not believe that the proposed DOE program can adequately address those needs with the proposed scale and distribution of funding.

COMMENTS ON THE DOE RD&D PROGRAM.

Our purpose here is to comment on the successes and gaps in the DOE's program from the point of view of producing technology options for clean coal combustion and con-

Figure 6.1 DOE RD&D Activity for Advanced Coal Technologies Program



version technology. We do not intend to do a detailed analysis of the DOE budget, or to assess its relationship to various roadmaps developed by DOE in partnership with others, notably the Coal Utilization Research Council and EPRI (for example, the Integrated Clean Coal Technology Roadmap [2]). We do not evaluate the program in terms of return on investment [1]. We also do not address the criticism that over the years the DOE coal program has been subject to political influence on project selection, siting, and structure.

The DOE program can be credited with a number of significant achievements.

Table 6.1 DOE Coal RD&D Program Overview for FY06 to FY07

	FY05, $MM	FY06, $MM	FY07, $MM	FY08, $MM	06 TO 07, $MM	
Coal Program, Total	**342.5**	**376.2**	**330.1**		**-46.1**	
Clean Coal Power Initiative	47.9	49.5	5.0		-44.5	Restricted funds to force program to better use funds already provided
FutureGen	17.3	17.8	54.0	203.0	36.2	To support detailed design and procurement activities, permitting etc. to keep project on schedule for 2008
Innovations for Existing Plants		25.1	16.0		-9.1	Advanced, low-cost emissions control technology development to meet increasingly strict regulations, including mercury.
IGCC		55.9	54.0		-1.9	Advanced, lower cost, improved performance technologies for gasification, gas cleaning, oxygen separation, carbon capture
Advanced Turbines		17.8	12.8		-5.0	Advanced technology development for coal-based hydrogen turbines with low emissions
Carbon Sequestration		66.3	73.9		7.6	Focused on GHG control technologies including lower-cost CO_2 capture, MMV, and field testing
Fuels (Hydrogen Focused)		28.7	22.1		-6.6	Focused on R&D of low-cost hydrogen production from clean coal.
Advanced Research		52.6	28.9		-23.7	Innovations and advanced concepts that support development of highly-efficient, clean coal power plants
Subtotal, Coal Research Initiative		**313.7**	**266.7**		**-47.0**	
Fuel Cells		61.4	63.4		2.0	Coal-based fuel cell development
U.S./ China Energy		1.0	0.0		-1.0	

For PC systems, the DOE has contributed to advances in developing fluid-bed technology for power generation, and commercially demonstrating Circulating Fluidized Bed technology; demonstrating low-NO_x burners, Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) for NO_x control; improved Flue Gas Desulfurization (FGD) scrubbers for SO_x control; and advancing mercury emissions quantification and mercury control technologies for PC plants.

For IGCC systems, the DOE has contributed to advances in improved syngas clean-up systems, advanced turbines (GE-H turbine, and Siemens-Westinghouse 501G), helping bring IGCC to the demonstration stage, and supporting two commercial demonstrations (Tampa Electric IGCC Project, 250 MW_e and Wabash River Coal Gasification Repowering Project, 262 MW_e) that provided significant information on the design and operation of utility-scale IGCC plants. As discussed in Chapter 3, in the past, the reason for support of IGCC demonstrations was to gain utility-scale experience with a technology that could be key if CO_2 capture would be required, although other reasons such as deep and efficient control of criteria pollutants and mercury, and polygeneration of multiple products, have also been suggested as benefits.

Public support was justified at the time as demonstration or risk reduction in integrating, at scale, the gasification/processing island with the power island. This integration posed substantial challenges: different syngas requirements from gasification applications that used coal instead of residual oil or coke as a feed stock; associated turbine operational requirements; different response times of the gasification and power components to load variations; bringing together distinct cultures for operating chemical and power plants; new design decisions concerning degree of heat and air integration, and trading off reliability concerns against operating efficiency.

Not all of these early DOE IGGC demonstration projects succeeded, but the Tampa and Wabash plants, in particular, provided valuable information. Useful information came from learning how these plants, and two similar scale plants in Europe, overcame difficulties in achieving reliable operation. For example, the Tampa Electric project had significant cost overruns and took five years to reach reliable operation, neither of which would be acceptable for a commercial project using established technology. However the project eventually realized over 80% availability operating with a single gasifier, and over 90% with backup fuel (natural gas) to the turbine. Today, the plant is a reliable contributor to that utility's base load electricity supply, at acceptable operating cost. The lessons learned will inform future IGCC plant investment decisions, as intended in such government-supported demonstrations.

Although there are remaining concerns about capital cost and availability, our judgment is that for IGCC without CCS, the remaining risks are at a level that the private sector commonly encounters in making investment decisions on specific projects. Our judgment is supported by the formation of several industrial consortia to make commercial offers for IGCC plants without CCS. Accordingly, we see no justification for further public subsidy of IGCC plants without CCS on the basis of first-mover technical uncertainty; it is not an appropriate government role to "buy down" costs of technologies that are not directly addressing a market imperfection.

Demonstration of novel technologies is best done at the sub-system level. On the other hand, the critical step of adding CCS to an IGCC plants leads again to performance risks outside the envelope of private sector risk-taking and merits appropriately structured public support for integrated systems.

However there have been important gaps in the DOE program — we mention four:

(1) **There has been too little emphasis on improvements in PC generating efficiency**, such as support for ultra-supercritical boiler and steam cycle technology. Europe and

Japan are more advanced in this technology with a number of large, ultra-supercritical units operating; in the United States, EPRI is taking the lead with DOE support.

(2) **There is a significant lack of modern analytical and simulation tools for understanding the dynamics of complex integrated coal systems, particularly with CCS**. Moreover, it does not appear to us that the private sector has adequately developed such tools either. The result is that neither the public nor private sector has the ability to assess tradeoffs between different technology options for carbon capture efficiency, much less analyze in sufficient depth questions such as transient behavior, plant reliability, or retrofit optimization.

(3) **The applied research and technology program has not been robust enough to support the demonstration projects or to explore potential for future innovations.**

(4) **The DOE has been slow to support advanced technology at process development unit (PDU) scale that explores new options for coal conversion, oxygen separation, and for CO_2 capture.**

In our view there is a near term need for appropriately structured, publicly supported, adequately resourced demonstrations of large-scale sequestration and of integrated coal combustion and conversion systems with CCS. We comment on components of the current DOE RD&D program that address important elements relevant to this purpose.

SEQUESTRATION

The DOE Carbon Sequestration Core Program was initiated in 1999 and has been supported with moderate but increasing funding (the proposed FY07 budget is $74 million, an 11% increase over FY06).

The program includes activities that cover the entire carbon sequestration cycle of capture, separation, compression, transportation and storage. The program has advanced carbon sequestration science and technology. The DOE program has promoted the formation of seven U.S. regional partnerships to build an information base for decision-making, including categorization and description of regional sources, sinks, and potential targets for pilot injections. The DOE and the State Department have established a Carbon Sequestration Leadership Forum as a platform for international collaboration on technical, regulatory, and policy issues in carbon sequestration.

To date, the DOE CCS program has not been pursued with an urgency to establish the key enabling science and technology needed for increased coal use in a carbon-constrained world. Importantly, developing advanced capture technologies or deployments of IGCC motivated by "capture readiness" are inconsequential if sequestration is not possible at very large scale, eventually reaching the gigatonne/year scale globally. Establishing sequestration as a practical large-scale activity requires work across the board, including science, technology, infrastructure design, regulation and international standards. None of the key technical and public acceptance issues have been addressed with sufficient intensity. The program is characterized instead by small projects, many performers (e.g., the regional partnerships), and conversations that may have the virtue of involving many constituencies, but does not grapple with answers to the hard questions.

FUTUREGEN Given its central role in the DOE program, we comment specifically on the FutureGen project. We support the concept of an integrated demonstration of IGCC+CCS; however, we have several concerns about this particular project structure.

First, there is continuing lack of clarity about the project objectives. Indeed, the DOE and consortium insist that FutureGen is a research project and not a demonstration project. This distinction appears to be motivated by the fact that higher cost sharing is required for a demonstration project, typically 50% or more from the private sector. However, the main purpose of the project should be to demonstrate commercial viability of coal-based power generation with CCS; it would be difficult to justify a project of this scale as a research project. And it would probably be unwise.

The ambiguity about objectives leads to confusion and incorporation of features extraneous for commercial demonstration of a power plant with CCS, and to different goals for different players (even within the consortium, let alone between the consortium and the DOE, Congress, regulators, and others). Second, inclusion of international partners can provide some cost-sharing but can further muddle the objectives; for example, is Indian high-ash coal to be used at some point? This effort to satisfy all constituencies runs the risk of undermining the central commercial demonstration objective, at a project scale that will not provide an agile research environment.

Congress and the administration should declare FutureGen to be a demonstration project, decide what level of cost sharing is appropriate to the risk without adherence to an arbitrary historical formula, and incorporate options for "experiments" only to the extent that they do not compromise the objective of commercial demonstration of the integrated system with proven components. The project design should be optimized by analysis of tradeoffs that an investor would require. FutureGen is a complex project; its success requires clarity of purpose.

It remains to be seen whether political realities will allow DOE and the FutureGen consortium the freedom to operate without the intrusion of federal procurement rules and government cost auditing. It is crucial that the sequestration program proposed in Chapter 4 not be dependent on progress of the FutureGen project. Of course, it is preferable that FutureGen, if built, support a proper sequestration demonstration. However, the sequestration projects must be accommodated with sufficiently reliable CO_2 supply to multiple sites, with the choice of sites optimized to provide the public with a benchmark for implementation of large-scale sequestration.

THE RECOMMENDED ARD&D PROGRAM

Our principal objectives in this chapter are to recommend a federally-supported coal analysis, research and development program based on the analysis in Chapters 3 and 4 and aligned with the strategic goals of enabling large-scale coal use in a carbon-constrained world and to discuss criteria for federal support of large-scale integrated demonstration projects with CCS.

ANALYSIS AND SIMULATION.

Powerful engineering-economic simulation tools are needed for analysis of integrated coal combustion and conversion systems, with CCS, under a variety of system configurations and operating conditions. This should be a very high priority in the DOE research program. We were struck many times in carrying out this study how the absence of such tools prevents reliable quantitative examination of many key questions, especially (though not exclusively) for gasification systems. A number of point designs have been studied in detail, but all are based on different assumptions and inputs. Robust models suitable for assisting large-scale engineering design should start with high-fidelity simulation of engineering-scale components and proceed to system integration for both steady-state and transient situations, including sub-systems with different dynamic characteristics (such as chemical process and power subsystems). In order to avoid mismatch between system components, the transfer function, the time resolved relation of an output variable to load variation, would need to be determined for elements of the system. Such a modeling and simulation capability will permit the exploration of important design tradeoffs, such as between carbon capture fraction and system response to grid requirements, or degree of gas cleanup and both turbine operation and sequestration requirements, and many others. The simulation tools should flexibly accommodate validated engineering and cost data.

We estimate \$50M/year is needed to support a strong program.

PC POWER GENERATION R&D

With the very large PC fleet in place (~325 GW_e in the U.S.) and the expected additions to this fleet over the next two decades, the possibility of imposition of a significant carbon emission charge indicates the need both for ultra-high efficiency and for much less costly CO_2 capture technology for PC combustion plants. Success in both could dramatically alter the relative cost of PC and IGCC with capture. The higher efficiency gains will come from operating at higher steam pressures and temperatures and thus require developing higher-strength corrosion-resistant materials and advanced fabrication technologies.

Reducing capture cost appreciably is especially important for PC plant retrofits; this calls for an integrated research effort starting with CO_2 chemistry and physical properties, combined with a theoretical and experimental program focused on designing (or identifying) absorbents or adsorbents that can effectively capture CO_2 and then release it with a much lower energy requirement than present solutions. Other approaches, beyond absorbents and adsorbents, should also be explored in a basic science program.

Oxy-fuel coal combustion appears to offer significant potential for new plants or retrofit CO_2 capture applications and is moving towards demonstration with a pilot plant under construction in Germany (30 MW_{th}) by Vattenfall. If successful, Vattenfall intends to build a 300-600 MW demonstration plant. SaskPower (Canada) has also announced its intention to build a 300 MW oxy-fuel power plant. Basic research to develop less costly oxygen separation technologies is a high priority, one that will also lower the cost of gasification systems. One attractive possibility for oxy-fuel combustion is to compress the entire flue gas stream (minus the water, which is relatively easy to remove) to CO_2 supercritical conditions, assuming the entire stream could be transported and injected as-is into a geologic formation. Much research is needed on the compositional requirements for pipeline transport as well as for injection into geologic formations, on process design and evaluation studies, and on process development units.

Thus, key elements of a PC power generation R&D program include:

- An R&D program to develop the next level of high-strength materials along with cost-effective fabrication technologies for ultra-supercritical (USC) PC operation beyond the current USC conditions (> 1250 °F). This effort should build on the European and Japanese USC programs and current U.S. efforts.
- A significantly increased, broadly-based, coordinated R&D program on CO_2 capture and recovery systems, aimed at developing more cost effective and energy efficient CO_2 capture systems.
- An integrated design and PDU program on oxy-fuel combustion, coordinated with related activities in Europe, Canada, and Australia, including oxygen separations research and a focused effort to understand the impact that other components in the supercritical CO_2, such as SO_2, could have on the geologic formations into which they are injected and on injectivity.
- A program to evaluate (via focused design studies) and provide data specific to oxy-fuel PC retrofit technology should be initiated. A retrofit demonstration could offer an opportunity to produce CO_2 for a major sequestration demonstration (as discussed below).

We estimate $100M/year as appropriate for this program.

IGCC POWER GENERATION R&D.

IGCC presents a different set of issues from PC generation because IGCC currently appears to offer, at least for high rank coals, the lowest COE with CO_2 capture if efficiency and availability are high. Availability centers on the gasifier, on turbine operation with hydrogen-rich gas, and on integrated operation of the IGCC power plant with capture. Unlike PC generation where the basic boiler design is relatively homogeneous, gasifier designs are quite heterogeneous with 5 to 10 major types that could eventually become commercial. Some key elements required for a gasification R&D program are:

- Pressing the limits of syngas clean-up to reduce emissions to very low levels could help gain acceptance for IGCC without and with capture.
- Development of turbines for hydrogen-rich syngas is particularly important to the success of IGCC with CO_2 capture.
- Improved coal injection technologies, refractory improvement or elimination, and instrumentation developments to facilitate operational analysis and control will enhance availability.
- Research into the processing in gasifiers of widely different coal types, including subbituminous coals and lignites, should be evaluated aggressively. This should include basic research for novel concepts and PDU-scale evaluation of promising technologies, combined with rigorous simulation and economic analysis. Advanced power cycles with high efficiency potential are an area of interest.
- System integration studies of electricity production with fuels, chemicals, and/or hydrogen production, with CCS, should go forward, initially through simulation.
- Basic research and PDU-level studies of syngas conversion should be supported more strongly.
- Research on advanced technology concepts related to IGCC should be expanded.

We estimate $100–125M/year as supporting a strong program.

CO_2 SEQUESTRATION RD&D

The priority needs for a sequestration R&D program are discussed in detail in Chapter 4. Because of the close integration of research and demonstration in the case of sequestration RD&D, these will be considered together. The key elements identified in Chapter 4 were:

- Detailed, "bottom-up" geological assessments of storage capacity and potential for injection rates. This should also include a risk analysis of potential geologic storage regions.
- An expanded and accelerated R&D program that includes simulation, testing, and integration of MMV technologies that should be employed in major geologic sequestration demonstrations and in commercial storage programs.
- Development of protocols and regulatory structures for the selection and operation of CO_2 sequestration sites and for their eventual transfer of liability to the government after a period of good practices is demonstrated. We stress the urgency of research in these areas, including development of viable options for setting international standards and monitoring mechanisms.
- Several large-scale injections within key plays and basins of the U.S. These need to be of the order of 1 million tons CO_2/year over several years with a substantial suite of MMV technologies employed to enable a quantitative understanding of what is happening and to identify the MMV tools that will be most effective in commercial operation. These will need major sources of CO_2. To maximize effectiveness of the sequestration studies, sources for the first projects should be "on demand" sources to the extent practical (i.e., if appropriately sized and located), such as natural sources, industrial by-products (e.g., from natural gas processing plants or refineries), or CO_2 captured from a flue gas slip stream at a large operating coal PC plant. Subsequently, the CO_2 source could be purchased from a demonstration plant that advances the knowledge base for advanced coal technologies with capture.

We estimate that \$100M/year is needed for this program in the research phase, with another \$75M-100M/year required for the full suite of sequestration demonstration programs (assuming pure sources of CO_2 are readily available, as incorporated into the Chapter 4 cost estimates).

ADVANCED CONCEPTS

A healthy R&D program needs a component that invites competitive proposals for basic research and innovative concepts that could lead to breakthroughs for high efficiency, clean, CO_2 emission "free" coal use, or for new sequestration approaches. The transport gasifier and chemical looping, mentioned in Chapter 3, are examples. New system ideas, such as integration of fuel cells with IGCC, is another example.. The program should be sufficiently large to allow for evolution of promising research results into pilot scale facilities. This is analogous to the role of the Advanced Research component of the DOE program. However, this program appears headed for reduction.

We estimate that \$100M/year would be appropriate for an advanced concepts program with the work carried out by universities, national labs, and industrial research organizations.

In total, we estimate that an appropriate AR&D program would require funding at about \$500-550M/year. This includes the large-scale sequestration demonstrations when they are ready to proceed, again assuming readily available pure CO_2 sources. The \$500-550M/year we propose should be compared to the \$215M included in the FY07 DOE coal R&D budget (excluding FutureGen), which furthermore is in decline.

COAL TECHNOLOGY DEMONSTRATION PROGRAMS WITH CCS

For power production, IGCC is the leading candidate for CCS using current technologies, at least for higher rank coals. Consequently, starting a demonstration program with IGCC with CCS, as the DOE is doing with FutureGen, is a reasonable choice. Even so, a key question, to which we will return later in this chapter and again in Chapter 8, is how the government can best stimulate and support such a demonstration project.

We have stated before the technical challenges that justified, in the past, public assistance for the first-of-a-kind plants without CCS. When CCS is added, the new plant faces significant additional challenges compared to an IGCC without CCS: different operating

conditions (such as higher pressure to facilitate capture), syngas shift reactors and hydrogen-rich gas for the combustion turbine, operation of the capture system, and interface with the sequestration operations. The purpose of federal support for an integrated system demonstration is to gain information on the cost and operability of the system and to disseminate the results, and not to risk the value of system demonstration by employing individual subsystem components for which there is little experience.

IGCC with CCS is a technically challenging, first of a kind activity that, because of its potential importance to coal utilization in a carbon-constrained world, deserves federal support. The objective of such support is to encourage timely deployment by absorbing some of the risk, but yet leaving sufficient risk with the private sector so as to distort commercial imperatives as little as possible. This suggests removing, to the extent possible, peculiarities of government administered projects: use of federal procurement rules, special requirements for government cost auditing, an annual appropriations cycle for financing the multi-year project and the technical capability of DOE personnel to manage the project, as a commercial entity. Moreover there is the reality that the federal government has "deep pockets", so it is important to assure that federal sponsorship does not invite poor project design on the part of private sector entities because of a reduced cost for delay or failure. There are many possible mechanisms for avoiding these frailties of DOE managed commercial demonstration projects, for example, significant cost-sharing (such as the earlier CCTP program required) and indirect mechanisms, such as a tax credit or guaranteed purchase for electricity produced or CO_2 captured.

While IGCC may sensibly be the first major demonstration project with CCS, we emphasize that it is only one of several possible projects needed to demonstrate the readiness of coal conversion technologies that control CO_2 emissions. For power production, a number of developments may give impetus to other utility-scale demonstrations with CCS: advances in carbon capture from flue gas or in oxygen separation; and the improved understanding of PC retrofit possibilities, with or without oxy-firing. Beyond this, coal conversion to chemicals, synthetic natural gas, or fuels, with CCS, could provide significant pathways to displace oil and natural gas use with an abundant domestic resource, and may offer opportunities to provide sufficient captured CO_2 to sequestration projects at costs significantly less than those for power plants. The central criterion for embarking on such government-assisted commercial demonstration projects is that one can reasonably expect, based on the available technologies and their straightforward extensions, that the products — electricity or otherwise — can be economically competitive in a world that prices CO_2 emissions. It should be clear that the absence of previous commercial demonstrations of any specific technology is not in itself a valid reason for public support.

What will this cost? The answer is project specific. However, a ballpark estimate can be provided for a portfolio of projects by the expected incremental cost of "buying" CO_2 from the various projects at a cost that makes the projects whole commercially, including a risk factor. One can anticipate the CO_2 "price" being in the range \$10-\$60/tonne-CO_2 depending on the nature of the project, with the highest price corresponding to purchase of CO_2 from amine capture from an existing PC plant, and with the lowest price corresponding to some coal to chemicals plants. Accounting for up to five projects of different types (power, fuels, chemicals, synthetic gas; new plants, retrofits) of ten year duration, at a million tonnes CO_2 each, leads to about \$2B over ten years. Adding a risk factor for performance of the underlying technology suggests perhaps \$3B over ten years as a crude estimate, an average comparable to but less than that of the recommended AR&D program. It is important that the U.S. government begin thinking about such a portfolio of demonstration projects and not be singularly focused on any one project, such as FutureGen.

At an average of \$300M/year for demonstrations, the total coal ARD&D program could reach \$800-850M/year if all plant and sequestration demonstrations were running simultaneously (which is not likely). This level corresponds to less than half a mill per coal-generated kilowatt-hour.

As discussed in Chapter 4, we see a need for at least three major sequestration demonstrations in the United States, each of which requires a substantial source of CO_2. It would be ideal if the CO_2 capture demonstration plants were the source of the CO_2. However, there are timing issues in such a scenario. The sequestration projects need "on demand" CO_2 to maximize scientific value and minimize cost of the sequestration project. The demonstration projects will produce CO_2 subject to uncertainty, from availability of first-of-a-kind systems to the vagaries of grid dispatch for power plants. Accordingly, it is likely that a mix of CO_2 sources will be needed for the sequestration demonstrations, from relatively high-priced sources that are "on demand" from existing base load PC plants to lower-priced, but less reliable sources from new coal technology demonstration plants with CCS. Furthermore, it may be that some CO_2 captured in the demonstration projects will be released due to a mismatch in CO_2 supply and demand between the coal conversion and sequestration facilities. While undesirable, this possibility should be accommodated as part of the technology demonstration need to explore a wide range of coal combustion and conversion technologies with CCS in a timely way.

In Chapter 8, we discuss and recommend other approaches to federal assistance to coal combustion and conversion plant demonstrations and to large-scale sequestration demonstrations that may lead to more effective execution of future system demonstrations.

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Chapter 7 — Public Attitudes Toward Energy, Global Warming, and Carbon Taxes

Any serious efforts by government or industry to address greenhouse gas emissions and global warming in the near term would impose a price or charge on carbon or constrain the use of CO_2-emitting fuels in some manner. The primary policy instruments available include restrictions on emissions, stricter regulation of the use of coal and other fossil fuels, subsidies for carbon-free fuels, such as nuclear, wind, biomass, and solar power, tradable rights to carbon emissions (called cap-and-trade systems), and direct carbon taxes. Price-based mechanisms, such as carbon taxes and cap-and-trade systems, would translate immediately into higher energy prices, as they are designed to incorporate the cost of greenhouse gas emissions in the price of electricity, fuels and other forms of energy. Regulations on fuel use and emissions would increase the cost of producing energy from coal and other carbon intensive sources. Subsidies would ostensibly lower the price of energy, but they would only do so through other forms of taxation, such as income and capital taxes, which should then also be considered as part of the price of energy. Moreover, by failing to incorporate the cost of carbon emissions into energy prices this approach would dilute incentives for consumers to invest in energy efficiency and to curtail energy use (e.g. drive more miles). By placing a price on CO_2 emissions, public policies could lead consumers to reduce their use of CO_2-emitting forms of energy and increase the competitiveness of less carbon-intensive fuels.

Policies that produce higher fuel prices have long been thought to be politically infeasible because the public reputedly reacts more negatively to higher fuel prices or taxes than to the threat of global warming. If true, only subsidies would be politically palatable. Public opinion research has documented increasing concern about global warming in the United States, but such research only addresses half of the issue.[1] How will the public react to higher energy prices were the government to follow an aggressive policy to stem greenhouse gas emissions?

Here we offer an assessment of one such option, a carbon charge that, however imposed, would be equivalent to a tax on CO_2-emitting energy forms. We focus on carbon taxes because research that compares the efficiency of alternative policy mechanisms to control greenhouse gas emissions concludes that carbon taxes and cap-and-trade systems offer the most efficient approaches.[2] Subsidies, emissions restrictions, and regulations on fuel use are much less efficient. Public attitudes about carbon and fuel taxes are more readily studied because taxes are more transparent to the public than the prices resulting from cap-and-trade systems and require less explanation. Carbon taxes, because of their transparency, are thought to be especially unpalatable politically, and public reaction to taxes therefore offers a conservative gauge of support for this line of policy-making. Economic analyses sometimes dismiss taxes as an instrument at the outset because of perceived public hostility toward taxes, though it should be noted that industrial nations have long histories of fuels taxes but have only recently experimented with tradable pollution rights.[3] Little opinion research addresses the willingness to pay for global warming and specific ways that such a tax could be implemented. Of particular interest are proposals to couple higher fuel taxes with lower income, payroll, or capital taxes.

There is, in fact, widening support for concrete government policies to avoid global warming. Beginning in 2003 we conducted a series of public opinion surveys designed to gauge concern about global warming and public willingness to pay much higher fuels taxes in order to reduce greenhouse gas emissions. In October 2003 and again in October 2006, we fielded a national random sample survey of 1200 adults to measure understanding of the carbon cycle, concern about energy, the economy, and the environment, and preferences over a range of technologies and policies to mitigate carbon emissions. Two separate surveys, conducted in May 2006 and November 2006, probed opinions about proposals to use the revenues from higher fuel taxes to reduce income taxes. All four surveys consist of national random samples of U. S. adults. See appendix for details, or consult the MIT Public Opinion Research and Training Lab http://web.mit.edu/polisci/portl/detailpages/index.html.

Four important survey results underlie our belief that public support is growing for policy measures that deal squarely with greenhouse gas emissions and climate change.

1. **The American public increasingly recognizes global warming as a problem**.

Three years ago, global warming ranked as the sixth most important environmental problem in our survey, behind problems such as clean water, clean air, and endangered species. Only 11 percent of respondents chose global warming from a list of 10 environmental problems as the most important environmental problem facing the country, another 9 percent ranked it second. Today, the public rates global warming as the top environmental problem facing the country. In October 2006, 35 percent of respondents identified global warming as the most important environmental problems facing the country, outpacing all other issues considerably. An additional 15 percent chose it second. Fully half of the American public now puts global warming at the top of the U.S. environmental agenda compared with just 20 percent three years ago.

2. **Over the past three years, Americans' willingness to pay to solve global warming has grown 50 percent.**

In 2003 and 2006 we asked survey respondents the same series of questions designed to elicit willingness to pay: "If it solved global warming, would you be willing to pay $5 more a month on your electricity bill?" Of those who answered yes, we then asked whether they would pay $10 more, and offered progressively higher amounts — $25, $50, $75, and $100. In 2003, support for such a tax was quite low. The median response was only $10, and the average amount came to just $14.

As interesting as the levels of support for the taxes are the changes over time. We repeated the survey in 2006 and found a 50 percent increase in willingness to pay. The median response was approximately $15 more a month (or a 15 percent levy on the typical electricity bill), compared with just $10 in 2003. The average amount came to $21 per month. The rising amount that the typical person would pay was matched by a decline in the percent unwilling to pay anything. In 2003, 24 percent of those surveyed said they were unwilling to pay anything. Three years later, a similarly constructed sample answered the identical series of questions, and the percent unwilling to pay anything fell to 18 percent, a statistically significant drop.

The rise in willingness to pay resulted in large part from the increased recognition of the importance of the problem. The percentage of those who consider global warming a top-tier environmental concern rose from 20 percent to 50 percent. Those who did not rank global warming as one of the top two environmental problems in 2006 were willing to pay, on average $16 per month in 2006, while those who did rank global warming as one of the top environmental concerns in the country were willing to pay $27 a month. In addition, willingness to pay among those who are concerned with this problem has risen considerably. Among those who consider global warming one of our chief environmental problems willingness to pay rose from $17 a month in 2003 to $27 a month in 2006. If global warming continues to rise as a concern, we expect to see growth, possibly very rapid growth, in willingness to pay fuel taxes that target greenhouse gas emissions.

While we would caution about interpreting firmly the level of the amount because people often exaggerate their willingness to pay, the dramatic growth in the percent of people concerned with the problem and the amount that they are willing to pay reveals a considerable growth in public recognition of the problem and support for serious policies designed to solve it.

3. Today the public views global warming equally compelling as oil dependence as a rationale for fuel taxes.

Since the oil price shocks of the 1970s, lowering dependence on foreign oil has served as an important objective for U. S. energy policy. Global warming represents quite a different goal, though a tax on gasoline and other petroleum products would still be implied. Another way to appreciate the priority of global warming for the American public is to compare support for fuel taxes when oil dependence is the question and when global warming is at issue.

In a separate survey conducted in November 2006, we sought to contrast oil imports and global warming as motivations for higher energy prices. We asked half of the sample (randomly chosen) whether they were willing to pay higher gasoline taxes in order to reduce oil imports; we asked the other half of the sample whether they would pay an equivalent tax in order to reduce greenhouse gas emissions. The distributions of responses were very similar, and statistically not distinguishable. Twenty-four percent were willing to pay $1.00 per gallon if it reduced oil imports by 30 percent (a very optimistic figure); 60 percent were opposed. Twenty-one percent said that they would pay $.50 per gallon and $25 per month more on electricity if it reduced U. S. greenhouse gas emissions 30 percent; 62 percent were opposed.[4] Further variations on these questions yielded the same result. Global warming and oil importation appear to present the typical person with equally strong rationales for higher fuel taxes.

4. Tying fuel tax increases to income tax reductions increases public support for high fuel taxes.

Rising public concern and willingness to pay signal some optimism that public will to address global warming will solidify soon. The carbon tax levels that Americans support, however, fall short of what may be needed in the short run to make carbon capture and sequestration feasible, let alone other alternative energy sources such as nuclear, wind and solar. Our assessment in Chapter 3 suggests that a carbon charge in the range of $30 per ton of CO_2 is necessary to reduce U. S. carbon emissions significantly and to reduce worldwide emissions of greenhouse gases. If consumers bore that cost directly, it would amount to $13.50 per month on a typical household electricity bill.[5]

The total cost to consumers also depends on how the revenues raised by the carbon charge are distributed. Early economic writing on carbon taxes argues that they be revenue neutral, that is, the revenue from carbon taxes would be used to reduce payroll or capital taxes. A fuel tax could be structured to reduce income taxes and even to offset the regressive incidence of the fuel tax itself.

Swapping income taxes for fuel taxes has considerable public appeal. We tested support for fuel taxes in isolation and when tied to reductions in other taxes in national sample surveys conducted in May 2006 and November 2006. In May 2006, we asked people whether they would support a $1.00 per gallon gasoline tax and a $25 per month electricity charge. Only

9 percent said yes, and 72 percent said no, the remaindering being unsure. When that same tax was presented with an equivalent reduction in income taxes for the typical family, support for the tax rose to 28 percent, and only a minority (47 percent) expressed opposition. In November 2006, as mentioned above, we asked a national sample whether they would support a $.50 per gallon gasoline tax and $25 per month electricity tax: 21 percent said yes; 17 percent, unsure; 62 percent, no. We paired the same proposal with a reduction in income taxes by an equivalent amount: 34 percent said yes; 23 percent, unsure; and 43 percent, no.

We followed up these questions by asking those opposed, why they did not support the tax swap. Only 10 percent stated that they opposed the fuel tax because the government would not also cut income taxes, and 18 percent said they could not afford to pay the tax. By far the most common answer (of roughly one in four of the 43 percent of those opposed) was that global warming is not a problem. This amounts to 10 percent of the public unwilling to pay because they view the claims about global warming to be exaggerated or unfounded. Another 20 percent of opponents thought that we could reduce global warming without the taxes. Approximately half of those opposed to the tax relied on a rationale that either denied the problem or thought that the solution could be implemented without the tax.[6]

We do not claim to have measured the magic number—the carbon charge that a majority of the public would unquestionably support. Rather, this series of surveys suggests that public opinion on global warming is changing and changing in ways that make a more substantial climate policy politically attainable.

Carbon taxes serve as a reference case. They are an efficient way to incorporate the costs of global warming in the price of energy, but they have been viewed as politically impossible owing to the unpopularity of taxes. While other price-based policy instruments, such as a cap-and-trade system, may not be perceived as a tax, they would have the same effect on energy prices.

Most encouraging, though, is the trend. Public discussion about global warming over the past three years has made a noticeable impact on public willingness to deal with this problem even through what is supposedly the least popular instrument, taxes. Willingness to pay has grown fifty percent in just 36 months. That growth is directly attributable to the increasing number of people who view global warming as one of the nation's top environmental problems. It also reflects a growing reality that global warming is as important as oil importation in the way the U.S. public thinks about public policy issues involving energy.

CITATIONS AND NOTES

1. Jeffrey Kluger, "Global Warming Heats Up" *Time* April 3, 2006, vol. 167, no. 4, page 25.
2. The observation that carbon taxes offer an efficient mechanism dates at least to 1990; see James Poterba, "Tax Policy To Combat Global Warming: On Designing a Carbon Tax," in *Global Warming: Economic Policy Responses*, Rudiger Dornbusch and James Poterba, eds. Cambridge, MA: MIT Press, 1990. For an excellent survey see James Poterba, "Global Warming Policy: A Public Finance Perspective" *Journal of Economic Perspectives* vol. 7, Fall 1993, pages 47-63. Subsequent analyses point out the importance of recycling revenues to reduce taxes on labor and capital. See A. Lans Bovenberg and Lawrence Goulder, "Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses." *American Economic Review*. Vol. 86 (September 1996), pages 985-1000, and A. Lans Bovenberg and Lawrence Goulder, "Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies: What Does It Cost" NBER Working Paper No. W7654, April 2000.
3. For example, see Poterba, "Tax Policy to Combat Global Warming," op cit., pages 72-75, and Bovenberg and Goulder, "Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies," op cit., pages 1-3. There are other political aspects to the choice of policy instruments, especially support or opposition from affected interests and the credibility of the government in setting up a program. The cap-and-trade system for sulfur dioxide reflected the political coalitions that supported and opposed the legislation. See Paul Joskow and Richard Schmalensee "The Political Economy of Market-Based Environmental Policy: The U. S. Acid Rain Program." *Journal of Law and Economics* vol. 41 (1998), pages 37-83.
4. The amount of reduction was selected in consultation with those managing the EPPA model, see Ch. 2. We kept the 30 percent figure in both versions of the question so that people focused on a similar number, which psychologically suggests an equivalence between the two savings. We do not imply any real equivalence here.
5. This calculation assumes 1 tonne CO_2 per MWh for coal-fired generation and half that amount for gas-fired generation, and that about half the hours would reflect the carbon cost of gas generation and the other half that of coal-fired generation. Average household use is estimated at 600 kwh/mo.
6. The remaining respondents thought that the tax should not be on fuels but on oil companies or that the income tax cut was unfair, or that this just wasn't a good reason for a tax.

Chapter 8 — Findings and Recommendations

Here we present our findings and recommendations from the analysis presented in prior chapters. The central message is:

> *Demonstration of technical, economic, and institutional features of carbon capture and sequestration at commercial scale coal combustion and conversion plants will (1) give policymakers and the public confidence that this carbon mitigation control option is practical for broad application, (2) shorten the deployment time and reduce the cost for carbon capture and sequestration should a carbon emission control policy be adopted, and (3) maintain opportunities for the use of coal in a carbon constrained world in an environmentally acceptable manner.*

Our basic finding that serves as the underpinning for many of our recommendations derives from the technical assessment reported in Chapter 3:

> *Finding #1:* Although possible in principle, it is very unlikely that any process that produces electricity from coal conversion/combustion with carbon capture will ever be as cheap as coal plants without CO_2 capture. Thus the cost of electricity from coal with capture will be significantly higher than it would be without CCS. Disciplined technology development and innovative advances can, however, narrow the cost gap and deserve support.

CO_2 capture requires that the steps that extract energy from coal either in the form of heat or by chemical transformation permit efficient separation of CO_2 to a form that can be transported efficiently to storage sites. This almost certainly requires a process more complicated than simple coal combustion in air.

FUTURE COAL USE

In Chapter 2 we used the MIT EPPA model to explore the impact on coal use of different economic assumptions including, in particular, a carbon charge imposed on CO_2 emissions either directly by a tax or indirectly through the market price of carbon emissions permits in the context of a cap and trade system. The EPPA model is most useful in illustrating the interconnected consequences of different policy measures, but its limitations should be kept in mind. The model shows that a significant reduction of carbon emissions is possible only when a significant price is placed on CO_2 emissions. The economic adjustment to the carbon emission charge includes higher end-user energy prices, less energy use, a shift to lower carbon-emitting sources of energy, including nuclear power, and importantly, if the carbon charge is high enough, coal combustion with CCS:

> *Finding #2:* A global carbon charge starting at \$25 per ton of CO_2 emitted (or nearly \$100 per tonne of carbon), imposed initially in 2015 and rising at a real rate of 4% per year, will likely cause adjustments to energy demand, supply technologies and fuel choice sufficient to stabilize mid-century global CO_2 emissions from all industrial and energy sources at a level of 26 to 28 gigatons of CO_2 per year. Depending on the expansion of nuclear power, the use of coal increases from 20% to 60% above today's level, while CO_2 emissions from coal are

reduced to half or a third of what they are today. This level of carbon charge implies an increase in the bus bar cost of U.S. electricity on average of about 40%, or about 20% of the retail cost. A significant contributor to the emissions reduction from coal is the introduction of CCS, which is utilized as an economical response to carbon charges at these levels. In the EPPA model simulations, approximately 60% of coal use employs CCS by 2050 with this carbon charge.

This finding assumes that the entire world adopts the same carbon charge. As discussed in Chapter 2, if the United States or developing economies do not adopt a carbon charge (or effectively reduce their emissions of CO_2 significantly below business-as-usual (BAU) levels through other means), worldwide CO_2 emissions from coal use will not stabilize. Our examination in Chapter 5 of the patterns of energy use in China and India shows how challenging it will be for these emerging economies to reduce their emissions significantly below business-as-usual levels. With respect to China:

Finding #3: China's focus on economic growth and the decentralized and fragmented character of the financial and environmental governance of their fuel, power, and industrial sectors suggests that it will be some time before China could adopt and effectively enforce a policy of significant carbon emission reduction from BAU levels.

However our analysis also showed that if developing economies (of which China is the largest example) were to delay adopting a CO_2 charge or equivalent with a modest lag (say, ten years) relative to the developed economies, the 'penalty' in terms of additional CO_2 emissions compared with the case of simultaneous global compliance would be relatively small: between 100 and 123 gigatonnes of CO_2 emitted during the 50 year period 2000–2050 compared to total cumulative global emissions during this period of about 1400 gigatonnes CO_2.

Finding #4: There is a relatively small CO_2 emission penalty associated with a modest lag in the adoption of a global carbon charge by developing economies as long as the United States and other developed countries adopt a credible CO_2 control policy that is consistent with the CO_2 prices identified here. The practical significance of this model result is the interesting opportunity for negotiating a global agreement featuring delayed adherence to a carbon charge for developing economies.

We see no evidence of progress towards a political framework that will result in convergence of the carbon emission policies of developed and developing economies. Whether or not a carbon charge is imposed sooner or later, **it is important that coal combustion is as thermally efficient as makes economic sense over the life of the plant**. This leads to our first recommendation:

Recommendation #1: New coal combustion units should be built with the highest thermal efficiency that is economically justifiable. Any carbon charge will make the economics of higher efficiency coal plants more attractive than those of lower efficiency plants. In addition, continuous advances in R&D make it likely that further reductions in heat rates will be possible. **For pulverized coal plants** this means super critical pulverized coal (SCPC) plants today and ultra-super critical pulverized coal (USCPC) plants soon. A 500 MWe USCPC plant will emit about 100 tonnes per operating hour less than a sub-critical plant, avoiding about 21% of the CO_2 emissions. [See Chapter 3, Table 3.1]. **For IGCC plants** this means attention to higher efficiency and high availability operation.

CARBON SEQUESTRATION

As explained in Chapter 2, if CSS is available at large scale and adopted worldwide, increased coal use to meet the world's pressing energy needs in a carbon constrained world will not increase CO_2 emissions, and this technology option can allow more effective constraints to be imposed on CO_2 emissions. This prospect assumes that CCS is implemented in a technically responsible manner at acceptable cost and, most importantly, that sequestration is demonstrated to a point where it is acceptable to the public. As discussed in Chapter 4, we find:

> *Finding #5:* Current evidence indicates that it is scientifically feasible to store large quantities of CO_2 in saline aquifers. In order to address outstanding technical issues that need to be resolved to confirm CCS as a major mitigation option, and to establish public confidence that large scale sequestration is practical and safe, it is urgent to undertake a number of large scale (on the order of 1 million tonnes/year injection) experimental projects in reservoirs that are instrumented, monitored, and analyzed to verify the practical reliability and implementation of sequestration. None of the current sequestration projects worldwide meets all of these criteria.

> *Recommendation #2:* The United States should undertake three to five sequestration projects — at a scale of about 1 million tonnes/year injection — in order to answer the outstanding technical questions concerning CO_2 sequestration.

The technical requirements for these sequestration projects are set forth in Chapter 4, as well as the estimated cost of about $15 million per year for each project, not including the cost of the significant supply of CO_2 to be injected Below, we discuss potential sources of the CO_2.

The introduction of CO_2 capture and sequestration on a significant scale will require the construction and operation of a large infrastructure of pipelines, surface injection facilities and a monitoring and analysis network. As discussed in Chapter 4, further work is needed to determine the location and capacity of sites suitable for CO_2 storage in relation to coal conversion plants and existing coal resources, and to develop the institutional arrangements that will govern CO_2 storage sites over very long time periods. Therefore we recommend:

> *Recommendation #3:* The DOE in cooperation with the USGS should undertake a bottom-up review of possible sequestration sites in relation to major coal burning facilities. The United States government should encourage surveys in other parts of the world, specifically in India and China, where large and growing use of coal is anticipated.

As mentioned in Chapter 4, the federal government's authority to regulate CO_2 injection rests with the U.S. Environmental Protection Agency (EPA)'s *Underground Injection Control* program. The purpose of this program is to protect drinking water. This authority does not provide a broad enough regulatory framework for CO_2 injection and storage.

Moreover, CO_2 storage is intended to be permanent. There is a possibility of leakage (especially from an injection failure) into ground water or, more improbably, a catastrophic leak that potentially might injure people, as noted in Chapter 4. Commercial firms do not have the longevity or capacity to warrant the integrity of the storage system for the required periods of time. Therefore an insurance system is needed (ultimately backed by a government guarantee) that covers liability after some period of time and for catastrophic events. The terms and structure of this liability are important parts of the needed regulatory framework. In particular, mechanisms must be put in place to ensure that those responsible for sequestration sites ensure that these sites are operated, maintained and monitored to the highest standards of safety and economic efficiency, despite the availability of social insurance and the potential "moral hazard" problems that might arise.

As discussed in Chapter 4, the regulatory framework must include criteria for site selection, procedures for injection, requirements for interim monitoring, and transfer of liability to the U.S. government after some period of operation. Moreover, the regulatory regimes of different nations must be consistent. This is a broad range of requirements that involve the interests of several agencies including the EPA, DOE, the Department of Interior and, importantly, the Department of State. We recommend:

> *Recommendation #4:* An element of the Executive Office of the President (the President might designate lead responsibility to the National Economic Council, the Office of Management and Budget, or the Office of Science and Technology Policy), should initiate an interagency process to determine the regulatory framework—including certification and closure of sites and the appropriate transfer of liability to the government—needed for a safe CO_2 transportation and storage system. Enforcement and inspection supporting the regulations should be the responsibility of the EPA.

COAL CONVERSION TECHNOLOGIES

Chapter 3 presents our analysis of alternative approaches to coal conversion with CCS. This analysis leads us to conclude:

> *Finding #6:* It is premature to select one coal conversion technology as the preferred route for cost-effective electricity generation combined with CCS. With present technologies and higher quality coals, the cost of electricity generated with CCS is cheaper for IGCC than for air or oxygen-driven SCPC. For sub bituminous coals and lignite, the cost difference is significantly less and could even be reversed by future technical advances. Since commercialization of clean coal technology requires advances in R&D as well as technology demonstration, other conversion/combustion technologies should not be ruled out today and deserve R&D support at the process development unit (PDU) scale.

The 2005 Energy Act contains significant incentives for demonstrating "clean coal" technologies and gives significant latitude to the Secretary of Energy to determine which technologies should receive benefits. The 2005 Energy Policy Act gives DOE authority to extend significant benefits to IGCC plants and to pulverized coal plants with advanced technology *without* capture. The Act extends greater benefits to gasification technology for a number of reasons:

Advocates believe IGCC plants to be more flexible for accommodating possible future environmental requirements on criteria pollutants or mercury control and because today IGCC plants are estimated to have a lower retrofit cost for CCS than pulverized coal plants or are easily made "capture ready."

The cost of control of criteria pollutants and of mercury. We find that while the control of conventional pollutants by IGCC is easier, i.e., less costly, than with SCPC, the difference in control cost is not sufficient to reverse the overall cost advantage of SCPC in the absence of a carbon charge. More stringent controls on criteria pollutants and mercury may be adopted in the future, but we do not believe it possible to predict today the net cost impact of tighter controls on IGCC and SCPC, especially since each of these technologies continues to improve in terms of performance and cost.[1]

Coal plants will not be cheap to retrofit for CO_2 capture. Our analysis confirms that the cost to retrofit an air-driven SCPC plant for significant CO_2 capture, say 90%, will be greater than the cost to retrofit an IGCC plant. However, as stressed in Chapter 3, the modifications needed to retrofit an IGCC plant for appreciable CCS are extensive and not a matter of simply adding a single simple and inexpensive process step to an existing IGCC plant. CO_2 capture requires higher pressures, shift reactors, and turbines designed to operate with a gas stream that is predominantly hydrogen. Turbines that do this are yet to be deployed. In fact, the low heat rate incentives in the 2005 Energy Act favor gasifier configurations that involve radiant heat recovery, or radiant and convective heat recovery. The gasifier configuration that would be used in the design of an IGCC system to be retrofitted for CO_2 capture is likely to be a straight quench gasifier, which would not meet the heat rate incentives in the Energy Act. Consequently, IGCC plants without CCS that receive assistance under the 2005 Energy Act will be more costly to retrofit and less likely to do so.

The concept of a "capture ready" IGCC or pulverized coal plant is as yet unproven and unlikely to be fruitful. The Energy Act envisions "capture ready" to apply to gasification technology.[2] Retrofitting IGCC plants, or for that matter pulverized coal plants, to incorporate CCS technology involves substantial additional investments and a significant penalty to the efficiency and net electricity output of the plant. As a result, we are unconvinced that such financial assistance to conventional IGCC plants without CCS is wise.

Currently four coal-fueled and five in-refinery coke/asphalt- fueled IGCC plants are operating around the world,[3] and many additional gasifier units are operating in the petrochemical industry. Each of the coal-fueled IGCC plants had a different and difficult start-up phase, but all are now operating with relatively high capacity factors. Despite the existence of these plants, IGCC advocates in the United States put forward a number of benefits as justification for federal assistance for IGCC plants designed without CCS.

Some suggest that the uncertainty about the imposition of a future carbon charge justifies offering federal support for a portion of the initial investment cost required to build new coal combustion plants without CCS today, so that if a carbon emission charge were imposed in the future, the CCS retrofit cost would be lower. We do not believe that sufficient engineering knowledge presently exists to define the relationship of the extent of pre-investment to the cost of future retrofit, and the design percentage of CO_2 removed. Moreover, the uncertainty about when a carbon charge might be imposed makes it difficult (for either a private investor or the government) to determine the value of incurring a cost for a benefit that is realized, if at all, at some uncertain future time. Other than a few low-cost measures such as providing for extra space on the plant site and considering the potential for geologic CO_2 storage in site selection, the opportunity to reduce the uncertain eventual cost of CCS retrofit by making preparatory investment in a plant without CO_2 capture does not look promising. In sum, **engineering and policy uncertainties are such that there is no meaningful basis to support an investment decision to add significant "capture ready" features to IGCC or pulverized coal plants, designed and optimized for operation without CO_2 capture.**

> *Recommendation #6a:* Technology demonstration of IGCC or pulverized coal plants without the contemporaneous installation of CCS should have low priority for federal assistance if the justification for this assistance is to reduce uncertainty for "first movers" of new technology.

Because the emphasis the 2005 Energy Policy Act gives to gasification technologies, we discus further in Appendix 8.A the issue of federal support for IGCC plants without carbon capture.

There is, however, a serious policy problem in that prospective investors in either SCPC or IGCC plants without CO_2 capture, may anticipate that potentially they will be "grandfathered" or "insured" from the costs of future carbon emission constraints by the grant of free CO_2 allowances to existing coal plants, including those built between today and the start of the cap-and-trade system. The possibility, indeed political likelihood of such grandfathering, means that there is a perverse incentive to build coal plants early—and almost certainly these will be SCPC plants—to gain the potential benefits of these future allowances while also enjoying the higher electricity prices that will prevail in a future control regime. The net effect is that early coal plant projects realize a windfall from carbon regulation and thus investment in these projects will raise the cost of future CO_2 control.

Recommendation #6b: Congress should act to close this potential "grandfathering" loophole before it becomes a problem for new power plants of all types that are being planned for construction.

In contrast to the arguments for federal assistance to IGCC without CCS, there is justification for government assistance to "first mover" IGCC plants with CO_2 capture. First, there is no operating coal plant that captures CO_2 at pressures suitable for pipeline transport, integrated with transfer and injection into a storage site. Second, as we have emphasized in Chapter 3 and above, there are major differences between an IGCC plant designed for CO_2 capture and an IGCC plant designed without CO_2 capture. Third, experience is needed in operating the IGCC plant and capture system under practical conditions of cycling plant operations and for a range of coals. Thus, there is a need for demonstration of an IGCC plant with CO_2 capture. As pointed out in Chapter 3, there are other technology choices that should also be considered for demonstrating CO_2 capture: (1) Oxy-fired SCPC or retrofit of a SCPC plant and (2) a coal to liquids plant. [We point out below why these technologies might be especially attractive demonstrations].

This suggests that the government provide assistance for projects that capture, transport, and sequester. The objective of such "first-of-a-kind" projects is to demonstrate (1) technical performance, (2) cost, and (3) compliance with environmental and safety regulations.

Recommendation #7: The federal government should provide assistance for 3 to 5 "first-of-a-kind" coal utilization demonstration plants with carbon capture. The scale of these should be on the order of 250 to 500 MWe power plants, or the product equivalent.

As discussed in Chapter 6, federal assistance for demonstration plants should be structured in a manner that interferes as little as possible with conventional commercial practice. One mechanism is for the government to purchase the pressurized, pipeline-ready CO_2 produced by the plant at a price needed to make carbon capture a viable private investment. Each technology choice will require a different level of assistance in terms of \$/ton CO_2 and therefore a tailored purchase arrangement is required for each technology. An open bidding process for the rights to government CO_2 purchase obligation is the best selection procedure, once the portfolio of desirable technologies is chosen. An estimate of the annual cost to the government to pay for capture at an IGCC facility is in the range of \$90 million/year[4] for a minimum of ten years.

The advantage of this approach is that the government pays only if the plant operates and the CO_2 it produces is captured, delivered to the site, and sequestered. The arrangement offers an incentive to have the plant function for the purpose of demonstrating carbon capture. In addition, the purchased CO_2 can act as the source of the CO_2 for sequestration demonstration facilities (see *Recommendation #2*).

Recommendation #8: The federal government, in the absence of any emission charge[5] should arrange to pay for CO_2, produced at a coal facility at a price that will make it attractive for private concerns to build and operate a coal conversion plant with carbon capture.

Some question whether a federal government commitment to "take or pay" for CO_2 produced at a CCS plant will be viewed by private investors and lenders as reliable. Experience indicates that once the U.S. government has signed a long-term contract, for example for purchase or supply of electricity, the terms of the contract are honored. Investors would however face other uncertainties, for example, an unexpected drop in competing natural gas prices or improper technical performance of the plant. The CO_2 price could be set to compensate for some of these uncertainties, although the principle of maintaining commercial practice means that not all risks should be taken out of the project.

INTEGRATING CARBON CAPTURE, TRANSPORTATION, AND STORAGE

Chapter 3 of this report is devoted to coal combustion and conversion technologies and to CO_2 capture, and Chapter 4 is devoted to CO_2 storage. However, successful CCS requires integration of these two activities and the transportation of CO_2 produced at the coal plant to the injection point at the reservoir site. There is a major challenge of achieving an integrated system from combustion to storage. A successful project needs to demonstrate the technical aspects of capture and sequestration but also the regulatory arrangements needed to site a CO_2 pipeline, injection practices, and storage site selection. **Accordingly, the appropriate objective is to demonstrate the system level integration of carbon capture with CO_2 storage.**

It is important to appreciate the complexity of this integration. The plant produces pressurized, transport-ready CO_2 at a rate determined by the operating tempo of the plant. In the case of IGCC, this occurs within a performance envelope constrained by the integration of the gasification process with turbine operation that is determined by the electricity dispatch on the regional grid. A pipeline or pipeline network is required to transport the liquid CO_2 at the rate of CO_2 production to an injection point at the reservoir, ideally not too distant, and accommodate any variation in the operating cycle of the producing plant. The reservoir injection system must have the capacity to inject the arriving gas at variable rates. Successful operation requires a sophisticated control system and as yet undemonstrated engineering integration.

In sum, the demonstration of an integrated coal conversion, CO_2 capture, and sequestration capability is an enormous system engineering and integration challenge. Difficult technical design and economic issues must be solved, a functioning regulatory framework needs to be established, and a sensible and politically acceptable federal assistance package must be worked out. All of this needs to be done while maintaining sufficient fidelity to commercial practice, so that both the government and the private sector can gain credible information on which to base future public and private investment decisions.

Successful execution of the demonstration program we recommend requires successful timing of five elements:

- Providing a supply of about one million tonnes/y CO_2 for the 3 to 5 sequestration projects.
- Utilizing the CO_2 produced by the coal conversion projects.
- Providing pipeline transport facilities between the coal conversion projects and the sequestration sites.[6]
- Injection and sequestration
- Detailed reservoir characterization and monitoring

This is an enormous and complex task and it is not helpful to assume that it can be done quickly or on a fixed schedule, if for no other reasons than the need for required regulatory, financing, and siting actions. In addition, a selection needs to be made about the coal conversion technologies for the CO_2 capture demonstrations. (IGCC, SCPC, Oxy-fuel combustion, coal to synfuels). It may be that timing considerations lead to a sequence that is less than optimal — for example, a supply of CO_2 for an early sequestration project may come from a relatively expensive capture option, such as chemical amine capture of CO_2 from the flue gas of an air-driven SCPC or from a non-utility source.

An effective mechanism is needed to assure efficient and prompt execution of the recommended demonstration program. As discussed in Chapter 6, the DOE has limited capability to carry out such a task: its staff has little experience with commercial practice, it is hampered by federal procurement regulations, and it is constrained by an annual budget cycle. A quicker and more effective way to achieve the objective of demonstrating a credible option for CO_2 capture and sequestration is for the president to recommend to Congress a structure, authorities, and functions for a quasi-public CCS corporation.

> *Recommendation #9:* The demonstration sequestration projects *(Recommendation #2)* and the demonstration carbon capture projects *(Recommendation #8)* must be designed and operated in a manner that demonstrate successful technical performance and cost, with acceptable environmental effects.

While a rigorous CO_2 sequestration demonstration program is a vital underpinning to extended CCS deployment that we consider a necessary part of a comprehensive carbon emission control policy, we emphasize there is no reason to delay prompt consideration and adoption of a U.S. carbon emission control policy until completion of the sequestration program we recommend.

We further recommend consideration of the creation of a quasi-public corporation for the purpose of managing this demonstration and integration effort. This special purpose corporation – *The Clean Coal Demonstration Corporation* – would be given multi-year authorization and appropriation to accomplish the limited demonstration program outlined above. A rough estimate for the cost of the entire program is about $5 billion for a ten-year period. The cost of this proposed demonstration program could be met by direct federal appropriation or by a small charge, less than ½ mill per kWe-h, on coal fired electricity plants.

The first one or two demonstration CO_2 sequestration projects (*Recommendation #7* above) will require a great deal of technical work to define design and operating characteristics as well as needed reservoir sensors and monitoring. Accordingly, the DOE will need to have a large role in these initial projects compared to the proposed *Clean Coal Demonstration Corporation*. The best way to realize progress for the initial sequestration projects may be to authorize the DOE to perform them directly, although close coordination with the *Clean Coal Demonstration Corporation* would be required. Alternatively, the *Clean Coal Demonstration Corporation* could contract with the DOE for the required technical assistance for the early sequestration projects.

ANALYSIS, RESEARCH, DEVELOPMENT, AND DEMONSTRATION (ARD&D) NEEDS

Chapter 6 discusses the analysis, R&D, and demonstration needs for the future of coal.

We present a framework for the types of work that are needed and explore whether the federal government or the private sector should be expected to sponsor such work.

In general, the role of the federal government is to fund long-term technical activities not tied to a particular commercial application where the social benefits of the results of the funding support cannot be appropriated, or only partially so, by private investors (e.g., through patents and trade secrets), or where the social benefits are so valuable that it is in the public interest to disseminate the results of the R&D widely and inexpensively. Many of the uncertainties about CCS that can be resolved by the R&D activities that we propose have one or both of these characteristics. The private sector should be expected to sponsor work that is in its foreseeable economic interest and adds to the attractiveness of the technologies and products they know.

Our focus is on support from the federal government, mainly through the DOE whose program was examined in Chapter 6.

> *Finding # 7:* The DOE Clean Coal ARD&D program is not on a path to address our priority recommendations because the

level of funding falls far short of what will be required in a world with significant carbon charges. The program is especially deficient in demonstrating the feasibility of CO_2 sequestration, as discussed in Chapter 4 and mentioned in *Finding #2*. The flagship DOE project, FutureGen, is consistent with our priority recommendation to initiate integrated demonstration projects at scale. However, we have some concerns about this particular project, specifically the need to clarify better the objectives (research vs. demonstration), the inclusion of international partners that may further muddle the objectives, and whether political realities will allow the FutureGen consortium the freedom to operate this project successfully. Finally, the DOE program should support a broader range of technology efforts at the process development unit (PDU) scale designed to explore new approaches that have technical and economic advantage.

The demonstration projects we recommend are discussed above. The Analysis and R&D efforts recommended for support as discussed in Chapter 6 are summarized in Table 8.1, along with an estimate of the required annual level of effort.

Recommendation #10 There is an urgent need to develop modeling and simulation capability and tools based on validated engineering and cost data for the purpose of analysis and comparison of coal-based generation, with and without carbon capture and sequestration. Such a capability will multiply the benefits of the many 'front end engineering studies' (FEED) underway both here and abroad, permitting comparison of the consequences of the assumptions of the various studies and enabling trade-off analysis between them. This will be great value both for the government and for private firms in planning their development and investment decisions, both for new plants and for retrofits.

These seven findings and ten recommendations provide the basis for our central message: The demonstration of technical, economic, and institutional features of carbon capture and sequestration, at commercial scale coal combustion and conversion plants, will: (1) give policymakers and the public greater confidence that a practical carbon emission control option exists, (2) shorten the deployment time and reduce the cost for carbon capture and sequestration should a carbon emission control policy be adopted, and (3) maintain opportunities for the lowest cost and most widely available energy form to be used to meet the world's pressing energy needs in an environmentally acceptable manner.

Table 8.1 Analysis, Research, And Development Needs*

RECOMMENDATION	ACTIVITY TYPE: ANALYSIS	ACTIVITY TYPE: R&D	ACTIVITY TYPE: PDU DEMO	ACTIVITY TYPE: COMMER DEMO**	RESPONSIBILITY***: U.S. GOV.***	RESPONSIBILITY***: INDUSTRY	ACTIVITY DESCRIPTION: NEXT 5 YEARS	ACTIVITY DESCRIPTION: 5+ YEARS AND BEYOND
	ANALYSIS AND SIMULATION							
1	X				P ($50)	S	Develop modeling and simulation capability and tools based on validated engineering and cost data for the purpose of analysis and comparison of coal-based generation technologies, with and without carbon capture and sequestration	Apply and refine said tools
	PC TECHNOLOGY							
2	X	X	X		P ($40)		Develop more cost effective and energy efficient CO_2 capture technology	Evaluate most promising systems at PDU scale to define parameter space & develop models
3		X	X		S ($10)	P	For USC above 675 C, develop the next level of new materials and fabrication technology	Demonstrate adequate creep rates and field performance at PDU scale
4			X	X	S ($20)	P	Develop and demonstrate improved technology to capture and fix mercuy	
	OXY-FUEL							
5		X		X	P ($5)		Define purity requirements of CO_2 stream for processing and pipelining, and for geologic sequestration as a function of the geology	Verify performance in the sequestration demonstrations
6	X	X	X		P ($10)	S	Develop and demonstrate novel, cheaper oxygen separation technologies	
7	X			X	P ($15)	S	Support analysis and design studies, and process development for oxy-fuel PC with CO_2 capture	Oxy-fuel demonstration project as a retrofit and as a CO_2 source
	IGCC							
8	X				S ($20)	P	System/technology trade-off studies (See #1) for optimization of capture, retrofit, & capture-ready designs (for various coal types)	
9		X			P ($60)	P	Component development: Improved refractory, better coal introduction technology, and improved instrumentation for gasifer measurement and control	
10		X	X	X	P ($15)	P	Develop turbines to burn high concentrations of hydrogen	Test and improve emissions performance
11	X			X	P($15)	P	IGCC commercial demonstration with CO_2 capture, and as a CO_2 source	Continue IGCC Demo with CCS, $ for R&D Support of Demo
	ADVANCED CONCEPTS							
12	X	X	X		P ($50)	S	Chemical Looping, flue and syngas cleaning & separations, in-situ gasification, supercritical water and CO_2 coal combustion, and other novel concepts	PDU studies of technologies showing unique potential
13	X	X			P ($10)		Hybrid IGCC + Fuel Cell power generation systems	
	POLYGENERATION: FUELS & CHEMICALS****							
14	X				P ($15)	S	Poly-generation in combination with #1 design and engineering studies of chemical + electricity production	
15	X	X	X		P ($25)	S	Coal to liquids, Coal to gas in combination with #1design and engineering studies, including CCS	
	SEQUESTRATION							
16	X				P ($40)		Detailed, bottom-up geological assessment of storage capacity and injectivity	
17	X				P ($20)		Risk analysis of potential geologic storage regions	
18	X	X			P ($40)		Design and develop sensors and monitoring system for CO_2 storage site, carry out site surveys, determine engineering protocols for injection &MMV R&D during demos	Proceed with 3–4 large-scale sequestration demo projects of order 1 million tonnes CO_2/y, $ are R&D in support of them

** This study focused on power generation from coal and did not include coal preparation, mining, transportation, or other industrial uses; ocean or biomass sequestration in the Gtonne scale, or novel approaches to criteria pollutant control from power generation facilities.*

***Key commercial-scale demonstrations indicated but $ indicated are only for supporting R&D*

**** P = primary responsibility; S = secondary responsibility; dollar amount in parenthesis is estimated needed annual R&D expenditure in millions by DOE*

***** Downstream technology for syngas conversion is not part of this report*

CITATIONS AND NOTES

1. Even if IGCC were more economical for meeting criteria pollutant and mercury emission constraints, this would not be a reason for federal support.
2. Conference report of the Energy Policy Act PL108-58 Sec48A(c)(5) CARBON CAPTURE CAPABILITY.—The term 'carbon capture capability' means a gasification plant design which is determined by the Secretary to reflect reasonable consideration for, and be capable of, accommodating the equipment likely to be necessary to capture carbon dioxide from the gaseous stream, for later use or sequestration, which would otherwise be emitted in the flue gas from a project which uses a nonrenewable fuel.
3. The table below gives the size and location of operating IGCC power plants.

Operating IGCC power plants
Fuel is either coal or coke/asphalt

SIZE MW_e	LOCATION	PRIMARY FEED
298	Puertollano, Spain	coal
253	Buggenum, Netherlands	coal/some biomass
250	Tampa Electric, Florida	coal/coke
262	Wabash River, Indiana	coal/coke
551	Sarlux, Italy	refinery resid/tars
552	Priolo, Italy	refinery asphalt
342	Negishi, Japan	refinery resid/tars
250	Sannazzaro, Italy	refinery resid/tars
180	Delaware City, Delaware	coke

4. For example, an efficient 500 MW_e IGCC power plant would produce about 3 million tons/y CO_2 and the differential cost might be about \$30/ton CO_2.
5. If a carbon charge is imposed, the price paid by the government would be adjusted downward accordingly.
6. This will be less of a problem if the coal conversion plants are located near or at the sequestration sites.