Should a coal-fired power plant be replaced or retrofitted?

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ABSTRACT

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 like 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/tonne in 2020 makes IGCC with carbon capture and sequestration attractive today even for planning horizons as short as 20 years. A carbon price below \$40/tonne is unlikely to produce investments in carbon capture for electric power.

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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 allowance purchases. The U.S. may put a value on carbon in the future, perhaps via a cap-and-trade system. If prices of tradable allowances are high over the life of a plant, they may provide an 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 (tonne) is required to justify investment in integrated gasification combined cycle (IGCC) generation plants. Bergerson and Lave[4] find that a price of approximately $30 per tonne is required before the cost of electricity from IGCC+CCS plants is lower than that from a conventional pulverized coal (PC) plant. These two are greenfield analyses, considering decisions for new plants. Reinelt and Keith [2] find that significant replacements of existing plants with IGCC with carbon capture and sequestration (IGCC+CCS) does not occur at CO_2 prices less than about $50 per tonne.

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 controls for emissions that may have an allowance price in the future (Hg and CO_2) to examine under what circumstances retrofitting coal-fired power plants with equipment to mitigate SO_2 emissions (e.g. a Wet Flue Gas Desulphurization System, WFGD) or NO_x emissions (e.g. 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.

The analysis identifies the key characteristics that air emissions regulations would need to have to motivate decision makers to invest in CCS. 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. We use as an example an existing 1700 MW plant, but our conclusions apply to a wide range of existing coal generators.

Acronyms and Notation

CCS: Carbon Capture and (geological) Sequestration (system)

ECD: Emissions Control Devices

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)

$Call_0(t, \omega, X_t, r)$: value at time 0 of a call option on an underlying asset (allowances) whose 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 material.

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

μ : drift parameter of the GBM process. It represents the expected rate of change in the price of allowances. Also denoted by $\mu^{\text{pollutant}}$ (e.g. μ^{SO2})

μ_s : 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

N_t :Number of units of emissions removed at time t by ECD. (Given in tons for SO_2, NO_x, and Hg allowances, in tonnes 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 $\sigma^{\text{pollutantt}}$ (e.g. σ^{SO2})

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 it takes to complete the installation of the ECD

υ : time it takes to complete the future installation of an ECD on top of another (e.g. time to install CCS on an existent SCPC)

ω : stochastic process followed by the allowance prices. Also denoted as $\omega^{\text{pollutantt}}$ (e.g. ω^{SO2})

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 and reduce emissions

Valuing emissions control devices as options

An emissions control device (ECD) may be an optimal investment even if the expected value of compliance cost via allowances is lower than the expected compliance cost with the ECD, since the ECD investment can be valued as an insurance contract against high allowances prices (this approach is different from the “real options” approach of [5] implemented by [6] and [7] in which the risk of making an irreversible investment is considered to be higher than the risk of relying in allowances with highly volatile prices. Because a shortage of allowances is plausible and the time to build a control might be significant, there is value in hedging against potentially high allowance prices)

If the ECD can be installed and then turned on and off as desired (units generally have bypass equipment that allows the flue gas to completely bypass the ECD and therefore are “flexible”), then in 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. 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 Notation section.) 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 generated allowances at time *t* are N_t, then installing the ECD is equivalent to getting 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 “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 units of pollutant 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 call options (options that can be exercised only on the expiration date).

Because before the ECD is ready to operate, there will be no emissions reductions and therefore no "options" to "buy allowances" will be obtained, the present value of installing an ECD with an installation time of τ is given by:

$$\text{Value of installing ECD} = \int_{\tau}^{T} N_t Call_0(t, \omega, X_t, r)dt \qquad (1)$$

If the stochastic process followed by allowance prices ω can be assumed to be GBM (see [8] for an introduction to Wiener processes and GBM) then (1) can be solved using the formula of [9], which is a special case of those presented in [10] and [11] (See section 1.1. of the supporting material).

If operating the ECD reduces emissions of more than one pollutant at the same time (for example a WFGD which reduces simultaneously SO_2 and Hg emissions), 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 material. 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 (1) is transformed to:

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

Therefore (1) and (1b) (along with assumptions about the time varying process followed by allowances prices) are useful to quantify the benefits associated to 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 integrated gasification combined cycle (IGCC) or supercritical pulverized coal (SCPC) generating plant that reduces emissions of SO_2, NO_x, mercury, and CO_2 and will allow 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 an “options” or “basket option” (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 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 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 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 $\omega^{SO2} = GBM\left(\mu^{SO2}, \sigma^{SO2}\right)$ then the present value of one allowance delivered at time t is given by:

$$f\left(0, t, A_0^{SO2}, \omega^{SO2}, r\right) = e^{-\delta^{SO2} t} A_0^{SO2} \text{ where } \delta^{SO2} = \mu_s^{SO2} - \mu^{SO2} \qquad (2)$$

Compound option analogy:

The installation of a WFGD allows the subsequent installation of a SCR and post-combustion 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 [13].

The option to install an ECD in the future can be seen as a “compound option” (section 11.2 of [12]) or a call option on call options, and valued as such. Since the option to install the other 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:

$$\begin{aligned}&\text{Value of option to install ECD2} = \\ &Max\left(0, \text{Value of option of installing ECD at time } t^* \text{for } \tau \le t^* \le T\right)\end{aligned} \qquad (3)$$

If installing the ECD at time t^* costs $K_{t^*}^{CCS}$ 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:

$$\begin{aligned}&\text{Value of option of installing ECD at time t}^* \text{(in today's \$)} = \\ &Max\left(0, -e^{-rt^*} k_{t^*} + \sum_{t=t^*+\upsilon}^{T} N_t call(0, t, X_t, A_0, \omega, r)\right)\end{aligned} \qquad (4)$$

Disjunctive option analogy:

Both for pre-combustion and post-combustion 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 comes together with the “obligation” to reduce SO_2 emissions. Because the CCS cannot be operated without operating the WFGD but the WFGD can be operated without operating the CCS, having 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 either WFGD or CCS. The operation of the WFGD gives 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 gives the option 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:

$$\begin{aligned}&\text{Value of the option of installing CCS at time t}^{*}\text{ (in today's \$)} = \\ &Max\left(0,-e^{-rt^{*}}k_{t^{*}} + \sum_{t=t^{*}+\upsilon}^{T} Max\left[N_{t}^{Basket1} call(Basket1), N_{t}^{Basket2} call(Basket2)\right]\right)\end{aligned} \qquad (5)$$

Considering different IGCC configurations

For a newly installed SCPC, the costs of later adding 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 this may not be the case. Combustion turbines in a power plant are designed according to the quantity and characteristics of the fuel used. In an SCPC the CCS is a post-combustion system and there are no changes in the conditions of the combustion component of the plant. In an IGCC, the CO_2 is removed from the flue gas prior 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 builds an IGCC thinking that in the future it may be necessary to install a CCS system has two alternatives: 1) install an IGCC that operates optimally without a CCS and, later on when the CCS is installed, to change major components in the plant (probably changing the combustion turbines) and 2) 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 below we consider both alternatives.

1 Install an emissions control device, or replace the plant?

We have computed the value of nine potential investments in a plant similar to the Hatfield's Ferry Power Station, a 1728 MW pulverized coal plant in southwest Pennsylvania that has been operating since 1971: installing a WFGD; installing an SCR system; installing both a WFGD and an SCR system; installing a WFGD, an SCR and a CCS (amine-based) system; replacing the plant with a new SCPC plant (including an ESP, WFGD and SCR); replacing the plant with a new SCPC with CCS (amine-based system); replacing the plant with a new IGCC "CO_2-capture ready" plant; replacing the plant with a new IGCC with CCS (selexol based system); and replacing the plant with a new IGCC plant.

We use the Environmental Control Model-Carbon Sequestration edition (IECM-cs), version 5.1.3(c)[14] to model the plant; parameters are given in the online supporting material (section 2). The initial value for the price of coal is \$1.27 per mmBTU, and the initial electricity price is \$55/MWh. 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 section according to the tables 5 and 6 in section 3 of the online supporting materials.

3P cap-and-trade

Table 1 describes a scenario for allowances prices without carbon dioxide regulation (see section 1.3 of the supporting material 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.

	Scenario # 1:Parameters of processes for allowances prices										
	Initial value per allowance	GBM		Year of Jump	Jump Price per allowance	New GBM		Year of Jump	Jump Price per allowance	New GBM	
		μ	σ			μ	σ			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
CO2	0	0	0	-	-	-	-	-	-	-	-

Table 1: Base case scenario: Parameters of the process followed by allowances prices in year 2007 dollars. SO_2 and NO_x allowances are given in short tons, Hg allowances are given in pounds and CO_2 allowances are given in tones.

Figure 1 shows a comparison of the value of the 9 investment strategies for different planning horizons. A planning horizon (*T* in equation 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. (The investor may be willing to count as benefits of the new plant only those occurring the first 30 years, even though it is possible to operate the plant for 50 years or more). For this case, retrofitting the plant with a WFGD, SCR, or both has the highest value for a planning horizon of less than 35 years. For longer planning horizons, investing in a SCPC is slightly favored over a retrofit, 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.

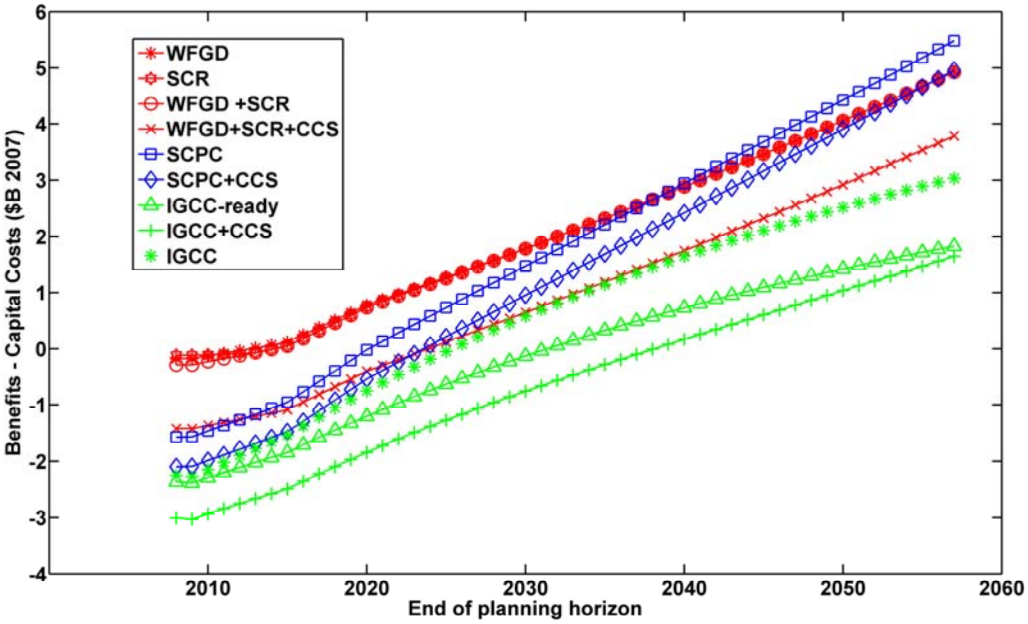

Figure 1: Value of investment alternatives when allowances prices are as in Table 1 (no carbon price)

4P cap-and-trade

Suppose a firm expects a cap-and-trade program for CO_2 to begin in 2025 at an allowance price of $20/tonne 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).

Scenario	Alternative scenario for CO2						
	Initial value	GBM		Year of Jump	Jump Price per tonne	New GBM	
		μ	σ			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

Table 2: Parameters for introduction of a \$20/tonne CO_2 price in 2025, \$10/tonne CO_2 price in 2010, and a \$40/tonne price in 2020; in 2007 dollars

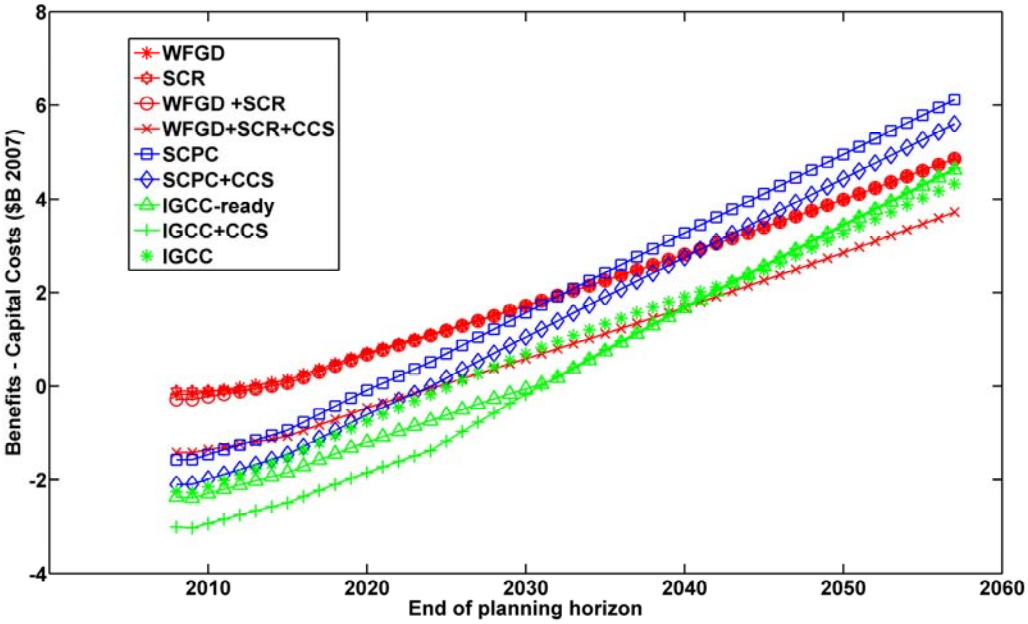

Figure 2: Value of investment alternatives if CO_2 prices are expected to jump to \$20/tonne (2007 dollars) in 2025

With the initial low CO_2 allowance price and low volatility, the upper bound of the 95% confidence interval price never exceeds $35/tonne (supporting materials, 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.

We next consider the introduction of a $10/tonne 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/tonne 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.

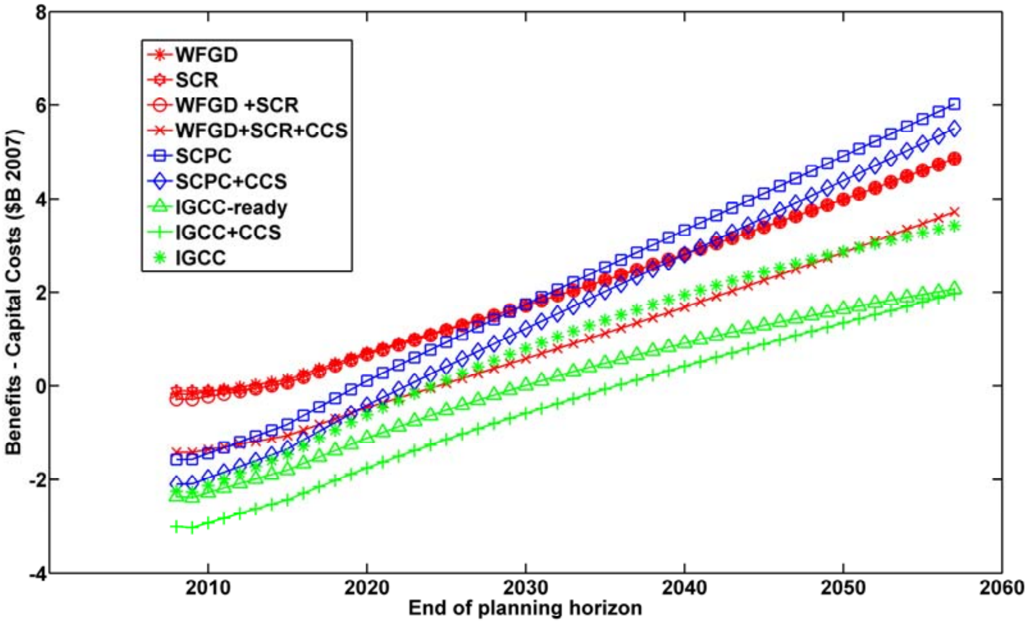

Figure 3: Value of investment alternatives if CO_2 prices are expected to jump to $10/tonne in 2010

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

Non-4P 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/ton 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 increase relative to the sales price of electricity. We re-ran the analysis of figure 4 (CO_2 price jumps to $20/tonne in 2025) with no drift in coal prices. The planning horizon for which retrofits are favored is found to lengthen to 30 years (see figure in supporting materials, section 6) from the 26 years shown in figure 2. Thus, if a firm believes that coal prices will be stable, 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%, which seems reasonable estimate considering reliability of SCPC in Japan is higher than (98%) [15] and reliability (including planned and unplanned outages) of two operating IGCC plants for which we have data (Wabash and PuertoLlano) is higher than 85% [16]. 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 “risk-premium” to the capital costs of installing a new plant. This “risk-premium” can also account for the possibility that future capital costs of these new technologies might be lower in the future due to learning [17]). 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/ton in 2025 (section 7 of supporting materials).

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/tonne to $58/tonne, (the highest price observed in the EU Emissions Trading Scheme during the period 4/22/05-10/31/06 [18]) assuming the volatility is 5% and the drift 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/ton. Installing a SCPC is favored for a scenario in which the price of CO_2 reaches $20/tonne in 2010. If the price of CO_2 is $40/tonne before 2014 or $50/tonne before 2020, then an IGCC+CCS is the best investment option (Figure 4).

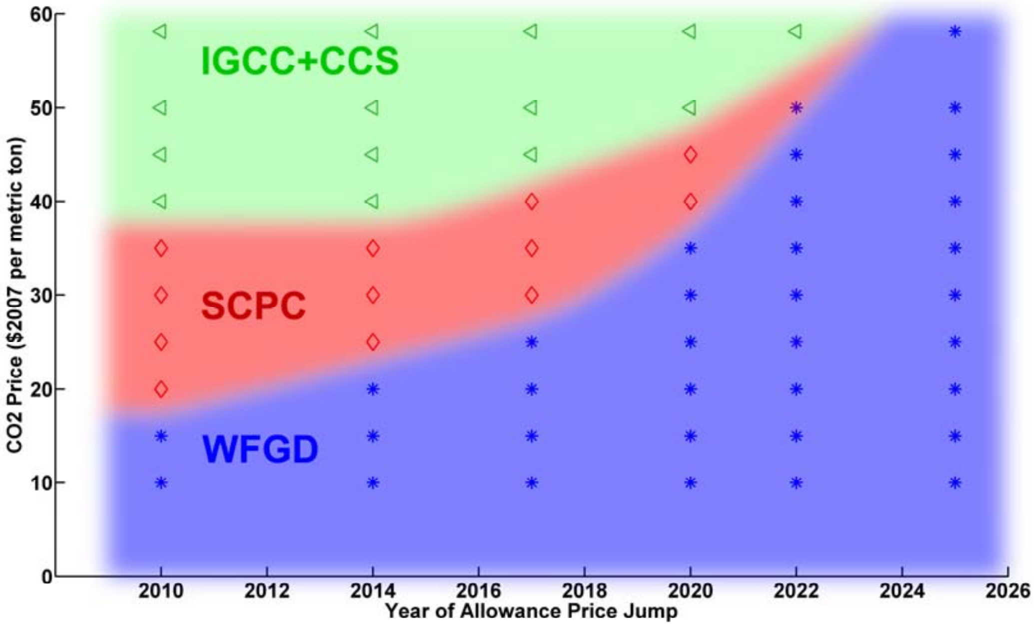

Figure 4: Best investment option when the CO_2 price jumps once and the planning horizon is 20 years (2027)

Figure 5 shows the best investment (for a planning horizon of 20 years) for scenarios in which prices jump first to $10/tonne in year 2010 and then jump again to prices between $15/ton and $58/tonne, assuming the volatility is 5% and the drift 4%. In this case an IGCC with CCS becomes the preferred investment for the scenarios in which the second jump occurs sooner than 2014 to $40/tonne, sooner than 2017 to $45/tonne or sooner than 2020 to $50/tonne. Section 8 of the supporting material presents the best investment alternative when all allowances have deterministic prices (the volatility σ quantities in Table 1 and Table 2 become zero); the region in which SCPC is favored is reduced and the WFGD region is enlarged in this case.

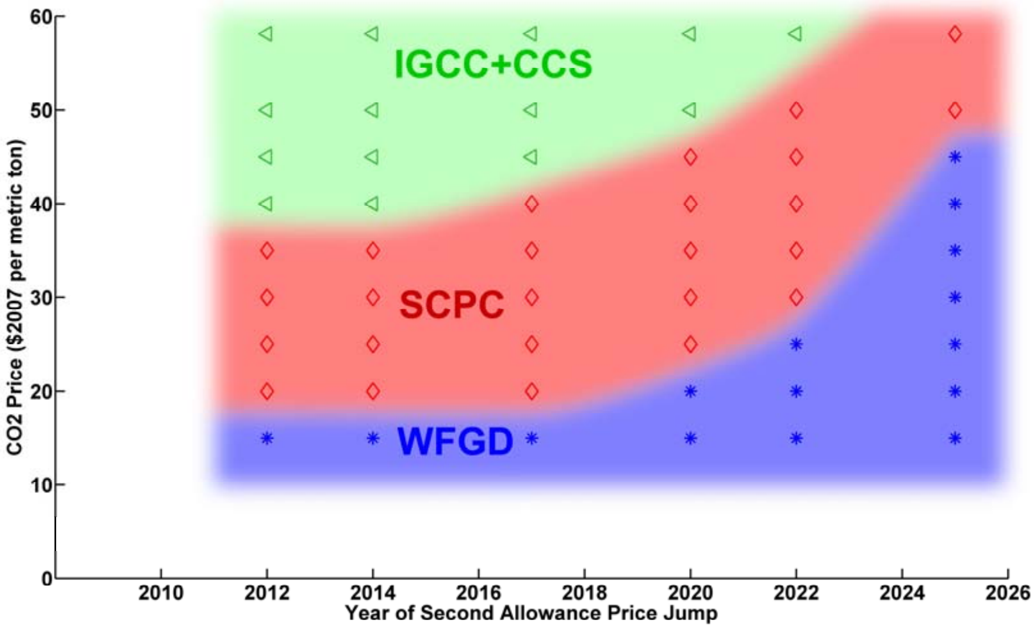

Figure 5: Best investment alternative when the CO_2 price jumps first to $10/tonne in 2010, then jumps to a higher price in a later year. The planning horizon is 20 years (2027)

Discussion

We have used options 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, 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 3P allowance costs). 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/tonne 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 less than 23 years. A $20/tonne 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.

If the owner expects a $40/tonne carbon price in 2025 or earlier, replacing the plant with an IGCC+CCS unit is favored except by firms with planning horizons shorter 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/ton, the power system (already responsible for 40% of CO_2 emissions in the U.S.) is likely to follow a path of high emissions and/or higher costs of abatement.

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Supporting Information Available

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

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Supporting information for: "Should a coal-fired power plant be replaced or retrofitted?"

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1.1 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 (See [1]for an introduction to Wiener processes and GBM). 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 SO2 and NOx allowances markets involve many participants and transactions ([2, 3]), 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 SO2 and NOx allowances prices is at least in principle acceptable. We can say the same for CO2 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 (GBM) with drift (or expected rate of change in the price of allowances) μ, and volatility σ, 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 [4] and[5]:

Equation 1

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

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

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

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[§] See Hull 1997 for an introduction to Wiener processes and GBM.

Equation 2

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

where μ_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 μ represents the expected rate of change in the price of allowances. If μ_m is the expected rate of return of the market portfolio, σ_m the variance of the rate of return of the market portfolio, and ρ_m 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[**] [††],

Equation 3

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

1.2 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 in the paper, but in this case the call option is on a basket that contains one SO2 allowance and 2.9206e-3 allowances of mercury[‡‡].

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.

[**] The assumption here is that there is a dynamic portfolio of assets whose price is perfectly correlated to At.

[††] 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 1 becomes the well known Black and Scholes equation for an European call option on a stock.

[‡‡] 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[§§].

1.3. 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 δ 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) [6]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 [6]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[***]. For SO2 allowances we assume a starting price of $539 which is the closing price on October 31 2006[†††]. We also assume that 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 $(\mu = i, \sigma = 0.3)$.

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

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[§§] It is common to assume that indexes of stocks follow GBM even though it is also assumed that stocks prices follow GBM.

[***] AEO 2006 page 104. We assume figures are given in 2004 dollars, as is the case throughout the report.

[†††] 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.

GBM process $(\mu = i + 0.0718, \sigma)$[‡‡‡], and then jump again in 2020 to $48,000 (2004 dollars) to follow a GBM process $(\mu = i + 0.0256, \sigma)$.

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 continues evolving according to $GBM(\mu_j, \sigma_j)$ the value of the investment of Equation 1 in paper changes to[§§§]:

Equation 4

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

2. Costs and performance of alternative technologies

The operational characteristics of the baseline plant and the capital and OM costs of emissions controls and replacement plants shown in Table 4[****] have been obtained from the Integrated Environmental Control Model-Carbon Sequestration Edition (IECM-cs), version 5.1.3(c)[7][††††], assuming that the extra-costs of installing add-on equipment after the plant has been built (retrofitting) are as given in Table 3. (see [8]for an alternative way to compare the costs and performance of IGCC).

[‡‡‡] $\hat{\mu}_1 = Ln\left(\frac{48{,}000 * \exp(i * (2020 - 2010))}{23{,}400}\right) / (2020 - 2010) = i + 0.0718\%$ where i is the average inflation rate for the period 2010 and 2020. Similarly, $\hat{\mu}_2 = i + 2.56\%$.

[§§§] 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. 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.

[****] 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.).

[††††] The IECMcs model is a tool for calculating the performance, emissions, and costs 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.

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)	1.05
IGCC	CCS (Selexol)	1.45

Table 3: 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 that there are no extra costs in delaying the installation of the CCS system on the IGCC "capture ready" plant. Table 4 and Table 5 summarize the characteristics of the nine possible investments:

Invesment	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	"	"
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 4: 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 CO2 capture; SO2 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) CO2 costs of sequestration based on pipeline transport distance of 161 km (100 miles); CO2 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)	
	SO2 (tons/yr)	NOx (tons/yr)	Hg (lbs/yr)	CO2 (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 5: Air emissions from different plants/configurations

The O&M costs for each component of the plant do not include an electricity penalty. We assume that 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	As given in Table 4	i
	SC		i
	IGCC ready		i
	IGCC		i

Table 6: Assumptions about electricity price, coal price, and OM costs

3. Investment value of each alternative

The investment value of each alternative is equal to the present value of the benefits minus the capital cost. As mentioned before, the benefits are related to any current or potential emissions reductions (after accounting for the corresponding OM costs and energy penalties), and savings in OM, fuel and extra electricity generated with respect to the original plant and are valued as a sum of several terms that include the forward contract or option valuation formulas (call, on a basket, disjunctive, compound) that better represent the operational characteristics of the technology. Tables 5 and 6 show how the benefits of each technology can be valued. For example, the value of the benefits of a WFGD is equal to:

Equation 5

$$Benefits(WFGD) = Benefits(NOx) + Benefits(Basket1) + Benefits(Disjunctive(Basket1, Basket2)$$

.

Equation 5 the benefits associated to NOx correspond to the value of the compound option of subsequently installing a SCR and getting NOx allowances at a cost equal to the OM of the SCR plus its energy penalty. The benefits associated to Basket1 correspond to the value of a stream of call options on a Basket that contains SO2 and Hg allowances. The benefits associated to Disjunctive(Basket1,Basket2) correspond to the option of installing a CCS system and being able to choose to operate it or not to obtain call options on Basket1 or Basket2 (with SO2, Hg and CO2 allowances). The installation of the WFGD does not reduce the use of coal with respect to the original plant, nor reduces the other O&M costs, nor produces extra electricity that can be sold. We do not include the benefits associated with a reduction in particulate matter (PM) because there is no associated market mechanism. For an analysis that accounts for the social costs of PM emissions see [9]

ECD	Benefits	Valuation	Equation
WFGD	1. Optional simultaneous reduction of SO_2 and NOx emissions (using the WFGD) 2. Opportunity to install SCR 3. Opportunity to install CCS	1. Call options on a basket with SO_2 and Hg 2. Embedded call option (to get call options on NOx allowances) 3. Compound disjunctive option (Basket with SO_2 and Hg vs Basket with SO_2,Hg and CO_2)	(1b) (1) (4) , (5)
SCR	1. Reduction of NOx emissions 2. Opportunity to install WFGD 3. Opportunity to install both WFGD and CCS	1. Call options on NOx allowances 2. Compound call options on a basket with SO_2 and Hg 3. Compound disjunctive option (Basket with SO_2, and Hg or Basket with SO_2,Hg and CO_2)	(1) (1b) (5),(6)
WFGD+SCR	1. Benefits 1 and 3 of WFGD 2. Benefit 1 of SCR	1. As for the WFGD 2. As for the SCR	
SCPC (with WFGD and SCR)	1. Reduced consumption of coal 2. Reduced base plant O&M costs and slightly less MWh per year than original plant 3. Non optional reductions of emissions of SO_2, NOx, Hg and CO_2. (Less emission due to increased efficiency) 4. Optional reductions of NOx (using the SCR) 5. Optional reduction of SO_2 and Hg emissions (using the WFGD) 6. Opportunity to install CCS	1. Forward contract on coal 2. Present value of difference between base plant O&M costs and electrical output for SCPC and base plant 3. Forward contracts on SO_2, NOx, Hg, and CO_2 allowances 4. Call options on NOx allowances 5. Call options on a basket with SO_2, and Hg allowances 6. Compound disjunctive option (basket 1 with SO_2, and Hg, or basket 2 with SO_2, Hg, and CO_2)	(2) (2) (1) (1b) (5),(6)
SCPC+CCS	1. Benefits 1 to 4 of SCPC 2. Opportunity to use only WFGD and reduce SO_2 and Hg or use both WFGD and CCS and reduce more SO_2, Hg and CO_2	1. Valued as above 2. Disjunctive option (basket 1 with SO_2, and Hg, or basket 2 with SO_2, Hg, and CO_2)	(6)
IGCC (CCS-Ready)	1. Reduced consumption of coal 2. Reduced base plant O&M costs and slightly more MWh per year than original plant 3. Non optional reductions of emissions of SO_2, NOx, Hg and CO_2. (Less emission due to increased efficiency) 4. Opportunity to install CCS (at a lower capital cost than regular IGCC) and get reductions on CO2 (and modest reductions in the 3 pollutants)	1. Forward contract on coal 2. Present value of difference between base plant O&M costs and electrical output for SCPC and base plant 3. Forward contracts on SO_2, NOx, Hg, and CO_2 allowances 4. Compound option on a basket with SO_2, NOx, Hg, and CO_2	(2) (2) (5)
IGCC+CCS	1.Benefits 1 to 3 of IGCC (CCS-Ready) 2.Opportunity to use the CCS and get reductions of CO2 and additional reductions of SO2, NOx and Hg	1.As valued for IGCC (CCS-Ready) 2. Compound option on a basket with SO_2, NOx, Hg, and CO_2	(5)
IGCC	Equal to the benefits of IGCC(CCS-Ready). It generates a higher electrical output than the original plant and the IGCC(CCS-Ready). The capital costs of installing the CCS (benefit 4) are higher than for the IGCC(CCS-Ready)	As valued for IGCC (CCS Ready)	

Table 7: Benefits of ECDs, valuation analogy and corresponding equations.

Asset:	Investment-->	WFGD	SCR	WFGD +SCR	WFGD+SCR+CCS	SCPC	SCPC+CCS	IGCC-ready	IGCC+CCS	IGCC
SO2	Gives non-optional	-	-	-	-	Yes	Yes	Yes	Yes	Yes
	Number of non-optional	-	-	-	-	35,050	35,050	161,458	161,458	161,656
	Additional capital to get compound ($M 2007)	-	175	-	-	-	-	-	-	-
NOx	Givesoptions	-	Yes	Yes	Yes	Yes	Yes	-	-	-
	Gives compound	Yes	-	-	-	-	-	-	-	-

	options									
	Gives non-optional	-	-	-	-	Yes	Yes	Yes	Yes	Yes
	Number of options	-	20,502	20,502	20,502	17,322	17,322	-	-	-
	Number of non-optional	-	-	-	-	4,868	4,868	27,391	27,391	27,452
	OM total ($M 2007)	-	9	9	9	9	9	-	-	-
	MWh consumed total	-	61,026	61,026	61,026	56,428	56,428	-	-	-
	Number of compound	20,502	-	-	-	-	-	-	-	-
	Additional OM to get compound (does not includes electricity)	9	-	-	-	-	-	-	-	-
	Additional MWh to get compound	61,026	-	-	-	-	-	-	-	-
	Additional capital to get compound ($M 2007)	111	-	-	-	-	-	-	-	-
Hg	Gives non-optional	-	-	-	-	Yes	Yes	Yes	Yes	Yes
	Number of non-optional	-	-	-	-	124	124	32	32	64
	OM total ($M 2007)	-	-	-	-	0.07	0.07	-	-	-
	MWh consumed total	-	-	-	-	0.17	0.17	-	-	-
CO2	Gives non-optional	-	-	-	-	Yes	Yes	Yes	Yes	Yes
	Number of non-optional (tonnes)	-	-	-	-	2,083,034	2,083,034	809,254	809,254	1,335,826
Coal	Gives Futures	-	-	-	-	Yes	Yes	Yes	Yes	Yes
	Number of non-optional per year (Annual savings in fuel (mmBTU)	-	-	-	-	22,511,315	22,511,315	5,751,845	5,751,845	11,617,911
Electricity	Gives non-optional	-	-	-	-	Yes	Yes	Yes	Yes	Yes
	Number of non-optional per year (MWh)	-	-	-	-	(48,044)	(48,044)	1,525	1,525	458,698
Basket1	Gives options	Yes	-	Yes	Yes	Yes	Yes	-	-	-
	Gives compound options	-	Yes	-	-	-	-	-	-	-
	Num SO2 Tons	132,926	132,926	132,926	132,926	126,747	126,747	-	-	-
	Num NOx Tons	-	-	-	-	-	-	-	-	-
	Num Hg Lbs	388	388	388	388	413	413	-	-	-
	Num CO2 Tons	-	-	-	-	-	-	-	-	-
	OM total ($M 2007)	18	18	18	18	17	17	-	-	-
	MWh consumed total	211,054	211,054	211,054	211,054	289,784	289,784	-	-	-
	Additional capital to get Basket1 ($M 2007)	-	175	-	-	-	-	-	-	-
Basket2	Gives options	-	-	-	Yes	-	Yes	-	Yes	-
	Gives compound options	Yes	Yes	Yes	-	Yes	-	Yes	-	Yes
	Num SO2 Tons	164,822	164,822	164,822	164,822	129,775	129,775	3,129	3,129	2,931
	Num NOx Tons	-	-	-	-	-	-	33	33	31
	Num Hg Lbs	524	524	524	524	413	413	496	496	463

	Num CO2 Tonnes	8,806,770	8,806,770	8,806,770	8,806,770	6,934,562	6,934,562	8,144,385	8,144,385	7,617,812
	OM total ($M)	163	163	163	163	137	137	86	86	89
	MWh consumed total	2,919,883	2,919,883	2,919,883	2,919,883	2,769,498	2,769,498	404,597	404,597	890,481
	Additional capital to get Basket2 ($M 2007)	1,136	1,311	1,136	-	624	-	676	-	1,062
Disjunctive	Gives disjunctive basket op	-	-	-	Yes	-	Yes	-	-	-
	Gives compound disjunctive	Yes	Yes	Yes	-	Yes	-	-	-	-
	Number of alternative basket	1	1	1	1	1	1	-	-	-
	Number of alternative basket	2	2	2	2	2	2	-	-	-
OM	O&M cost (no fuel included) ($M 2007)	46	46	46	46	41	41	69	69	67
	Annual O&M growth %	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Table 8: Classification of benefits of each technology for valuation with options formulas

4. Scenarios

Table 1 describes the baseline scenarios for allowances prices as they have been described in section 1.3 and Figure 6 shows the corresponding 95th-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	
		μ	σ			μ	σ			μ	σ
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 9: Base case scenario: Parameters of process followed by allowances prices

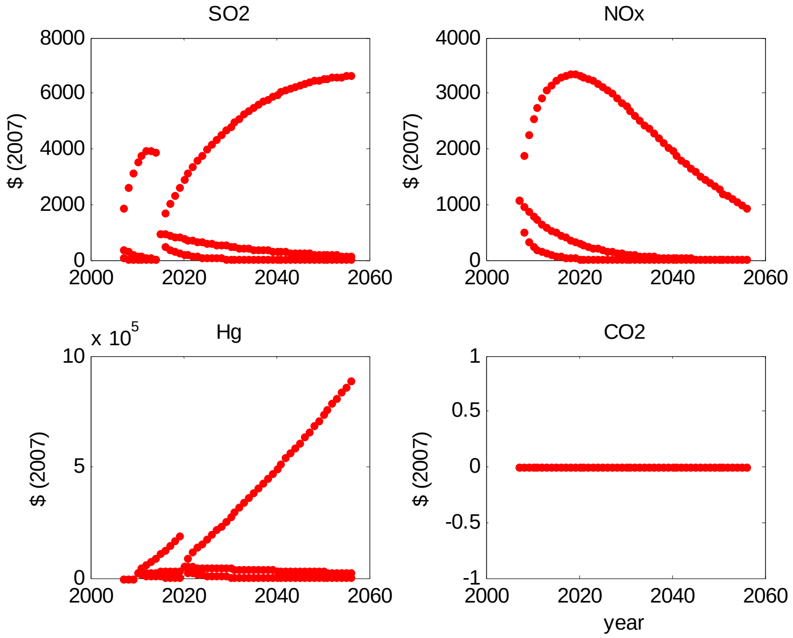


Figure 6: 95%-Confidence intervals for Baseline Scenarios

Figure 7 shows the median and the 95$^{\%}$ confidence interval for CO2 allowance prices under the scenario described in Table 2.

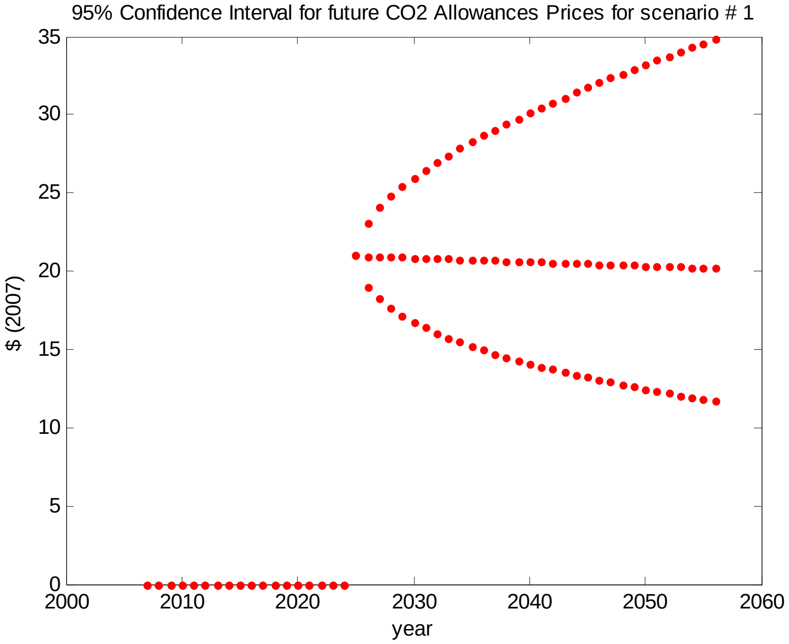
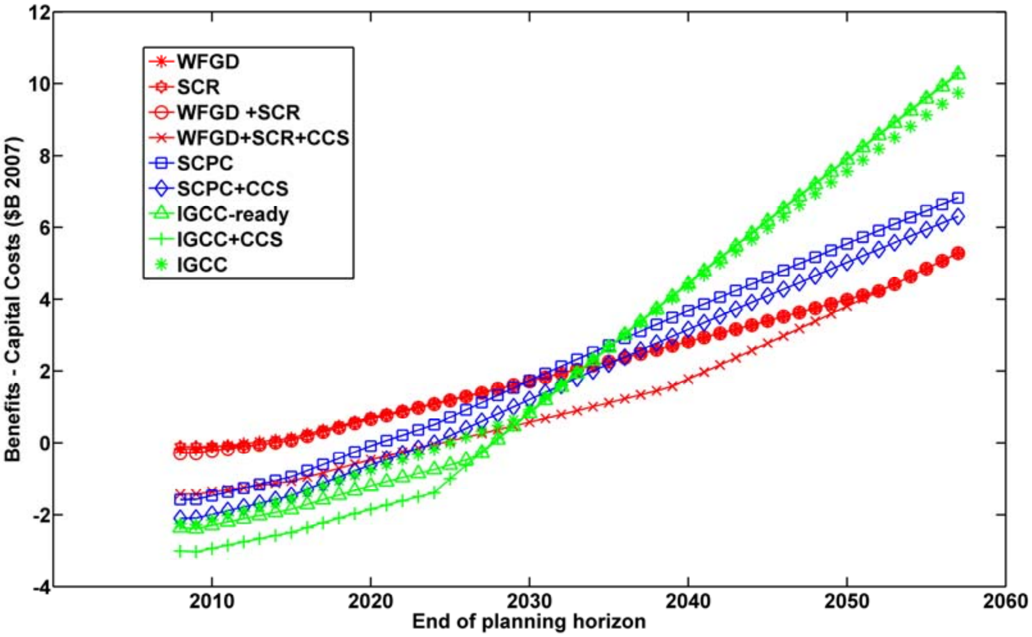


Figure 7: 95$^{\%}$ Confidence intervals for allowance prices for CO2 under scenario 2 (Jump to $20/tonne in 2025)

5. Value of investment alternatives if CO2 prices are expected to jump to $40/tonne in 2025



6. Keeping the old plant is favored by lower expected price of coal

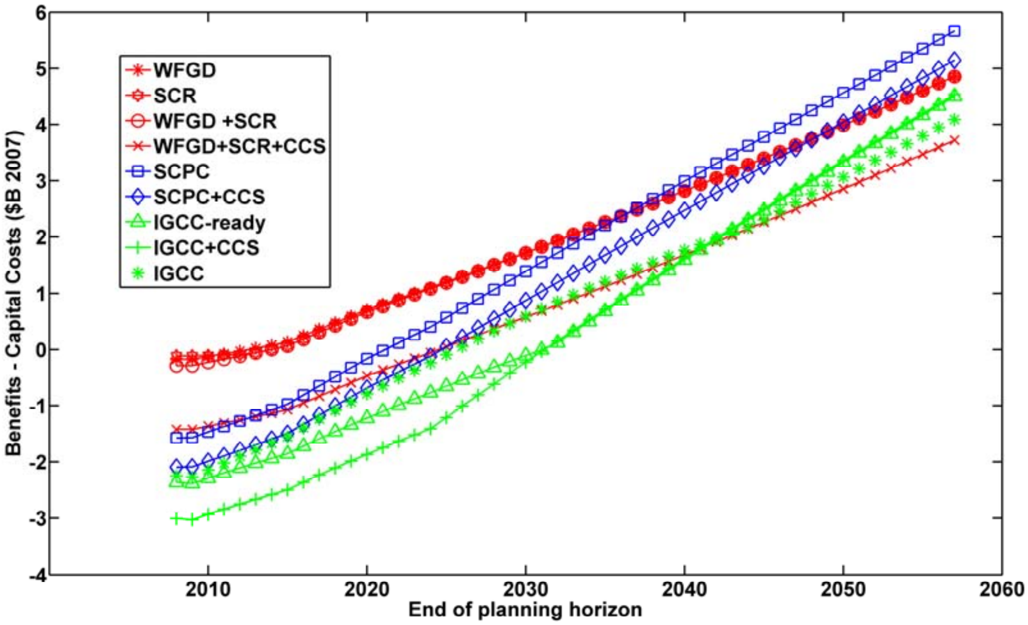


Figure 8: Value of investment alternatives when allowances prices are as in Table 2 in Paper (CO_2 price jumps to $20/tonne in 2025) and coal prices evolve with no drift (e.g. price of coal decreases in real terms)

7. Keeping the old plant is favored by increased capital costs (risk premium) of SC and IGCC

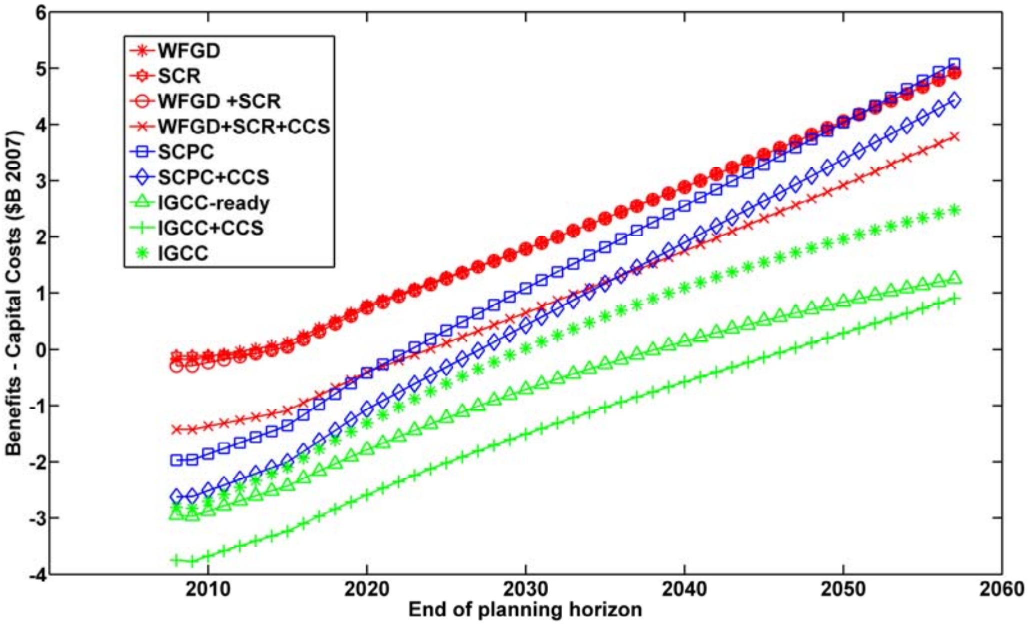


Figure 9: Value of investment alternatives when allowances prices are as in Table 1 in paper (no carbon price), and capital costs of SC, SC+CCS, IGCC, IGCC capture ready and IGCC+CCS are 25% higher.

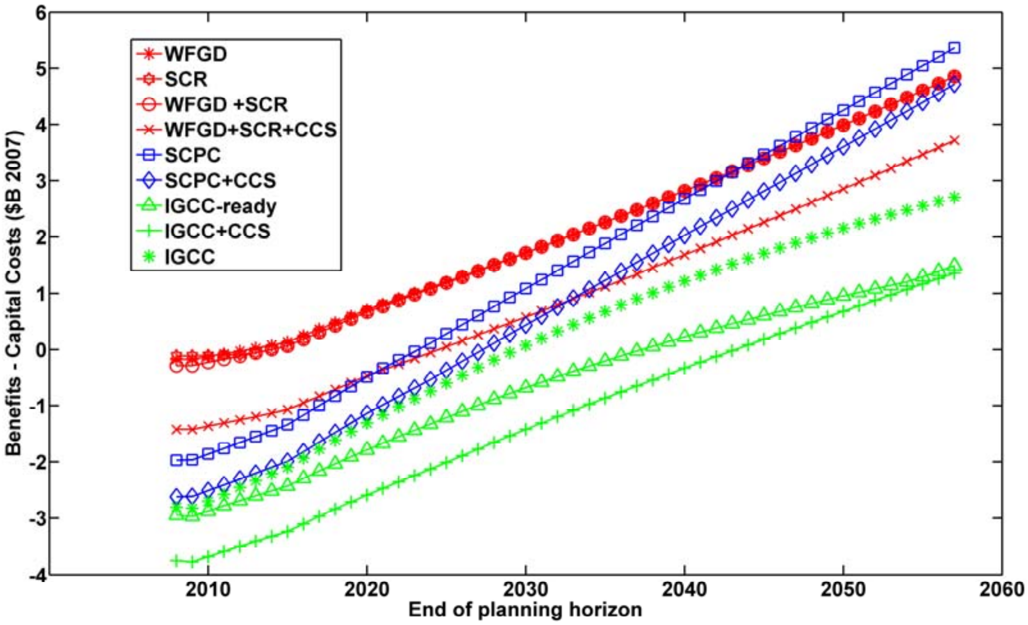


Figure 10: Value of investment alternatives when allowances prices are as in Table 2 in paper (CO_2 price jumps to $20/tonne in 2025) and capital costs of SC, SC+CCS, IGCC, IGCC capture ready and IGCC+CCS are 25% higher.

8. Results when allowances prices are deterministic.

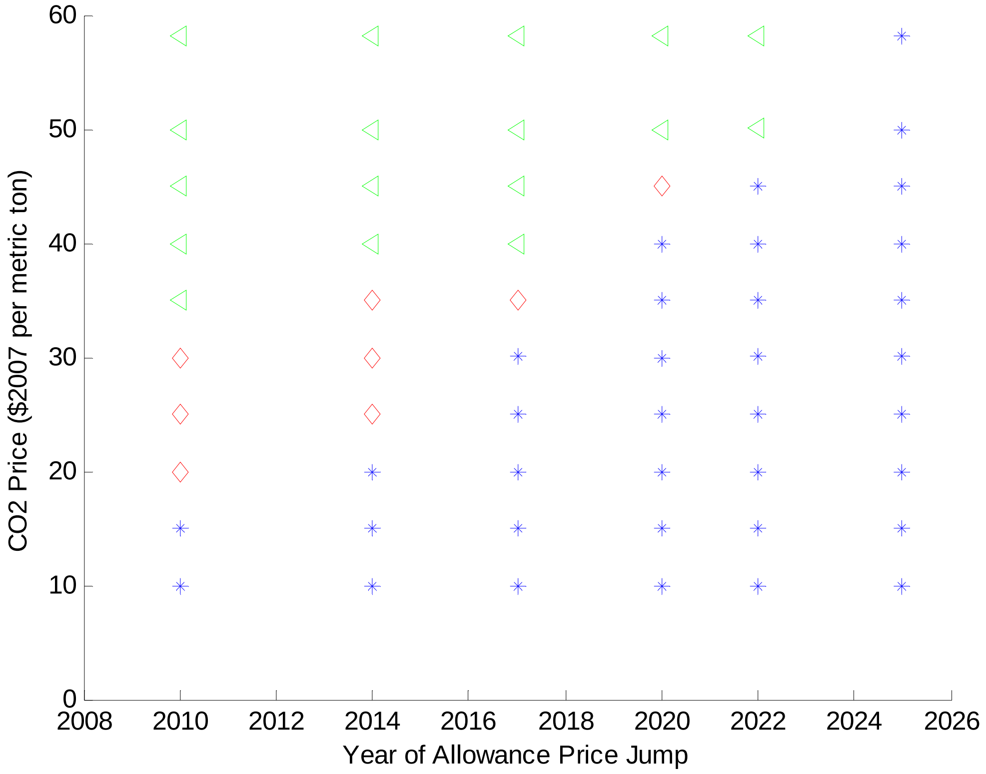


Figure 11: Best investment option when the volatility of all allowances is zero, the CO_2 price jumps once and the planning horizon is 20 years (2027)

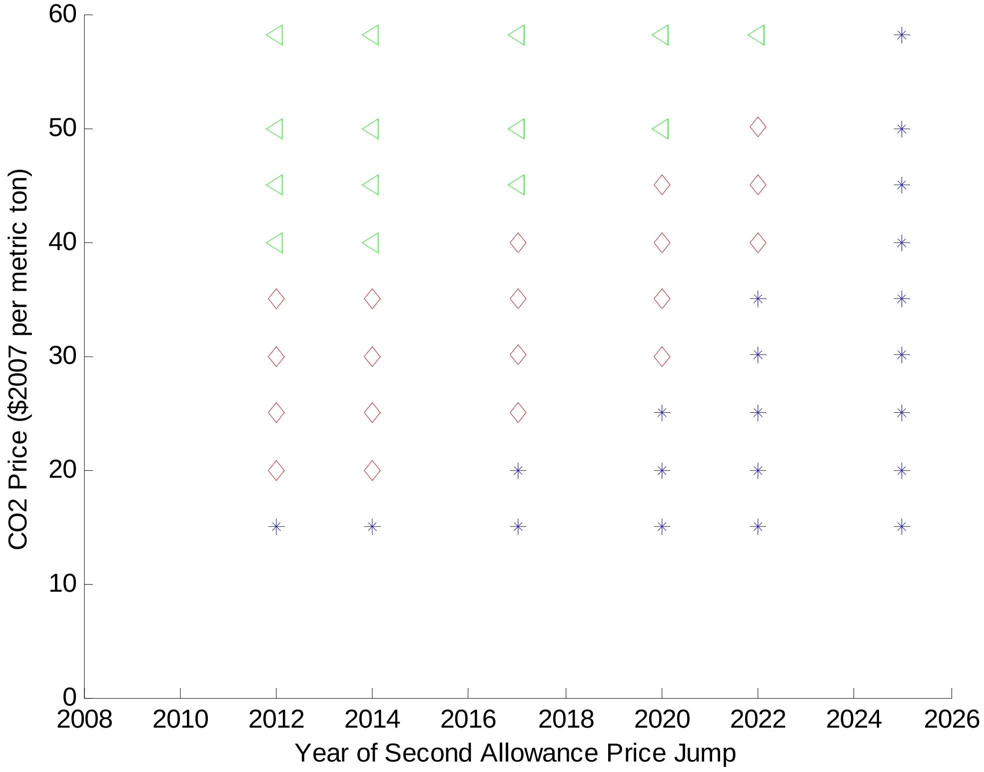


Figure 12: Best investment option when the volatility of all allowances is zero, the CO_2 price jumps twice and the planning horizon is 20 years (2027)

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