MIT Joint Program on the Science and Policy of Global Change

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Ram C. Sekar, John E. Parsons, Howard J. Herzog and Henry D. Jacoby

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Future Carbon Regulations and *Current* Investments in Alternative Coal-Fired Power Plant Designs

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Abstract

This paper assesses the role of uncertainty over future U.S. carbon regulations in shaping the current choice of which type of power plant to build. The pulverized coal technology (PC) still offer the lowest cost power— assuming there is no need to control emissions of carbon. The integrated coal gasification combined cycle technology (IGCC) may be cheaper if carbon must be captured. Since a plant built now will be operated for many years, and since carbon regulations may be instituted in the future, a U.S. electric utility must make the current investment decision in light of the uncertain future regulatory rules. This paper shows how this decision is to be made. We start by describing the economics of the two key coal-fired power plant technologies, PC and IGCC. We then analyze the potential costs of future carbon regulations, including the costs of retrofitting the plant with carbon capture technology and the potential cost of paying charges for emissions. We present the economics of each design in the form of a cash flow spreadsheet yielding the present value cost, and show the results for different scenarios of emissions regulation. We then discuss how to incorporate uncertainty about the future regulation of carbon emissions into the decision to build one plant design or the other. As an aid to decision making, we provide some useful benchmarks for possible future regulation and show how these benchmarks relate back to the relative costs of the two technologies and the optimal choice for the power plant investment. Few of the scenarios widely referenced in the public discussion warrant the choice of the IGCC technology. Instead, the PC technology remains the least costly. The level of future regulation required to justify a current investment in the IGCC technology appears to be very aggressive, if not out of the question. However, the current price placed on carbon emissions in the European Trading System, is higher than these benchmarks. If it is any guide to possible future penalties for emissions in the U.S., then current investment in the IGCC technology is warranted.

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1. Introduction

Electric power plants last a lifetime. The plants built today—and over the next ten years—will be a substantial element of the fleet for a long time to come. And yet electric utilities responsible for investing in new plants face an enormous uncertainty about which technology is most economical. Updated versions of the traditional pulverized coal technology (PC) still offer the lowest cost power—assuming there is no need to control emissions of carbon. But should control be mandated sometime in the future, retrofitting these plants to capture the carbon is extremely expensive and the economic equation is substantially altered. Newer technologies—notably integrated coal gasification combined cycle (IGCC)—offer the prospect of more affordable

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capture of the carbon. But the higher upfront investment cost can only be justified as a means to avoid sizeable penalties for carbon emissions.

Currently the U.S. government does not mandate control of carbon emissions, so a naïve economic calculation favors investment in PC plants. But the government has the power to change the regulations in the future, either because the scientific evidence implicating carbon emissions in dangerous levels of global warming becomes stronger or because the political winds change and power shifts to those who feel the existing evidence is compelling enough. An electric utility that makes its investment decision solely on the basis of today's regulations may find—if regulations change—that it has saddled itself with plants that must either be retrofitted at high cost or that entail high charges for uncontrolled emissions. Of course, if carbon emissions in the U.S. remain unregulated, today's investment in a PC plant will be vindicated.

A wise investment decision today must be made with eyes wide open about the full range of future conditions within which the plants might have to operate. How is this decision to be made? What factors must be incorporated? Does the specter of future regulation of carbon argue for construction of IGCC plants? Or is that specter too remote and too uncertain, so that current investment should be in PC plants?

This paper is designed to answer these questions. We start by describing the economics of the two key coal-fired power plant technologies, PC and IGCC. We then analyze the potential costs of future carbon regulations, including the costs of retrofitting the plant with carbon capture technology and the potential cost of paying charges for emissions. We present the economics of each design in the form of a cash flow spreadsheet yielding the present value cost, and show the results for different scenarios of emissions regulation. We then discuss how to incorporate uncertainty about the future regulation of carbon emissions into the decision to build one plant design or the other. As an aid to decision making, we provide some useful benchmarks for possible future regulation and show how these benchmarks relate back to the relative costs of the two technologies and the optimal choice for the power plant investment.

2. Cost and Performance of Alternative Power Plant Technologies—PC and IGCC With And Without Carbon Capture

In order to make a consistent comparison between the two technologies, we compare total capital, fuel, operating and carbon capture costs for a hypothetical power plant with 500 MW capacity operating at a factor of 80%. For the PC plant we chose the sub-critical air-fired technology. This is the most ubiquitous technology in the power plant fleet today. For CO_2 capture at the PC plant we assume flue gas scrubbing using the MEA process. For CO_2 capture at the IGCC plant we assume scrubbing of shifted syngas using the Selexol process which results in H_2 being combusted in the gas turbine. We keep the total capacity constant both before and after retrofit for carbon capture. Since retrofitting a given plant results in a decrease in electric output, our comparison requires investment in additional capacity to keep the total capacity at 500 MW and the costs of this additional capacity are factored into our estimates.[1]

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[1] We use this single plant size purely for narrative convenience. Where sources describe a different optimal plant size for a given technology, we have incorporated the unit costs—capital and operating—at this optimal plant size, and simply adjusted it proportionally to yield a comparable 500 MW plant. Where retrofitting a given plant requires installation of incremental capacity to bring the total back up to 500 MW, it would not be optimal to

Table 1 shows our assumptions about the key technical and economic parameters for both of the two technologies with and without carbon capture. We derived these assumptions based upon a broad review of the literature, and, in particular, on the results reported in EPRI (2000) and the National Coal Council (2004).[2] Arguably the numbers in Table 1 present an optimistic representation of the IGCC technology.

Without carbon capture, the two technologies differ primarily in up front capital costs: for the PC technology the cost is $726 million, while for the IGCC technology it is $759 million. The net heat rates for the two technologies are very close to one another—8,690 Btu/KWh$_e$ for the PC technology and 8,630 Btu/KWh$_e$ for the IGCC technology. Consequently the fuel inputs required in a year and the annual fuel costs for the two technologies are also very close—30.4 million MMBtus and $45.7 million for the PC technology and 30.2 million MMBtus and $45.4 million for the IGCC technology. The annual fuel cost is calculated assuming a coal price of $1.50/MMBtu. The annual operating and maintenance (O&M) costs for the PC technology are

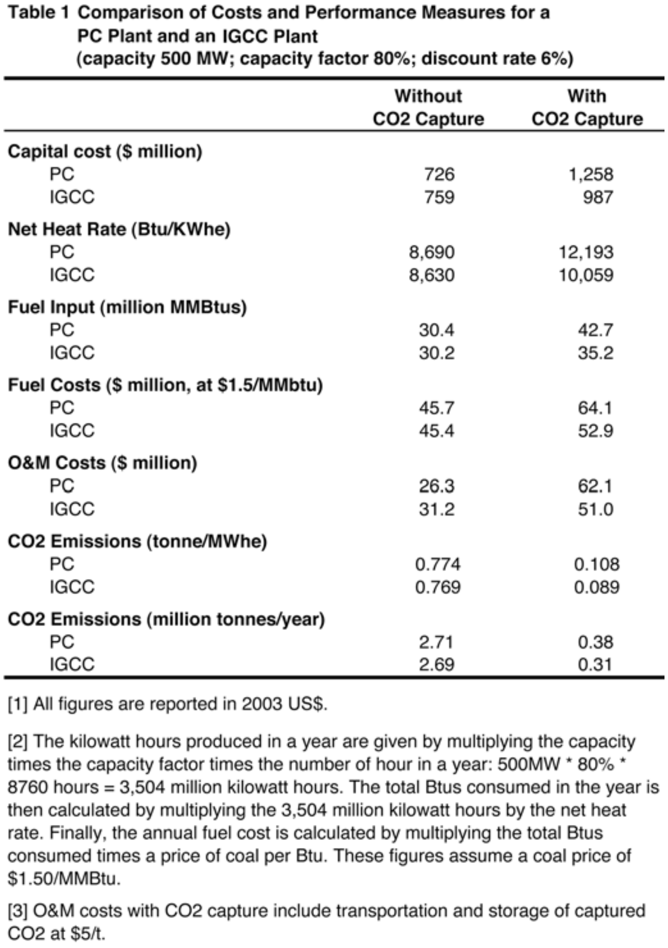

Table 1 Comparison of Costs and Performance Measures for a PC Plant and an IGCC Plant (capacity 500 MW; capacity factor 80%; discount rate 6%)

	Without CO2 Capture	With CO2 Capture
Capital cost ($ million)		
PC	726	1,258
IGCC	759	987
Net Heat Rate (Btu/KWhe)		
PC	8,690	12,193
IGCC	8,630	10,059
Fuel Input (million MMBtus)		
PC	30.4	42.7
IGCC	30.2	35.2
Fuel Costs ($ million, at $1.5/MMbtu)		
PC	45.7	64.1
IGCC	45.4	52.9
O&M Costs ($ million)		
PC	26.3	62.1
IGCC	31.2	51.0
CO2 Emissions (tonne/MWhe)		
PC	0.774	0.108
IGCC	0.769	0.089
CO2 Emissions (million tonnes/year)		
PC	2.71	0.38
IGCC	2.69	0.31

[1] All figures are reported in 2003 US$.

[2] The kilowatt hours produced in a year are given by multiplying the capacity times the capacity factor times the number of hour in a year: 500MW * 80% * 8760 hours = 3,504 million kilowatt hours. The total Btus consumed in the year is then calculated by multiplying the 3,504 million kilowatt hours by the net heat rate. Finally, the annual fuel cost is calculated by multiplying the total Btus consumed times a price of coal per Btu. These figures assume a coal price of $1.50/MMBtu.

[3] O&M costs with CO2 capture include transportation and storage of captured CO2 at $5/t.

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actually expand capacity of the given retrofitted plant. The cheaper solution would be to makeup the lost capacity through installation of new optimally sized plants. In doing our calculation of the cost of makeup capacity, we assume this new construction of optimally sized units and simply allocate a portion of that cost to the production of the constant 500 MW capacity for this plant.

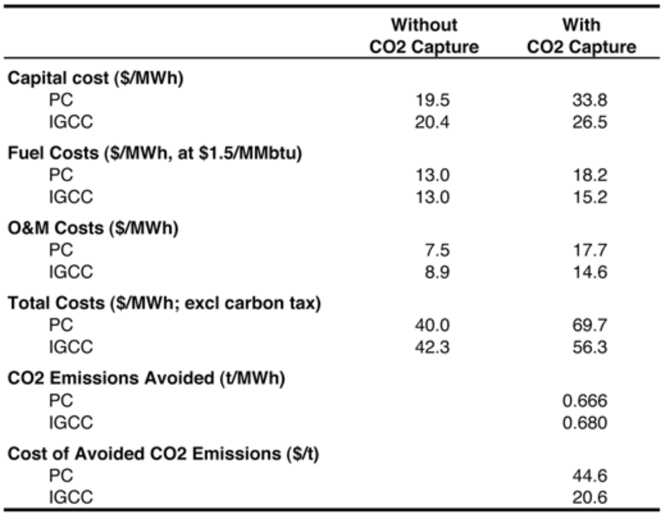
[2] Other sources include EPRI (2003), Rubin, Rao & Chen (2004), NETL-DOE (2002), Nsakala *et al*. (2003), Gottlicher (2004) and McPherson (2004).

less than for the IGCC technology—\$26.3 million *vs*. \$31.2 million, respectively. Finally, CO_2 emissions for the PC plant are 0.774 ton/MWh_e or 2.71 million ton/year *vs*. 0.769 t/MWh_e or 2.69 million t/yr for the IGCC plant.

With carbon capture the PC technology has both higher capital costs and lower relative performance than the IGCC technology. The total up front capital cost for the PC technology is \$1,258 million, while for the IGCC technology with carbon capture it is \$987 million. With carbon capture, the net heat rate for the PC is 12,193 Btu/KWh_e while the net heat rate for the IGCC is now 10,059 Btu/Kwh_e. Therefore, the annual fuel cost for the PC is \$64.1 million while the annual fuel cost for the IGCC is \$52.9 million. With carbon capture, the annual O&M costs for the PC are \$62.1 million *vs.* \$51.0 million for the retrofitted IGCC. These figures include a \$5/t cost of transport and storage of the captured CO_2, *i.e*., annual CO_2 transport and storage costs of \$17.15 million and \$14.15 million for PC and IGCC respectively. The residual CO_2 emissions of the PC plant are 0.38 million t/yr *vs*. 0.31 million t/yr for the IGCC plant.

Another way to represent the costs of the different technologies is on a dollar per megawatt hour basis—*i.e*., as levelized costs. We show these in **Table 2**. All costs are calculated assuming constant output at 80% capacity over the 40 year life of the plant. These levelized costs are calculated in real terms, *i.e*., without making any assumption about inflation. We use a real, risk-adjusted discount rate of 6%.[3] Costs are shown after-tax, using a 40% tax rate and with the value

Table 2 Comparison of Levelized Costs for a PC Plant and an IGCC Plant (capacity 500 MW; capacity factor 80%; discount rate 6%)



	Without CO2 Capture	With CO2 Capture
Capital cost (\$/MWh)		
PC	19.5	33.8
IGCC	20.4	26.5
Fuel Costs (\$/MWh, at \$1.5/MMbtu)		
PC	13.0	18.2
IGCC	13.0	15.2
O&M Costs (\$/MWh)		
PC	7.5	17.7
IGCC	8.9	14.6
Total Costs (\$/MWh; excl carbon tax)		
PC	40.0	69.7
IGCC	42.3	56.3
CO2 Emissions Avoided (t/MWh)		
PC		0.666
IGCC		0.680
Cost of Avoided CO2 Emissions (\$/t)		
PC		44.6
IGCC		20.6

[1] All cost figures derived from Table 1 based on 40 years of operation and a 6% real discount rate.

[2] Capital costs recognize the value of depreciation tax shields. These are calculated assuming a 30% depreciation rate and an expected inflation rate of 2.5%. See notes to tables 2-5 for more details.

[3] Capital costs include the annual expense for insurance and property taxes which equals 1.78% of the initial capital investment.

[4] Emissions avoided derived from Table 1.

[5] Cost of avoided CO2 emissions equals CO2 emissions avoided divided by the difference between the Total Cost with and without carbon capture.

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[3] As a point of reference, a rate of 6% would be implied by a real risk-free rate of 2%, a risk premium of 6% and an asset beta of 0.66. Assuming an inflation rate of 2.5% this is comparable to a nominal risk-adjusted discount rate of 8.5%.

of depreciation tax shields being allocated to the capital costs. We assume a constant depreciation rate of 30% times the undepreciated capital account balance.[4] Capital costs also include the annual expense for insurance and property taxes, which equals 1.78% of the initial capital investment. Without carbon capture, the PC technology produces power at a cost of \$40.0/MWh while the IGCC technology produces power at a cost of \$42.3/MWh—5.7% more than the cost of the PC. Carbon capture increases these costs to \$69.7/MWh for the PC and \$56.3/MWh for the IGCC technology, so that the IGCC now costs 19% less. The cost of avoided emissions is \$44.6/t CO_2 for the PC technology and \$20.6/t CO_2 for the IGCC technology.

If there is a discrepancy between the costs shown in Table 2 and the costs produced by others and circulating in the literature, that discrepancy is likely to arise in the levelized capital cost figure. This may arise due to either differences in ancillary cash flows associated with the capital costs—*e.g.*, various owner's costs such as insurance and property taxes—or differences in the discount rate, or differences in the term over which the costs are capitalized. We believe our assumptions on the first two factors conform more or less to the assumptions others are making. For example, the numbers in Table 2 are roughly consistent with those generated in the recently published EPRI (2005) study on Financial Incentives for Deployment of IGCC—see their Table II. The nominal discount rate they use is 7.35% given a 2% inflation rate—see their Table XV—which is roughly comparable to our 6% real discount rate. In some cases, however, other reports have used a shorter capitalization period of twenty to thirty years, where we use a forty year capitalization period—see for example EPRI (2000) and the National Coal Council (2004). So although we use these two studies to develop the data for Table 1, the resulting levelized cost shown in Table 2 differs from what they report.

It is interesting to compare the cost differentials between the PC and the IGCC technology displayed in Tables 1 and 2 to the size of the tax incentives recently created as a part of the Energy Policy Act that was signed into law in August 2005. One feature of the legislation is a potential tax credit for up to 20% of qualified investments in coal gasification projects. There is no requirement that a qualifying IGCC plant include carbon capture. In our example of an IGCC plant without carbon capture, if 20% of the total capital costs qualified for the tax credit, then after netting out the foregone depreciation tax shields, this would lower the present value capital investment cost of the technology by 13.8%. Since this cost is in turn nearly 50% of the total levelized cost of electricity, this credit would lower the total levelized cost by between 6 to 7%. This is just slightly more than the 5.7% total cost differential between the PC and the IGCC technologies without carbon capture. Based on the cost figures used here, then, the tax incentives in the Energy Policy Act push electric utilities just to the brink of choosing the IGCC design whenever this would qualify—other factors being excluded.

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[4] For costs such as fuel and O&M, using real cash flows allows us to avoid making any assumption about inflation. However, depreciation is an inherently nominal account, and the expected rate of inflation affects the expected real value of depreciation tax shields. We assume an expected inflation rate of 2.5%. We then calculate the expected nominal value of the capital investment in a given year. This fixes the expected nominal value of the depreciation in all future years. We then adjust the nominal depreciation schedule back to real terms by deflating the values.

3. Capitalizing the Costs of Future Carbon Regulations

The levelized cost figures shown in Table 2 assume that carbon capture begins from the first moment of operation of the plant. The problem we want to examine is one in which the firm begins operation of the plant without carbon capture, since that is not currently required in the U.S., but subsequent regulations penalize carbon emissions and incentivize carbon capture. We focus on the case in which the power plant is built in the year 2010 and begins operations in 2011, and new regulations penalize emissions from the fifth year of operation onward, *i.e*. from 2015. The company therefore has to choose in year 2014 or later whether or not to retrofit its plant for carbon capture in order to avoid the penalty for carbon emissions. Although there are many different types of regulatory schemes the government could employ, we limit our attention to a simple charge or tax per unit of carbon emitted. This allows us to parameterize increasingly strict regulations in the simplest manner possible.

We analyze this case in a few simple steps. First, we construct four cash flow tables displaying the total annual cost of each technology, PC and IGCC, with and without carbon capture. The costs shown are exclusive of any carbon emissions charges, which we account for separately below. Second, we evaluate the present value cost of cumulative carbon emissions charges over the life of the plant at various rates per ton of CO_2 emitted. Finally, we evaluate the decision whether and when to retrofit the plant, and calculate the total present value cost under the optimal retrofit policy.

Tables 3 and **4** show the annual cash flows and net present value (NPV) of costs for the PC and for the IGCC plants, respectively, without carbon capture. We assume that the up front capital investment shown in Table 1 is made in a single lump sum at the start of the project, which we set in the year 2010. The total present value cost of the PC plant is $1,267.3 million. The total present value cost of the IGCC plant is $1,336.8 million. This is $69.6 million or about 5.5% more expensive. This calculation takes no account of the cost for possible future carbon emission regulations or taxes.

Tables 5 and **6** show the annual cash flows and NPV of costs for the two technologies assuming that the plants are retrofitted for carbon capture after 4 years of operation—*i.e*., at year end 2014 and the start of 2015. We assume that the cost of retrofitting the plant is equal to the difference between the cost of a plant with and without carbon capture as shown in Table 1—$532.0 million for the PC *vs*. $228.0 million for the IGCC. This is obviously a lower bound on the cost of retrofitting, and we make this assumption simply because most studies of the cost of carbon capture only report the cost of a plant designed for capture from the start, and do not estimate an explicit cost of retrofit.[5]

Depreciation bumps up in year 2015 reflecting the incremental depreciation for the second installment of capital. Fuel costs and O&M costs both increase in 2015, but are constant at this higher level thereafter. The total present value cost of the retrofitted PC plant is $2,000.4 million. This is the value in 2010 anticipating the retrofitting at year end 2014 and the start of 2015. The total present value cost of the retrofitted IGCC plant is $1,679.5 million.

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[5] The exception is EPRI (2003).

Table 3 500 MW PC Plant without carbon capture
(capacity 500 MW; capacity factor 80%; discount rate 6%)

Project Year Calendar Year	0 2010	1 2011	2 2012	3 2013	4 2014	5 2015	6 2016	7 2017	...	38 2048	39 2049	40 2050
Capital Investment	(726.0)											
Depreciation		(212.5)	(145.1)	(99.1)	(67.7)	(46.2)	(31.6)	(21.6)	...	(0.0)	(0.0)	(0.0)
Insurance and Property Taxes		(12.9)	(12.9)	(12.9)	(12.9)	(12.9)	(12.9)	(12.9)		(12.9)	(12.9)	(12.9)
Fuel Cost		(45.7)	(45.7)	(45.7)	(45.7)	(45.7)	(45.7)	(45.7)		(45.7)	(45.7)	(45.7)
O&M Cost		(26.3)	(26.3)	(26.3)	(26.3)	(26.3)	(26.3)	(26.3)		(26.3)	(26.3)	(26.3)
Tax Shield @ 40%		119.0	92.0	73.6	61.0	52.5	46.6	42.6		34.0	34.0	34.0
Total Cash Flow	(726.0)	34.0	7.1	(11.3)	(23.9)	(32.5)	(38.3)	(42.3)		(51.0)	(51.0)	(51.0)
Present Value @ 6%	(726.0)	32.1	6.3	(9.5)	(18.9)	(24.3)	(27.0)	(28.2)		(5.6)	(5.3)	(5.0)
NPV through 2050, year 40	(1,267.3)											

Notes:

[1] Depreciation is calculated using the declining balance depreciation method where the depreciation in year t is a constant percent of the remaining book value of the asset. We use a depreciation rate of 30%. Therefore D(t)=30%*BV(t), and BV(t+1)=BV(t)−D(t).

Table 4 500 MW IGCC Plant without carbon capture
Annual cash flow and NPV of costs, excluding carbon taxes

Project Year Calendar Year	0 2010	1 2011	2 2012	3 2013	4 2014	5 2015	6 2016	7 2017	...	38 2048	39 2049	40 2050
Capital Investment	(759.0)											
Depreciation		(222.1)	(151.7)	(103.6)	(70.8)	(48.3)	(33.0)	(22.5)	...	(0.0)	(0.0)	(0.0)
Insurance and Property Taxes		(13.5)	(13.5)	(13.5)	(13.5)	(13.5)	(13.5)	(13.5)		(13.5)	(13.5)	(13.5)
Fuel Cost		(45.4)	(45.4)	(45.4)	(45.4)	(45.4)	(45.4)	(45.4)		(45.4)	(45.4)	(45.4)
O&M Cost		(31.2)	(31.2)	(31.2)	(31.2)	(31.2)	(31.2)	(31.2)		(31.2)	(31.2)	(31.2)
Tax Shield @ 40%		124.9	96.7	77.5	64.3	55.4	49.2	45.1		36.0	36.0	36.0
Total Cash Flow	(759.0)	34.8	6.6	(12.6)	(25.8)	(34.7)	(40.9)	(45.1)		(54.1)	(54.1)	(54.1)
Present Value @ 6%	(759.0)	32.8	5.9	(10.6)	(20.4)	(26.0)	(28.8)	(30.0)		(5.9)	(5.6)	(5.3)
NPV through 40 years	(1,336.8)											

Notes:

[1] Depreciation is calculated using the declining balance depreciation method where the depreciation in year t is a constant percent of the remaining book value of the asset. We use a depreciation rate of 30%. Therefore D(t)=30%*BV(t), and BV(t+1)=BV(t)−D(t).

Table 5 500 MW PC Plant, retrofitted for carbon capture after 4 years of operation
Annual cash flow and NPV of costs, excluding carbon taxes

Project Year	0	1	2	3	4	5	6	7	...	38	39	40
Calendar Year	2010	2011	2012	2013	2014	2015	2016	2017		2048	2049	2050
Capital Investment	(726.0)				(532.0)							
Depreciation		(212.5)	(145.1)	(99.1)	(67.7)	(201.9)	(137.9)	(94.2)	...	(0.0)	(0.0)	(0.0)
Insurance and Property Taxes		(12.9)	(12.9)	(12.9)	(12.9)	(12.9)	(12.9)	(12.9)		(12.9)	(12.9)	(12.9)
Fuel Cost		(45.7)	(45.7)	(45.7)	(45.7)	(64.1)	(64.1)	(64.1)		(64.1)	(64.1)	(64.1)
O&M Cost (incl CO2 trans&strg)		(26.3)	(26.3)	(26.3)	(26.3)	(62.1)	(62.1)	(62.1)		(62.1)	(62.1)	(62.1)
Tax Shield @ 40%		119.0	92.0	73.6	61.0	140.2	114.6	97.1		59.4	59.4	59.4
Total Cash Flow	(726.0)	34.0	7.1	(11.3)	(555.9)	(8.4)	(34.0)	(51.5)		(89.2)	(89.2)	(89.2)
Present Value @ 6%	(726.0)	32.1	6.3	(9.5)	(440.3)	(6.3)	(24.0)	(34.3)		(9.7)	(9.2)	(8.7)
NPV through 40 years	(2,000.4)											

Notes:

[1] Depreciation is calculated using the declining balance depreciation method where the depreciation in year t is a constant percent of the remaining book value of the asset. We use a depreciation rate of 30%. Therefore D(t)=30%*BV(t), and BV(t+1)=BV(t)−D(t).

Table 6 500 MW IGCC Plant, retrofitted for carbon capture after 4 years of operation
Annual cash flow and NPV of costs, excluding carbon taxes

Project Year	0	1	2	3	4	5	6	7	...	38	39	40
Calendar Year	2010	2011	2012	2013	2014	2015	2016	2017		2048	2049	2050
Capital Investment	(759.0)				(228.0)							
Depreciation		(222.1)	(151.7)	(103.6)	(70.8)	(115.1)	(78.6)	(53.7)	...	(0.0)	(0.0)	(0.0)
Insurance and Property Taxes		(13.5)	(13.5)	(13.5)	(13.5)	(13.5)	(13.5)	(13.5)		(13.5)	(13.5)	(13.5)
Fuel Cost		(45.4)	(45.4)	(45.4)	(45.4)	(52.9)	(52.9)	(52.9)		(52.9)	(52.9)	(52.9)
O&M Cost (incl CO2 trans&strg)		(31.2)	(31.2)	(31.2)	(31.2)	(51.0)	(51.0)	(51.0)		(51.0)	(51.0)	(51.0)
Tax Shield @ 40%		124.9	96.7	77.5	64.3	94.6	80.0	70.1		48.6	48.6	48.6
Total Cash Flow	(759.0)	34.8	6.6	(12.6)	(253.8)	(26.9)	(41.5)	(51.4)		(72.9)	(72.9)	(72.9)
Present Value @ 6%	(759.0)	32.8	5.9	(10.6)	(201.0)	(20.1)	(29.2)	(34.2)		(8.0)	(7.5)	(7.1)
NPV through 40 years	(1,679.5)											

Notes:

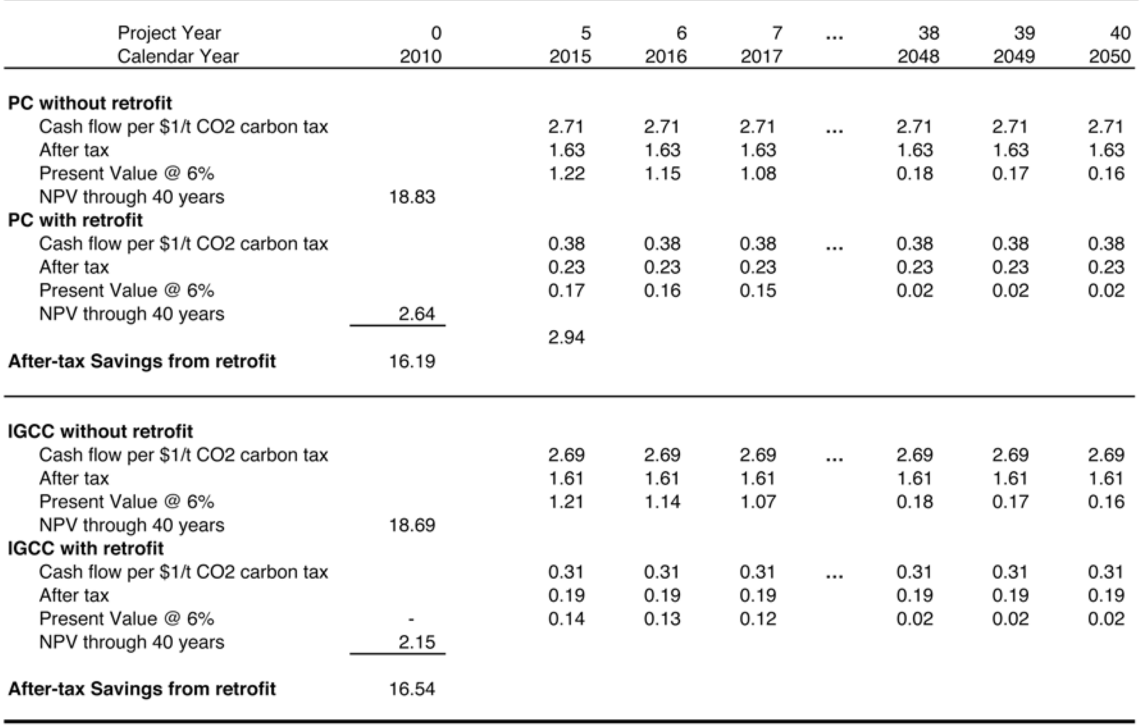
[1] Depreciation is calculated using the declining balance depreciation method where the depreciation in year t is a constant percent of the remaining book value of the asset. We use a depreciation rate of 30%. Therefore D(t)=30%*BV(t), and BV(t+1)=BV(t)−D(t).

Comparing the figures from Tables 3 and 5 we see that the incremental present value cost of retrofitting the PC plant in year 2014 is $733.2 million. Comparing the figures from Tables 4 and 6 the incremental present value cost of retrofitting the IGCC plant in year 2014 is $342.6 million.

We now turn to accounting for the cost of carbon regulations under different scenarios. One complication that needs to be taken into account is that the ultimate cost depends upon how the plant owner responds to the regulations. The plant owner may respond to the imposition of a carbon tax by either choosing to operate the plant as before and pay the carbon tax on the full level of emissions, or retrofit the plant for carbon capture and pay the carbon tax on the reduced level of emissions. Indeed, it can choose to pay the tax on emissions for a number of years and then retrofit. It may make sense to do this if the initial tax rate is low, but the rate is expected to grow over time. Assuming that the company maximizes its value, the actual cost of the regulation will be the minimum cost across the company’s full range of options on whether and when to retrofit.

Table 7 shows the annual cash flow impact when a carbon tax is levied on emissions starting in 2015, *i.e*., 5 years into the life of the project, and held constant for the remaining 35 years. The PC plant’s annual CO_2 emissions are 2.71 million t/yr, so every $1/t CO_2 charged translates into an annual cost of $2.71 million before tax and $1.63 million after-tax. The net present value across the full 35 years of charges totals $18.83 million. Retrofitting the PC plant lowers CO_2 emissions to 0.38 million t/yr, translating to a net present value for total emissions charges across the full 35 years of $2.64 million—a savings of $16.19 million in net present value for every $1/t charged. Since retrofitting the PC plant to lower emissions costs $733.2 million, a company

Table 7 Incrementatal Cashflow and Present value of $1/t CO2 carbon tax ($ millions)
(capacity 500 MW; capacity factor 80%; discount rate 6%)



Project Year	0	5	6	7	...	38	39	40
Calendar Year	2010	2015	2016	2017		2048	2049	2050
PC without retrofit								
Cash flow per $1/t CO2 carbon tax		2.71	2.71	2.71	...	2.71	2.71	2.71
After tax		1.63	1.63	1.63		1.63	1.63	1.63
Present Value @ 6%		1.22	1.15	1.08		0.18	0.17	0.16
NPV through 40 years	18.83							
PC with retrofit								
Cash flow per $1/t CO2 carbon tax		0.38	0.38	0.38	...	0.38	0.38	0.38
After tax		0.23	0.23	0.23		0.23	0.23	0.23
Present Value @ 6%		0.17	0.16	0.15		0.02	0.02	0.02
NPV through 40 years	2.64							
		2.94						
After-tax Savings from retrofit	16.19							
IGCC without retrofit								
Cash flow per $1/t CO2 carbon tax		2.69	2.69	2.69	...	2.69	2.69	2.69
After tax		1.61	1.61	1.61		1.61	1.61	1.61
Present Value @ 6%		1.21	1.14	1.07		0.18	0.17	0.16
NPV through 40 years	18.69							
IGCC with retrofit								
Cash flow per $1/t CO2 carbon tax		0.31	0.31	0.31	...	0.31	0.31	0.31
After tax		0.19	0.19	0.19		0.19	0.19	0.19
Present Value @ 6%	-	0.14	0.13	0.12		0.02	0.02	0.02
NPV through 40 years	2.15							
After-tax Savings from retrofit	16.54							

would choose to retrofit whenever the tax charged is \$45.23/t CO_2 or more.[6] The IGCC plant's CO_2 emissions are 2.69 million t/yr, so every \$1/t charged translates into an annual cost of \$2.69 million before tax and \$1.61 million after-tax. The net present value across the full 35 years of charges totals \$18.69 million. Retrofitting the IGCC plant lowers CO_2 emissions to 0.31 million t/yr, translating to a net present value across the full 35 years of \$2.15 million—a savings of \$16.54 million in net present value for every \$1/t charged. Although these savings are very close to the savings for the PC plant, since the cost of retrofitting the IGCC plant is so much lower—\$342.6 million—a company would choose to retrofit the IGCC plant at a much lower level of carbon tax—*i.e.*, whenever the tax charged is \$20.72/t CO_2 or more.

Figure 1 graphs the total net present value cost of both the PC and the IGCC technologies, inclusive of the cost of CO_2 emissions or emissions control, as a function of the level of carbon tax levied. The graph for the PC starts at a cost of \$1,267.3 million when no carbon tax is levied and increases at the rate of \$18.83 million for each \$1/t CO_2 tax. At a tax of \$45.23/t CO_2—which is off the scale of the chart—the company chooses to retrofit, reducing the rate of increase to \$2.64 million for each \$1/t CO_2 tax. At a \$35/t CO_2 tax, the total cost of the PC plant is \$1,769.7 million. The graph for the IGCC starts at a cost of \$1,336.8 million when no carbon tax is levied and increases at the rate of \$18.69 million for each \$1/t CO_2 tax. At a tax of \$20.72/t CO_2, the company chooses to retrofit, reducing the annual CO_2 emissions and therefore reducing the rate of increase in the cost to \$2.15 million for each \$1/t CO_2 tax. At a \$35/t CO_2 tax the total cost for the IGCC plant is \$1,574.0 million. The PC technology is cheaper so long as the tax levied is less than \$23.27/t CO_2. If the tax is greater than \$23.27/t CO_2, the IGCC technology is cheaper.

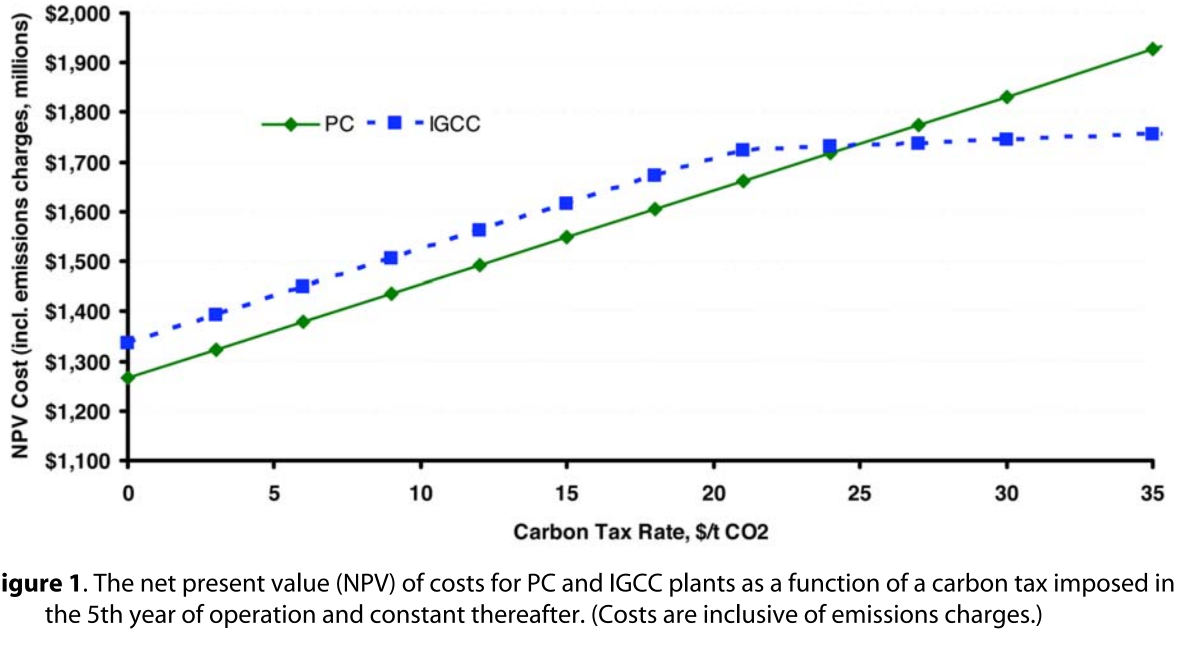


Figure 1. The net present value (NPV) of costs for PC and IGCC plants as a function of a carbon tax imposed in the 5th year of operation and constant thereafter. (Costs are inclusive of emissions charges.)

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[6] Since the emissions charge is assumed to be constant after it is initiated in 2015, there is no benefit to the company from delaying a retrofit by a few years: it either makes sense to retrofit immediately, or not at all.

Table 7 and Figure 1 were constructed on the assumption that the carbon tax rate is held constant for the remaining life of the plant, *i.e*., between 2015 and 2050. What if the tax rate is expected to grow over time? Facing a growing carbon tax, a company must decide not simply whether to retrofit, but when to retrofit. Each year of delay of the retrofit saves the time value of the investment cost and similarly pushes off by one year the incremental fuel and operating costs that carbon capture imposes. But delay means paying that year's level of the carbon tax on the higher level of emissions. Once the cost of the carbon tax for the year equals the time value of the retrofit investment it makes sense for the company to retrofit.

Figure 2 shows the marginal benefits and costs of delaying retrofit by one year at each year of operation for the PC technology. The marginal benefits and costs shown for each year are valued at that year, when the decision to retrofit or to delay is taken. These benefits and costs are not discounted back to the start of the project. The figure assumes an initial carbon tax rate in 2015 of \$20/t CO_2 growing at 4% annually thereafter. As the figure shows, the marginal benefit of delay is greater than marginal cost in the early years so that delaying retrofit makes sense. The marginal benefit of delay is constant, while the marginal cost of delay is increasing as the carbon tax rate increases. Consequently, it makes sense to retrofit in year 25 (2035).

Figure 3 shows the marginal benefit and marginal cost for the IGCC technology. The marginal benefit of delay is always less than the marginal cost, so that it is optimal to retrofit as soon as the tax is imposed, in year 5 (2015). If one considers a different initial carbon tax rate,

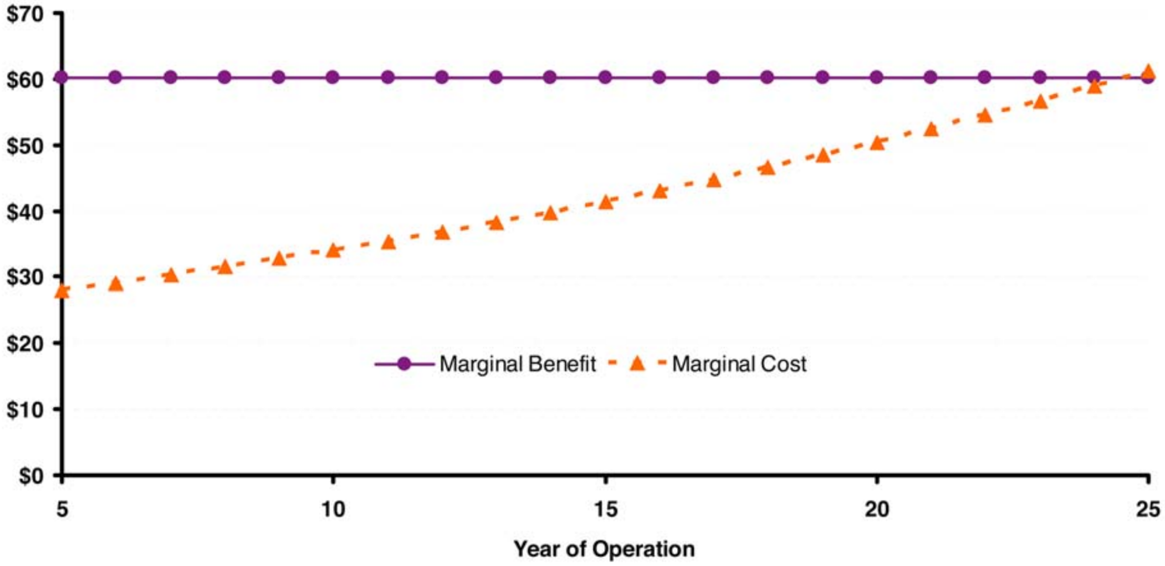

Figure 2. Marginal benefit and marginal cost of delaying retrofit of a PC plant by one year. Assumes an initial carbon tax of \$20/t CO2 growing at 4%/yr. *Note*: Unlike other values shown in this paper, which have all been discounted back to year 0 of operation (calendar year 2010), the marginal benefit and marginal cost are measured at the point the decision to delay is taken, *i.e*., to the year shown along the horizontal axis. So, for example, in year 5 of operation (calendar year 2015), the marginal benefit of delaying retrofit is the time value of postponing the investment one year. This is approximately the dollar amount of the investment, plus the value of the depreciation tax shields discounted to this date, times the discount rate. Since this is approximately constant from year to year, the marginal benefit line is approximately constant. The reason for speaking only approximately is that the real value of the tax shields does vary as time moves along. The marginal cost of delaying retrofit is the amount of the incremental carbon tax incurred this year.

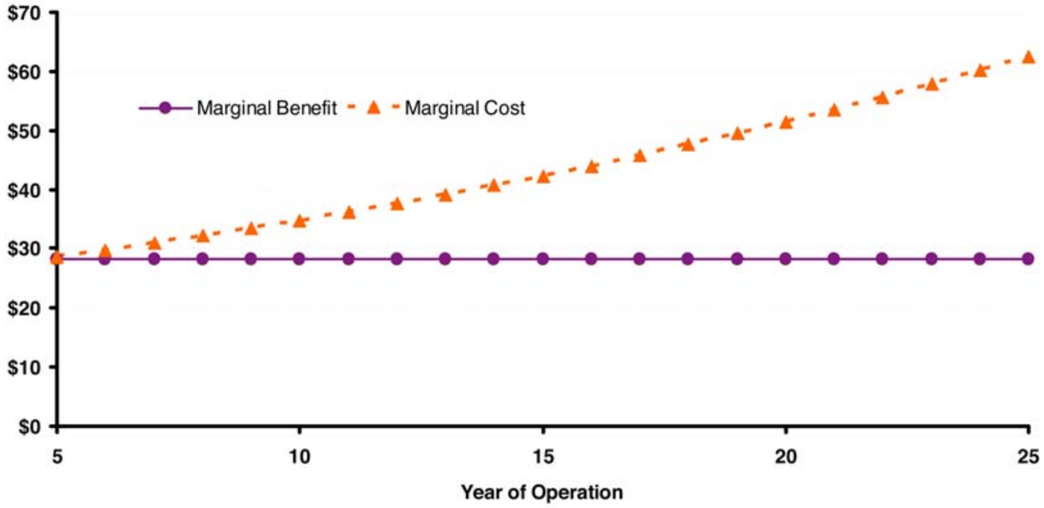

Figure 3. Marginal benefit and marginal cost of delaying retrofit of an IGCC plant by one year. Assumes an initial carbon tax of \$20/t CO_2 growing at 4%/yr. (See also Note in Figure 2.)

then the date chosen for retrofit changes; similarly, if one considers a different growth rate for the tax, then the date chosen for retrofit also changes.[7] In calculating the costs for a given regulatory scenario, we incorporate the optimal choice of a retrofit date.

Figure 4 graphs the total net present value cost of both the PC and the IGCC technologies, inclusive of the cost of CO_2 emissions or emissions control, as a function of the initial level of carbon tax levied, but assuming that the tax rate increases at 4% thereafter. As in Figure 1, the graph for the PC starts at a cost of \$1,267.3 million when no carbon tax is levied and therefore the plant operates without carbon capture. At a low initial tax rate the plant is never retrofitted.

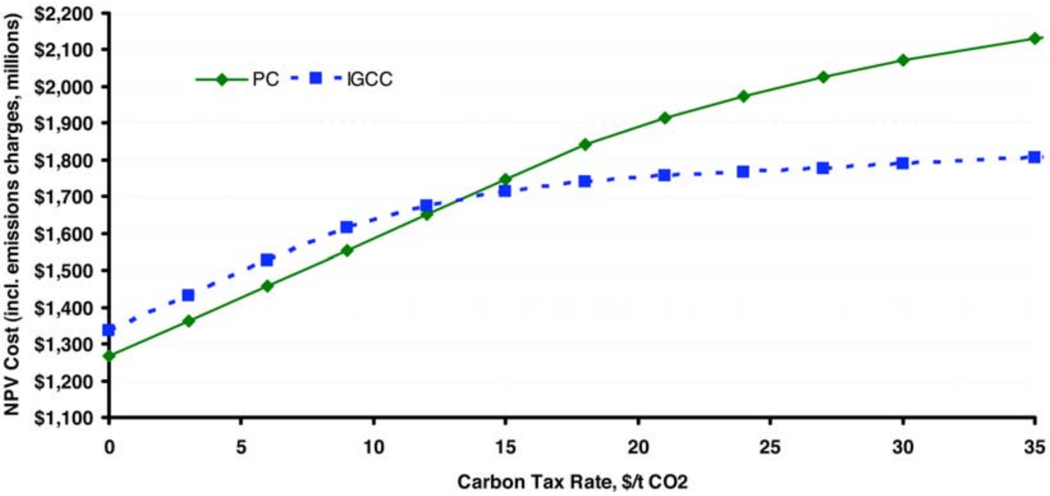

Figure 4. The NPV of costs for PC and IGCC plants as a function of a carbon tax imposed in the 5th year of operation with a 4% growth rate thereafter. (Costs are inclusive of emissions charges.)

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[7] These calculations assume that there is one known path of future regulation, so that the decision on timing the retrofit can be easily evaluated. In reality, once an initial carbon tax is imposed, there remains uncertainty about the future path. Our analysis abstracts from this uncertainty, but see Sekar (2005) for a methodology that addresses it.

However, as the rate is increased, it eventually becomes optimal for the plant to be retrofitted, albeit late in its life. Because the plant is eventually retrofitted, the rate of increase in the cost per \$1/t CO_2 tax begins to fall. Because the date of retrofit is earlier for higher initial tax rates, the slope of the graph is non-linear in the initial carbon tax rate, declining gradually. Once the tax rate reaches \$35/t CO_2 the total cost for the PC plant is \$1,906.7 million. As in Figure 1, the graph for the IGCC starts at a cost of \$1,336.8 million when no carbon tax is levied. At lower initial tax rates it becomes optimal to retrofit the IGCC plant, so that the slope of the line falls sooner. At a \$35/t CO_2 tax rate the total cost for the IGCC plant is \$1,626.6 million. The PC technology is cheaper so long as the initial tax levied is less than \$13.71/t CO_2. If the tax is greater than \$13.71/t CO_2, the IGCC technology is cheaper.

4. ‘Capture Ready’

One issue that has been raised in the public policy discussion surrounding the next generation of power plants currently being constructed is the question of whether or not new plants should be designed to be ‘capture ready’. Indeed, at their recent summit at Gleneagels, the leaders of the G8 agreed to a plan of action on climate change that included working “to accelerate the development and commercialization of Carbon Capture and Storage technology by…(c) inviting the IEA to work with the CSLF to study definitions, costs, and scope for ‘capture ready’ plant and consider economic incentives…”

In the most general sense, a ‘capture ready’ design involves some additional up front expense in order to make it easier and less costly for a plant to be retrofitted at a later date for carbon capture. This can be as simple as developing a PC plant with extra real estate where post combustion capture equipment could be positioned should the plant eventually be retrofitted. Or it could involve designing in extra capacity on the gasifier and the turbine of an IGCC plant for optimal operation once the plant is retrofitted for capture.

These examples focus on minor variations on the architecture within the constraints of a pre-specified plant design. But the choice between the two basic plant designs, PC and IGCC, should also be seen as a ‘capture ready’ choice. The IGCC design is more expensive up front, but making this up front investment lowers the expense of switching to carbon capture at a later date. Indeed, we show that a firm that has chosen the IGCC design retrofits it for carbon capture at a lower level of a carbon tax and at an earlier date than a firm that has chosen the PC design. The calculus we present in this paper for choosing up front between the PC and the IGCC design is exactly the calculus a company will undertake in evaluating investments in any ‘capture ready’ features for any fundamental design.

We believe the choice between the PC and the IGCC design should be the real focus of any discussion of making power plants ‘capture ready’. We have examined elsewhere other types of ‘capture ready’ investments and whether the danger of future carbon regulations in the U.S. justifies the costs—see Sekar (2005). Most other types of ‘capture ready’ expenses fall into one of two categories. One category is those investments that involve relatively trivial cost, but also make relatively minor impact on the ultimate cost of carbon capture. The incorporation of extra space into PC plant designs belongs in this category. A second category is those investments that involve so great an initial cost that the costs of these investments are insufficiently distinguishable from the cost of investing up front in full carbon capture itself. If the specter of future carbon regulation would motivate these types of investments, then you have covered substantial ground towards motivating full scale carbon capture. The overdesign of IGCC components belongs in this category.[8]

5. The Initial Investment Decision—PC or IGCC

The basic tradeoff complicating an electric utility's initial investment decision is clearly illustrated in Figures 1 and 4. At a zero or low level of a tax the optimal power plant to construct is the PC. On the other hand, if the path of future carbon taxes is flat, then for any tax above \$23.27/t CO_2, the IGCC plant is optimal. If the tax rate is expected to grow over time at 4% per year, then the switch point occurs at the lower initial tax rate of approximately \$13.71/t CO_2. Clearly whether an electric utility should construct a plant using the PC technology or a plant using the IGCC technology will depend upon the company's expectation about the likelihood of any *future* level of a carbon tax.

No one knows with certainty what level of carbon tax—if any—may be levied in the future. A company will confront the range of possible outcomes like any decision under uncertainty, and assign its best estimate of the probability of each scenario, averaging the results and determining the power plant technology with the greatest expected value. In our case that means the plant technology with the lowest possible cost inclusive of expected future carbon related costs, whether those costs be in the form of emissions charges paid or capital expenditures for retrofitting to capture carbon. If the company assigns high probability to the no carbon tax or to the low carbon tax scenarios, then it makes sense for it to build PC plants. But if it assigns sufficient probability to the higher carbon tax scenarios, then the value of the company will be maximized by building the IGCC technology.

Complicating the problem is the wide range of possible paths of future regulation. New regulations could be instituted in any given year, tax rates could be increased in some years but not in others, and then increased again at a steeper rate. Regulations could be reversed or relaxed. Fully encompassing all of these possibilities is a feasible, but technically difficult task—see Sekar (2005) for a comprehensive solution. Our strategy here is to limit ourselves to a restricted range of possibilities that nevertheless captures the essence of the problem and helps key decision makers gain sufficient insight to address the issue under the widely varying circumstances they may face.

Figure 5 shows a matrix of various possible initial tax rates and various possible growth rates for the level of the tax. Consistent with the presentation above, we limit ourselves to future scenarios in which a carbon tax is initiated in 2015 and grows at a constant rate thereafter. This includes the special case of no future regulation, *i.e.*, a \$0/t tax rate, at least until 2050, the time horizon considered for this plants operation. It also includes the case of a flat tax starting at some rate in 2015 and staying constant through 2050.

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[8] See Pre-investment IGCC design in EPRI (2003)

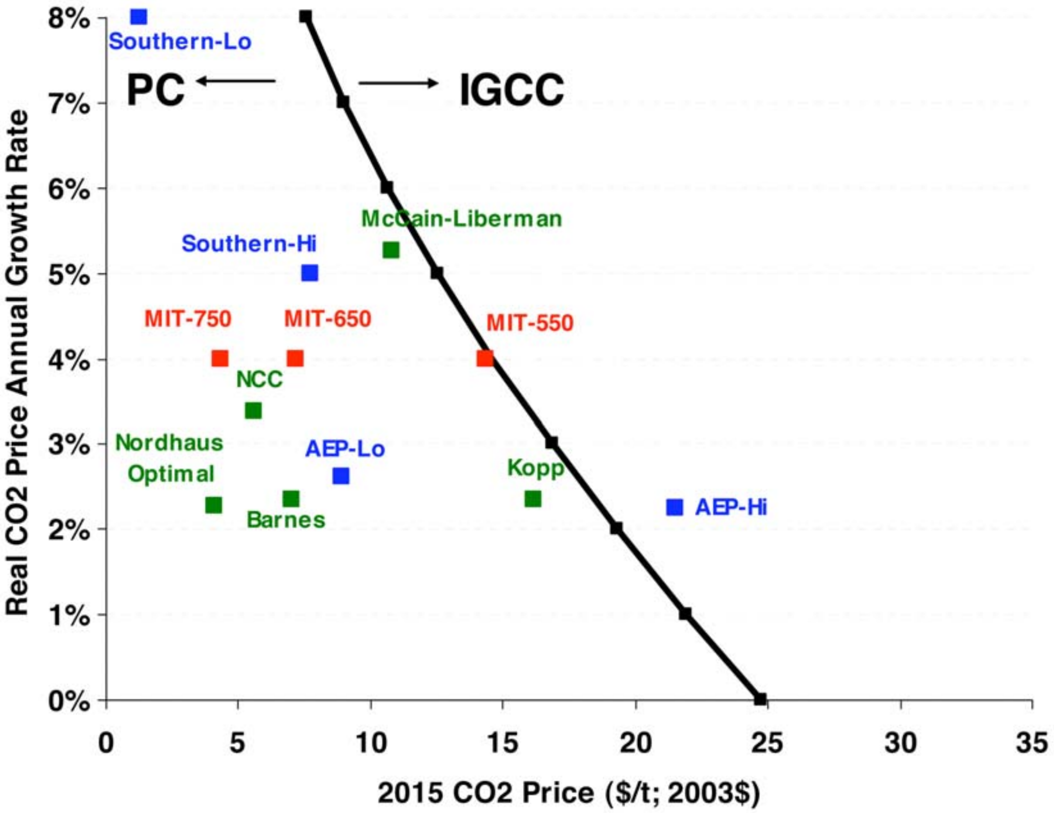

Figure 5. Benchmark Future Carbon Tax Regimes *vs*. Optimal Technology Choice.

The solid line starting at the bottom of Figure 5 at a tax rate of nearly \$25/t CO_2 and growth rate of 0% and sloping up and to the left to a tax rate of about \$7.5/t CO_2 and growth rate of 8% divides the matrix into two areas. This line defines the switch point at which the expected cost of an investment in a PC plant exactly equals the expected cost of an investment in an IGCC plant. To the left and below this line the PC plant is less costly. To the right and above this line the IGCC plant is less costly. Which plant is best to build depends upon the probability a company places on all the different scenarios in the matrix and whether the weight of the probability lies on one side or the other of the line.

To put this range of regulatory scenarios into perspective, we have also marked on the matrix points corresponding to benchmarks that may help to calibrate the discussion about potential or likely future carbon tax rates.

One type of benchmark maps various proposals that have actually been a part of the public policy debate onto the different level of initial emissions charges and growth rates. Some of these benchmarks are shown with the green squares in Figure 5.[9] Perhaps the most widely discussed proposal for regulation of carbon emissions in the U.S. has been the McCain-Lieberman

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[9] We quote all figures here in terms that are comparable to the other numbers used in this paper—*i.e.*, emissions charges for 2015, denominated in 2003 dollars, and quoted as \$/t CO_2. Where figures quoted in the original sources are benchmarked in different years, denominated in dollars quoted in a different year, or quoted as \$/t C instead of CO_2, we show our calculations in the Appendix.

proposal. Although the proposal failed in the U.S. Senate in 2003, it nevertheless garnered votes from 43 of the 100 Senators and revised versions of the legislation continue to be considered. There have been other serious proposals as well. Some that we have chosen to include in the figure are:

- McCain-Lieberman. An analysis made by MIT researchers in the time leading up to the 2003 vote showed a cost of \$10.82/t CO_2 in 2015 growing at an annualized rate of 5.25%,
- The National Commission on Energy Policy (2004) proposed emissions caps that would yield a price of \$5.57/t CO_2 in 2015 with a real annual growth rate of 3.4%,
- Nordhaus and Boyer (2000) analyzed an optimal policy involving an estimated compliance cost of \$4.1/t CO_2 growing annually at a rate 2.34%,
- Barnes (2001) made an early recommendation for U.S. implementation of some sort of Kyoto-like obligations, but with a safety valve on costs of approximately \$7/t CO_2 figure in 2015; we assume a real annual growth rate of 2.34%,
- Kopp *et al*. (2001) is another early recommendation suggested as an alternative to a quantity based target set by the Kyoto Protocol which corresponds to a compliance payment of \$16.2/t CO_2; we assume a real annual growth rate of 2.34%.

Another type of benchmark simply identifies scenarios that other business people seem to be focusing on as they evaluate this kind of decision under uncertainty. For example, a couple of U.S. electric utilities have recently published their own consideration of the effect of possible future regulation on their business—AEP and the Southern Co. These are show as the blue squares in Figure 5.

A third type of benchmark identifies the levels of initial emissions charges and growth rates required to hold the projected climate impact within some specified bound. For example, the U.S. government's Climate Change Science Program directed certain research institutions to determine the carbon prices required to achieve several different stabilization scenarios, ranging from 450 ppm to 750 ppm of CO_2 in the atmosphere. Under certain assumptions, these concentrations correspond to different levels of change in the global mean temperature relative to pre-industrial times, ranging from 1.5 to 3 degrees. Stabilization at 450 ppm implies an extremely aggressive level of emissions control relative to current economic activity—far more aggressive than what is contained in the Kyoto Protocol by even those countries making a commitment to act. The 550 ppm is also very aggressive relative to current economic activity. MIT's Joint Program on the Science and Policy of Global Change estimated the level of carbon tax required to achieve each of these scenarios, and the points corresponding to their estimates are charted as the red squares in Figure 5. The MIT analyses are based on a policy scenario whereby all nations apply the same tax on CO_2 emissions and this tax rises at a constant rate of 4% per year. The various stabilization levels then imply different initial-year prices for the resulting trajectory to achieve the particular goal. The analysis yields prices starting at anywhere from a low initial tax rate of \$4.31/t CO_2 for the 750 ppm scenario to a high initial tax rate of \$53.82/t CO_2 for the 450 ppm scenario. This last scenario lies outside to the right of the scale of Figure 5.

6. Conclusions

The decision about what type of technology to select for current investments in new power plants clearly depends upon conjectures about future regulations of carbon. Electric utilities cannot simply assume that because there are currently no carbon regulations, therefore the apparently cheaper PC technology maximizes shareholder value. The choice of a technology for such a long-lived capital investment is a standard decision under uncertainty. If there is sufficient probability that stringent carbon emission regulations will be imposed sometime in the future, then the IGCC technology becomes the most profitable choice.

We have characterized the key economic parameters of the two technologies, and we have made assumptions about the other key economic variables—notably the cost of fuel and the discount rate. We then identified exactly how different levels of future carbon regulations shifted the calculus between the PC and the IGCC technologies. The choice then requires an assessment of the likelihood of different levels of penalty for emissions under future regulation. We presented the range of possible future levels of regulation in a simple matrix and presented some useful benchmarks.

The matrix in Figure 5 presents a striking picture of the range of widely discussed scenarios for future regulation against the set of scenarios for which investment in new IGCC plants is warranted. Few of the widely discussed scenarios fall within the space where IGCC is less costly. Under most of the widely discussed scenarios the PC technology remains the least costly. The level of future regulation required to justify a current investment in the IGCC technology appears to be very aggressive, if not out of the question.

A final interesting benchmark against which to view this critical decision is the price at which carbon emissions allowances are currently trading in the European Union's Emission Trading System (ETS). Recent (July 2005) prices in the ETS have been in the range of \$27.3/t CO_2 (\$100/t C). If these actual prices in Europe are any guide to possible levels of charges under future U.S. regulations, then looking back at Figure 5, this clearly argues in favor of the selection of the IGCC technology. A number of analysts, however, suggest that the current price in this new market should not be given too much credence—that it is not a good guide to the future price. Economic modeling of the commitments under the Protocol and the costs of compliance across various industries suggests a price less than \$1/t CO_2—see Reilly & Paltsev (2005) and also Babiker *et al*. (2002), Manne & Richels (2001), Nordhaus (2001), Den Elzen & de Moor (2001) and Bohringer (2001). But this conjecture has yet to be borne out.

Acknowledgements

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APPENDIX

In Section 5 we quoted various benchmark levels of a carbon emissions charge and annual growth rate. These benchmarks are also shown in Figure 5. As noted in footnote 9 above, “We quote all figures here in terms that are comparable to the other numbers used in this paper—*i.e.*, emissions charges for 2015, denominated in 2003 dollars, and quoted as $/t CO_2. Where figures quoted in the original sources are benchmarked in different years, denominated in dollars quoted in a different year, or quoted as $/t C instead of CO_2, we show our calculations in the Appendix.” This Appendix provides those calculations, taking the figures from the original source and producing the figures quoted here.

Nordhaus & Boyer (2000). We use the figures in their Table 8.5 on p. 133 showing an optimal policy with an initial carbon tax of $12.7/t C, growing annually at a rate 2.34%. Putting the initial cost figure into the same terms as the cash flow figures we have been using yields an estimated compliance cost of $4.1/t CO_2 growing annually at a rate 2.28%. This is done as follows.

Growth Rate: {ln ([$31.64/t C]/[$12.71/t C])}/(2055–2015) = 2.28% per year.
2015 CO2 Price in 2003$: ($12.71/t C)/[3.67 (t C/t CO_2)] x (138.1/116.3) = $4.1/t CO_2.
(Producer Price Index data: 2003PPI = 138.1, 1990PPI = 116.3)

McCain-Lieberman. Paltsev *et al*. (2003), p. 20, Table 6 showed a cost in 2015 of approximately $10/t CO_2 rising to a cost in 2020 of $13/t CO_2, reported in 1997 dollars. This translates to an annualized growth rate of 5.25%. The calculations of the real growth rates and 2015 CO_2 price in 2003$ is as follows.

Growth Rate: {ln [($13/t CO_2)/($10/t CO_2)]}/(2020–2015) = 5.25% per year.
2015 CO_2 Price in 2003$: ($10/t CO_2) x (138.1/127.6) = $10.82/t CO_2. (1997PPI = 127.6)

The National Commission on Energy Policy (2004) proposed emissions caps that they estimated would yield a price of $5/t CO_2 in 2010 and $7/t CO_2 in 2020, both denominated in 2004 dollars. This implies a real annual growth rate of 3.4%. Translating 2004 dollars to 2003 dollars using realized inflation figures, and then calculating the price in 2015 yields a $5.57/t CO_2 figure. The calculations of the real growth rates and 2015 CO_2 price in 2003$ is as follows. (2004PPI = 146.7)

Growth Rate: {ln [($7/t CO_2)/($5/t CO_2)]}/(2020–2010) = 3.36% per year.
2015 CO_2 Price in 2003$: ($5/t CO_2) x [(1+3.36%)$^{(2015–2010)}$] x (138.1/146.7) = $5.55/t CO_2.

Barnes (2001). The safety valve was set at initial cost of $25/t C starting in 2003. Translating this to a rate per ton CO_2, and then translating 2001 dollars to 2003 dollars using realized inflation figures yields the $7/t CO_2 figure. The calculations of the 2015 CO_2 price in 2003$ is as follows. (2001PPI = 134.2)

2015 CO_2 Price in 2003$: {($25/t C)/[3.67 (t C/t CO_2)]} x (138.1/134.2) = $7.01/t CO_2.

Kopp *et al.* (2001). This corresponds to a compliance payment of $50/t C. Translating this payment to a rate per ton CO_2, and then translating 1995 dollars to 2003 dollars using realized inflation figures yields the $16.2/t CO_2 figure. A real annual growth rate of 2.34% has been assumed for this price starting 2015. The calculation of the 2015 CO_2 price in 2003$ is as follows. (1995PPI = 116.3)

2015 CO_2 Price in 2003$: {($50/t C)/[3.67 (t C/t CO_2)]} x (138.1/116.3) = $16.18/t CO_2.

MIT stabilization scenarios. The forthcoming report provides carbon prices starting in 2010 and growing at 4% per year. These prices are denominated in 1997 dollars. We take the 2010 prices, grow them at 4% per year, compounded, to give the carbon price in 2015. We then translate this to a price for CO_2 by dividing by 3.67. Finally, we translate this to 2003 dollars by multiplying by the ratio of the 2003 PPI to the 1997 PPI, 138.1/127.6.

Stabilization	***Carbon Price in Specified Year***			
Scenario (ppm)	**2010 ($/t C)** (1997$)	**2015 ($/t C)** (1997$)	**2015 ($/t CO_2)** (1997$)	**2015 ($/t CO_2)** (2003$)
750	12.00	14.60	3.98	4.31
650	20.00	24.33	6.63	7.18
550	40.00	48.67	13.26	14.35
450	150.00	182.50	49.73	53.82

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