More than 50% of electricity in the U.S. is generated by coal. The U.S. has large coal resources, the cheapest fuel in most areas. Coal fired power plants are likely to continue to provide much of U.S. electricity. However, the type of power plant that should be built is unclear. Technology can reduce pollutant discharges and capture and sequester the CO₂ from coal-fired generation. The U.S. Energy Policy Act of 2005 provides incentives for large scale commercial deployment of Integrated Coal Gasification Combined Cycle (IGCC) systems (e.g., loan guarantees and project tax credits). This analysis examines whether a new coal plant should be Pulverized Coal (PC) or IGCC. Do stricter emissions standards (PM, SO₂, NOₓ, Hg) justify the higher costs of IGCC over PC? How does potential future carbon legislation affect the decision to add carbon capture and storage (CCS) technology? Finally, can the impact of uncertain carbon legislation be minimized? We find that SO₂, NOₓ, PM, and Hg emission standards would have to be far more stringent than twice current standards to justify the increased costs of the IGCC system. A CO₂ tax less than $29/ton would lead companies to continue to choose PC, paying the tax for emitted CO₂. The earlier a decision-maker believes the carbon tax will be imposed and the higher the tax, the more likely companies will choose IGCC w/CCS. Having government announce the date and level of a carbon tax would promote more sensible decisions, but government would have to use a tax or subsidy to induce companies to choose the technology that is best for society.

Introduction

This paper has three goals: 1. To show how an engineering-economic analysis should be done for a utility that needs new capacity now and is choosing among coal technologies. 2. To provide insight for a decision maker thinking about a new capacity now and is choosing among coal technologies. 3. To provide insight to the U.S. Department of Energy, other regulators, and society about the differences between the choices that a private company would make and those that society would prefer. We examine policy instruments that would lead a private party to choose the optimal public decision. The rising demand for electricity in the United States together with the high price of electricity from natural gas generation plants leads to a demand for additional baseload generation capacity. Faced with the need for more baseload generation, American Electric Power proposes to build an IGCC plant, in part to resolve technology uncertainties before baseload capacity is needed in the future (1). Texas Utilities recently proposed 11 new PC plants with full environmental controls and provisions to retrofit them for carbon capture. Due to increased public pressure, they have recently modified their proposal to 3 plants; 2 of which will be IGCC and they will issue a request for proposals for capture technologies to be installed during plant construction (2).

While some new capacity will come from renewable resources, such as wind and photovoltaic, much of it will be powered by coal or nuclear. In many regions of the U.S., a coal-fired generation plant will produce the cheapest reliable, dispatchable electricity.

Coal-fired power plants have a history of generating massive amounts of air pollution and carbon dioxide. Someone planning a new coal-fired plant today faces uncertainty concerning how restrictive emissions standards will be on conventional pollutants, heavy metals, and greenhouse gases. Available technologies could handle all of these problems, but they are more expensive than a simple pulverized coal plant. In the extreme, a planner must decide between building a low cost plant that might be obsolete in a decade or a super-clean plant whose generation costs are so high that the plant could not compete in the current market.

We examine the current choices and uncertainties that a planner faces. The analysis clarifies, subject to the expectations of the planner, what is the best choice for a new plant.

Method

While comparing the costs and performance of operating plants is most desirable, advanced plants with the technology required to overcome future problems have not been built. Thus, we base our analysis on the IECM v. 5.02 (Integrated Environmental Control Model), a publicly available model developed at Carnegie Mellon University to enable the U.S. Department of Energy and others to compare the performance, emissions, and cost of various electricity generation technologies, assuming a range of plant characteristics, fuel types, and emissions constraints (3). Although this is a model, it has been fitted to the best recent costs of actual plants and of detailed engineering estimates of new plants.

We model plants with similar power output (approximately 450–480 MW-net) and burn the same coal (Illinois #6 with 3.25% sulfur and a heating value of 10 900 BTU per pound; we also consider Pittsburgh #8 coal). We assume the following: 1. a capacity factor of 75%; 2. Illinois #6 coal costs $33/ton; 3. private companies use an interest rate of 10%; 4. plants last 30 years; and 5. society makes decisions using an interest rate of 3%, reflecting the social rate of return on new investment. Several parameters are varied in a sensitivity analysis. The costs are in 2002 dollars, corrected for inflation. All weights are in short tons.

Literature Review

Previous studies compare PC and IGCC systems (4, 5) and the capital costs can differ by 1–20% (1–3, 6). Efficiencies of 30–40% (HHV) are generally assumed for both technologies, depending on technology type, coal type, environmental controls, and operating conditions. Carbon capture technology has substantial energy and cost penalties. The cost penalty is higher for the PC system (61–84%) than the IGCC system (20–55%) (2). IGCC or PC plants could be made “sequestera-
The best control technologies remove 98%, 90%, and more into a boiler, and generating steam, which turns a turbine. Technology, grinding the coal into tiny particles, blowing it commercially.

FutureGen Initiative (and continue to be developed in projects such as the U.S. plants in operation, newer technologies have been developed of IGCC generation plants. Although there are several IGCC Energy Policy Act of 2005 provides incentives for construction new investment. Recognizing the need for new generation investment, the IGCC plant becomes the slightly more efficient and lower cost option, as shown in Table 2. The attractiveness of building an IGCC plant is limited by uncertainty concerning the performance and reliability of the technology, since it is new (see ref 7).

Control measures decrease efficiency, requiring more coal and resulting in more SO2 emissions. We estimate the levelized cost of electricity (COE) from each plant as the sum of capital costs, operations, and maintenance and the cost of the pollution emissions over its assumed operating life.

The PC system is a supercritical plant with higher efficiency than a subcritical plant (used in most analysis) with little cost increase. The IGCC system uses a GE (formerly Texaco) gasifier; the system minimizes cost at the expense of efficiency. Other configurations of the GE gasifier (or other gasification technologies) could be more efficient but less competitive economically. A higher quality coal, Pittsburgh no. 8, is relatively more helpful for the IGCC plant (e.g., the IGCC baseline run increases from 34% efficiency using Illinois coal no. 6 to 37% using Pittsburgh coal no. 8). Lower ranked coals have a relatively greater penalty for the IGCC plant (13).

Results: 1. Can Increased Stringency of Pollution Regulations Justify the Use of IGCC?

We create a pollution emissions index with a value of 100 for current standards, measured by the current prices for emissions allowances, the estimated social benefit of reducing particulate matter emissions, and the EPA estimate of the social benefit of reducing mercury emissions. When the index number is 50 or 200, the amounts charged for emissions are

### TABLE 1. Environmental Controls for PC and IGCC Systems

<table>
<thead>
<tr>
<th>plant type</th>
<th>CO2 capture system</th>
<th>SO2</th>
<th>NOx</th>
<th>PM</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>efficiency</td>
<td>supercritical</td>
<td>amine</td>
<td>FGD</td>
<td>90%</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td>GE gasifier</td>
<td>shift + Selexol</td>
<td>Selexol</td>
<td>90%</td>
<td>98%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>efficiency</td>
<td>SCR</td>
<td>50%</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>raw gas cleanup</td>
<td>100%</td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>injected carbon</td>
<td>93%</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 2. Output of IECM Based on Input Specifications for Each Case

<table>
<thead>
<tr>
<th>Private cost ($/kWh)</th>
<th>Emissions (lb/kWh)</th>
<th>Electricity produced (billion kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SO2</td>
<td>NOx</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.059</td>
</tr>
<tr>
<td></td>
<td>0.0612</td>
<td>0.0011</td>
</tr>
<tr>
<td></td>
<td>0.00000080</td>
<td>0.00014</td>
</tr>
<tr>
<td></td>
<td>0.0012</td>
<td>0.00019</td>
</tr>
<tr>
<td></td>
<td>0.0013</td>
<td>0.00011</td>
</tr>
<tr>
<td></td>
<td>0.0015</td>
<td>0.00014</td>
</tr>
</tbody>
</table>

The IGCC technology partially burns coal, creating a stream of CO, H2, and CO2 (about 300 BTU/cubic foot). Impurities such as sulfur are removed before the gas is combusted to produce electricity in a combined cycle system. The IECM software does not currently provide an option to add NOx or mercury controls to the IGCC system. For the IGCC system to meet the same NOx emissions standards as the PC system (i.e., 95% removal), an SCR unit operating at 50% removal efficiency was added to the system (outside the model). The mercury control was assumed to attain the same level of removal as the PC system using activated carbon in the IGCC system (at similar cost to the PC system).

Both technologies offer effective pollution control and removal of 90% of the CO2. When this technology is included, the IGCC plant becomes the slightly more efficient and lower cost option, as shown in Table 2. The attractiveness of building an IGCC plant is limited by uncertainty concerning the performance and reliability of the technology, since it is new (see ref 7).

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The Technology Options for Coal

Recognizing the need for new generation investment, the Energy Policy Act of 2005 provides incentives for construction of IGCC generation plants. Although there are several IGCC plants in operation, newer technologies have been developed (and continue to be developed in projects such as the U.S. FutureGen Initiative (12)) but not demonstrated commercially.

Almost all current coal plants use a pulverized coal (PC) technology, grinding the coal into tiny particles, blowing it into a boiler, and generating steam, which turns a turbine. The best control technologies remove 98%, 90%, and more than 99% of the SO2, NOx, and particles, respectively. These plants could be fitted with an amine scrubber to remove 90% of the CO2 from the flue gas, but the capital cost increases and the net efficiency declines, since 30% more coal is required to maintain output; see Table 1.

The IGCC technology partially burns coal, creating a stream of CO, H2, and CO2 (about 300 BTU/cubic foot). Impurities such as sulfur are removed before the gas is combusted to produce electricity in a combined cycle system. The IECM software does not currently provide an option to add NOx or mercury controls to the IGCC system. For the IGCC system to meet the same NOx emissions standards as the PC system (i.e., 95% removal), an SCR unit operating at 50% removal efficiency was added to the system (outside the model). The mercury control was assumed to attain the same level of removal as the PC system using activated carbon in the IGCC system (at similar cost to the PC system).

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Results: 1. Can Increased Stringency of Pollution Regulations Justify the Use of IGCC?

We create a pollution emissions index with a value of 100 for current standards, measured by the current prices for emissions allowances, the estimated social benefit of reducing particulate matter emissions, and the EPA estimate of the social benefit of reducing mercury emissions. When the index number is 50 or 200, the amounts charged for emissions are
halved or doubled, respectively. As shown in Figure 1, the cost of electricity is not changed appreciably for the "controlled" plants as the pollution index goes from 0 to 200, since the plants are so tightly controlled that emissions are small. In contrast, the costs of an uncontrolled pulverized coal plant rise rapidly as the pollution index is increased. At a pollution index above 20 (the "crossover" point), stringent emissions control technologies should be added. The figure also shows that the costs of the PC and IGCC systems are similar. The costs of the two systems converge slightly, since the PC has slightly higher PM emissions. For a Pollution Index greater than 50, the IGCC plant with full controls is cheaper than the baseline IGCC plant. Within the limits of the IECM model, emissions standards do not favor IGCC over PC. Hereafter, we assume that current emissions constraints apply (an Index of 100). See the Supporting Information for further details.

Results 2: What Carbon Tax Justifies the IGCC?

Few people agree on the date and stringency of carbon regulation in the U.S. We represent stringency as a penalty for emitting a ton of CO2, ranging from 0 to $100 per ton of CO2 (equivalent to $367 per ton of carbon). Figure 2 shows the cost of electricity for both technologies with and without CCS (assumed to remove 90% of CO2).

If a company were committed to build an IGCC plant, a tax greater than $20/ton ($22/tonne) of CO2 favors the IGCC system with CCS. If they were committed to a PC system, the carbon price would have to be $46 per ton (the crossover point) or more to justify adding CCS. If they are simply looking for the cheapest generation, they would choose a PC without CCS for a CO2 tax less than $29/ton and an IGCC system with CCS for a higher tax. At the current price of $10—$15 per ton (currently discussed by companies and regulators in the U.S. as well as roughly the price of CO2 being trading currently in the E.U.), companies generating electricity from coal would simply pay the tax. Unless the tax were at least $29 per ton, companies would continue to use PC plants.

The timing of a carbon tax is important, as in Figure 3 for IGCC. The vertical axis is the present discounted cost of electricity capacity; the lower the cost, the better. The horizontal axis is the number of years between when the plant is built and when the carbon tax is imposed (we assume the tax continues after that). In this analysis, there is no option to add a carbon capture technology after the plant is built. Figure 3 shows that delaying the tax until year 30, when the plant is shut, is equivalent to not imposing the tax: To the basic IGCC plant, we impose a CO2 tax of 0, $29, $50, or $100 per ton. If a tax of $29 is applied in year 0, the cheapest plant is IGCC with CCS. Figure 4 shows the same trend, using the cost of electricity (using a weighted average of discount rates) instead of the total discounted plant cost. For tax levels of $29, $50, and $100, the plant’s owner would have to expect that tax would be applied before year 6, 10, or 16, respectively, to warrant building the plant with CCS. If the tax is imposed later, the owner would build the plant without CCS and pay the tax when it is imposed. Discounting at 10% per year makes later tax imposition less costly; for example, the present discounted cost of a $100/ton tax in the 29th year to $1.70/ton in year 0. (Note that the crossover points would be slightly...
later if the IGCC plant with CCS were charged the same tax as the plant without CCS, but the differences are small.)

A carbon tax of $50/ton or $100/ton raises the cost of electricity from an IGCC without CCS from $3.8/MW-net to $7.4 or $11/kW-net, respectively (if the tax is imposed in year 0).

**Results 3: What Can Be Done To Minimize the Impact of Uncertain Carbon Legislation?**

Preinvestment can lower the cost of building a power plant today that would have to be retrofitted with CCS. The idea of a “Capture Ready” plant can mean many things: (1) identification of sequestration site, 2. allocate space for equipment at various levels, 3. install and run shift reactors (partially or fully), 4. size for IGCC w/CCS, 5. capture CO2 but do not sequester, or 6. some combination of these activities.

The following analysis considers 4 technology options: 1. an IGCC system without CCS, 2. an IGCC system designed and built with CCS, 3. a system that is built to run as an IGCC plant optimized without carbon capture (as same as option 1) and is then retrofitted to have CCS when a carbon tax is implemented, and 4. a system built to run as an IGCC plant without carbon capture but preinvestment has been made in order to prepare adding the CCS equipment when the carbon tax is implemented.

The last option is designed to minimize the costs associated with the transition when the carbon tax is imposed as well as maintaining the same electricity output, despite the CCS energy penalty. The preinvestment includes allocating space for the future CCS equipment. The composition of the syngas changes when CO2 is removed which means that the flow rate and heat content of the syngas entering the gas turbine also changes. In order to compensate for these changes, a larger gasifier is added when the carbon tax is imposed in the fourth option. The original gasifier could either be sold or used as an additional train. This larger gasifier will process more coal, producing more syngas. The size is determined by matching the BTU content of the syngas and the volumetric flow rate.

Table 3. Summary of Costs, Emissions, and Electricity Produced for Each of the Options Considered*  

<table>
<thead>
<tr>
<th></th>
<th>CO2 emissions (lb/kWh)</th>
<th>cost ($/kWh)</th>
<th>electricity produced (kWh/yr)</th>
<th>CO2 emissions (lb/kWh)</th>
<th>cost ($/kWh)</th>
<th>electricity produced (kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC controlled</td>
<td>1.8</td>
<td>0.051</td>
<td>3.0E+09</td>
<td>1.8</td>
<td>0.051</td>
<td>3.0E+09</td>
</tr>
<tr>
<td>PC w/CCS</td>
<td>0.25</td>
<td>0.087</td>
<td>2.3E+09</td>
<td>0.25</td>
<td>0.087</td>
<td>2.3E+09</td>
</tr>
<tr>
<td>PC w/CCS retrofit</td>
<td>1.8</td>
<td>0.051</td>
<td>3.0E+09</td>
<td>0.25</td>
<td>0.105</td>
<td>2.3E+09</td>
</tr>
<tr>
<td>PC w/CCS retrofit w/preinvestment</td>
<td>1.8</td>
<td>0.052</td>
<td>3.0E+09</td>
<td>0.25</td>
<td>0.089</td>
<td>2.3E+09</td>
</tr>
<tr>
<td>IGCC</td>
<td>2.1</td>
<td>0.055</td>
<td>3.5E+09</td>
<td>2.10</td>
<td>0.055</td>
<td>3.5E+09</td>
</tr>
<tr>
<td>IGCC w/CCS</td>
<td>0.25</td>
<td>0.074</td>
<td>3.2E+09</td>
<td>0.25</td>
<td>0.074</td>
<td>3.2E+09</td>
</tr>
<tr>
<td>IGCC w/CCS retrofit</td>
<td>2.1</td>
<td>0.055</td>
<td>3.5E+09</td>
<td>0.25</td>
<td>0.089</td>
<td>2.9E+09</td>
</tr>
<tr>
<td>IGCC w/CCS retrofit w/ preinvestment</td>
<td>2.1</td>
<td>0.059</td>
<td>3.5E+09</td>
<td>0.25</td>
<td>0.078</td>
<td>3.5E+09</td>
</tr>
</tbody>
</table>

* With and without a carbon tax of $100/ton of CO2.

The Social Choice

No nation is likely to go from a carbon tax of 0 to one of $50 or $100 per ton, although EU prices will likely rise over time. We chose the tax levels for exploration, rather than to represent our best forecast. Until the tax crossed the $29 point, the cheapest generation would be PC with no CCS. Only after that point is there pressure to build CCS or go to an IGCC plant with CCS.

We focus on the best actions that plant owners can take, given the uncertainty. Figure 5 shows the optimal action for a private company facing a cost of capital of 10% per year. Figure 6 shows the optimal action for society, based on a capital cost of only 3% per year. Not surprisingly, the difference in discount rates leads to different decisions; we examine the social cost of these differences.

If a CO2 tax of $100/ton were imposed in year 0 or year 1, the optimal technology would be the same using either the private or public cost of capital, as shown in Table 4. Thus, no policy intervention would be needed. If the tax was imposed in years 2–10, the company would select a PC with retrofit and preinvestment, while the public would prefer an IGCC with retrofit and preinvestment. Because the company selected the “wrong” technology, society would have to pay $0.011/kWh-net more. Similarly, in years 11–15, the company would select a PC with retrofit and preinvestment, while the public would prefer an IGCC with retrofit and preinvestment, costing society $0.0085/kWh. In years 16–25, the company would prefer a PC with retrofit, while society would add preinvestment. The social loss would be $0.010/kWh. If the tax were not imposed until after year 25, both the company and society would select the same technology.

Thus, if society knew today that we were going to impose a $100/ton tax in year 10, we should either offer to subsidize an IGCC with retrofit and preinvestment or impose a tax on a PC with retrofit and preinvestment (as well as technologies other than the preferred one).
Uncertainty

The estimates made in this analysis are uncertain. The IECM software was used to conduct sensitivity analyses for the PC and IGCC plants. The variables considered for the PC plant were coal type (a range of bituminous coals), coal price ($27–$50/ton), and capacity factor (70–80%). Atmospheric pressures from 12 to 15 psia were also considered, since they affect efficiency. However, the range in pressures changed plant costs less than 1%. The variables considered for the IGCC plant were coal type (Illinois #6 or Pittsburgh #8), coal price ($27–$50/ton), atmospheric pressure (12–15 psia), capacity factor (65–85%), gasifier temperature (2350–2550 F), and whether additional trains are included (0, 1, or 2). As expected, reasonable differences in the assumptions and IECM costs and performance lead to a broad range of crossover points. Before spending billions of dollars on a new PC or IGCC plant, we recommend that the decision makers using this analysis explore their best judgments about the costs and performance of the available technologies. Please see the Supporting Information for further details.

Discussion

The analysis assumes the accuracy of the technologies as modeled in IECM. The costs of actual plants are likely to differ. The precise results shown are subject to uncertainty. To help an investment decision, the parameters for that plant and its fuel are needed, together with expectations about future carbon regulation. The following insights are drawn from this analysis: 1. Tighter SO2, NOx, PM, and Hg emission standards would not favor a controlled IGCC system over a PC system. 2. If a carbon tax were imposed before a coal burning electricity generation plant were built, the tax would have to be at least $29/ton of CO2 before the company would...
decide to add CCS and would choose an IGCC plant. For a lower tax, they would build a PC plant and pay the tax. With no current tax on carbon, a decision-maker would have to expect a sharp increase in the tax over the lifetime of a new plant before he/she would invest in a carbon capture plant.

3. If a company is committed to building an IGCC plant, despite its higher cost, and a CO$_2$ tax greater than $20/ton was imposed before the plant was built, CCS should be added.

4. More generally, a CO$_2$ tax less than $29/ton would not change the choice of technology: PC without CCS would produce the lowest cost electricity.

5. The earlier a decision-maker believes the carbon tax will be imposed and the higher the tax, the more likely he/she will build IGCC w/CCS. High discount rates make building an IGCC w/CCS less likely.

6. The option to retrofit becomes more important with higher carbon tax and lower retrofit penalty. A low retrofit penalty leads to delaying the installation of CCS until the CO$_2$ tax is imposed, while a high retrofit penalty motivates initial CCS installation.

7. Current assessment of “capture ready pre-investment” makes only a small difference in this analysis, but further options for pre-investment should be investigated.

8. If companies make their decisions using a 10% discount rate and society bases its decisions on a 3% discount rate, there will be significant conflicts between public and private decisions. Having government announce the date and level of a carbon tax would promote more sensible decisions, but government would have to use a tax or subsidy to close the gap between decisions made on a 3% versus 10% discount rate.

9. Current uncertainty concerning the costs and reliability of IGCC and the carbon capture technologies as well as the date and stringency of carbon emissions constraints make investors reluctant to build any new coal technology today. Both power producers and society would gain from resolving uncertainties on the timing and level of a carbon tax and by clarifying the cost and reliability of alternative technologies.

**Acknowledgments**

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**Supporting Information Available**

Additional text, tables, and figures. This material is available free of charge via the Internet at http://pubs.acs.org.

**Literature Cited**


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