The Future of Coal

AN INTERDISCIPLINARY MIT STUDY

SUMMARY REPORT

The Future of Coal

OPTIONS FOR A CARBON-CONSTRAINED WORLD

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Members did not approve or endorse the report and individual members of the advisory committee have different views on one or more of matters addressed in this report

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Foreword

In 2002, a group of MIT Faculty decided to undertake a series of interdisciplinary studies about how the United States and the world would meet future energy demand without increasing emissions of carbon dioxide (CO_2) or other greenhouse gases. The first study "The Future of Nuclear Power" appeared in 2003. In 2004 a similar group of MIT faculty undertook the present study, "The Future of Coal." The purpose of the study is to examine the role of coal in a world where constraints on carbon emissions are adopted to mitigate global warming. The study's particular emphasis is to compare the performance and cost of different coal combustion technologies when combined with an integrated system for CO_2 capture and sequestration.

Our audience is government, industry and academic leaders and decision makers interested in the management of the interrelated set of technical, economic, environmental, and political issues that must be addressed in seeking to limit and to reduce greenhouse gas emissions to mitigate the effects of climate change. Coal is likely to remain an important source of energy in any conceivable future energy scenario. Accordingly, our study focuses on identifying the priority actions needed to reduce the CO_2 emissions that coal use produces. We trust that our integrated analysis will stimulate constructive dialogue both in the United States and throughout the world.

This study reflects our conviction that the MIT community is well equipped to carry out interdisciplinary studies of this nature to shed light on complex socio-technical issues that will have major impact on our economy and society.

Acknowledgments

This study is better as a result of comments and suggestions of members of the advisory committee, and we are especially grateful for their participation. It should be understood, however, that the study is the responsibility of the MIT participants; the advisory committee was not asked to approve or endorse the study and indeed individual advisory committee members may have differing views on many subjects that were addressed.

Our study benefited greatly from the participation of a number of graduate student research assistants, notably,

Mark Bohm,

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In addition, during the course of the Coal Study two successive classes of MIT undergraduate seniors participated in the Chemical Engineering Senior Design Subject, 10.491. Each year, approximately 60 students were assigned in teams of 4 to analyze and design solutions to component parts of the CO_2 capture system. The final reports from the teams and the efforts of the course's teaching assistants led to important contributions to this study:

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Executive Summary

This MIT study examines the role of coal as an energy source in a world where constraints on carbon emissions are adopted to mitigate global warming. Our first premise is that the risks of global warming are real and that the United States and other governments should and will take action to restrict the emission of CO_2 and other greenhouse gases. Our second and equally important premise is that coal will continue to play a large and indispensable role in a greenhouse gas constrained world. Indeed, the challenge for governments and industry is to find a path that mitigates carbon emissions yet continues to utilize coal to meet urgent energy needs, especially in developing economies. The scale of the enterprise is vast. (See Box 1).

Our purpose is to identify the measures that should be taken to assure the availability of demonstrated technologies that would facilitate the achievement of carbon emission reduction goals, while continuing to rely on coal to meet a significant fraction of the world's energy needs. Our study has not analyzed alternative carbon emission control policies and accordingly the study does not make recommendations on what carbon mitigation measure should be adopted today. Nevertheless, our hope is that the study will contribute to prompt adoption of a comprehensive U.S. policy on carbon emissions.

We believe that coal use will increase under any foreseeable scenario because it is cheap and abundant. Coal can provide usable energy at a cost of between $1 and $2 per MMBtu compared to $6 to $12 per MMBtu for oil and natural gas. Moreover, coal resources are distributed in regions of the world other than the Persian Gulf, the unstable region that contains the larg-

BOX 1 ILLUSTRATING THE CHALLENGE OF SCALE FOR CARBON CAPTURE

- Today fossil sources account for 80% of energy demand: Coal (25%), natural gas (21%), petroleum (34%), nuclear (6.5%), hydro (2.2%), and biomass and waste (11%). Only 0.4% of global energy demand is met by geothermal, solar and wind.[1]
- 50% of the electricity generated in the U.S. is from coal.[2]
- There are the equivalent of more than five hundred, 500 megawatt, coal-fired power plants in the United States with an average age of 35 years.[2]
- China is currently constructing the equivalent of two, 500 megawatt, coal-fired power plants per week and a capacity comparable to the entire UK power grid each year.[3]
- One 500 megawatt coal-fired power plant produces approximately 3 million tons/year of carbon dioxide (CO_2).[3]
- The United States produces about 1.5 billion tons per year of CO_2 from coal-burning power plants.
- If all of this CO_2 is transported for sequestration, the quantity is equivalent to three times the weight and, under typical operating conditions, one-third of the annual volume of natural gas transported by the U.S. gas pipeline system.
- If 60% of the CO_2 produced from U.S. coal-based power generation were to be captured and compressed to a liquid for geologic sequestration, its volume would about equal the total U.S. oil consumption of 20 million barrels per day.
- At present the largest sequestration project is injecting one million tons/year of carbon dioxide (CO_2) from the Sleipner gas field into a saline aquifer under the North Sea.[3]

Notes

1. IEA Key World Energy Statistics (2006)
2. EIA 2005 annual statistics (www.eia.doe.gov)
3. Derived from the MIT Coal Study

est reserves of oil and gas. In particular the United States, China and India have immense coal reserves. For them, as well as for importers of coal in Europe and East Asia, economics and security of supply are significant incentives for the continuing use of coal. Carbon-free technologies, chiefly nuclear and renewable energy for electricity, will also play an important role in a carbon-constrained world, but absent a technological breakthrough that we do not foresee, coal, in significant quantities, will remain indispensable.

However, coal also can have significant adverse environmental impacts in its production and use. Over the past two decades major progress has been made in reducing the emissions of so-called "criteria" air pollutants: sulfur oxides, nitrogen oxides, and particulates from coal combustion plants, and regulations have recently been put into place to reduce mercury emissions. Our focus in this study is on approaches for controlling CO_2 emissions. These emissions are relatively large per Btu of heat energy produced by coal because of its high carbon content.

We conclude that CO_2 capture and sequestration (CCS) is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs.

To explore this prospect, our study employs the *Emissions Predictions and Policy Analysis* (EPPA) model, developed at MIT, to prepare scenarios of global coal use and CO_2 emissions under various assumptions about the level and timing of the carbon charge[1] that might be imposed on CO_2 emissions and the cost of removing CO_2 from coal. The response of the global economy to placing a price on CO_2 emissions is manifold: less energy is used, there is switching to lower carbon fuels, the efficiency of new and existing power plants is improved, and new carbon control technologies are introduced, for example CCS. In characterizing the CO_2 emission price, we employ a "high" price trajectory that starts at \$25/tonne-CO_2 in 2015 and increases thereafter at a real rate of 4% per year. The \$25 per tonne price is significant because it approaches the level that makes CCS technology economic.

1. This carbon charge may take the form of a direct tax, a price imposed by a cap-and-trade mechanism, or some other type of regulatory constraint on CO_2 emissions. We shall refer to this charge as a tax, price, penalty, or constraint interchangeably throughout this report and the use of one form or another should not be taken as an indication of a preference for that form unless so stated.

We also examine a "low" price trajectory that begins with a CO_2 emission price of \$7/tonne in 2010 and increases at a rate of 5% thereafter. The key characteristic of the "low" price is that it reaches the initial "high" price level nearly 25 years later. Other assumptions studied include the development of nuclear power to 2050 (limited or expanded) and the profile of natural gas prices (as calculated by the model or at a lower level).

Our conclusion is that coal will continue to be used to meet the world's energy needs in significant quantities. The high CO_2-price scenario leads to a substantial reduction in coal use in 2050 relative to "business as usual" (BAU), but still with increased coal use relative to 2000 in most cases. In such a carbon-constrained world, CCS is the critical future technology option for reducing CO_2 emissions while keeping coal use above today's level. Table 1 shows the case with higher CO_2 prices and applying the EPPA model's reference projection for natural gas prices. The availability of CCS makes a significant difference in the utilization of coal at mid-century regardless of the level of the CO_2 prices (not shown in the table) or the assumption about nuclear power growth. With CCS more coal is used in 2050 than today, while global CO_2 emissions from all sources of energy are only slightly higher than today's level and less than half of the BAU level. A major contributor to the global emissions reduction for 2050 is the reduction in CO_2 emissions from coal to half or less of today's level and to one-sixth or less that in the BAU projection.

Table 1 Exajoules of Coal Use (EJ) and Global CO_2 Emissions (Gt/yr) in 2000 and 2050 with and without Carbon Capture and Storage*

	BUSINESS AS USUAL		LIMITED NUCLEAR 2050		EXPANDED NUCLEAR 2050	
	2000	2050	WITH CCS	WITHOUT CCS	WITH CCS	WITHOUT CCS
Coal Use: Global	100	448	161	116	121	78
U.S.	24	58	40	28	25	13
China	27	88	39	24	31	17
Global CO_2 Emissions	24	62	28	32	26	29
CO_2 Emissions from Coal	9	32	5	9	3	6

** Universal, simultaneous participation, High CO_2 prices and EPPA-Ref gas prices.*

The "low" CO_2 price scenario reaches the level where CCS becomes economic some 25 years later than under the higher price case. As a result coal consumption is higher in 2050 relative to the high CO_2 price scenario and, in addition, the contribution of CCS is much lower, thus leading to substantially higher CO_2 emissions.

Today, and independent of whatever carbon constraints may be chosen, **the priority objective with respect to coal should be the successful large-scale demonstration of the technical, economic, and environmental performance of the technologies that make up all of the major components of a large-scale integrated CCS system — capture, transportation and storage.** Such demonstrations are a prerequisite for broad deployment at gigatonne scale in response to the adoption of a future carbon mitigation policy, as well as for easing the trade-off between restraining emissions from fossil resource use and meeting the world's future energy needs

Successful implementation of CCS will inevitably add cost for coal combustion and conversion. We estimate that for new plant construction, a CO_2 emission price of approximately \$30/tonne (about \$110/tonne C) would make CCS cost competitive with coal combustion and conversion systems without CCS. This would be sufficient to offset the cost of CO_2 capture and pressurization (about \$25/tonne) and CO_2 transportation and storage (about \$5/tonne). This estimate of CCS cost is uncertain; it might be larger and with new technology, perhaps smaller.

The pace of deployment of coal-fired power plants with CCS depends both on the timing and level of CO_2 emission prices and on the technical readiness and successful commercial demonstration of CCS technologies. The timing and the level of CO_2 emission prices is uncertain. However, there should be no delay in undertaking a program that would establish the option to utilize CCS at large scale in response to a carbon emission control policy that would make CCS technology economic. Sequestration rates of one to two gigatonnes of carbon (nearly four to eight gigatonnes of CO_2) per year by mid-century will enable appreciably enhanced coal use and significantly reduced CO_2 emissions.

What is needed is to demonstrate an integrated system of capture, transportation, and storage of CO_2, at scale. This is a practical goal but requires concerted action to carry out. The integrated demonstration must include a properly instrumented storage site that operates under a regulatory framework which includes site selection, injection and surveillance, and conditions for eventual transfer of liability to the government after a period of good practice is demonstrated.

An explicit and rigorous regulatory process that has public and political support is prerequisite for implementation of carbon sequestration on a large scale. This regulatory process must resolve issues associated with the definition of property rights, liability, site licensing and monitoring, ownership, compensation arrangements and other institutional and legal considerations. Regulatory **protocols need to be defined for sequestration projects including site selection, injection operation, and eventual transfer of custody to public authorities after a period of successful operation.** In addition to constraints of CO_2 emissions, the pacing issues for the adoption of CCS technology in a greenhouse gas constrained world are resolution of the scientific, engineering, and regulatory issues involved in large-scale sequestration in relevant geologies. These issues should be addressed with far more urgency than is evidenced today.

At present government and private sector programs to implement on a timely basis the required large-scale integrated demonstrations to confirm the suitability of carbon sequestration are completely inadequate. If this deficiency is not remedied, the United States and other governments may find that they are prevented from implementing certain carbon control policies because the necessary work to regulate responsibly carbon sequestration has not been done. **Thus, we believe high priority should be given to a program that will demonstrate CO_2 sequestration at a scale of 1 million tonnes CO_2 per year in several geologies.**

We have confidence that large-scale CO_2 injection projects can be operated safely, however no CO_2 storage project that is currently operating (Sleipner, Norway; Weyburn, Canada; In Salah, Algeria) has the necessary modeling, monitoring, and verification (MMV) capability to resolve outstanding technical issues, at scale. Each reservoir for large- scale sequestration will have unique characteristics that demand site-specific study, and a range of geologies should be investigated. We estimate that the number of at-scale CCS projects needed is about 3 in the U.S. and about 10 worldwide to cover the range of likely accessible geologies for large scale storage. Data from each project should be thoroughly analyzed and shared. The cost per project (not including acquisition of CO_2) is about $15 million/year for a ten-year period.

CO_2 injection projects for enhanced oil recovery (EOR) have limited significance for long-term, large-scale CO_2 sequestration — regulations differ, the capacity of EOR projects is inadequate for large-scale deployment, the geological formation has been disrupted by production, and EOR projects are usually not well instrumented. The scale of CCS required to make a major difference in global greenhouse gas concentrations is massive. For example, sequestering one gigatonne of carbon per year (nearly four gigatonnes of carbon dioxide) requires injection of about fifty million barrels per day of supercritical CO_2 from about 600 1000MW_e of coal plants.

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 adoption of U.S. carbon emission control policy until the sequestration demonstration program is completed.

A second high-priority requirement is to demonstrate CO_2 capture for several alternative coal combustion and conversion technologies. At present Integrated Gasification Combined Cycle (IGCC) is the leading candidate for electricity production with CO_2 capture because it is estimated to have lower cost than pulverized coal with capture; however, neither IGCC nor other coal technologies have been demonstrated with CCS. **It is critical that the government RD&D program not fall into the trap of picking a technology "winner,"** especially at a time when there is great coal combustion and conversion development activity underway in the private sector in both the United States and abroad.

Approaches with capture other than IGCC could prove as attractive with further technology development for example, oxygen fired pulverized coal combustion, especially with lower quality coals. Of course, there will be improvements in IGCC as well. R&D is needed on sub-systems, for example on improved CO_2 separation techniques for both oxygen and air driven product gases and for oxygen separation from air. The technology program would benefit from an extensive modeling and simulation effort in order to compare alternative technologies and integrated systems as well as to guide development. Novel separation schemes such as chemical looping should continue to be pursued at the process development unit (PDU) scale. The reality is that the diversity of coal type, e.g. heat, sulfur, water, and ash content, imply different operating conditions for any application and multiple technologies will likely be deployed.

Government support will be needed for these demonstration projects as well as for the supporting R&D program. Government assistance is needed and should be provided to demonstrate the technical performance and cost of coal technologies with CCS, including notably IGCC. There is no operational experience with carbon capture from coal plants and certainly not with an integrated sequestration operation. Given the technical uncertainty and the current absence of a carbon charge, there is no economic incentive for private firms to undertake such projects. Energy companies have advanced a number of major projects and all have made clear the need for government assistance in order to proceed with unproved "carbon-free" technology.

The U.S 2005 Energy Act contains provisions that authorize federal government assistance for IGCC or pulverized coal plants containing advanced technology projects with or without CCS. We believe that this assistance should be directed only to plants with CCS, both new plants and retrofit applications on existing plants. Many electric utilities and power plant developers who are proposing new coal-fired electricity generating units are choosing super-critical pulverized coal units because in the absence of charges on CO_2 emissions, the bus bar cost of generating electricity (COE) from pulverized coal (PC) power plants is lower than IGCC and its availability is higher. These prospective new plants, as well as the existing stock of coal-fired power plants, raise the issue of the future retrofit of coal-fired power plants that are in existence at the time when a carbon charge is imposed. This problem is distinct from that of the technology to be chosen for the new power plants that will be built after a carbon charge has been imposed. Pending adoption of policies to limit CO_2 emissions, if federal assistance is extended to coal projects, it should be limited to projects that employ CCS.

It has been argued that the prospect of a future carbon charge should create a preference for the technology that has the lowest cost of retrofit for CO_2 capture and storage, or that power plants built now should be "capture-ready," which is often interpreted to mean that new coal-fired power plants should be IGCC only.

From the standpoint of a power plant developer, the choice of a coal-fired technology for a new power plant today involves a delicate balancing of considerations. On the one hand, factors such as the potential tightening of air quality standards for SO_2, NO_x, and mercury, a future carbon charge, or the possible introduction of federal or state financial assistance for IGCC would seem to favor the choice of IGCC. On the other hand, factors such as near-term opportunity for higher efficiency, capability to use lower cost coals, the ability to cycle the power plant more readily in response to grid conditions, and confidence in reaching capacity factor/efficiency performance goals would seem to favor the choice of super critical pulverized coal[2] (SCPC). Other than recommending that new coal units should be built with the highest efficiency that is economically justifiable, we do not believe that a clear preference for either technology can be justified.

2. Pulverized coal plants can be subcritical (SubCPC), supercritical (SCPC) or ultra-supercritical (USCPC). For simplicity, we refer to the latter two as SCPC except when, as in Chapter 3, a specific comparison is made. There is no clear dividing line between SCPC and USCPC.

Moreover, retrofitting an existing coal-fired plant originally designed to operate without carbon capture will require major technical modification, regardless of whether the technology is SCPC or IGCC. The retrofit will go well beyond the addition of an "in-line" process unit to capture the CO_2; all process conditions will be changed which, in turn, implies the need for changes to turbines, heat rate, gas clean-up systems, and other process units for efficient operation. Based on today's engineering estimates, the cost of retrofitting an IGCC plant, originally designed to operate without CCS so as to capture a significant fraction of emitted carbon, appears to be cheaper than the retrofit cost of a SCPC plant. However, this characteristic of IGCC has not been demonstrated." Also, even if the retrofit cost of an IGCC plant is cheaper, the difference in the net present value of an IGCC and SCPC plant built now and retrofitted later in response to a future carbon charge depends heavily on the estimate of the timing and size of a carbon charge, as well as the difference in retrofit cost. Essentially, there is a trade-off between cheaper electricity prior to the carbon charge and higher cost later.

Opportunity to build "capture ready" features into new coal plants, regardless of technology, are limited. Other than simple modification to plant layout to leave space for retrofit equipment such as shift reactors, **pre-investment in "capture ready" features for IGCC or pulverized coal combustion plants designed to operate initially without CCS is unlikely to be economically attractive.** It would be cheaper to build a lower capital cost plant without capture and later either to pay the price placed on carbon emissions or make the incremental investment in retrofitting for carbon capture when justified by a carbon price. However, there is little engineering analysis or data to explore the range of pre-investment options that might be considered.

There is the possibility of a perverse incentive for increased early investment in coal-fired power plants without capture, whether SCPC or IGCC, in the expectation that the emissions from these plants would potentially be "grandfathered" by the grant of free CO_2 allowances as part of future carbon emissions regulations and that (in unregulated markets) they would also benefit from the increase in electricity prices that will accompany a carbon control regime. Congress should act to close this "grandfathering" loophole before it becomes a problem.

The DOE Clean Coal program is not on a path to address our priority recommendations because the level of funding falls far short of what is required and the program content is not aligned with our strategic objectives. 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 project 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 in a manner that will inform private sector investment decisions.

Responsibility for the integrated CCS demonstration projects, including acquisition of the CO_2 needed for the sequestration demonstration, should be assigned to a new quasi-government Carbon Sequestration Demonstration Corporation. The corporation should select the demonstration projects and should provide financial assistance that will permit industry to manage the projects in as commercial a manner as possible.

Success at capping CO_2 emissions ultimately depends upon adherence to CO_2 mitigation policies by large developed and developing economies. We see little progress to moving toward the needed international arrangements. Although the European Union has implemented a cap-and-trade program covering approximately half of its CO_2 emissions, the United States has not yet adopted mandatory policies at the federal level to limit CO_2 emissions. U.S. leadership in emissions reduction is a likely pre-requisite to substantial action by emerging economies.

A more aggressive U.S. policy appears to be in line with public attitudes. Americans now rank global warming as the number one environmental problem facing the country, and seventy percent of the American public think that the U.S. government needs to do more to reduce greenhouse gas emissions. Willingness to pay to solve this problem has grown 50 percent over the past three years.

Examination of current energy developments in China and India, however, indicate that it will be some time before carbon constraints will be adopted and implemented by China. The same is likely true for India.

An international system with modestly delayed compliance by emerging economies is manageable from the point of view of incremental accumulated CO_2 emissions. However, if other nations, and especially China and India, are to deal with this problem then CCS is a crucial technology for these countries as well, and the R&D and commercial demonstration focus proposed here is no less important in readying CCS for quick adoption if and when they begin to take more stringent control measures.

The central message of our study is that 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 a practical carbon mitigation 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.

Chapter 1 – Purpose of the Study

The risk of adverse climate change from global warming forced in part by growing greenhouse gas emissions is serious. While projections vary, there is now wide acceptance among the scientific community that global warming is occurring, that the human contribution is important, and that the effects may impose significant costs on the world economy. As a result, governments are likely to adopt carbon mitigation policies that will restrict CO_2 emissions; many developed countries have taken the first steps in this direction. For such carbon control policies to work efficiently, national economies will need to have many options available for reducing greenhouse gas emissions. As our earlier study — *The Future of Nuclear Power* — concluded, the solution lies not in a single technology but in more effective use of existing fuels and technologies, as well as wider adoption of alternative energy sources. This study —*The Future of Coal* — addresses one option, the continuing use of coal with reduced CO_2 emissions.

Coal is an especially crucial fuel in this uncertain world of future constraint on CO_2 emissions. Because coal is abundant and relatively cheap — \$1–2 per million Btu, compared to \$ 6–12 per million Btu for natural gas and oil — today, coal is often the fuel of choice for electricity generation and perhaps for extensive synthetic liquids production in the future in many parts of the world. Its low cost and wide availability make it especially attractive in major developing economies for meeting their pressing energy needs. On the other hand, coal faces significant environmental challenges in mining, air pollution (including both criteria pollutants and mercury), and importantly from the perspective of this study, emission of carbon dioxide (CO_2). Indeed coal is the largest contributor to global CO_2 emissions from energy use (41%), and its share is projected to increase.

This study examines the factors that will affect the use of coal in a world where significant constraints are placed on emissions of CO_2 and other greenhouse gases. We explore how the use of coal might adjust within the overall context of changes in the demand for and supply of different fuels that occur when energy markets respond to policies that impose a significant constraint on CO_2 emissions. Our purpose is to describe the technology options that are currently and potentially available for coal use in the generation of electricity if carbon constraints are adopted. In particular, we focus on **carbon capture and sequestration** (CCS) — the separation of the CO_2 combustion product that is produced in conjunction with the generation of electricity from coal and the transportation of the separated CO_2 to a site where the CO_2 is sequestered from the atmosphere. Carbon capture and sequestration add significant complexity and cost to coal conversion processes and, if deployed at large scale, will require considerable modification to current patterns of coal use.

We also describe the research, development, and demonstration (RD&D) that should be underway today, if these technology options are to be available for rapid deployment in the future, should the United States and other countries adopt carbon constraint policies. Our recommendations are restricted to what needs to be done to establish these technology options to create viable choices for future coal use.

Our study does not address climate policy, nor does it evaluate or advocate any particular set of carbon mitigation policies. Many qualified groups have offered proposals and analysis about what policy measures might be adopted. We choose to focus on what is needed to create technology options with predictable performance and cost characteristics, if such policies are adopted. If technology preparation is not done today, policy-makers in the future will be faced with fewer and more difficult choices in responding to climate change.

We are also realistic about the process of adoption of technologies around the world. This is a global problem, and the ability to embrace a new technology pathway will be driven by the industrial structure and politics in the developed and developing worlds. In this regard, we offer assessments of technology adoption in China and India and of public recognition and concern about this problem in the United States.

The overarching goal of this series of MIT energy studies is to identify different combinations of policy measures and technical innovations that will reduce global emissions of CO_2 and other greenhouse gases by mid-century. The present study on *The future of coal* and the previous study on *The future of nuclear power* discuss two of the most important possibilities.

An outline of this study follows:

Chapter 2 presents a framework for examining the range of global coal use in all energy-using sectors out to 2050 under alternative economic assumptions. These projections are based on the MIT Emissions Predictions and Policy Analysis (EPPA) model. The results sharpen understanding of how a system of global markets for energy, intermediate inputs, and final goods and services would respond to imposition of a carbon charge (which could take the form of a carbon emissions tax, a cap and trade program, or other constraints that place a de facto price on carbon emissions) through reduced energy use, improvements in energy efficiency, switching to lower CO_2-emitting fuels or carbon-free energy sources, and the introduction of CCS.

Chapter 3 is devoted to examining the technical and likely economic performance of alternative technologies for generating electricity with coal with and without carbon capture and sequestration in both new plant and retrofit applications. We analyze air and oxygen driven pulverized coal, fluidized bed, and IGCC technologies for electricity production. Our estimates for the technical and environmental performance and for likely production cost are based on today's experience.

Chapter 4 presents a comprehensive review of what is needed to establish CO_2 sequestration as a reliable option. Particular emphasis is placed on the need for geological surveys, which will map the location and capacity of possible deep saline aquifers for CO_2 injection in the United States and around the world, and for demonstrations at scale, which will help establish the regulatory framework for selecting sites, for measurement, monitoring and verification systems, and for long-term stewardship of the sequestered CO_2. These regulatory aspects will be important factors in gaining public acceptance for geological CO_2 storage.

Chapter 5 reports on the outlook for coal production and utilization in China and India. Most of our effort was devoted to China. China's coal output is double that of the United States, and its use of coal is rapidly growing, especially in the electric power sector. Our analysis of the Chinese power sector examines the roles of central, provincial, and local actors in investment and operational decisions affecting the use of coal and its environmental impacts. It points to a set of practical constraints on the ability of the central government to implement restrictions on CO_2 emissions in the relatively near-term.

Chapter 6 evaluates the current DOE RD&D program as it relates to the key issues discussed in Chapters 2, 3, and 4. It also makes recommendations with respect to the content and organization of federally funded RD&D that would provide greater assurance that CC&S would be available when needed.

Chapter 7 reports the results of polling that we have conducted over the years concerning public attitudes towards energy, global warming and carbon taxes. There is evidence that public attitudes are shifting and that support for policies that would constrain CO_2 emissions is increasing.

Chapter 8 summarizes the findings and presents the conclusions of our study and offers recommendations for making coal use with significantly reduced CO_2 emissions a realistic option in a carbon constrained world.

The reader will find technical primers and additional background information in the appendices to the report.

Massachusetts
Institute of
Technology

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