

# **Retrofitting or Replacing: The Decision of Installing Equipment to reduce emissions from a coal-fired power plant**

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## **Abstract**

In this paper we examine the firm-level decision to buy allowances for an existing plant, retrofit the plant with emissions controls, or build a new plant with emissions control technology. We model the evolution of allowance prices for SO<sub>2</sub>, NO<sub>x</sub>, Hg, and CO<sub>2</sub> using geometric Brownian motion with drift, volatility, and jumps, and use an options-based analysis to find the value of the different investment alternatives.

Our results indicate that even under scenarios with no CO<sub>2</sub> emissions constraints, a decision maker that has a planning horizon longer than ~30 years should choose to replace the old plant instead of retrofitting it. Changes in some of the assumptions about key variables such as lower prices of coal, or the presence of a risk premium in the capital costs of the new technologies, require a longer planning horizon for the replacement strategy to be the preferred option. The introduction of CO<sub>2</sub> emissions constraints favors the replacement of the plant for shorter planning horizons.

## **1 Introduction**

The average U.S. coal-fired electric generator is 34 years old, and 10% of plants are at least 48 years old. The 2005 Clean Air Interstate Rule (capping SO<sub>2</sub> and NO<sub>x</sub> emissions in 28 states), the Clean Air Mercury Rule, state emissions standards, and state and regional CO<sub>2</sub> emission caps force firms to make capital investment choices for their generation assets.

Although some of these programs, for example Pennsylvania's mercury requirement, are command-and-control, most establish a cap-and-trade system with an allowance market. If allowance prices are high over the life of a plant, they may provide an incentive to consider capital investments to reduce emissions.

Here we examine the firm-level decision to buy allowances for an existing plant, retrofit the plant with emissions controls, or build a new plant with emissions control technology. We model the evolution of allowance prices for SO<sub>2</sub>, NO<sub>x</sub>, Hg, and CO<sub>2</sub> using geometric Brownian motion with drift, volatility, and jumps.

We analyze the profitability of investments in controls for emissions that may have an allowance price in the future (Hg and CO<sub>2</sub>) to examine under what circumstances retrofitting coal-fired power plants with equipment to mitigate SO<sub>2</sub> emissions (like a Wet Flu Gas Desulphurization System, WFGD) or NO<sub>x</sub> emissions (like a Selective Catalytic Reduction System, SCR) is preferable to replacing the plant with a Super Critical Pulverized Coal (SCPC) power plant or an Integrated Coal Gasification Combined Cycle power plant (IGCC). For the latter choices, we consider cases with and without carbon capture and sequestration (CCS) under scenarios with and without a carbon dioxide allowance price. Although oxyfuel technology may enter the U.S. generation mix in the future, its costs and operating characteristics are not as well known as those for SCPC and IGCC, and we have not modeled such plants for this study.

We use an options-based analysis to determine the optimal capital investment for owners of an existing pulverized coal power plant should make today, given their beliefs about the future values of key variables that affect the investment outcomes. We use the results of this analysis to identify the key characteristics that air-emissions regulations applying to that plant would have to have to motivate decision makers to invest in CCS. We use as an example an actual 1700 MW plant, but our conclusions apply to a wide range of existing coal generators.

In section 2, we discuss how to value emissions control devices (ECDs) as “insurance policies against high costs of air emissions” using options theory. In section 3 we discuss how to value investments that include the replacement of a plant using the concepts of compound options and disjunctive options. In section 4 we present results of a comparison between different investment alternatives for a large coal-fired power plant under different scenarios. In section 5 we present our conclusions.

## **2 Valuation of a emissions control devices as insurance against high allowance prices**

High prices of allowances and increasing public pressure are forcing large emitters to install scrubbers to reduce SO<sub>2</sub> emissions. Beliefs about future prices of allowances, and the expectation about the time it will be possible to operate the retrofits determines investment decisions.

The backlog in the installment of ECDs (currently vendors of ECDs have all their production sold for the next 5 years) and the expectation of changes in emissions regulations makes real the possibility of a shortage of allowances and the corresponding increase in prices, which motivates us to think of investors as more concerned about the risk of high allowance prices than about the risk of incurring in an irreversible investment than might prove to be suboptimal. Under a scenario with highly volatile prices of emissions allowances, having “insurance” for those high prices might indeed be very valuable. If we look at ECDs as insurance against high prices of allowances, it might be possible to recommend the installation of the ECD even if the expected value of the compliance cost with allowances is lower than the expected compliance cost with the ECD.<sup>1</sup>

The investment on an Emissions Control Device (ECD) that reduces the number of tons emitted of a pollutant regulated with a Cap and Trade (CAT) approach can be seen as an insurance contract against high prices of allowances and valued as such.

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<sup>1</sup> This approach is different from the traditional “real options” approach (Dixit and Pindyck 1994) of investment under uncertainty. Herbelot (Herbelot 1994), and Insley (Insley 2003) examine the problem of whether or not to install an ECD, looking at the ECD as an irreversible investment and the allowances as the alternative that allows delaying such investment. The option to install an ECD is valuable only if it has not been yet exercised, and therefore it may be optimal to rely on allowances even if the present value of the expected cost of compliance with allowances is higher than the present value of the expected cost of compliance with the ECD

If the ECD can be installed and then turned on and off as desired<sup>2</sup>, then every period the plant operator has the “option” of deciding whether to operate the ECD and reduce air emissions or to buy the corresponding allowances in the market. In this sense, the ECD can be seen as an “allowances-producing machine” and can be valued as such using the analogy of “call options” or options to buy<sup>3</sup>.

Turning on the scrubber will have the same practical effect of buying allowances at the O&M cost/ton of pollutant removed, making the installation of the ECD analogous to engaging in a transaction that gives the investor the right, but not the obligation, to “buy” a determined quantity of allowances at a specified price at different time periods. The price “paid” per “allowance” (“strike price” in finance parlance) is the variable operating and maintenance (VOM) cost of the ECD’s (OM cost per ton of pollutant removed). Whenever the capital cost of the ECD is exceeded by the value of these call options, the investment should be undertaken.

In this context “exercising the option” means using the ECD. If the expected lifetime of the ECD is  $T$ , and the expected “generated allowances” at time  $t$  are  $N_t$ , then we can state that installing the ECD is equivalent to getting  $N_1$  call options that will expire at time  $t=1$ ,  $N_2$  call options that will expire at time  $t=2$ , and  $N_T$  call options that will expire at time  $T$ . The number of allowances  $N_t$  that can be “obtained” at time  $t$  cannot be more than the initial emissions at time  $t$  times the removal efficiency of the control. Because we cannot change the throughput of the power plant the option to abate  $N_2$  tons of pollution can be exercised only at  $t=2$  and not earlier or later. In this sense the options obtained by the installation of the ECD are equivalent to European<sup>4</sup> call options.

The time between the decision to install an ECD and the moment when it is ready to operate might be considerable for most technologies. Before the ECD is ready to operate, there will be no emission reductions and therefore no “options” to “buy allowances” will be obtained. If  $\tau$  is the (certain) time when the ECD will be ready, then the present value of installing an ECD is given by Equation 1:

**Equation 1**

$$\int_{\tau}^T N_t Call_0(t, \omega, X_t, r) dt$$

where  $Call_0(t, \omega, X_t, r)$  represents the value at time 0 of a call option that expires at time  $t$  on an underlying asset (allowances) whose future price follows a stochastic process represented by  $\omega$ , when the exercise price is equal to  $X_t$  and the risk-free discount rate is  $r$ .

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<sup>2</sup> This is feasible for both an SO<sub>2</sub> and an SCR because both generally have “bypass” units that allow the flue gas to completely bypass the vessels.

<sup>3</sup> A call option gives the holder the right (but not the obligation) to buy the underlying asset by a certain date for a certain price. The price agreed in the contract is known as the “exercise price” and the date is known as the “expiration date”.

<sup>4</sup> European options are those options that can be exercised only on the expiration date itself.

The installation decision rule is therefore given by a comparison between the ECD's capital cost and the value of the call options bundle.

## 2.1 The option to buy one allowance

A common assumption about stock prices that facilitates enormously the calculation of the value of financial options is that they follow Geometric Brownian Motion (GBM), that is that at each point in time, the log of the stock price  $A_t$  follows a normal distribution or equivalently that the stock price follows a log-normal distribution. This assumption is consistent with the Hypothesis of Efficient Markets assumed to hold for stock markets: current prices are the best estimate of future prices.

Because both SO<sub>2</sub> and NO<sub>x</sub> allowances markets involve many participants and transactions (EPA 2006), (Burtraw, Evans et al. 2005), and have now become more active with futures traded for as far as 2010 it is fair to say that the assumption of GBM for SO<sub>2</sub> and NO<sub>x</sub> allowances prices is at least in principle acceptable. We can say the same for CO<sub>2</sub> and Hg allowances.

Structural factors such as improving ECD technology or increasing ECD demand can cause a slow drift of prices up or down. Assuming that allowance prices follow Geometric Brownian Motion<sup>5</sup> (GBM) with drift (or expected rate of change in the price of allowances)  $\mu$ , and volatility  $\sigma$ , so  $\frac{dA}{A} = \mu dt + \sigma dz$ , the value of a European Call

Option on a commodity can be calculated as shown by McDonald and Siegel (McDonald and Siegel 1985)<sup>6</sup>:

### Equation 2

$$Call_0(t, A_0, \omega = GBM(\mu, \sigma), X_t, r) = A_0 e^{-\delta t} \Phi(d_1) - X_t e^{-rt} \Phi(d_2)$$

$$d_1 = \frac{\ln\left(\frac{A_0}{X_t}\right) + \left(r - \delta + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}}, \quad d_2 = d_1 - \sigma\sqrt{t}$$

Where  $A_0$  is the price of allowances at time 0,  $X_t$  is the exercise price (or ECD's variable O&M cost per ton of pollutant abated at time t),  $\Phi(x)$  is the cumulative distribution function (cdf) of the standard-normal distribution,  $r$  is the risk-free rate,  $\sigma$  is the volatility of the process that describes allowance prices, and  $\delta$  called the "payout rate" or "return shortfall" is given by

### Equation 3

$$\delta = \mu_s - \mu$$

where  $\mu_s$  is the risk-adjusted expected return on allowances, or the equilibrium rate of return on a financial asset which has the same covariance with the market as allowances prices and  $\mu$  represents the expected rate of change in the price of allowances. If  $\mu_m$  is

<sup>5</sup> See a good introduction of Wiener processes and GBM on Hull 1997.

<sup>6</sup> Shown by McDonald and Siegel 1985, indirectly shown by Merton 1973 Merton, R. C. (1973). "Theory of Rational Option Pricing." Bell Journal of Economics and Management Science 4: 142-183.

the expected rate of return of the market portfolio,  $\sigma_m$  is the variance of the rate of return of the market portfolio, and  $\rho_m$  is the correlation coefficient between the rate of return of the market portfolio and the return on the commodity then according to the Capital Asset Pricing Model CAPM<sup>7 8</sup>,

**Equation 4**

$$\mu_s = r + \frac{(\mu_m - r)}{\sigma_m} \rho_m \sigma$$

### 2.1.1 Characterizing the uncertainty in allowances prices: GBM with jumps

The assumption of GBM with constant drift and volatility for a long period of time can be difficult to justify for allowance prices. Regulations changes and other factors can have a noticeable effect in the price of allowances causing sudden up or down movements in the prices which implies that we can think of the long-term process of allowance prices as a GBM with jumps in which the parameters might change.

Here we characterize the uncertainty on prices specifying scenarios in which prices jump from one GBM process to another at a known time. We use information about upcoming regulation changes and future prices to set the timing of the jumps, their size, and the drift parameters for the GBM processes of each sub period. To calculate the  $\delta$  parameter we assume  $\mu_s = r + 2\%$ .

For characterizing the jumps and estimating the drifts of SO2 and Hg allowance prices we use the forecast of the Annual Energy Outlook (AEO) (EIA 2006) which is based on information about unit's retirements and installations of abatement equipment. The process for prices of CO2 will be informed by observed prices in the EU ETS.

The AEO 2006 (EIA 2006) forecasts indicate that SO2 allowance prices will rise to nearly \$890 per ton in 2015 and will remain between \$880 and \$980 per ton from 2015 through 2030<sup>9</sup>. For SO2 allowances we assume a starting price of \$539 which is the closing price on October 31 2006<sup>10</sup>. We also assume SO2 allowances follow a GBM process with a volatility equal to the one observed in the 30 months of historical data from 03/15/04 to 10/31/06 and a drift that reflects the trend that would allow prices to evolve from \$539 to the value forecast by AEO 2006 in 2015 ( $\mu = i + 0.0106, \sigma = 0.05$ ) from  $t = 2006$ , to  $t = 2015$ , and then jump to a value of \$890 (2004 dollars) and follow a GBM process ( $\mu = i, \sigma = 0.3$ ).

<sup>7</sup> The assumption here is that there is a dynamic portfolio of assets whose price is perfectly correlated to At.

<sup>8</sup> For risk-neutral investors  $\mu_m = r$  which makes  $\mu_s = r$ , implying that  $\delta = r - \mu$ . In the case of  $\mu = r$  (as is the case of a non-dividend paying stock)  $\delta = 0$ , and Equation 2 becomes the well known Black and Scholes equation for an European call option on a stock.

<sup>9</sup> AEO 2006 page 104. We assume figures are given in 2004 dollars, as is the case throughout the report.

<sup>10</sup> We choose to assume a GBM with drift and volatility given by the estimates from a long historical data series (the last 30 months) because the "options" we are valuing are long lived.

For NOx we assume a starting price equal to the October 31, 2006 price of allowances for vintage 2007, a volatility of 0.3, a drift equal to the inflation rate minus 0.05, and no jumps.

We assume the price of mercury allowances follows the AEO 2006 forecast, that is mercury allowances jump to a price of \$23,400 /lb in 2010 (2004 dollars) and follow a GBM process  $(\mu = i + 0.0718, \sigma)$ <sup>11</sup>, and then jump again in 2020 to \$48,000 (2004 dollars) to follow GBM  $(\mu = i + 0.0256, \sigma)$ .

Our baseline scenario for CO2 allowances prices corresponds to the case in which there are no changes in emissions regulations and CO2 allowances prices are zero. Later we analyze alternative scenarios in which CO2 emissions reductions become valuable.

If we expect the price process of allowances to start at a current price of  $A_0$  and evolve according to  $GBM(\mu, \sigma)$  and then at year  $T_j$  to jump to a price process for which the current price would be  $A_j$  and evolves according to  $GBM(\mu_j, \sigma_j)$  the value of the investment of Equation 1 changes to<sup>12</sup>:

### Equation 5

$$\int_{\tau}^{T_j} N_t Call_0(t, A_0, GBM(\mu, \sigma), X_t, r) dt + \int_{T_j}^{\tau} N_t Call_0(t, A_j, GBM(\mu_j, \sigma_j), X_t, r) dt$$

## 2.2 The “basket options” analogy

Besides reducing SO2 emissions, the operation of a WFGD reduces mercury emissions. For the plant analyzed in this paper the operation of the WFGD causes a reduction of 431 lbs mercury per year. Therefore the installation of the WFGD gives the option of getting simultaneously in a “basket” both SO2 and mercury “allowances” at a price equal to the OM cost of the WFGD. We can treat the “basket” of allowances as a single underlying asset and apply the same reasoning as before to value the investment. The payoff of the investment is then given by Equation 1, but in this case the call option is on a basket that contains one SO2 allowance and 2.9206e-3 allowances of mercury<sup>13</sup>.

The stochastic process followed by  $B_t$  is also assumed to be GBM with parameters estimated from the simulation of several uncorrelated observations of both SO2 and mercury allowances. The final drift and volatility estimates are obtained from the average of the drift and volatility obtained for each series.

<sup>11</sup>  $\hat{\mu}_1 = Ln\left(\frac{48,000 * \exp(i * (2020 - 2010))}{23,400}\right) / (2020 - 2010) = i + 0.0718\%$  where  $i$  is the average inflation rate

for the period 2010 and 2020. Similarly,  $\hat{\mu}_2 = i + 2.56\%$ .

<sup>12</sup> Note that in this case, we are specifying two different price processes that have different initial values and parameters. The jump is from one of these price processes to the other one. Expressing the jump in this way allows us to calculate the value of the option today and discounting is not necessary. Also expressing the mark-up price  $A_j$  as a price in today’s dollars facilitates the interpretation of different scenarios.

<sup>13</sup> Allowances of SO2 are given in tons; allowances of Hg are given in pounds. The operation of the WFGD reduces 435/147,637 pounds of Hg per ton of SO2 removed.

Although the random variable that results from adding two lognormal random variables does not have a lognormal distribution it is common to assume so, because it has been shown that the practical consequences of this imprecision are negligible<sup>14</sup>.

### **3 Considering the installment of a new “clean-coal” power plant**

It is prudent to consider the option of replacing the old coal-fired power plant with a new “clean-coal” generating plant that besides reducing emissions of SO<sub>2</sub> will reduce emissions of NO<sub>x</sub>, mercury and CO<sub>2</sub> and will allow savings in fuel and reductions in other O&M costs.

The most promising “clean coal” technology is the IGCC in which coal is turned into fuel gas to drive a gas turbine (with the waste heat driving a steam turbine). The CO<sub>2</sub> can be separated from the fuel gas and captured, transported and stored/sequestered at a cost per ton lower than what could be achieved with post-combustion CO<sub>2</sub> capture systems at coal-fired power plants (Rubin, Rao et al. 2004). A SCPC is another alternative which can make cheaper the abatement of CO<sub>2</sub> emissions. In a supercritical, the operating pressure in the evaporator part of the boiler exceeds 22.1MPa, and creates a homogeneous mixture of water and steam that makes unnecessary the separation of water and steam that is required in sub critical boilers before the steam is heated and led into the turbine. While old sub critical coal-fired power plants have efficiencies lower than 30% current SC and IGCC plants can have efficiencies above 40%. The increased efficiencies of both alternatives imply that less energy is fed into the cycle to get electricity and therefore air emissions of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub> and particulates are lower.

The investment value of a given ECD is the sum of the payoffs associated to O&M costs and the five relevant commodities; fuel, and SO<sub>2</sub>, NO<sub>x</sub>, mercury, and CO<sub>2</sub> allowances. As discussed below, the payoff associated with each commodity might be calculated using an “options”, “compound option”, “forward contract”, “basket option” or “disjunctive option” analogy.

#### **3.1 When there is no flexibility to stop reducing emissions: The “Forward Contract” analogy**

Even if the ECDs that control emissions in an SCPC plant are turned off there are still emissions reductions (relative to the baseline plant) that occur because of improved efficiency. Similarly, for the IGCC the reductions of SO<sub>2</sub>, NO<sub>x</sub> and mercury emissions are not a decision variable and therefore we cannot use the analogy of call options to value those benefits. Obtaining a constant reduction of for example SO<sub>2</sub> emissions is equivalent to having a bundle of forward contracts to purchase SO<sub>2</sub> allowances for every year the SC is online. We can see that the installation of an IGCC is equivalent to buying a forward contract for SO<sub>2</sub>, NO<sub>x</sub>, and mercury allowances. Also for the SC we can say that its installation gives both call options and forward contracts.

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<sup>14</sup> It is common to assume that indexes of stocks follow GBM even though it is also assumed that stocks prices follow GBM.

If the process followed by future SO2 allowances prices is given by  $\omega^{SO_2} = GBM(\mu^{SO_2}, \sigma^{SO_2})$  we have that the present value of one allowance delivered at time  $t$  is given by

**Equation 6**

$$f(0, t, A_0^{SO_2}, \omega^{SO_2}, r) = e^{-\delta^{SO_2} t} A_0^{SO_2} \quad \text{where } \delta^{SO_2} = \mu_s^{SO_2} - \mu^{SO_2} \text{ as in Equation 3.}$$

**3.2 The option to install an ECD in the future: The “compound option” analogy**

Installing an SC or an IGCC allows the subsequent installation of a carbon capture and sequestration system (CCS). The benefits that come with the possibility of installing a CCS can be seen as a “compound option” or “the option of buying options” (See section 11.2 of Willmott, 2002). The installation of a CCS system can be valued with Equation 1, that is, using the options analogy and modeling its installation as providing “call options” on CO2 allowances. In this way installing an SC or an IGCC gives a compound option on CO2 allowances<sup>15</sup>.

The option of installing a CCS can be exercised at any time before the end of the lifetime of the plant, so the payoff corresponding to the alternative of installing a CCS system is equal to the value of installing a CCS at time  $t^*$ , for the  $t^*$  that maximizes its value:

**Equation 7**

$$Payoff^{CO_2} = Max\left(0, Value \text{ of Option Of Installing CCS at time } t^* \text{ for } \tau \leq t^* \leq T\right)$$

If installing a CCS at time  $t^*$  gives a stream of call options on CO2 allowances for years  $t^* + \nu$  on, then its payoff is given by:

**Equation 8**

$$Payoff \text{ Of Installing CCS at time } t^* \text{ (in today's \$)} = N^{CO_2} \sum_{t=t^*+\nu}^T call(0, t, X_t^{CO_2}, A_0^{CO_2}, \omega^{CO_2}, r)$$

where  $\nu$  is the time it takes to complete the installment of the CCS system.

The value of the option of installing a CCS at time  $t^*$  by paying the capital cost  $K_{t^*}^{CCS}$  is equal to the difference between the discounted value of  $K_{t^*}^{CCS}$  and the payoff of installing a CCS at time  $t^*$ , or zero, whichever is larger<sup>16</sup>. Assuming CO2 allowance prices evolve according to GBM with drift  $\mu^{CO_2}$ , and volatility  $\sigma^{CO_2}$  we have:

<sup>15</sup> As it will be discussed later, the installation of a scrubber on the old plant also gives the option of installing a post-combustion amine-based CO2 capture system (with higher Capital and O&M costs). We account for this later in section 5 where we compare the value of the investments of all alternatives.

<sup>16</sup> Because the capital cost is a certain quantity we discount it at the risk-free rate.

### Equation 9

$$\text{Value Option Installing CCS at time } t^* = \text{Max} \left( 0, -e^{-rt^*} K_t^{CCS} + N^{CO2} \sum_{t=t^*+v}^T A_0^{CO2} e^{-\delta t} \Phi(d_1) - X_t^{CO2} e^{-rt} \Phi(d_2) \right)$$

With  $d_1$  and  $d_2$  defined as in Equation 2, and  $\delta^{CO2}$  as in Equation 3.

### 3.3 CCS and Disjunctive options

The formula proposed for valuing a CCS in the previous section must be modified to incorporate SO<sub>2</sub> control. Both for pre-combustion and post combustion CCS systems it is necessary to remove the SO<sub>2</sub> from the flue gas before capturing the CO<sub>2</sub>. This implies that the option of operating the CCS to achieve CO<sub>2</sub> reductions comes together with the “obligation” to reduce SO<sub>2</sub> emissions. Because the CCS cannot be operated without operating the WFGD but the WFGD can be operated without operating the CCS, then having a CCS in a pulverized coal plant presents a set of 3 mutually exclusive or “disjunctive” options: a) to operate the WFGD, b) to operate both the WFGD and the CCS, and c) to operate the plant without WFGD or CCS. The operation of the WFGD as it has been said before gives call options on a basket that contains SO<sub>2</sub> and mercury allowances<sup>17</sup>. In turn the operation of the CCS besides reducing CO<sub>2</sub> emissions causes also further reductions in SO<sub>2</sub>, and mercury and a modest additional reduction of NO<sub>x</sub> emissions<sup>18</sup>. Therefore the installation of a CCS gives the option to choose between call options on two different baskets; one basket with SO<sub>2</sub> and mercury allowances and another basket with more SO<sub>2</sub>, mercury, CO<sub>2</sub> (and NO<sub>x</sub>) allowances. The value of a disjunctive option is the maximum value between the two exclusive options.

### Equation 10

$$\text{Payoff Of Installing CCS at time } t^* \text{ (in today's \$)} = \max[\text{call}(\text{Basket1}), \text{call}(\text{Basket2})]$$

### 3.4 Retrofitting an IGCC with CCS

In the case of a newly installed SC the costs of later adding a CCS are not significantly larger than the costs of adding the CCS at the time of installation of the plant, provided that the plant is designed with that in mind. For an IGCC the same is not as clear. Combustion turbines in a power plant are designed according to the quantity and characteristics of the fuel used. In an SC the CCS is a post-combustion system and there are no changes in the conditions of the combustion component of the plant. Instead, in an IGCC, the CO<sub>2</sub> is removed from the fuel gas previously to the combustion and therefore the specifications for the combustion system of an IGCC with CCS differ significantly from those of an IGCC without a CCS. An investor that today wants to build an IGCC thinking that maybe in the future it will be necessary to install a CCS system has two alternatives; 1) to install an IGCC that operates optimally without a CCS and, later on

<sup>17</sup> If the WFGD is limestone (CaCO<sub>3</sub>) based then in a SC plant the operation of the WFGD will increase CO<sub>2</sub> emissions by 2 pounds per MBtu because CO<sub>2</sub> from the limestone is generated from the process (CaCO<sub>3</sub>=CaO+CO<sub>2</sub>). In this case the “basket” obtained with the operation of the WFGD includes negative CO<sub>2</sub> allowances.

<sup>18</sup> NO<sub>x</sub> emissions from an IGCC with CCS are 0.07e-2 lbs/MBtu lower than the reference IGCC. NO<sub>x</sub> emissions from an SC+WFGD+SCR+CCS are 1.9e-3 lbs/MBtu lower than the SC+WFGD+SCR (From the IECM-cs).

when the CCS is installed, to change major components in the plant (probably changing the combustion turbines) and 2) to install an IGCC that would operate optimally if it had a CCS system in place but that is suboptimal compared to 1) when it is operated before the CCS is installed. Alternative 2) can be labeled as “capture ready” and implies larger capital costs and O&M costs than 1) but lower CCS retrofit costs. In our analysis in the next section we consider both alternatives.

#### **4 Comparative value of installing different ECDs or replacing a dirty large power plant**

In this section, we find and compare the value of nine different investments that could be made today to reduce air emissions from a large coal-fired power plant. The plant analyzed resembles closely a major emitter of SO<sub>2</sub>, NO<sub>x</sub>, Hg, and CO<sub>2</sub> whose managers have recently committed to install a scrubber<sup>19</sup>. The nine different investments considered are:

1. Installing a WFGD
2. Installing an SCR system
3. Installing both a WFGD and an SCR system
4. Installing a WFGD an SCR and a CCS (amine-based) system
5. Replacing the plant with a new SC plant (includes an ESP, WFGD and SCR)
6. Replacing the plant with a new SC with CCS (amine-based system)
7. Replacing the plant with a new IGCC “CO<sub>2</sub>-capture ready” plant
8. Replacing the plant with a new IGCC with CCS (selexol based system)
9. Replacing the plant with a new IGCC plant

The installment of the SC and IGCC gives the option to install a CCS system later. Because the installation of one ECD on the original plant does not preclude the installation of the other ones, in quantifying the investment value of the WFGD, the SCR or the WFGD, we account for the option of installing later the other ECDs (an SCR and CCS in the case of the WFGD, a WFGD and CCS in the case of the SCR, and a CCS in the case of the WFGD+SCR).

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<sup>19</sup> Hatfield’s Ferry power station in Green County, Pennsylvania was the second largest U.S. emitter of SO<sub>2</sub> (165,695 tons) in 2002 and 5th by emissions rate (33.8lbs/MWh). It also emitted 23,234 tons of NO<sub>x</sub> (4.74lbs/MWh), and 10 million tons of CO<sub>2</sub> every year (1ton/MWh). In July 2006 Allegheny Energy, Inc announced plans to install flue gas desulphurization equipment at Hatfield's Ferry Power Station to reduce the plant's sulfur dioxide emissions by approximately 95 percent. The plant analyzed in this paper is similar to Hatfield in size, emissions amount, annual capacity utilization, and net efficiency. Our assumptions about capital costs for retrofits are 50% lower than what has been reported in the news for Hatfield.

#### 4.1 Costs and performance of alternative technologies, allowances prices and other assumptions

The operational characteristics of the baseline plant and the capital and OM costs of emissions controls and replacement plants shown in Table 2<sup>20</sup> have been obtained from the Integrated Environmental Control Model-Carbon Sequestration Edition (IECM-cs), version 5.1.3(c) (CMU 2006)<sup>21</sup>, assuming extra-costs of installing add-on equipment after the plant has been built (retrofitting) are as given in Table 1

Plant	Retrofits	Retrofit factor
Old Pc	WFGD	1.2
	SCR	
	SCR on top of WFGD	
	WFGD on top of SCR	
	WFGD+SCR	
SC	CCS (Amine)	1.2
IGCC "Capture ready"	CCS (Selexol)	1
IGCC	CCS (Selexol)	1.4

**Table 1: Retrofit Factors for each type of plant. Multiply Capital Costs given by IECM to obtain cost of retrofitting**

Availability of the new plants is assumed to be 83%, and the nameplate capacity is selected so the electricity generation is roughly the same as the one generated by the original plant. We assume there are no extra costs in delaying the installation of the CCS system on the IGCC “capture ready” plant. Table 2 and Table 3 summarize the characteristics of the nine possible investments:

Investment	Gross Electrical Output (MW)	Gross Plant Heat Rate HHV (Btu/kWh)	Capacity Factor (%)	Annual Operating Hours	Base Plant Energy Requirements (Boiler+ESP use) (MW)	Net Electrical Output (MW)	Annual Gross Power Generation (BkWh/yr)	Capital cost (\$M)	OM Base Plant (Excluding fuel) (\$M/yr)	Fuel Consumed (MBtu)
Base line Plant	1,836	10,120	65	5,698	108	1,728	9,850		46	105,870,663
WFGD	"	"	"	"	"	1,691	"	175	"	"
SCR	"	"	"	"	"	1,717	"	111	"	"
WFGD+SCR	"	"	"	"	"	1,680	"	286	"	"
WFGD+SCR+CCS	"	"	"	"	"	1,205	"	1,422	"	"
SC	1,370	7,960	83	7,644	89	1,236	9,802	1,580	41	83,359,349
SC+CCS	"	"	"	"	"	912	"	2,100	"	"

<sup>20</sup> The Gross Electrical Output, the Capacity Factor, and the types of installed environmental controls are inputs in the IECM model, while emissions and costs are outputs. We have chosen a type of coal for which resulting emissions of the baseline plant match reported numbers for Hatfield on the EGRID database (EPA, U. S. (2002, May 1st 2006). "eGRID2002yr00\_plant.xls." from <http://www.epa.gov/cleanenergy/egrid/archive2002.htm>).

<sup>21</sup> The IECMcs model is a tool for calculating the performance, emissions, and cost of a fossil-fueled power plant developed by the Department of Engineering and Public Policy of Carnegie Mellon University with support from the United States Department of Energy's National Energy Technology Laboratory NETL.

IGCC "capture ready"	1,485	8,820	83	"	196	1,289	9.851	2,339	65	100,118,819
IGCC+CCS	"	"	"	"	"	1,236	9.851	2,982	"	"
IGCC	1,534	8,038		"	185	1,349	10.308	2,231	63	94,252,752

**Table 2: Operating characteristics and costs of retrofits and replacement plants**

(a) Supercritical boiler unit; environmental controls include SCR, ESP and FGD systems, followed by MEA system for CO<sub>2</sub> capture; SO<sub>2</sub> removal efficiency is 98% for reference plant and 99% for capture plant.

(b) Based on Texaco quench gasifier (2 + 1 spare), 2 GE 7FA gas turbine, 3-pressure reheat HRSG with steam parameters 1400 psig/1000 F/1000 F. Sulfur removal efficiency is 98% via hydrolyser + Selexol system; Sulfur recovery via Claus plant and Beavon-Stretford tailgas unit.

(c) CO<sub>2</sub> costs of sequestration based on pipeline transport distance of 161 km (100 miles); CO<sub>2</sub> stream compressed to 13.7 MPa (2000 psig) with no booster compressors.\* All costs given in 2007 dollars.

Investment	Annual Emissions					Energy consumed by the ECDs (kWh/yr)	OM of the ECDs (not including electricity) (\$M/yr)	
	SO <sub>2</sub> (tons/yr)	NO <sub>x</sub> (tons/yr)	Hg (lbs/yr)	CO <sub>2</sub> (tonne/yr)	Particulate (tons/yr)			
Baseline Plant	164,841	28,442	584	9,796,506	1,588			
WFGD	31,915	28,442	196	9,796,506	1,588	211,054		18.09
SCR	164,841	7,940	584	9,796,506	1,588	61,026		9.14
WFGD+SCR	31,915	7,940	196	9,796,506	1,588	as in rows 1 and 2		
WFGD+SCR+CCS	19	7,840	60	989,735	794	2,708,829	145.33	for CCS
						WFGD and SCR as previous		
SC	3,044	6,252	47	7,789,094	1,250	289,784	17	WFGD
						56,428	9.01	SCR
SC+CCS	15	6,173	47	778,909	625	2,479,714	119.65	CCS
						WFGD and SCR as in previous		
IGCC "Capture ready"	3,383	1,051	552	8,987,252	50			
IGCC+CCS	254	1,018	56	842,867	50	404,597	86.42	CCS
IGCC	3,184	990	520	8,460,679	47			

**Table 3: Air emissions from different plants/configurations**

The O&M costs for each component of the plant do not include an electricity penalty. We assume the electricity used to operate the ECDs can be purchased and sold at the same price for all the investment strategies, and use this price to account for the energy penalties in each case, and for the extra electricity that could be generated with the SC relative to the original plant. Assumptions about electricity, coal and OM costs are:

Parameter	Initial Value	Annual drift parameter
Coal Price (\$/Mbtu)	1.269	i
Electricity Price (\$/MWh)	55	i
OM excluding fuel	Old PC	i
	SC	i
	IGCC ready	i
	IGCC	i

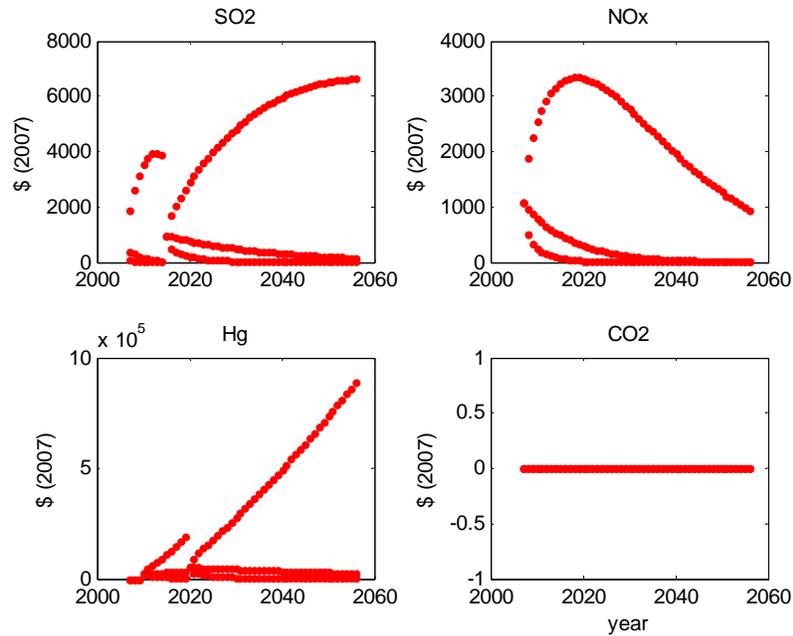
**Table 4: Assumptions about electricity price, coal price, and OM Costs**

## 4.2 Base case Scenario

Table 5 describes the baseline scenarios for allowances prices as they have been described in section 2.1.1 and Figure 1 shows the corresponding 95<sup>th</sup>-confidence intervals.

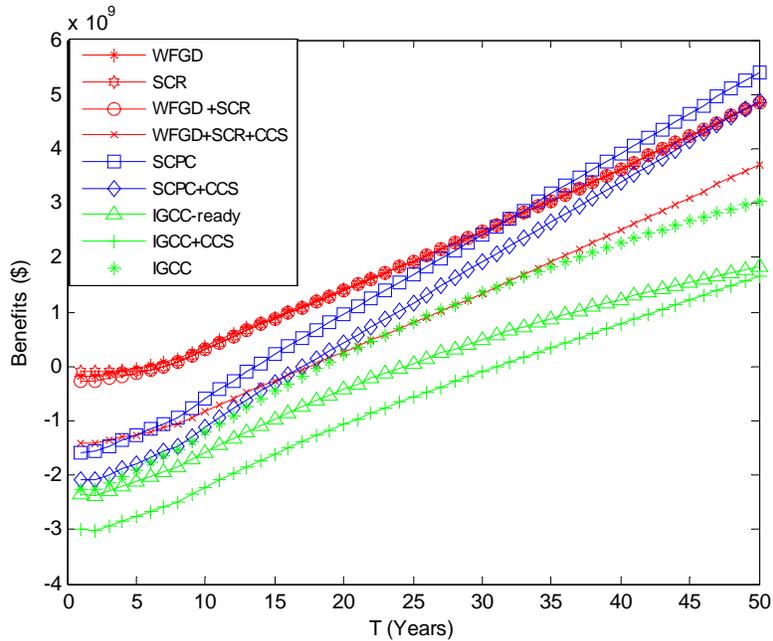
Pollutant	Scenario # 2: Parameters of processes for allowances prices										
	initial value*	GBM		Year Jump	Jump Price*	New GBM		Year Jump	Jump Price*	New GBM	
		$\mu$	$\sigma$			$\mu$	$\sigma$			$\mu$	$\sigma$
SO2	539	0.0506	0.78	2015	1394.8	0.04	0.3	-	-	-	-
NOx	1,075	i-0.05	0.3	-	-	-	-	-	-	-	-
Hg	0	0	0	2010	23,753	i+0.0718	0.3	2020	52,785	i+0.02559	0.3
CO2	0	0	0	-	-	-	-	-	-	-	-

**Table 5: Base case scenario: Parameters of process followed by allowances prices**



**Figure 1: 95%-Confidence Intervals for Baseline Scenarios**

Figure 2 shows a comparison of the value of the 9 possible investment strategies for the case in which SO2 mercury, NOx and CO2 allowances evolve according to the corresponding baseline scenarios.



**Figure 2: Value of different investment alternatives when lifetime T, and allowances prices are as in baseline scenarios (no CO2 price)**

In this case the SCPC investment becomes a competitive alternative for planning horizons longer than 35 years; for shorter planning horizons the best strategy is to retrofit the old plant. The higher value of the SCPC is due in part to the fuel savings corresponding to its higher efficiency (39% HHV) relative to the PC plant (33.68% HHV) and the IGCC plant(37.33%), and its lower capital costs relative to the IGCC plant.

### 4.3 Alternative Scenario: CO2 emissions regulations become valuable in the future

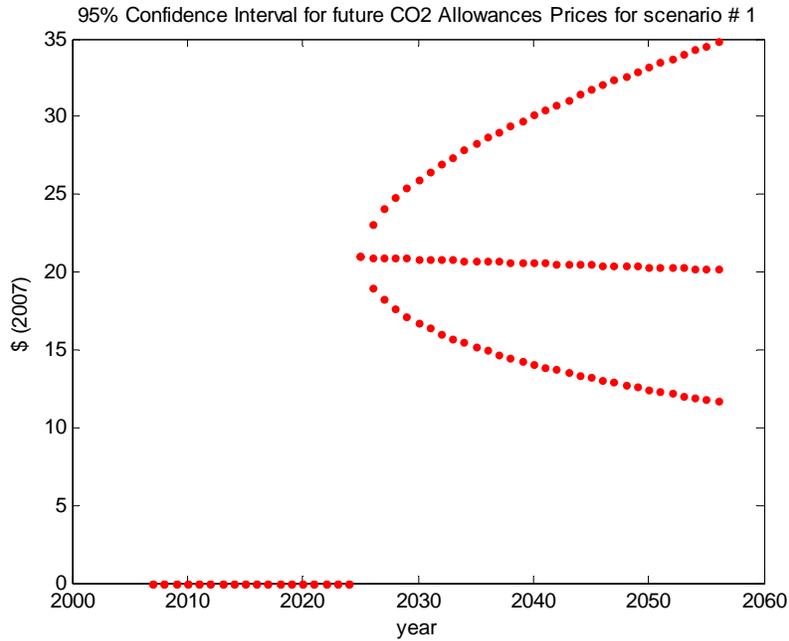
How would the investment value of the different alternatives change if CO2 emissions reductions are expected to become valuable in the future? Consider a scenario in which it is expected that a Cap-and-trade program for CO2 will start in year 2025 with prices of allowances equal to the price of Oct 31<sup>st</sup> 2006 at the EU ETS (\$20.99/tonne). Assume prices are expected to evolve according to a GBM with a low volatility of 0.05. The new scenario for CO2 prices is described in Table 6.

Pollutant	Scenario # 2: Parameters of processes for allowances prices										
	initial value*	GBM		Year Jump	Jump Price*	New GBM		Year Jump	Jump Price*	New GBM	
		$\mu$	$\sigma$			$\mu$	$\sigma$			$\mu$	$\sigma$
CO2	0	0	0	2025	20.99	0.04	0.05	-	-	-	-

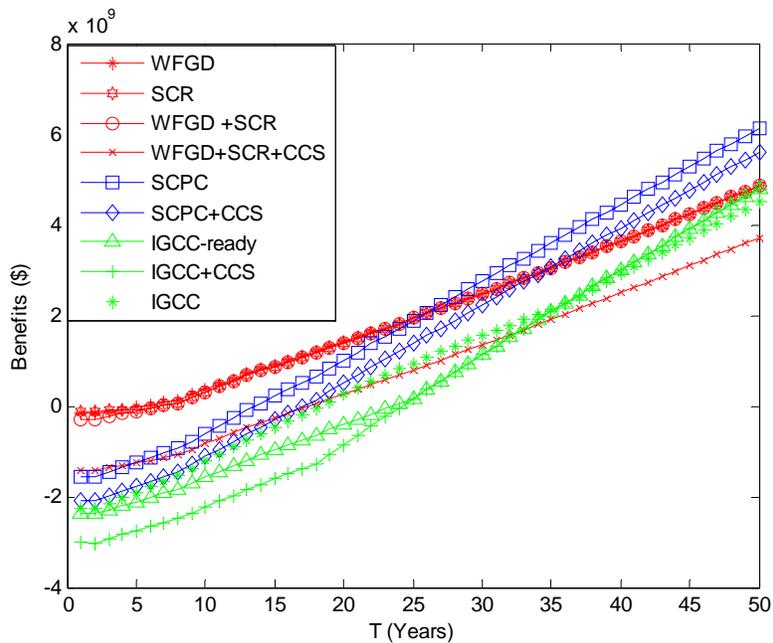
**Table 6: Scenario # 2a: Parameters of Processes Followed by CO2 Allowance's Prices**

\*in dollars of Oct 31 2006 ~ dollars of 2007. For drift value  $i$  = average inflation rate for period 2015-2030.

Figure 3 shows the median and the 95% confidence interval for CO2 allowance prices under the scenario described in Table 6.



**Figure 3: Confidence Intervals 95% for allowance prices for CO2 under scenario of Table 6**



**Figure 4: Value of different investment alternatives when lifetime is T and scenarios are as given in Table 6 (CO2 has a price)**

In this case replacing the old plant with an SCPC is better than retrofitting the old plant for planning horizons of ~30 years or more. SCPC+CCS is competitive for planning horizons longer than ~40 years and the IGCC for planning horizons longer than 50years.

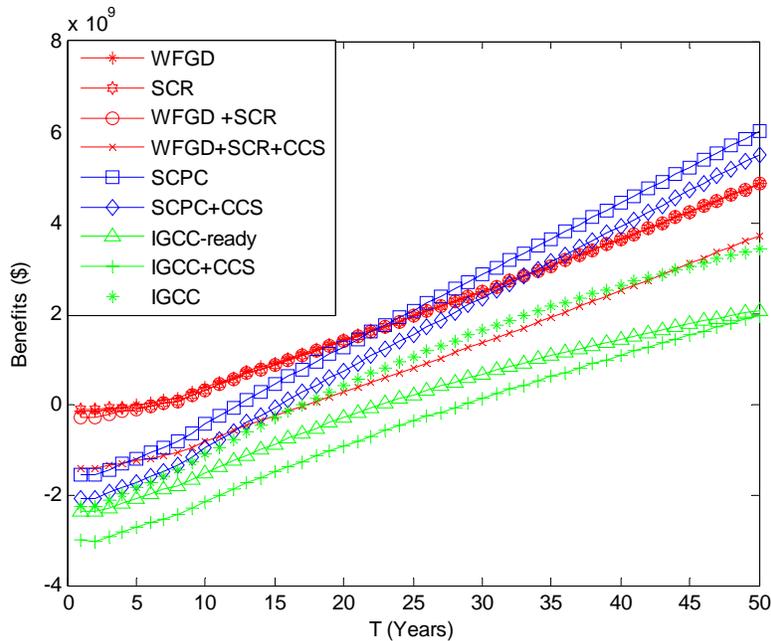
### 5.3. A mild carbon constraint sooner or a though carbon constraint later?

What are the effects of having soon a mild carbon price? How do these effects compare to those of a high carbon price later in the future? Figure 5 and Figure 6 show the Investment value of the different alternatives when the scenarios for SO<sub>2</sub>, NO<sub>x</sub> and Hg are as in Table 6, and the scenarios for CO<sub>2</sub> are as given in Table 7.

Scenario	Alternative Scenarios for CO <sub>2</sub>						
	Ao	GBM		Year Jump	Jump Price*	New GBM	
		miu	sigma			miu	sigma
1	0	0	0	2010	10	0.04	0.05
2	0	0	0	2020	40	0.04	0.05

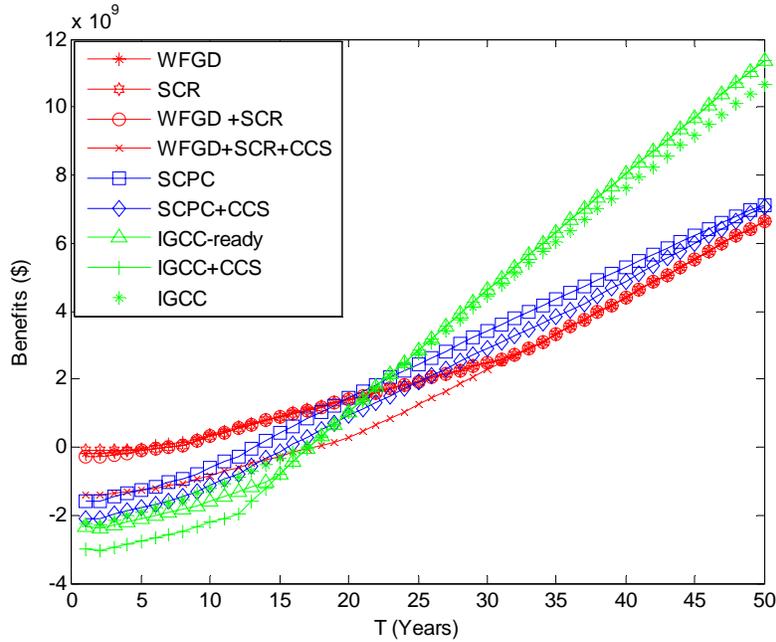
**Table 7: Parameters for Alternative Scenarios for CO<sub>2</sub>**  
\*in dollars of Oct 31 2006 ~ dollars of 2007.

A mild (and almost certain, volatility 0.05) price of \$10/tonne for CO<sub>2</sub> in year 2010 has a non negligible impact in favor of the strategy of replacing the plant to take advantage of the reductions that occur via improved efficiency. A low price like this might not be enough to induce CCS installation on the SC and is not enough to encourage investment in an IGCC.



**Figure 5: Value of different investment alternatives when lifetime is T and CO<sub>2</sub> gets a price of \$10/tonne in year 2010 (as shown in Table 7 Scenario 1).**

A price of \$40/tonne in year 2020 makes attractive the installation of an IGCC, even for planning horizons of ~20-25 years.



**Figure 6: Value of different investment alternatives when lifetime is T and CO<sub>2</sub> jumps to a price of \$40/tonne in 2020 (as shown in Table 7 Scenario 1).**

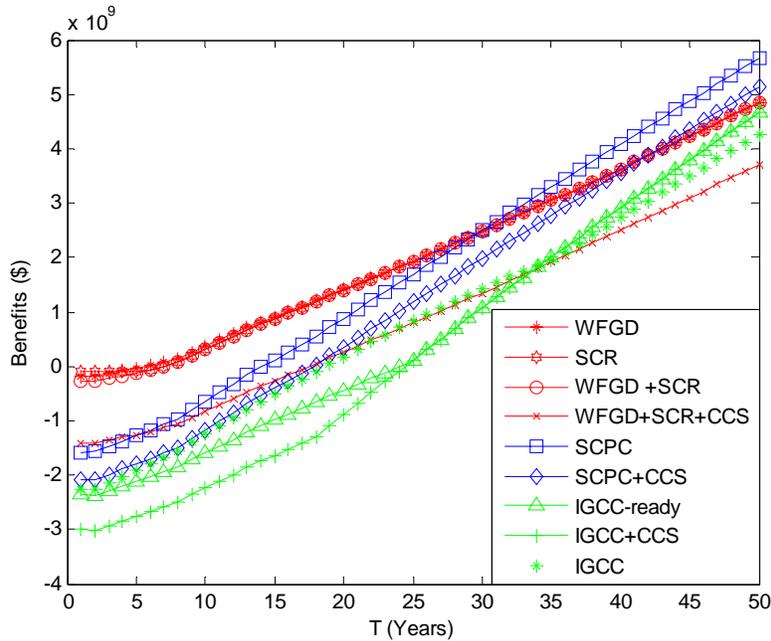
### 5.3. Other factors that favor the alternative of retrofitting the old plant

The previous analysis indicates that replacing the old plant is a good strategy in almost any case (a planning horizon longer than 23 and shorter than 50 years), yet the predominant strategy in today's industry is not to replace large-emitters with new plants. Instead a number of plants have plans for retrofitting with WFGD and SCRs.

One could think of a number of possible explanations of why investing on an SC is not as attractive as our base case analysis suggests. In the following sections we explore the effects of different factors that might make retrofits look more attractive.

#### 5.3.1. Lower expected cost of coal favors keeping the old plant

One of the main economical advantages of a new plant over retrofits in a scenario with no CO<sub>2</sub> constraints is the fuel efficiency. The value of the savings for lowering the coal consumption is directly related to the price the plant pays for that resource. Until now we have assumed that the price paid for medium-sulfur coal during the entire planning horizon is \$1.269/mmBtu (constant 2006 dollars). How would our analysis change if we assume instead that the drift on coal prices is going to be zero (so there is a real decline in Coal prices equal to the inflation rate)? Figure 7 shows that the economic value of installing a new plant is lowered and the planning horizon should increase to 35 years or more (5 years more than in the base case analysis of Figure 4) to make this investment competitive.

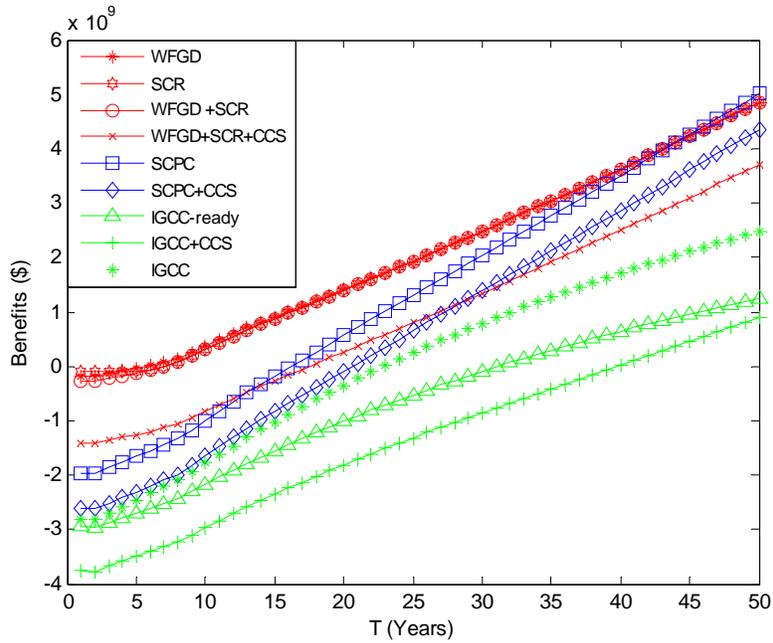


**Figure 7: Value of different investment alternatives when lifetime  $T$ , scenarios are given by Table 6 (CO<sub>2</sub> has a price) and coal prices have a zero drift**

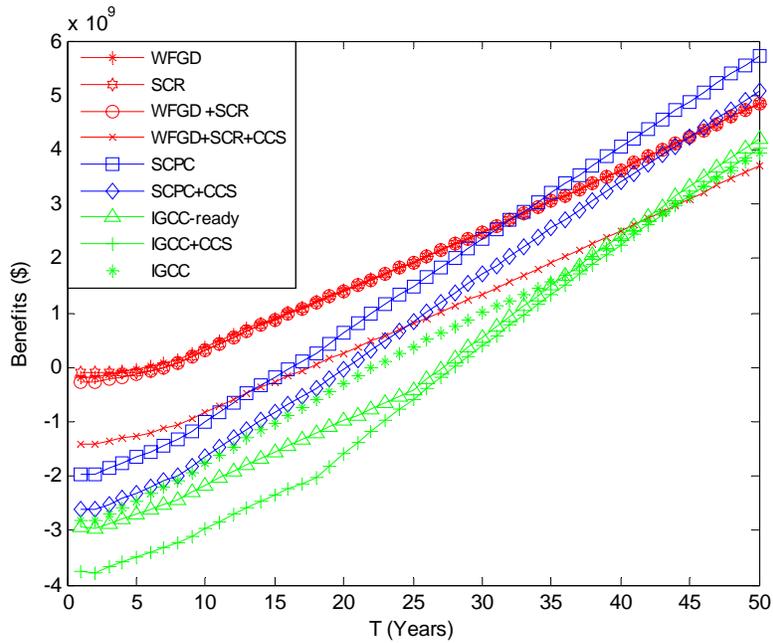
### 5.3.3. Premium cost for new technologies

The previous analyses are based on capital costs retrieved for the IECM model and on the assumption that both the SC and the IGCC can operate at a capacity factor of 83%. It is very possible that because both IGCC and SC are new technologies, investors might add a “risk-premium” to their capital costs to account for all the contingencies that could increase the capital and operating costs. This also serves as a proxy for the value that investors might give to the option of waiting until SC and IGCC mature and both the capital and O&M costs decrease.

Figure 8 and Figure 9 show the value of the different investment strategies for 1) Base case scenario, and 2) Scenario # 2 (table 13) assuming both the SC and the IGCC capital costs are increased by 25%.



**Figure 8: Value of different investment alternatives under the base case scenario (CO<sub>2</sub> does not have a price) when Capital Costs of SCPC and IGCC are 25% higher**



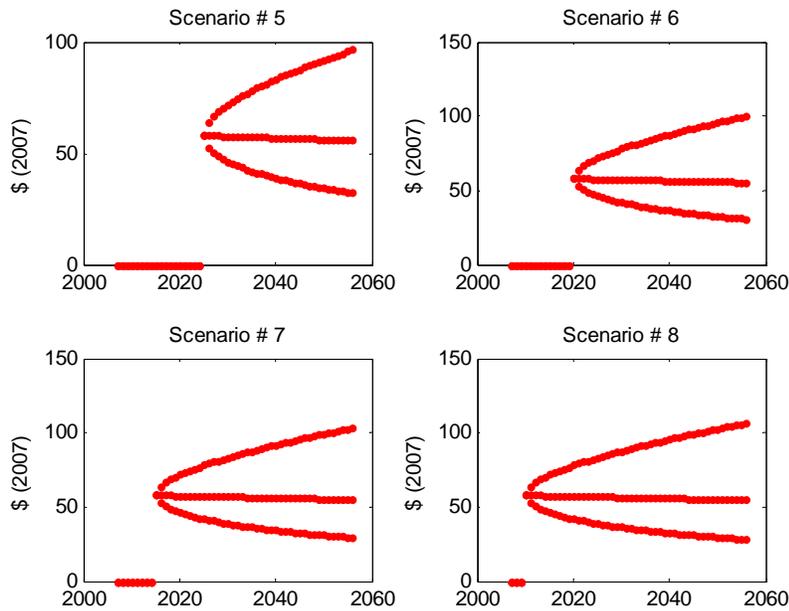
**Figure 9: Value of different investment alternatives when lifetime T, scenarios are given by Table 6 (CO<sub>2</sub> has ETS price) and Capital Costs of SCPC and IGCC are 25% higher**

### 5.3.3. Effects of different timing of CO<sub>2</sub> emissions regulations

Table 8 describes 9 different scenarios for which prices jump to either the price of CO2 allowances at the ECX for 10/31/06 (\$20.99/Tonne) or the highest price observed during the period 4/22/05-10/31/06 (\$58.11/tonne), assuming the volatility is equal to the one observed in that market for the same period.

Scenario	CO2						
	A <sub>0</sub>	GBM		Year Jump*	Jump Price	New GBM	
		$\mu$	$\sigma$			$\mu$	$\sigma$
1	0	0	0	2025	20.99	0.04	0.05
2	0	0	0	2020	20.99	0.04	0.05
3	0	0	0	2015	20.99	0.04	0.05
4	0	0	0	2010	20.99	0.04	0.05
5	0	0	0	2025	58.11	0.04	0.05
6	0	0 <td 0	2020	58.11	0.04	0.05	
7	0	0	0	2015	58.11	0.04	0.05
8	0	0	0	2010	58.11	0.04	0.05

**Table 8: Different Scenarios for CO2, SO2, NOx and Mercury as in Base Case Scenario** \*in dollars of Oct 31 2006 ~ dollars of 2007. For drift value  $i$  = average inflation rate for period 2015-2030.



**Figure 10: 95% Confidence Interval for CO2 allowances prices as described in Table 8 (scenarios 5 to 8)**

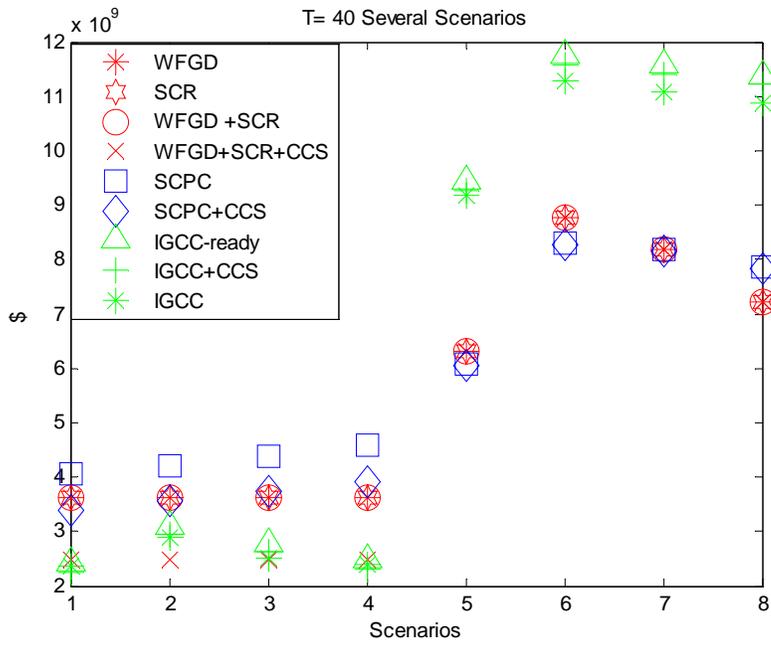
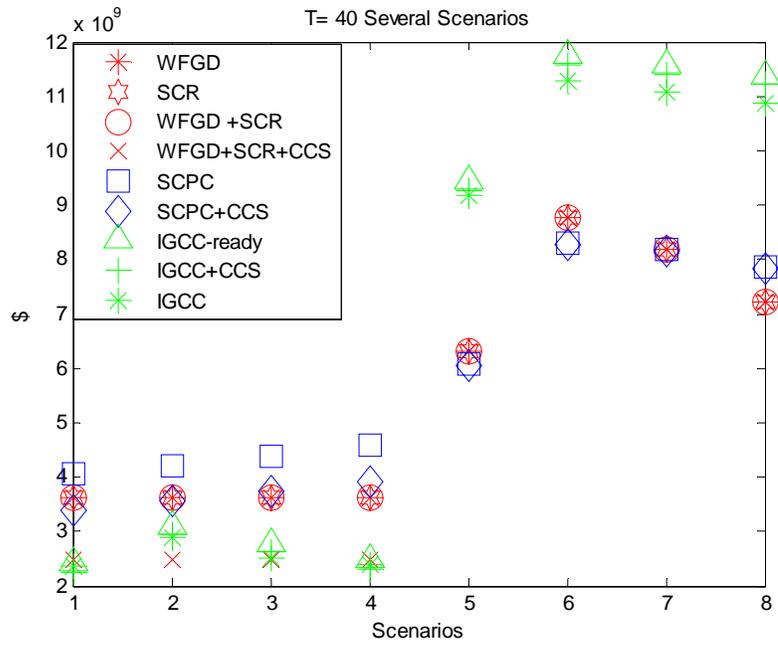
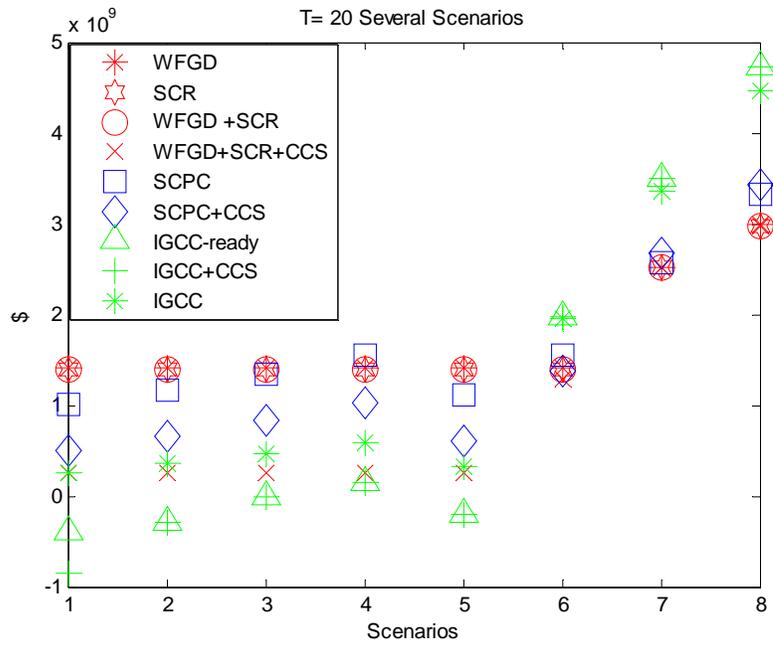


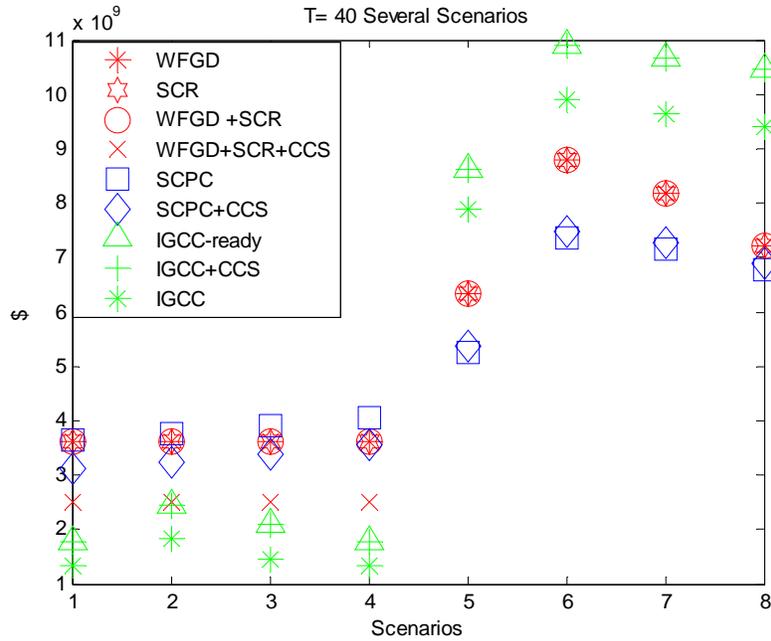
Figure 11 shows that for a planning horizon of 40 years, replacing the plant is better than retrofitting for every scenario in which CO<sub>2</sub> emissions reductions become valuable at year 2025 or earlier (at a price of \$20/tonne or higher). Installing an IGCC is better for the scenarios in which CO<sub>2</sub> emissions allowances reach a price of \$58.11/tonne.



**Figure 11: Value of different investment alternatives for scenarios 1-8 as defined in Table 8, assuming planning horizon T=40 years**



**Figure 12: Value of different investment alternatives for scenarios 1-8 as defined in Table 8, assuming planning horizon T=20 years**



**Figure 13: Value of different investment alternatives for scenarios 1-8 as defined in Table 8, assuming planning horizon T=40 years and discount rate 2% higher**

## 6. Discussion:

In this paper we have proposed a method to compare the value of alternative investments that could be made today in a coal-fired power plant accounting for 1) the uncertainty of the costs of compliance with air-emissions regulations, 2) the value of the flexibility of not reducing emissions when allowance prices are lower than the cost of abatement, and 3) the flexibility of installing other ECDs in the future. This method allows the consideration of scenarios that differ in the assumptions about current and expected evolution of allowance's prices and an assessment of the effects of different policies to reduce CO<sub>2</sub> emissions. To account for the operational characteristics of the ECDs we introduce the concepts of Basket-options and Disjunctive-options.

Our base-case analysis suggests that even under a scenario with no CO<sub>2</sub> emissions constraints, a decision maker that has a planning horizon longer than ~30 years should choose to replace the old plant instead of retrofitting it. Changes in some of the assumptions about key variables such as lower prices of coal, uncertainty about the allocation of grandfathered allowances to the replacement plant, or the presence of a risk premium in the capital costs of the SCPC or IGCC (alone or in combination) require a longer planning horizon for the replacement strategy to be preferred. For a decision maker considering a planning horizon of 40 years, and scenarios in which CO<sub>2</sub> allowances reach a price of \$20.11/tonne or more at a year 2025 or earlier, the best strategy is to replace the old plant.

Short planning horizons, and a combination of factors that discount the value of installing a new plant might make the strategy of retrofitting an old plant with a WFGD and an

SCR look like the best option. However this strategy is clearly suboptimal for scenarios that consider a planning horizon of more than 30 years and/or constraints on CO<sub>2</sub> emissions. Once old and inefficient plants are retrofitted with equipment to abate SO<sub>2</sub> and NO<sub>x</sub> it will be more difficult to make the case for the reduction of CO<sub>2</sub> emissions. In the absence of incentives to invest in low-carbon technologies today, the power system (already responsible for 40% of CO<sub>2</sub> emissions in the U.S.) is likely to end upon a path of high emissions and/or higher costs of abatement.

## 7. Acknowledgements

We thank Mike Berkenpas for helpful information on the IECM model.

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