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Future carbon regulations and current investments in alternative coal-fired power plant technologies[☆]

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Abstract

We analyze how uncertain future US carbon regulations shape the current choice of the type of power plant to build. Our focus is on two coal-fired technologies, pulverized coal (PC) and integrated coal gasification combined cycle technology (IGCC). The PC technology is cheapest—assuming there is no need to control carbon emissions. The IGCC technology may be cheaper if carbon must be captured. Since power plants last many years and future regulations are uncertain, a US electric utility faces a standard decision under uncertainty. A company will confront the range of possible outcomes, assigning its best estimate of the probability of each scenario, averaging the results and determining the power 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 no regulation or to less stringent regulation of carbon, then it makes sense for it to build the PC plant. But if it assigns sufficient probability to scenarios with more stringent regulation, then the IGCC technology is warranted. We provide some useful benchmarks for possible future regulation and show how these relate back to the relative costs of the two technologies and the optimal technology choice. Few of the policy proposals widely referenced in the public discussion warrant the choice of the IGCC technology. Instead, the PC technology remains the least costly. However, recent carbon prices in the European Emissions Trading System are higher than these benchmarks. If it is any guide to possible future penalties for emissions in the US, then current investment in the IGCC technology is warranted. Of course, other factors need to be factored into the decision as well.

Keywords: Carbon; Coal; Power plant

1. Introduction

Electric power plants last a lifetime. The plants built today—and over the next several 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 capture of the carbon together with other potential advantages. But these technologies have higher upfront investment costs that must be justified.

Currently the US 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

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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 US 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 addresses these questions. Drawing on studies of the costs of various plant designs, we compare the costs of power from two key coal-fired power plant technologies, PC and IGCC, under a single base case scenario. 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 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

A number of studies have examined the economics of various coal and other fossil fuel power plant technologies with and without carbon capture, including EPRI (2000), EPRI (2003), Gottlicher (2004), McPherson (2004), National Coal Council (2004), NETL (2002), Nsakala et al. (2003), and Rubin et al. (2004). These studies examine a plethora of scenarios recognizing the variability and uncertainty of key parameters such as capital costs, fuel costs, operating efficiencies, among others. To maintain a sharp focus on the effect of uncertainty about future carbon regulations we limit our presentation to a single scenario for two key technologies. We chose the sub-critical air-fired PC technology, the most ubiquitous 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. 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%. 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] We present a scenario with a coal price of $1.50/MMBtu and a cost of $5/t for transportation and storage of CO_2.

Table 1 lays out our assumptions about the key technical and economic parameters for the two technologies with and without carbon capture. Table 2 translates these into levelized costs of power based on assumptions about plant life, the capacity factor, the appropriate discount rate and tax rules. All numbers are calculated in real dollars using 2003 as the base year. The figures in Table 1 are directly based upon figures reported in the EPRI (2000) and the National Coal Council (2004) studies. However, anticipating our later results that the higher capital costs of IGCC are difficult to justify based on the threat of future regulations, we have made relatively optimistic assumptions for the cost of IGCC in order to give the greatest potential for current investment and so to be conservative in our conclusions. The levelized costs in Table 2 differ since we use a 40 year plant life in contrast to the 20 year book life used in those reports.

Without carbon capture levelized capital costs for the IGCC plant are nearly 5% greater than for the PC plant, fuel costs are approximately equal and O&M costs are 19% greater, so that the total cost is nearly 6% greater. With carbon capture, capital costs for the IGCC plant are nearly 22% less than for the PC plant, fuel costs are 16% less and O&M costs are 18% less, so that the total cost is 19% less.

The focus of this paper is on whether the specter of future carbon regulations is large enough to justify the added cost of building a coal-fired power plant using the IGCC technology. Of course there may be other motivations in favor of using the IGCC technology. And there are other ways to change the economic calculus besides the specter of future regulation, notably the use of subsidies for construction of IGCC plants such as those recently created as a part of the Energy Policy Act that was signed into law in August 2005. It is interesting to compare the cost

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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 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.

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 CO_2 capture	With CO_2 capture
Capital cost ($ million)		
PC	726	1258
IGCC	759	987
Net heat rate (Btu/KWhe)		
PC	8690	12,193
IGCC	8630	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
CO_2 emissions (tonne/MWhe)		
PC	0.774	0.108
IGCC	0.769	0.089
CO_2 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: $500\,\text{MW}*80\%*8760\,\text{h} = 3504$ million kilowatt hours. The total Btus consumed in the year is then calculated by multiplying the 3504 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 CO_2 capture include transportation and storage of captured CO_2 at $5/t.

Table 2
Comparison of levelized costs for a PC plant and an IGCC plant (capacity 500 MW; capacity factor 80%; discount rate 6%)

	Without CO_2 capture	With CO_2 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 ($/MWh; excl carbon tax)		
PC	40.0	69.7
IGCC	42.3	56.3
CO_2 emissions avoided (t/MWh)		
PC		0.666
IGCC		0.680
Cost of avoided CO_2 emissions ($/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. As a point of reference, this 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%.
(2) Capital costs recognize the value of depreciation tax shields. These are calculated assuming a 30% depreciation rate so that the nominal depreciation is $D(t) = 30\%*\text{BV}(t)$, and $\text{BV}(t+1) = \text{BV}(t) - D(t)$. Although all other costs are calculated in real terms, avoiding any assumption about inflation rates, depreciation is an inherently nominal account and so an assumption about expected inflation is necessary. Nominal depreciation tax shields are deflated to real figures using an expected inflation rate of 2.5%.
(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 CO_2 emissions equals CO_2 emissions avoided divided by the difference between the total cost with and without carbon capture.

differentials between the PC and the IGCC technology displayed in Tables 1 and 2 to the size of the Act's 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 cost of the technology by 13.8%. Since the capital cost is in turn nearly 50% of the total levelized cost of electricity, this credit would lower the total levelized cost by between 6% and 7%. This is just slightly more than the 6% total cost differential between the PC and the IGCC technologies without carbon capture. Therefore, based on the cost figures used here, 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 excluded.

3. Capitalizing the costs of future carbon regulations

We now turn to accounting for the cost of carbon regulations under different scenarios. There are many different types of regulatory policies the government could employ some time in the future. One simple policy would be a charge or tax for carbon emissions. Another would be the creation of a cap and trade system like the European Union's carbon Emissions Trading System or the US SO_2 program, from which would arise a market price for carbon permits in the US. Other policies do not so obviously result in a price of carbon, although economists sometimes calculate one or multiple shadow prices. For simplicity, we limit our analysis of possible future regulatory policies to an analysis of various carbon prices, without discussing the details of the regulatory policy. This allows us to parameterize increasingly strict regulations in the simplest manner possible.

Determining the total cost of a plant requires understanding how the plant owner will respond to the regulations. The plant owner may respond to the imposition of a price on carbon by either choosing to operate the plant as before and paying the price on the full level of emissions, or by retrofitting the plant for carbon capture and paying the price on the reduced level of emissions. Indeed, the owner can choose to pay the price on emissions for a number of years and then retrofit. It may make sense to do this if the initial carbon price is low but rapidly increasing. 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.

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 US, 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. We assume initially that the carbon price is constant once the regulations are imposed. 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.[2]

Table 3 lays out the decision problem for the owner of the PC plant. The top half of the table shows the present value of costs exclusive of carbon charges if the plant continues to operate without carbon capture and if the plant is retrofitted for capture.[3] The incremental cost of capture is \$733.2 million. The bottom half of the table shows the present value of carbon charges paid per \$1/t CO_2 price. This is calculated for the case that the plant operates without carbon capture and for the case that the plant is retrofitted. The incremental cost of carbon charges paid per \$1/t CO_2 price is \$16.2 million. Therefore, the plant owner would choose to retrofit if the price is above \$45.29/t CO_2 tax rate. Table 4 lays out the same problem for the owner of the IGCC 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 carbon price—i.e., whenever the price is \$20.72/t CO_2 or more.

Fig. 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 the carbon price. The graph for the PC starts at a cost of \$1267.3 million when no regulations are imposed and the price is zero and increases at the rate of \$18.83 million for each \$1/t CO_2. At a price 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. At a \$35/t CO_2, the total cost of the PC plant is \$1926.2 million. The graph for the IGCC starts at a cost of \$1336.8 million when no regulations are imposed and the price is zero and increases at the rate of \$18.69 million for each \$1/t CO_2. At a price 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. At \$35/t CO_2 the total cost for the IGCC plant is \$1754.7 million. The PC technology is cheaper so long as the carbon price is less than \$23.27/t CO_2. If the price is greater than \$23.27/t CO_2, the IGCC technology is cheaper.

Tables 3 and 4 and Fig. 1 were constructed on the assumption that the carbon price is constant for the remaining life of the plant, i.e., between 2015 and 2050. What if the price is expected to grow over time? Facing a growing carbon price, 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 1 year the incremental fuel and operating costs that carbon capture imposes. But delay means paying that year's carbon price on the higher level of emissions. Once the cost of the carbon charges for the year equals the time value of the retrofit investment it makes sense for the company to retrofit.

Fig. 2 shows the marginal benefits and costs of delaying retrofit by 1 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 price 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 price increases. Consequently, it makes sense to retrofit in year 25, i.e., in calendar year 2035.

Fig. 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 regulations are imposed, in year 5,

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[2] Since the carbon price 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.

[3] We assume that the cost of retrofitting each plant is equal to the difference between the cost of the plant with and without carbon capture as shown in Table 1—\$532.0 million for the PC vs. \$228.0 million for the IGCC plant. 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 from the start for capture, and do not estimate an explicit cost of retrofit. The exception is EPRI (2003).

Table 3
Evaluation of the retrofit decision for a PC plant after 4 years of operation

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
Present value of costs exclusive of carbon charge ($ millions)												
Without carbon capture												
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 at 40%		92.0	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 at 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	(1267.3)											
Retrofitted for carbon capture after 4 years of operation												
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. CO_2 trans. & strg.)		(26.3)	(26.3)	(26.3)	(26.3)	(62.1)	(62.1)	(62.1)		(62.1)	(62.1)	(62.1)
Tax shield at 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 at 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	(2000.4)											
PV incremental cost of capture	(733.2)											
Present value of carbon charge per$1/t$CO_2$ price ($ millions)												
Without carbon capture												
Cash flow per $1/t CO_2 carbon tax						(2.7)	(2.7)	(2.7)	…	(2.7)	(2.7)	(2.7)
After tax						(1.6)	(1.6)	(1.6)		(1.6)	(1.6)	(1.6)
Present value at 6%						(1.2)	(1.1)	(1.1)		(0.2)	(0.2)	(0.2)
NPV through 40 years	(18.83)											
Retrofitted for carbon capture after 4 years of operation												
Cash flow per $1/t CO_2 carbon tax						(0.4)	(0.4)	(0.4)	…	(0.4)	(0.4)	(0.4)
After tax						(0.2)	(0.2)	(0.2)		(0.2)	(0.2)	(0.2)
Present value at 6%						(0.2)	(0.2)	(0.2)		(0.0)	(0.0)	(0.0)
NPV through 40 years	(2.6)											
PV savings from capture per $1/t charge	16.2											
Carbon price required to warrant retrofit ($/t CO_2)	45.29											

i.e., in calendar year 2015. If one considers a different initial carbon price, then the date chosen for retrofit changes; similarly, if one considers a different growth rate for the price, then the date chosen for retrofit also changes.[4] In calculating the costs for a given regulatory scenario, we incorporate the optimal choice of a retrofit date.

Fig. 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 carbon price, but assuming that the price increases at 4% thereafter. As in Fig. 1, the graph for the PC starts at a cost of $1267.3 million when no regulation is imposed and therefore the plant operates without carbon capture. At a low initial carbon price the plant is never retrofitted. However, if we consider successively higher initial carbon prices growing at the 4% rate, 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 begins to fall. Because the date of retrofit is earlier for higher initial carbon prices, the slope of the graph is non-linear in the initial carbon price, declining gradually. Once the price reaches $35/t CO_2 the total cost for the PC plant is $2131.8 million. As in Fig. 1, the graph for the IGCC starts at a cost of $1336.8 million when no regulations are imposed. It becomes optimal to retrofit the IGCC plant even at low initial carbon prices, so that the slope of the line falls sooner. At a $35/t CO_2 the total cost for the IGCC plant is $1807.2 million. The PC technology is cheaper so long as the initial price is less than

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[4] 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.

Table 4
Evaluation of the retrofit decision for an IGCC plant after 4 years of operation

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
Present value of costs exclusive of carbon charge ($ millions)												
Without carbon capture												
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 at 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 at 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 2050, year 40	(1336.8)											
Retrofitted for carbon capture after 4 years of operation												
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. CO_2 trans. & strg.)		(31.2)	(31.2)	(31.2)	(31.2)	(51.0)	(51.0)	(51.0)		(51.0)	(51.0)	(51.0)
Tax shield at 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 at 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	(1679.5)											
PV incremental cost of capture	(342.6)											
Present value of carbon charge per$1/t$CO_2$ price ($ millions)												
Without carbon capture												
Cash flow per $1/t CO_2 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 at 6%						(1.21)	(1.14)	(1.07)		(0.18)	(0.17)	(0.16)
NPV through 40 years	(18.69)											
Retrofitted for carbon capture after 4 years of operation												
Cash flow per $1/t CO_2 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 at 6%						(0.14)	(0.13)	(0.12)		(0.02)	(0.02)	(0.02)
NPV through 40 years	(2.15)											
PV savings from capture per $1/t charge	16.5											
Carbon price required to warrant retrofit ($/t CO_2)	20.72											

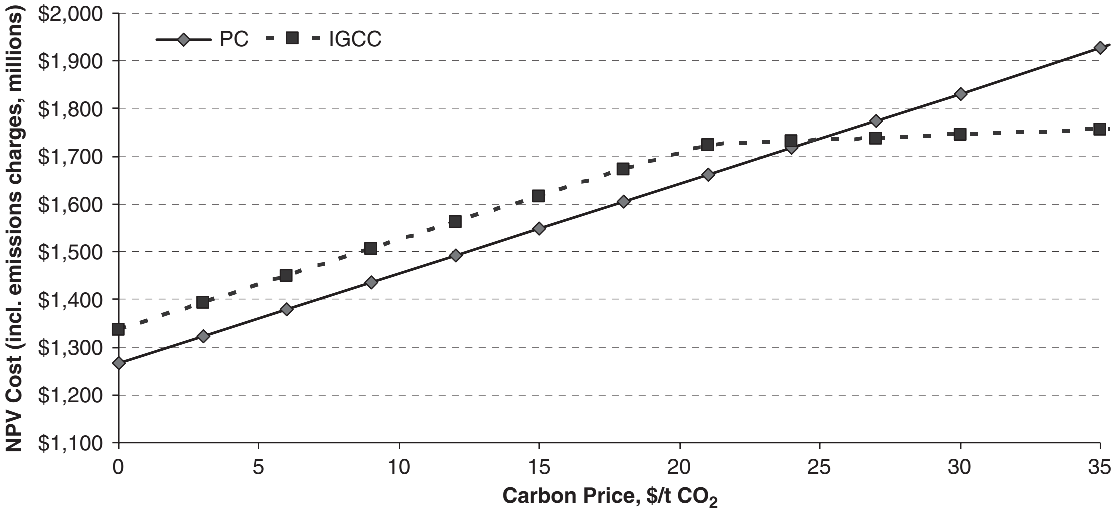

Fig. 1. The NPV of costs for PC and IGCC plants as a function of a carbon price imposed in the 5th year of operation and constant thereafter (costs are incl. of emissions charges).

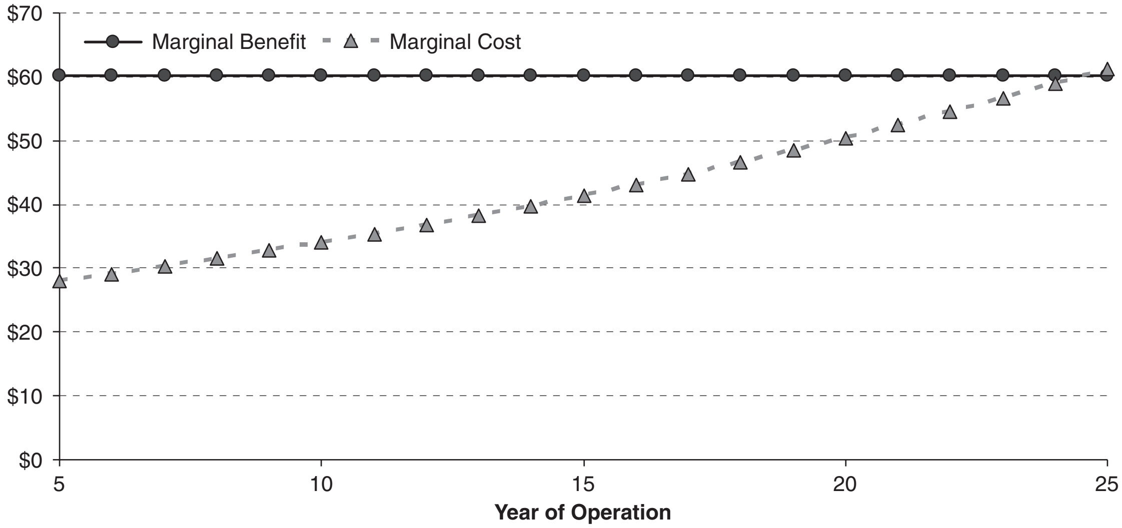

Fig. 2. Marginal benefit and marginal cost of delaying retrofit of a PC plant by 1 year. Assumes an initial carbon price of \$20/t CO_2 growing at 4%/yr. *Note*: Unlike other values shown in this paper which have all been discounted back to year 0 of operation (calendar year 2010), the marginal benefit 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 1 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 price incurred that year.

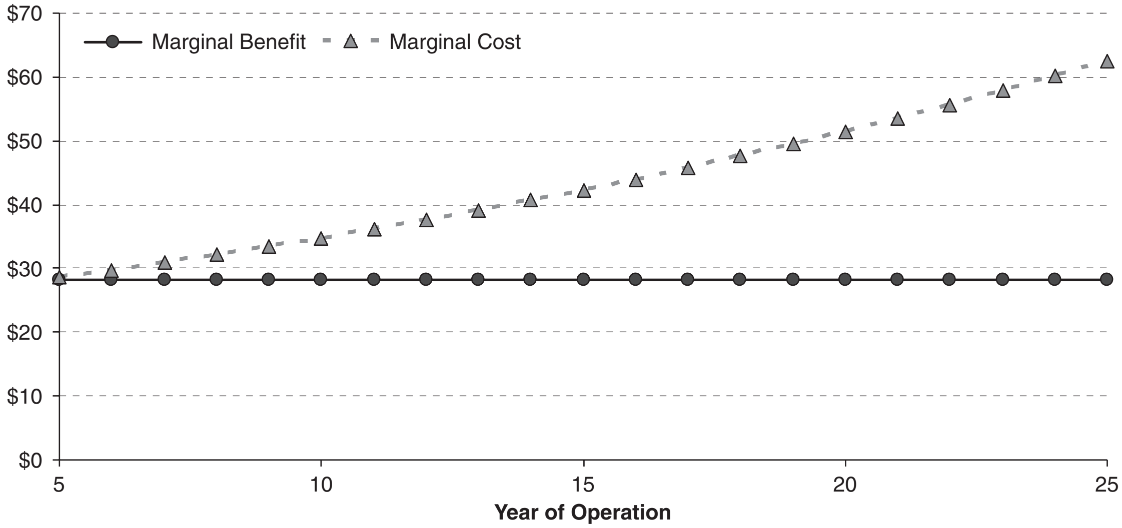

Fig. 3. Marginal benefit and marginal cost of delaying retrofit of an IGCC plant by 1 year. Assumes an initial carbon price of \$20/t CO_2 growing at 4%/yr. *Note*: Unlike other values shown in this paper which have all been discounted back to year 0 of operation (calendar year 2010), the marginal benefit 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 1 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 price incurred that year.

\$13.71/t CO_2. If the initial price is greater than \$13.71/t CO_2, the IGCC technology is cheaper.

4. The initial investment decision—PC or IGCC

The basic tradeoff complicating an electric utility's initial investment decision is clearly illustrated in Figs. 1 and 4. At a zero or low level of a carbon price it is optimal to build the PC plant over the IGCC. On the other hand, if the path of future carbon prices is flat, then for any price above \$23.27/t CO_2, it is optimal to build the IGCC plant. If the carbon price is expected to grow over time at 4% per year, then the switch point occurs at the lower initial price of approximately \$13.71/t CO_2. Clearly whether an electric

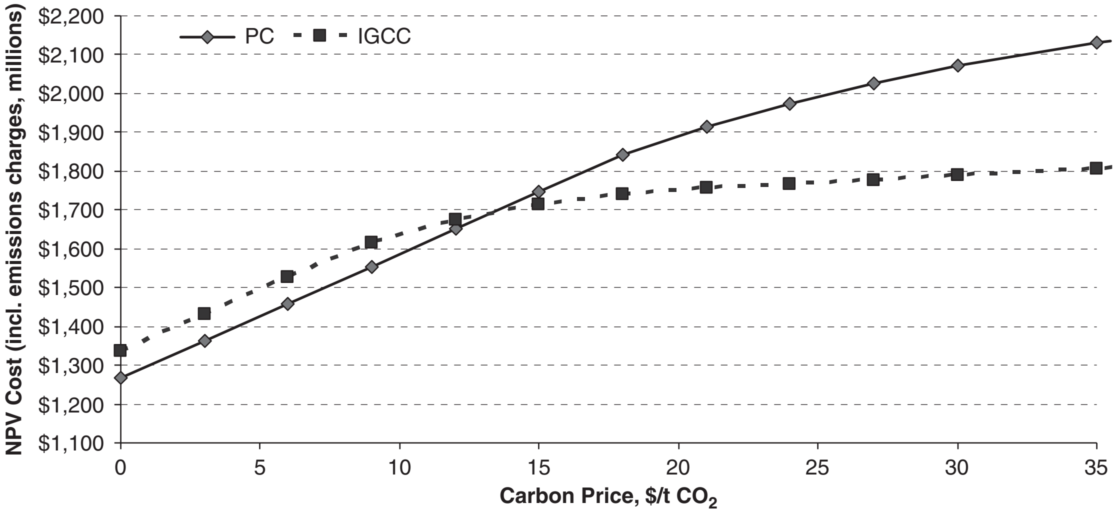

Fig. 4. The NPV of costs for PC and IGCC plants as a function of a carbon price imposed in the 5th year of operation with a 4% growth rate thereafter (costs are incl. of emissions charges).

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 the carbon price.

No one knows with certainty what degree of control will be imposed in the future—if any—and therefore what the level of the carbon price may be. 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 regulation or to the low carbon price scenarios, then it makes sense for it to build PC plants. But if it assigns sufficient probability to the higher carbon price 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, the carbon price 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 complex task—Sekar (2005), for example, uses the real options framework and parameterizes a model of beliefs over the dynamic evolution of regulations. 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.

Fig. 5 shows a matrix of various possible initial carbon prices and various possible growth rates for the price. Consistent with the presentation above, we limit ourselves to future scenarios in which a regulation is initiated in 2015 and the resulting carbon price grows at a constant rate thereafter. This includes the special case of no future regulation, i.e., a $0/t price, at least until 2050, the time horizon considered for this plant's operation. It also includes the case of a flat carbon price starting in 2015 through to 2050.

Dividing the matrix into two regions is a solid line starting at the bottom of Fig. 5 at a price of $23.27/t CO_2 and growth rate of 0% and sloping up and to the left to a price of $7.09/t CO_2 and a growth rate of 8%. 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 of the line or the other.

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. Perhaps the most widely discussed proposal for regulation of carbon emissions in the US has been the McCain-Lieberman proposal. In 2003 the proposal failed but garnered votes from 43 of the 100 Senators. In 2005 it received fewer votes, and an alternative, less stringent proposal was put forward by Senator Bingaman based on

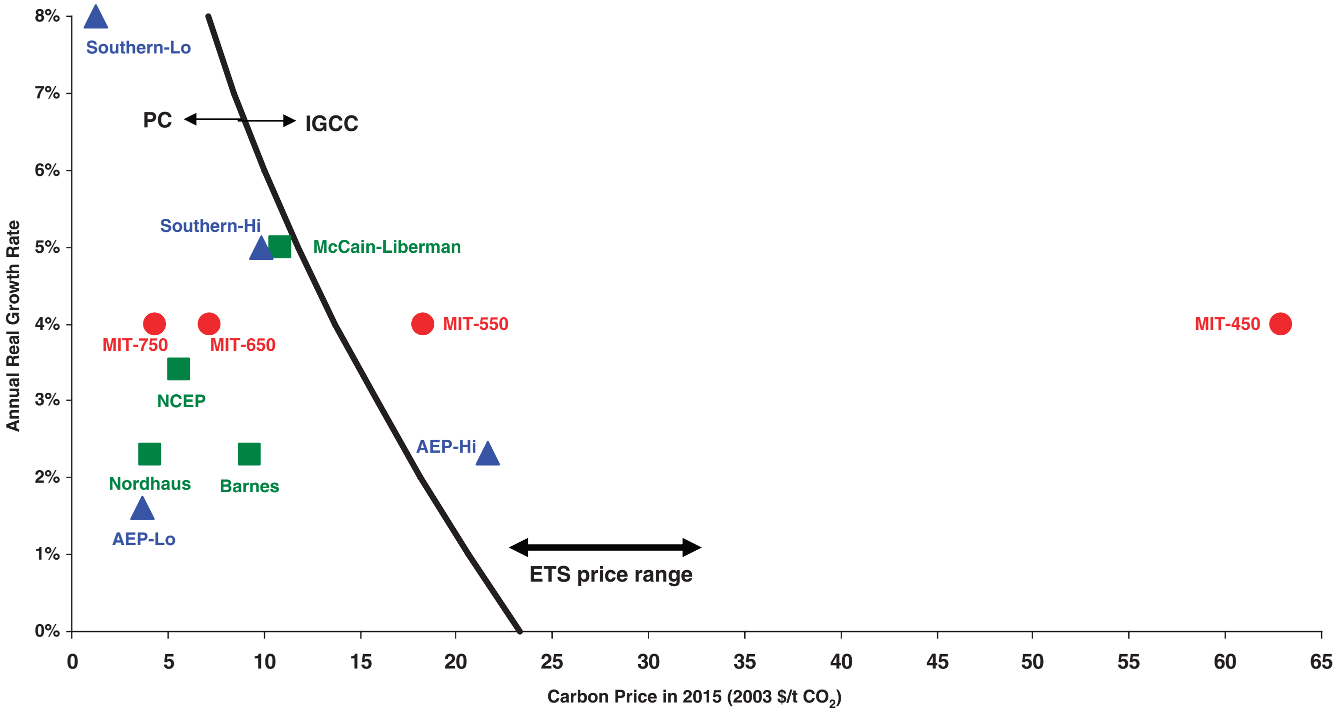

Fig. 5. Benchmark future carbon prices vs. optimal technology choice. The solid line running from the bottom at a CO_2 price of $23.27/t and growth rate of 0% and sloping up and to the left to $7.09/t and a growth rate of 8% defines the switch point at which the expected cost of an investment in a PC 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. Three types of benchmarks are shown. The squares show forecasted carbon prices for regulations proposed by various parties. The triangles show carbon price scenarios used in corporate planning reports. The circles show forecasted carbon prices required to stabilize CO_2 concentrations at various levels. The double-sided arrow near the bottom shows the recent range of carbon emission allowance prices in the European Union ETC.

recommendations made by the National Commission on Energy Policy. These and two other proposals are shown as squares in Fig. 5:

- McCain-Lieberman. Various estimates have been made of the likely carbon price under this legislation. We mark it using results reported by MIT researchers in the time leading up to the 2003 vote, Paltsev et al. (2003, p. 20, Table 6), which showed a cost growing from $8/t CO_2 in 2010 to $10/t CO_2 in 2015 and $13/t CO_2 in 2020 (in 1997 dollars), i.e., growing at a 5% real rate. We translate the 2015 price into 2003 dollars using the ratio of the Producer Price Index (PPI) in 2003 and 1997, 138.1/127.6, yielding $10.82/t CO_2.
- The National Commission on Energy Policy (2004, p. 26) proposed emissions caps that they estimated would yield a price growing from $5/t CO_2 in 2010 and $7/t CO_2 in 2020 (in 2004 dollars), i.e., at 3.4%. We calculate the 2015 price of $5.92/t CO_2 in 2004 dollars and translate this into 2003 dollars using the ratio of the PPI in 2003 and 2004, 138.1/146.7, yielding $5.57/t CO_2.
- Nordhaus and Boyer (2000, p. 133, Table 8.5) derive an optimal policy with an initial carbon tax of $12.71/t C, growing at 2.3% to $31.64/t C in 2055 (in 1990 dollars). We translate the 2015 price into a price per ton CO_2 by dividing by 3.67, and then into 2003 dollars using the ratio of the PPI in 2003 and 1990, 138.1/116.3, yielding $4.11/t CO_2.
- Barnes (2001, p. 66) made an early recommendation for US implementation of some sort of Kyoto-like obligations, but with a safety valve on costs of $25/t C starting in 2003 and rising gradually. We chart this with an annual real growth rate of 2.3%. We calculate the resulting 2015 level of the safety valve, translate it into a price per ton CO_2 by dividing by 3.67, and then into 2003 dollars using the ratio of the PPI in 2003 and 2001, 138.1/134.2, yielding $9.25/t CO_2.

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, at least two U.S. electric utilities have recently published their own consideration of the effect of possible future regulation on their business—AEP (2004) and the Southern Company (2005) complete with scenarios for possible future carbon prices. These are not entirely independent from the earlier group of benchmarks since the scenarios have been chosen as the carbon prices likely to arise from legislation such as the McCain-Lieberman bill or the Carper bill. Nevertheless, since estimates in this regard can differ widely, it is interesting to take note of them. These are shown as triangles in Fig. 5.

- AEP (2004, Appendix B to Annex E) provides a high and low range of CO_2 prices for both the McCain-Lieberman bill and the Carper bill, with the prices for the McCain-Lieberman bill defining the high range and those for the Carper bill the low range. The high price scenario is \$29/t CO_2 in 2015 and \$37/t in 2020, quoted in nominal dollars. Deflating these to real dollar using a 2.5% inflation rate gives a price of \$21.60 growing at 2.31%. The low price scenario is \$5/t CO_2 in 2015 and \$6/t in 2020, which, when deflated, gives a price of \$3.70 growing at 1.6%.
- Southern Company (2005, p. 21) use a high price of \$30/t C (in 2004 dollars) starting in 2010 and growing at 5% and a low price of \$5/t C starting in 2015 and growing at 8% in real terms. For the high price scenario we translate the 2010 price to 2015. Then for both scenarios we translate the figures into a price per ton CO_2 by dividing by 3.67, and then into 2003 dollars using the ratio of the PPI in 2003 and 2004, 138.1/146.7, yielding a high price \$9.82/t CO_2 and a low price of \$1.28/t CO_2.

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 US government's Climate Change Science Program directed certain research institutions to determine the carbon prices required to achieve stabilization scenarios with concentrations ranging from 450 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. Nevertheless, stabilization at 450 ppm is considered by many to be an important target. Stabilization at 550 ppm is also very aggressive relative to current economic activity. In a forthcoming report, MIT's Joint Program on the Science and Policy of Global Change estimated the carbon prices required to achieve each of these scenarios, and the points corresponding to these estimates are charted as the circles in Fig. 5. The MIT analyses are based on a policy scenario whereby all nations apply the same price on carbon emissions and this price 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: \$12/t C in 2010 for 750 ppm, \$20/t C for 650 ppm, \$50/t C for 550 ppm and \$175/t C for 450 ppm. We calculate the resulting 2015 prices using the 4% growth rate, translate it into a price per ton CO_2 by dividing by 3.67, and then into 2003 dollars using the ratio of the PPI in 2003 and 1997, 138.1/127.6, yielding 2015 prices of \$4.31/t CO_2 for 750 ppm, \$7.18/t CO_2 for 650 ppm, \$18.26/t CO_2 for 550 ppm, and \$62.93/t CO_2 for 450 ppm.

A final interesting benchmark against which to view this critical decision is the price at which carbon emission allowances are currently trading in the European Union's Emission Trading System (ETS). Recent prices (July 2005–January 2006) in the ETS have fluctuated between \$23 and \$33/t CO_2. We have marked this range in Fig. 5 with an arrow, and it clearly stands in the region for which IGCC is the preferred 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 permit allocations under the ETS and the costs of compliance across various industries suggests a price less than \$1/t CO_2—see Reilly and Paltsev (2005). But this conjecture has yet to be borne out.[5]

5. Conclusions

Beliefs about future carbon regulation clearly affect the economic case for building new coal-fired power plants using either the PC or the IGCC technology. Electric utilities cannot simply assume that because of the current lack of 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, this bolsters the case that the IGCC technology is the most profitable choice despite the higher initial capital cost.

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. To properly evaluate the profitability of a current investment in either technology, a decision maker must assess the likelihood of different levels of future regulation. We presented the range of possible future levels of regulation in a simple matrix and presented some useful benchmarks.

The matrix in Fig. 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 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.

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[5] Earlier modeling of European commitments under the Kyoto Protocol reached similar conclusions, although results varied widely depending upon assumptions about how the commitments would be implemented, for example, about whether use would be made of Russian and Eastern European hot air—see Babiker et al. (2002), Manne and Richels (2001), Nordhaus (2001), Den Elzen and De Moor (2001) and Böhringer (2001).

This conclusion must be tempered by the fact that actual prices for carbon in Europe are already high enough that, were one to anticipate future US regulation with comparable carbon prices, it would justify a US utility's current investment in IGCC plants so that its units would be capture ready.

This conclusion should also be tempered by the carbon prices required for stabilization at 450 or 550 ppm. If one accepts that goal and looks for future regulations that make it possible to achieve it, then the level of future carbon prices is clearly sufficient to warrant current investments in IGCC plants. On the other hand, if one sees that goal as unrealistic, and looks for future regulations targeted to a higher stabilization level, then the specter of those future carbon prices, by itself, is inadequate to justify current investment in IGCC plants. Other factors, whether federal government subsidies or non-carbon benefits from IGCC technology, would be needed to justify current investment.

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