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Should a Coal-Fired Power Plant be Replaced or Retrofitted?

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In a cap-and-trade system, a power plant operator can choose to operate while paying for the necessary emissions allowances, retrofit emissions controls to the plant, or replace the unit with a new plant. Allowance prices are uncertain, as are the timing and stringency of requirements for control of mercury and carbon emissions. We model the evolution of allowance prices for SO_2, NO_x, Hg, and CO_2 using geometric Brownian motion with drift, volatility, and jumps, and use an options-based analysis to find the value of the alternatives. In the absence of a carbon price, only if the owners have a planning horizon longer than 30 years would they replace a conventional coal-fired plant with a high-performance unit such as a supercritical plant; otherwise, they would install SO_2 and NO_x controls on the existing unit. An expectation that the CO_2 price will reach \$50/t in 2020 makes the installation of an IGCC with carbon capture and sequestration attractive today, even for planning horizons as short as 20 years. A carbon price below \$40/t is unlikely to produce investments in carbon capture for electric power.

Introduction

Electric power generation firms in the United States must make decisions affecting their 645 existing coal-fired plants in an atmosphere of regulatory uncertainty (*1*, *2*). SO_2, NO_x, and mercury controls may require retrofits or emissions allowance purchases. The United States may put a value on carbon in the future—perhaps via a cap-and-trade system. If prices of tradable allowances are high for the lifetime of a plant, it may provide incentive to consider capital investments to reduce emissions.

Recent work by Sekar et al. (*3*) found that a CO_2 price of at least \$28 ± 5 per metric ton (t) is required to justify investment in integrated gasification combined cycle (IGCC) generation plants. Bergerson and Lave (*4*) found that a price of approximately \$30 per t is required before the cost of electricity from IGCC with carbon capture and sequestration (IGCC+CCS) plants is lower than that from a conventional pulverized coal (PC) plant. Reinelt and Keith (*2*) find that significant replacements of existing plants with IGCC+CCS do not occur at CO_2 prices less than about \$50 per t.

Here we consider 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_2, NO_x, Hg, and CO_2 using geometric Brownian motion (GBM) with drift, volatility, and jumps.

We analyze the profitability of investments in emissions controls that may have a future allowance price in order to examine under what circumstances retrofitting a coal-fired power plant with equipment to mitigate SO_2 emissions or NO_x emissions is preferable to replacing the plant. For the latter choice, 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 United States generation mix in the future, its costs and operating characteristics are not as well known as those for supercritical pulverized coal plants (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 to make today, given their beliefs about the future values of key variables that affect the investment outcomes. Although our model can be applied to a wide range of existing coal generators, we have chosen to analyze the decision in a pulverized coal plant similar to Hatfield's Ferry Power Station, a 1728 MW plant in southwest Pennsylvania that has announced plans to install a WFGD.

Valuing Emissions Control Devices As Options

When is it justified to invest in a WFGD? We are aware of the studies by Herbelot (*5*), Insley (*6*), and Chao and Wilson (*7*), who have used the real options approach (see Dixit and Pindyck (*8*)) to address this question.

We also use an options approach to analyze the investment decision, but our analysis differs from previous ones in that it (1) analyzes the decision of investing in different ECDs or in a new plant in the context of a multipollutant regulation, (2) accounts for expected increases in the SO_2 and Hg allowance prices and for the possibility of changes in CO_2 emissions regulations, (3) values the strategic flexibility obtained with the installation of an ECD or a new plant, (4) makes use of the McDonald and Siegel formula, which provides a closed-form solution for the value of the option to turn the ECDs on and off as required and to reduce emissions only when it is cheaper to do so.

ECDs that can be turned on and off as desired by the plant operator (units generally have bypass equipment that allow the flue gas to completely bypass the ECD and therefore are "flexible") can be seen as an "allowance-producing machine" and can be valued as such using the analogy of call options. Turning on the scrubber will have the same practical effect as buying allowances at the O&M cost per unit 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 quantity of allowances at a specified price at different time periods. The price "paid" per "allowance" ("strike price" in finance parlance) is the per unit variable operating and maintenance cost of the ECD X_t (see Appendix A). Whenever the capital cost of the ECD is exceeded by the value of these call options, the investment should be made.

In this context "exercising the option" means using the ECD. If the expected lifetime of the ECD is T, and the expected number of generated allowances at time t is N_t, then installing the ECD is equivalent to purchasing N_1 call options (on allowances) 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 $t = T$. The number of allowances N_t that can be

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"obtained" at time t cannot be more than the initial emissions at time t times the removal efficiency of the control. Because the throughput of the power plant cannot be modified, the option to abate N_t units of pollutant can be exercised only at t and not earlier or later. In this sense the options obtained by the installation of the ECD are equivalent to European call options (options that can be exercised only on the expiration date).

The present value of installing an ECD with a construction time of τ is given by

$$\text{Value of installing ECD} = \sum_{t=\tau}^{T} N_t Call(t, \omega, X_t, r) \quad (1)$$

If the stochastic process followed by allowance prices ω can be assumed to be GBM (see Hull (*9*) for an introduction to Wiener processes and GBM), then eq 1 can be solved using the formula of McDonald and Siegel (*10*), which is a special case of those presented by Merton (*11*) and Black and Scholes (*12*) (see Supporting Information, Section 1.1).

If operating the ECD reduces emissions of more than one pollutant at the same time (for example a WFGD reduces SO_2 and Hg emissions simultaneously), ω refers to the stochastic process followed by the price of one unit of a basket that contains allowances for the pollutants abated, as discussed in Section 1.2 of the Supporting Information. For the ECDs that reduce emissions of pollutants whose prices are assumed to follow GBM and experience a jump at a time J to a price A_j and a change in the GBM parameters (eq 1) is transformed to

$$\sum_{t=\tau}^{T_1} N_t Call_0(t, A_0, \omega = GBM(\mu, \sigma), X_t, r) + \sum_{t=T_1}^{T} N_t Call_0(t, A_j, \omega_j = GBM(\mu_j, \sigma_j), X_t, r) \quad (1b)$$

Therefore eqs 1 and 1b (along with assumptions about the time varying process followed by allowances prices) are useful to quantify the benefits associated with the stream of call options (on allowances or baskets of allowances) obtained with the installation of an ECD. If there are no additional benefits, then a simple comparison between these and the capital costs of the ECD will be enough to determine the value of the investment.

The Replacement Decision

An older coal-fired power plant might be replaced with a new IGCC or SCPC generating plant that includes SCR, ESP, and WFGD, and reduces emissions of SO_2, NO_x, mercury, and CO_2 while allowing savings in fuel and operating and maintenance (O&M) costs. To find the value of investing in a new plant or in a retrofit, it is necessary to sum the payoffs associated with fuel and other O&M costs, as well as with the SO_2, NO_x, mercury, and CO_2 emissions reductions. The payoff associated with each commodity can be calculated using "options" or "basket options" (introduced above) or using a "forward contract", "compound option", or "disjunctive option" analogy as presented below.

Forward Contract Analogy. When there is no flexibility to stop reducing emissions, a "forward contract" analogy (an agreement to buy or sell an asset at a certain future time and for a certain price) is useful. Even if the ECDs 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_2, NO_x, and mercury occur whenever the plant operates; therefore, the analogy of call options is not useful to value those benefits. Obtaining a constant reduction of emissions is equivalent to having a bundle of forward contracts to purchase allowances for every year the generator is online. Thus, the installation of an IGCC unit is equivalent to buying a forward contract for SO_2, NO_x, and mercury allowances. Installation of an SCPC gives both call options and forward contracts.

If the process followed by future SO_2 allowances prices is given by $\omega^{SO_2} = GBM\,(\mu^{SO_2}, \sigma^{SO_2})$ then the value at time 0 of one allowance delivered at time t is given by

$$f_0\left(t, A_0^{SO_2}, \omega^{SO_2}, r\right) = e^{-\delta^{SO_2} t} A_0^{SO_2} \text{ where } \delta^{SO_2} = \mu_5^{SO_2} - \mu^{SO_2} \quad (2)$$

Compound Option Analogy. The installation of a WFGD allows the subsequent installation of a SCR and postcombustion, amine-based CCS; the installation of a SCR allows the subsequent installation of a WFGD or a WFGD+CCS; and the installation of a SCPC or an IGCC allows the subsequent installation of CCS (see Rubin et al. (*13*)).

The option to install an ECD in the future can be seen as a "compound option" (Section 11.2 of Wilmott (*14*)) or a call option on a bundle of call options, and valued as such. Since the option to install the ECD can be exercised at any time before the end of the lifetime of the plant (but after the previous installation has been completed), then the payoff corresponding to installing it is given by

$$\text{Value of option to install ECD} = \text{Value of option of installing ECD at time } t^* \text{ for } \tau \le t^* \le T \quad (3)$$

If installing the ECD at time t^* costs K_t^* and gives a stream of call options (on allowances or baskets) for years $t^* + \upsilon$ and later, then the value of the option of installing the ECD at time t^* is given by (see Supporting Information, Section 1.3)

$$\text{Value of option of installing ECD at time } t^* \text{ (in today's \$} = e^{-rt*} E\left[Max\left(0, -K_{t^*} + N \sum_{t=t^*+\upsilon}^{T} call_{t^*}(t, X_t, A_{t^*,} \omega, r)\right)\right] \quad (4)$$

Disjunctive Option Analogy. Both for precombustion and postcombustion CCS systems it is necessary to remove the SO_2 from the flue gas before capturing the CO_2. This implies that the option to operate the CCS to achieve CO_2 reductions

TABLE 1. Base Case Scenario: Parameters of the Process Followed by Allowance Prices in year 2007 Dollars[a]

Scenario 1: Parameters of Processes for Allowances Prices

		GBM				New GBM				New GBM	
	initial value per allowance	μ	σ	year of jump	jump price per allowance	μ	σ	year of jump	jump price per allowance	μ	σ
SO_2	\$539	0.051	0.78	2015	\$1394.8	0.04	0.3				
NO_x	\$1,075	−0.01	0.3								
Hg	0	0	0	2010	\$23,753	0.118	0.3	2020	\$52,785	0.0656	0.3
CO_2	0	0	0								

[a] SO_2 and NO_x allowances are given in short tons, Hg allowances are given in pounds, and CO_2 allowances are given in t.

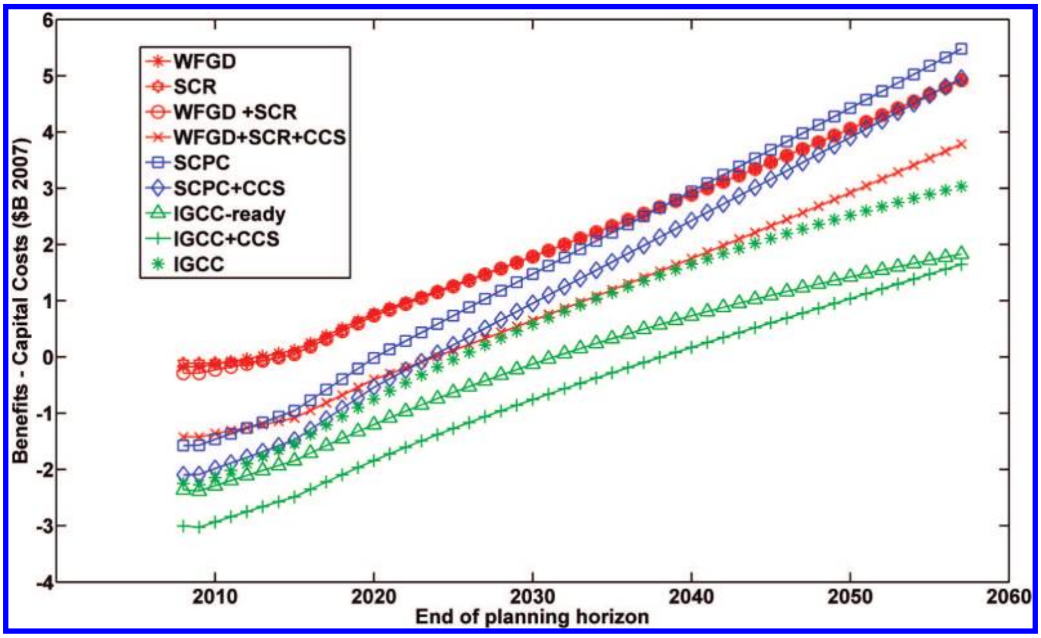

FIGURE 1. Value of investment alternatives when allowances prices are as in Table 1 (no carbon price).

comes together with the "obligation" to reduce SO_2 emissions. Because the CCS cannot operate without the WFGD, but the WFGD can operate without the CCS, having CCS in a pulverized coal plant presents a set of three 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 either WFGD or CCS. The operation of the WFGD "produces" call options on a basket that contains SO_2 and mercury allowances. The operation of the CCS system also reduces SO_2 and mercury and achieves a modest additional reduction of NO_x emissions. Therefore, the installation of CCS allows the operator to choose between call options on two different baskets: one basket with SO_2 and mercury allowances and another basket with more SO_2, mercury, CO_2 (and NO_x) allowances. The value of a disjunctive option is the maximum value between the two exclusive options:

Value of the option of installing CCS at time t^*

$$\text{(in today's \$)} = e^{-rt*}E\left[Max\left(0, -k_{t^*} + \sum_{t=t^*+v}^{T} Max[N^{Basket1}call_{t^*}(Basket1), N^{Basket2}call_{t^*}(Basket2)]\right)\right] \quad (5)$$

Considering Different IGCC Configurations

For a SCPC, the cost of adding CCS later is not significantly larger than the cost of adding the CCS at the time of installation of the plant, because the CCS is a postcombustion system. For an IGCC, this is not the case. The removal of CO_2 from the flue gas changes its flow rate before entering the gas turbines, which makes the specifications for the combustion system of an IGCC with and without CCS differ significantly, as discussed by Bohm et al. (*15*) and Rutkowski et al. (*16*). An investor considering the installation of an IGCC in a world with no carbon constraints has two alternatives: (1) install an IGCC that operates optimally without a CCS or (2) install an IGCC that would operate optimally if it had a CCS system in place but is suboptimal compared to (1) when it is operated before the CCS is installed. Alternative (2) can be labeled as "capture ready" or "IGCC with pre-investment" and implies larger capital costs and O&M costs than (1) but lower CCS retrofit costs. In our analysis below we consider both alternatives.

Install an Emissions Control Device or Replace the Plant?

We have computed the value of nine potential investments in a plant similar to Hatfield's Ferry Power Station: (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 SCPC plant (including an ESP, WFGD, and SCR); (6) replacing the plant with a new SCPC with CCS (amine-based system); (7) replacing the plant with a new IGCC "CO_2-capture ready" plant; (8) replacing the plant with a new IGCC with CCS (selexol-based system); and (9) replacing the plant with a new IGCC plant.

We use the Environmental Control Model-Carbon Sequestration edition (IECM-cs), version 5.1.3(c) (*17*) to model the plant; parameters are given in the online Supporting Information, Section 2. We assume the prices of coal and electricity remain stable (increase only by inflation) at $1.27 per mmBTU, and $55/MWh, and a discount rate of 6%. The value of each investment is given by the benefits associated with current or potential emissions reductions, fuel and O&M savings, and extra profits for increased electricity generation (if any). The benefits are valued using the equations presented in the previous sections according to Tables 5 and 6 in Section 3 of the online Supporting Information.

Cap-and-Trade for SO_2, NO_x, and Hg

Table 1 describes a scenario for allowance prices without carbon dioxide regulation (see Section 1.4 of the Supporting Information for more information on the scenarios and section 4 for the corresponding 95% confidence intervals). We model a large jump in SO_2 price and two jumps in mercury price. The carbon price remains at zero.

Figure 1 shows a comparison of the value of the nine investment strategies for different planning horizons. A planning horizon (T in eq 1) represents the length of time over which the benefits of the investment can be collected, or the time for which those benefits are considered by the investor—whichever is smaller. (Even though it is possible to operate the plant for 50 years or more, the investor may be willing to only count on the benefits of the investment occurring during the first 30 years.) In this case, retrofitting the plant with a WFGD, SCR, or both has the highest value

TABLE 2. Parameters for Introduction of a \$20/t CO_2 Price in 2025, a \$10/t CO_2 Price in 2010, and a \$40/t Price in 2020 (in 2007 Dollars)

	Alternative Scenarios for CO_2						
		GBM				New GBM	
scenario	initial value	μ	σ	year of jump	jump price per tonne	μ	σ
2	0	0	0	2025	\$20	0.04	0.05
3	0	0	0	2010	\$10	0.04	0.05
4	0	0	0	2020	\$40	0.04	0.05

for a planning horizon of less than 35 years. For longer planning horizons, investing in a SCPC is slightly favored over a retrofit, due in part to the fuel savings corresponding to its higher efficiency (39% HHV) relative to the PC plant (33.7% HHV). In the absence of a carbon price, the high capital cost of the IGCC plant makes it an unfavorable investment.

Cap-and-Trade for SO_2, NO_x, Hg, and CO_2

Suppose a firm expects a cap-and-trade program for CO_2 to begin in 2025 at an allowance price of \$20/t and expects prices to evolve according to GBM with a low volatility of 0.05 and a drift of 0.04 (scenario 2, Table 2). The allowance prices for SO_2, NO_x, and Hg are the same as those considered in the base case scenario (Table 1).

With the initial low CO_2 allowance price and low volatility, the upper bound of the 95% confidence interval price never exceeds \$35/t (see Supporting Information, Section 4). While the IGCC plant is a somewhat more valuable investment than in the scenario with no carbon price, it is not a favorable investment. Replacing the old plant with an SCPC is better than retrofitting the old plant with ECDs only for planning horizons of 26 years or more. The carbon price is never high enough for SCPC+CCS to be more favorable than an SCPC without CCS.

Next we consider the introduction of a \$10/t carbon price in 2010 (scenario 3, Table 2), one plausible outcome of the current U.S. political process. As shown in Figure 3, investment decisions are virtually identical to that of the previous scenario (no carbon price until 2025, then a \$20/t price). The planning horizon for which a SCPC plant is favored is somewhat shortened (to 23 years); for shorter planning horizons a retrofit with ECDs is still favored. As before, no carbon control investments are favored for any planning horizon.

On the other hand, if a plant owner expects free carbon until 2025, but a subsequent \$40/t price (scenario 4, Table 1), the favored investment is different (see figure in Supporting Information, section 5). For planning horizons longer than 29 years, IGCC, including IGCC+CCS, is the favored investment.

Other Decision-Making Criteria

The above analysis indicates that replacing the plant is slightly favored (with no or low carbon price) or significantly favored (with a \$40/t carbon price) over retrofitting for planning horizons longer than 23 years, yet the predominant strategy in today's industry is to retrofit with WFGD and SCRs. We now consider factors that may explain the preference for retrofits.

The efficiency advantage of supercritical plants over PC plants is important only if coal prices stay stable or increase relative to the sales price of electricity. We reran the analysis of Figure 2 (CO_2 price jumps to \$20/t in 2025) for coal prices that decrease in real terms. The planning horizon for which retrofits are favored is found to lengthen to 30 years (see figure in Supporting Information, section 6) from the 26 years shown in Figure 2. Thus, if a firm believes that coal prices will decrease, it is more likely to install a WFGD or SCR than to replace the plant with a supercritical unit.

The previous analyses are based on IECM model capital costs and on the assumption that new SCPC and IGCC units can operate at a capacity factor of 83%. This seems to be a reasonable estimate, considering that the reliability of SCPC

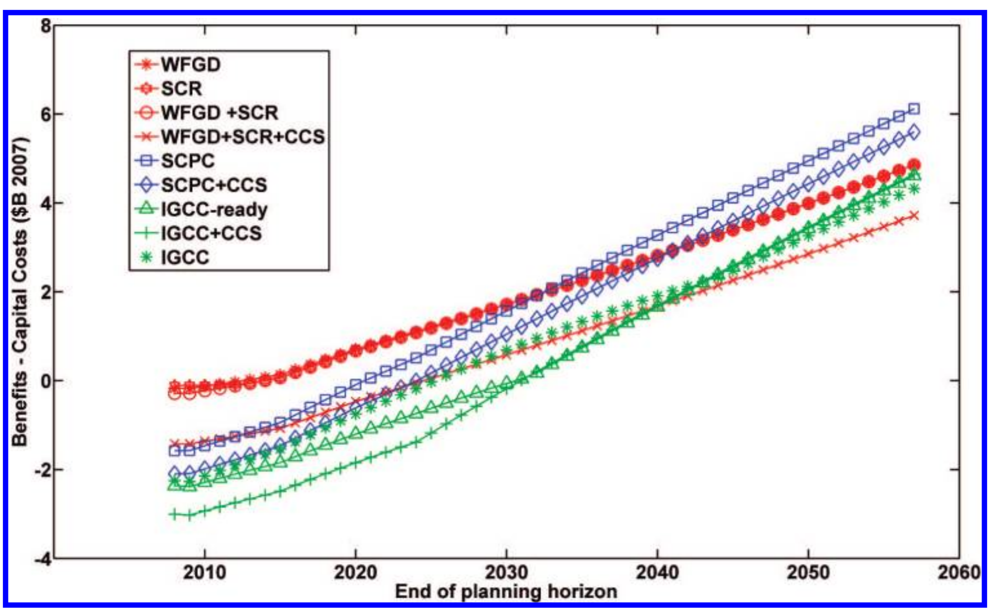

FIGURE 2. Value of investment alternatives if CO_2 prices are expected to jump to \$20/t (2007 dollars) in 2025.

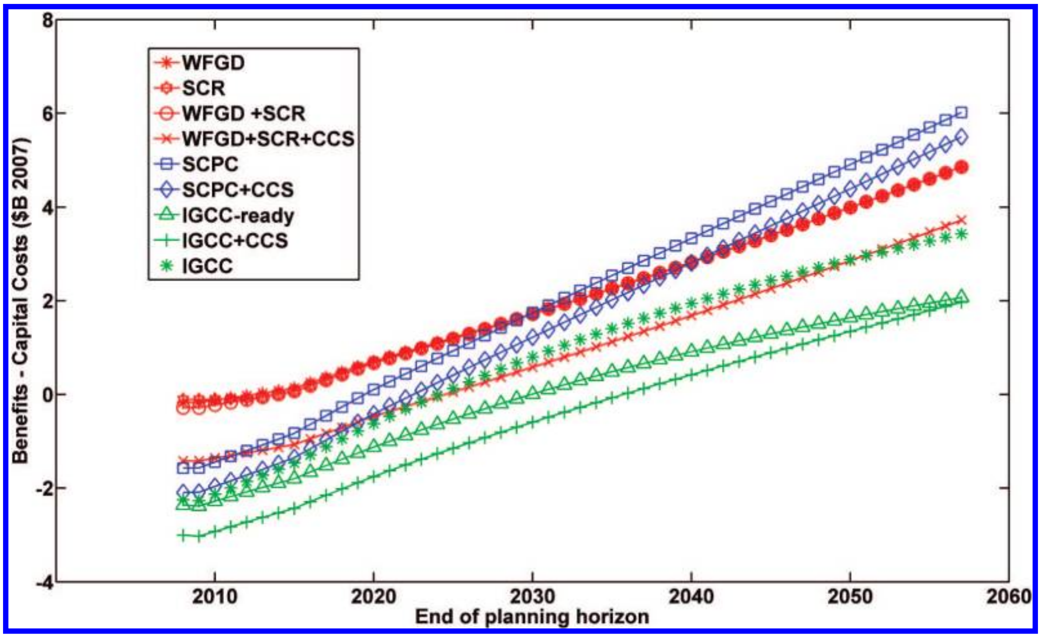

FIGURE 3. Value of investment alternatives if CO_2 prices are expected to jump to \$10/t in 2010.

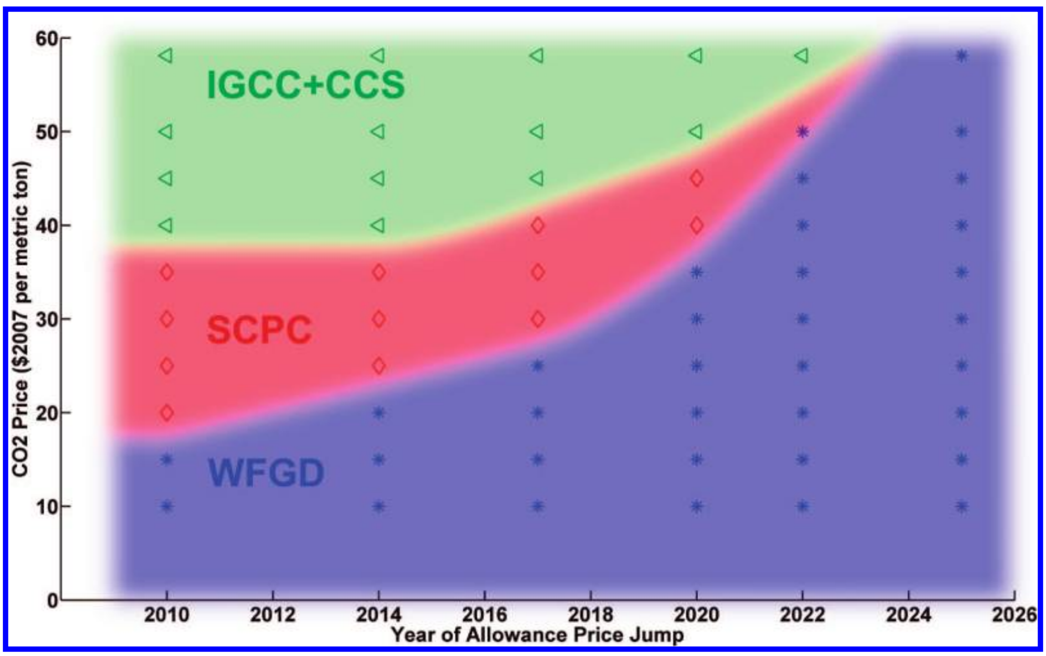

FIGURE 4. Best investment option when the CO_2 price jumps once and the planning horizon is 20 years (2027).

in Japan is higher than (98%) (*18*), and the reliability (including planned and unplanned outages) of two operating IGCC plants for which we have data (Wabash and PuertoLlano) is higher than 85% (*19*). However, because the IGCC and the SCPC technologies are less proven than a conventional PC, investors might perceive higher uncertainty in its reliability. Instead of trying to account for this in the valuation equations (which assume known electrical output and known emissions reductions), we analyze what would happen if investors added a premium to the capital costs of installing a new plant. This premium can also account for the possibility that future capital costs of these new technologies might be lower in the future (*20*)). We find that if investors add a 25% risk premium for SCPC and IGCC plants, a retrofit is favored for virtually all planning horizons (less than 44 years) with no CO_2 price and, for planning horizons as long as 32 years, with a CO_2 price of \$20/t in 2025 (see Supporting Information, section 7).

Effects of Timing and Magnitude of CO_2 Allowance Price Changes

To examine the effects of investors' perceptions of the future of CO_2 prices on investment decisions, we examined scenarios in which prices jump once to prices between \$10/t and \$58/t (the highest price observed in the EU Emissions Trading Scheme from April 2005 through October 2006 (*21*)), assuming the volatility is 5% and the drift is 4%.

For a planning horizon of 20 years, retrofitting the plant is favored over replacing for every scenario in which CO_2 emissions reductions become valuable at a price of \$10/t. Installing a SCPC is favored for a scenario in which the price of CO_2 reaches \$20/t in 2010. If the price of CO_2 is \$40/t before 2014 or \$50/t before 2020, then an IGCC+CCS is the best investment option (Figure 4).

Figure 5 shows the best investment (for a planning horizon of 20 years) for scenarios in which prices jump first to \$10/t

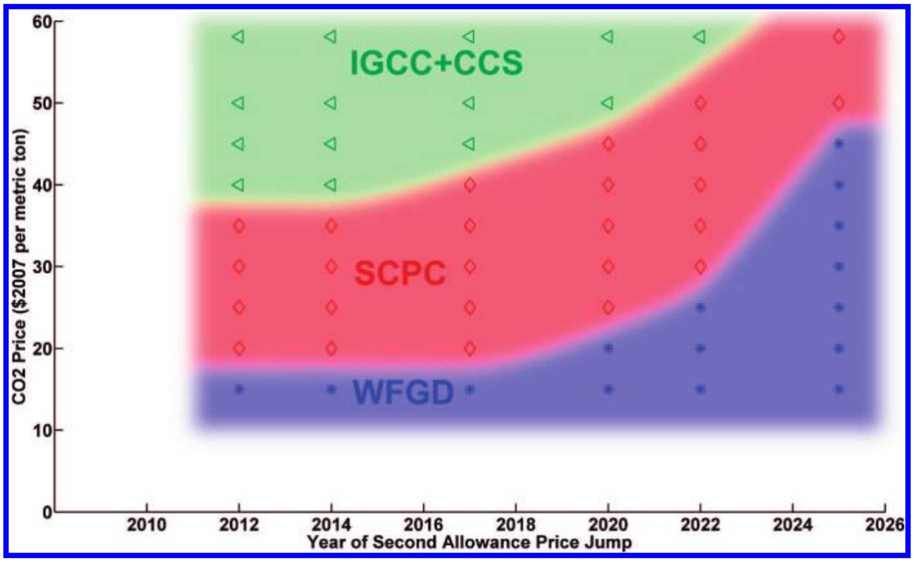

FIGURE 5. Best investment alternative when the CO_2 price jumps first to \$10/t in 2010, then jumps to a higher price in a later year. The planning horizon is 20 years (2027).

in 2010 and then jump again to prices between \$15/t and \$58/t, assuming the volatility is 5% and the drift is 4%. In this case, an IGCC with CCS becomes the preferred investment for the scenarios in which the second jump, to \$40/t, \$45/t, or \$50/t, occurs before 2014, 2017, or 2020, respectively.

Higher discount rates lower the value of all investments and favor retrofits relatively to plant replacement. A discount rate 2% higher than the one considered makes a retrofit the preferred strategy in almost all cases in which the CO_2 allowance price does not increase relatively soon (e.g., \$40/t before 2014 or \$45/t before 2017; see Supporting Information, section 8). Section 9 of the Supporting Information presents the best investment alternative when all allowances have deterministic prices (e.g., the volatility σ quantities in Tables 1 and 2 become zero); the region in which SCPC is favored is reduced, and the WFGD region is enlarged.

Discussion

We have used option analogies to value the benefits of different investments. One advantage of this approach is that if we assume a cap-and-trade system and GBM for allowance prices, most of the benefits (that depend on uncertain quantities) can be valued with a formula that has a closed-form solution (McDonald–Siegel formula). The use of stochastic dynamic optimization that accounted for uncertainty and managerial flexibility is a feasible extension of this approach that we believe should give similar results.

The optimality of the replace or retrofit decision depends heavily on the planning horizon and the timing and stringency of the cost of carbon dioxide (as well as on expectations for fuel and emissions allowance costs for SO_2, NO_x, and Hg). If the owner of an existing pulverized coal plant without emission controls expects that CO_2 emissions will not be penalized, the higher efficiency of a supercritical plant is not sufficient to favor its installation over installing a WGFD or SCR on the existing plant unless the owner has a planning horizon of 32 years or longer.

A \$10/t CO_2 price expected even as early as 2010 is not a sufficient incentive to change the investment decision from retrofit to replacement for firms with a planning horizon of less than 23 years. A \$20/t price (unless very early) is likely to provide insufficient incentive to replace rather than to retrofit, particularly if investors believe that the capital cost of a new SCPC or IGCC carries a substantial risk premium. A \$40/t carbon price in 2025 favors replacing the plant with an IGCC unit (and later with CCS) only for firms with planning horizons longer than 29 years.

Once old and inefficient plants are retrofitted with equipment to abate SO_2 and NO_x, they will continue to be a source of significant CO_2 emission for decades. Unless policies are enacted that raise the CO_2 carbon price to ~\$40/t, the power system (already responsible for 40% of CO_2 emissions in the United States) is likely to follow a path of high emissions and/or higher costs of abatement.

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Appendix A

CCS	Carbon Capture and (geological) Sequestration (system)
ECD	Emissions Control Devices (e.g., WFGD, SCR, CCS, ESP)
ESP	Electrostatic Precipitator
GBM	Geometric Brownian Motion
HHV	Higher Heating Value
IECM-cs	Integrated Environmental Control Model–carbon sequestration edition
IGCC	Integrated Coal Gasification Combined Cycle Power Plant
O&M	Operations and Maintenance (costs)
PC	Pulverized Coal (power plant-subcritical)
SCPC	Supercritical Pulverized Coal (power plant)
SCR	Selective Catalytic Reduction (system)
WFGD	Wet Flue Gas Desulphurization (system)
A_0	Price of allowances at time 0
Basket	Contains emissions allowances for two or more pollutants (e.g., the operation of a WFGD gives a number of call options on a basket that contains both SO_2 allowances and Hg allowances)

Call$_0$ (t, w, X_t, r) Value at time 0 of a call option on an underlying asset (allowance) in which future price follows a stochastic process represented by ω, for an exercise price X_t and risk-free discount rate r; the option expires at time t

δ Payout rate or "return shortfall"; (difference between risk-adjusted expected return and expected rate of change $\mu_s - \mu$; see Supporting Information, section 1.1)

$K_{t^*}^{CCS}$ Capital cost of CCS at a future time t

μ Drift parameter of the GBM process (represents the expected rate of change in the price of allowances, also denoted by: $\mu^{pollutant}$(e.g., μ^{SO_2}); given in nominal value: real drift equal μ minus r)

μ_s Risk-adjusted expected return on allowances (or the equilibrium rate of return on a financial asset that has the same covariance with the market as prices of allowances)

N_t Number of units of emissions removed at time t by ECD or new plant with respect to the original old plant (e.g., number of generated allowances); given in t for SO_2, NO_x, and Hg allowances, in t for CO_2, and in baskets for ECDs that abate more than one pollutant simultaneously)

r Risk-free discount rate

σ Volatility parameter of the GBM, also denoted by: $\sigma^{pollutant}$(e.g., σ^{SO_2})

T Expected lifetime of the ECD

t Time

t^* $\tau \le t^* \le T$ optimal time to exercise the compound option (option to install an ECD (e.g., call option on call options))

τ Time taken to complete the installation of a new plant or an ECD in the original plant

v Time it takes to complete the future installation of an ECD on a new plant or on the original plant when another ECD has been installed previously (e.g., time to install CCS on an existent SCPC)

ω Stochastic process followed by the allowance prices, also denoted as: $\omega^{pollutant}\omega^{SO_2}$)

X_t Exercise price of the call option (price that has to be paid (per unit of emissions removed) to exercise the option of using the ECD to reduce emissions)

Supporting Information Available

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

Literature Cited

(1) Patiño Echeverri, D. The Cost of Regulatory Uncertainty in Air Emissions for a Coal-fired Power Plant; Carnegie Mellon Electricity Industry Center Working Paper CEIC-03-03; 2003; http://wpweb2k.gsia.cmu.edu/ceic/papers/ceic-03-03.asp.

(2) Reinelt, P. S.; Keith, D. W. Carbon capture retrofits and the cost of regulatory uncertainty. *Energy J.* 2007, *28*(4), 100–128.

(3) Sekar, R. C.; Parsons, J. E.; Herzog, H. J.; Jacoby, H. D. Future carbon regulations and current investments in alternative coal-fired power plant technologies. *Energy Policy* **2007**, *35* (2), 1064–1074.

(4) Bergerson, J. A.; Lave, L. B. Baseload Coal Investment Decisions Under Uncertain Carbon Legislation. *Environ. Sci. Technol.* **2007**, *41* (10), 3431–3436.

(5) Herbelot, O. *Option Valuation of Flexible Investments: The Case of a Scrubber for Coal-Fired Power Plant*;Working Paper WP-94001; MIT Center for Energy and Environmental Policy Research: Cambridge, MA, 1994.

(6) Insley, M. C. On the option to invest in pollution control under a regime of tradable emissions allowances. *Can. J. Econ.* **2003**, *36* (4), 860–883.

(7) Chao, H.; Wilson, R. Option value of emissions allowances. *J. Regul. Econ.* **1993**, *5*, 233–249.

(8) Dixit, A. K.; Pindyck, R. S. *Investment Under Uncertainty*; Princeton University Press: Princeton, NJ, 1994; 468 pp; See Chapter 6, pp 175–212.

(9) Hull, J. C. *Options, Futures, and Other Derivatives*, 3rd ed.; Prentice-Hall, Inc: Upper Saddle River, NJ, 1997;572 pp; See Chapter 10, pp 209–227.

(10) McDonald, R. L.; Siegel, D. R. Investment and the valuation of firms when there is an option to shut down. *Int. Econ. Rev.* **1985**, *26* (2), 331–349.

(11) Merton, R. C. Theory of Rational Option Pricing. *Bell J. Econ. Manage. Sci.* **1973**, *4* (1), 142–183.

(12) Black, F.; Scholes, M. The pricing of Options and Corporate Liabilities. *J. Political Econ.* **1973**, *81* (3), 637–654.

(13) Rubin, E. S.; Rao, A. B.; Chen, C. Comparative Assessments of Fossil Fuel Power Plants with CO_2 Capture and Storage. In *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*; Elsevier Science: Oxford, UK, 2005;Vol. 1, Peer-Reviewed Papers and Overviews, pp 285–293.

(14) Wilmott, P.; Howison, S.; Dewynne, J. *The Mathematics of Financial Derivatives*; Cambridge University Press: Cambridge, 2002;317 pp; See Chapter 11, pp 197–205.

(15) Bohm, M. C.; Herzog, H. J.; Parsons, J. E.; Sekar, R. C. Capture-ready coal plants -- Options, technologies and economics. *Int. J. Greenhouse Gas Control I* **2007**, 113–120.

(16) Rutkowski, M. D.; Schoff, R. L.; Holt, A. H.; Booras, G. Pre-Investment of IGCC for CO_2 Capture with the Potential for Hydrogen Co-Production. Presented at Gasification Technologies Conference 2003; October 12–15, 2003; Available at http://www.gasification.org/Docs/2003_Papers/29RUTK_paper.pdf; accessed 02/07.

(17) Center for Energy and Environmental Studies, Carnegie Mellon University. Integrated Environmental Control Model Carbon Sequestration Edition. IECM-cs, 5.1.3(c) ed., 2006; http://www.iecm-online.com; accessed 11/06.

(18) Kazuhiko, S.; Yoshio, Y.; Richardson, M.; Fukuda, Y. Reliability of Supercritical Boiler and its Advantages. Hitachi; 2003; http://www.hitachi.us/supportingdocs/forbus/inverters/Support/EP2004A.pdf; accessed 07/07.

(19) Higman, C.; DellaVilla, S.; Steele, B. Reliability of IGCC Power Plants. Presented at Gasification Technologies Conference: San Francisco, 2005; http://www.gasification.org/Docs/2005_Papers/38HIGM.pdf; accessed 07/07.

(20) Rubin, E. S.; Yeh, S.; Antes, M.; Berkenpas, M.; Davison, J. Use of Experience Curves to Estimate the Future Cost of Power Plants with CO_2 Capture. *Int. J. Greenhouse Gas Control* **2007**, *1* (2), 188–197.

(21) ECX. European Climate Exchange - Market Data 2006; http://www.europeanclimateexchange.com/.

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