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ORIGINAL ARTICLE

# Flexible mandates for investment in new technology

**Dalia Patino-Echeverri · Dallas Burtraw · Karen Palmer**

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**Abstract** Environmental regulators often seek to promote forefront technology for new investments; however, technology mandates are suspected of raising cost and delaying investment. We examine investment choices under an inflexible (traditional) emissions rate performance standard for new sources. We compare the inflexible standard with a flexible one that imposes an alternative compliance payment (surcharge) for emissions in excess of the standard. A third policy allows the surcharge revenue to fund later retrofits. Analytical results indicate that increasing flexibility leads to earlier introduction of new technology, lower aggregate emissions and higher profits. We test this using multi-stage stochastic optimization for introduction of carbon capture and storage, with uncertain future natural gas and emissions allowance prices. Under perfect foresight, the analytical predictions hold. With uncertainty these predictions hold most often, but we find exceptions. In some cases investments are delayed to enable the decision maker to discover additional information.

**Keywords** Technology standards · Climate change · Uncertainty · Carbon capture and storage

**JEL Classification** Q52 · Q55 · Q58

D. Patino-Echeverri
Nicholas School of the Environment, Duke University, Durham, NC, USA

D. Burtraw (✉) · K. Palmer
Resources for the Future, Washington, DC, USA
e-mail: burtraw@rff.org

## 1 Introduction

Environmental regulators often impose technology standards on new investments that require better performance than incumbent technology. For example, corporate average fuel economy standards require efficiency that exceeds the average of the existing vehicle fleet and new source performance standards impose an emissions rate benchmark for stationary sources that is typically more stringent than observed at existing facilities.

The intuition for such policy is straightforward—it is thought to be less expensive to achieve reductions in emissions at new sources than at existing sources, and those emissions reductions will continue over the entire life of the facility. Unfortunately, vintage-differentiated technology standards may lead to extension of the operating lives of existing vehicles or stationary sources because they raise the cost of new investment. In the short run, this could result in worse environmental performance because any new facility, even if it does not have state-of-the-art pollution controls, is likely to perform better than existing older facilities without such controls. In addition, delay in investment postpones the dynamic process of cost reductions for new technology. Hence, regulators face a dilemma in the design of policies to promote new technology—technology mandates may have the unintended consequence of increasing pollution in the short run and possibly in the long run.

This paper investigates this dilemma. In an analytical framework, we examine the incentives created under an inflexible (traditional) emissions rate performance standard and propose two alternatives that improve dynamic consistency by providing endogenous incentives for new investment. Many economists would advocate the introduction of a Pigouvian price to internalize the marginal costs of emissions into investment and operational decisions. Without detracting from this policy guidance, we suppose that political barriers exist to the efficient introduction of an emissions price. Even with the possible introduction of such fees, for example through national cap and trade or emissions fees, there is an apparent requirement under the Clean Air Act to develop technology standards for emissions of $CO_2$. Given this requirement, the challenge that motivates this investigation is how to design standards that provide incentives to accelerate rather than delay the adoption of new technology.

The first alternative introduces an element of flexibility by allowing for an alternative compliance payment (ACP) in the form of an emissions surcharge for investments that fail to meet the maximum emission rate standard.[1] The ACP is not based on a Pigouvian estimate of external cost but rather it is calibrated to provide an endogenous incentive to invest in new technology. In this policy we do not account for the use of revenues that accrue from the surcharge. Finally, in a second alternative we extend the ACP by proposing that revenue from the surcharge be held in an escrow account and used to offset some of the capital cost of later retrofit investment.

An ACP has several potentially virtuous characteristics. First, it bounds costs at the level of the surcharge, potentially facilitating investments even if control technology

[1] Alternative compliance payment options have been a component of recent legislative proposals to promote renewable energy including Senator Bingaman's Clean Energy Standard Act of 2012 and of several state renewable portfolio standard policies.

is not yet commercially mature. Second, if the ACP is set above the variable cost of control technology that is expected to be realized in the future then there is likely to come a time when a retrofit investment is less expensive than continued payment of the surcharge, providing an endogenous incentive to adopt the new technology. Third, if ACP payments are allowed to accumulate and are available to offset the capital cost of the retrofit investment, the time when a retrofit investment is endogenously chosen could come even sooner. Fourth, consumers in the present would begin to contribute to the cost of technological innovation. In contrast, under an inflexible standard, present consumers free ride and the costs of technological innovation are fully passed forward to future consumers and investors, thereby introducing dynamic inconsistency.

In the analytical framework it is straightforward to demonstrate that the inflexible emissions rate standard can delay new investment and potentially increase cumulative emissions. We make precise several hypotheses. An ACP for emissions above the emissions standard is predicted to lead to earlier investments than under the inflexible standard, with lower aggregate emissions and greater profits to investors. When surcharge funds are held in escrow and available to pay for part of the capital costs of retrofits the model predicts investment should occur most quickly, aggregate emissions should be lowest and profits to investors should be highest.

We test these conjectures in a case study for installation of carbon capture and storage (CCS) technology on new fossil-fired power plants. We do so using a simulation framework that combines national and regional level electricity market equilibria with the multi-stage optimization problem facing an individual first-mover investor in CCS in a specific power region of the U.S. over a 43-year horizon.[2] The model examines the incentives for an individual investor choosing generation technology and timing of investment from among five technology options, with CCS installed initially or with subsequent retrofit with CCS. The decision is considered in twelve potential scenarios combining future natural gas prices and future national climate policies that introduce a price on $CO_2$ emissions. In this way, the technology standards are examined as a complement to price-based carbon policy.

With perfect foresight over these twelve scenarios we find an inflexible technology policy delays investment in every scenario except one, consistent with hypotheses that are developed in the analytical framework. Second, we identify an ACP under a flexible policy that leads to investment in CCS at the same time or earlier as would occur under the inflexible standard. Further, the introduction of an escrow fund with the ACP leads to investment in CCS at the same time or earlier than without the fund; however, in one interesting case the operation of the CCS is delayed. Total cumulative emissions are always lower for the flexible policy, and lower still in several scenarios (and never higher) with the escrow fund.[3] Profits are higher with the flexible policy, and higher still in several scenarios (and never lower) with the escrow fund.

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[2] Two years are required for the minumum lag between an investment decision and operation of a facility.

[3] The improved environmental performance with an ACP relative to an inflexible standard stands in contrast to the potential for higher emissions with a ceiling or safety valve on emissions prices under a cap-and-trade program. This outcome illustrates that the use of supplemental price policies can have positive environmental consequences in certain settings.

Finally we investigate the technology policies under multi-stage stochastic optimization with uncertainty over the twelve scenarios reflecting different future natural gas prices and prices on $CO_2$ emissions. In the model, the probability over which scenario will ultimately obtain evolves over time. For every scenario, compared to a setting with perfect foresight, investment is never accelerated and usually delayed under uncertainty reflecting the option value of waiting to make investments until uncertainty is resolved (Dixit and Pindyck 1994). Often different technology is chosen. Indeed, the effect of uncertainty is comparable in magnitude to the introduction of an inflexible policy on the delay in investment.

However, the more meaningful comparison is the influence of each policy in an uncertain context. The inflexible policy has the expected effect of delaying investment in generation capital in most scenarios, as occurs under perfect foresight, but the effect is muted considerably. Against the backdrop of uncertainty, the effect of the anticipated bias against new investment is much less significant under an inflexible standard.

Further, with uncertainty, there are exceptions where investment occurs earlier under an inflexible policy than under no technology policy because the inflexible policy interacts with the usual option value of waiting to invest by eliminating some investment alternatives. With the altered (reduced) set of investment alternatives, an earlier investment can be chosen under the inflexible policy than in the absence of the policy. This suggests a new hypothesis about the anticipated bias against investment described in previous literature. An inflexible policy has two effects. On the one hand it raises the cost of new investment and provides an incentive to keep existing facilities in operation; but on the other hand it reduces the set of investment options and thereby may reduce the option value under uncertainty of waiting to make new investments, which could speed up investment. An inflexible policy may delay investment in most cases, but under uncertainty the outcome is ambiguous in general and less important in magnitude than under perfect foresight.

Nonetheless, with uncertainty as with perfect foresight, compared to an inflexible performance standard the introduction of flexibility generally leads to the earlier (or no later) adoption of CCS for a given type of generation technology, and/or the earlier adoption of new or different generation technology. Both of these outcomes lead to reductions in cumulative emissions and increased profits in our model, suggesting that flexibility should unequivocally improve welfare.

The paper is organized as follows. The next section describes the policy context and reviews the economics literature. Section 3 formalizes the research questions. Section 4 summarizes the technological choices for baseload electricity generation in the specific context of the Illinois basin that forms the basis for the case study. It also presents the simulation model and parameters that are used in the simulations. Section 5 describes simulation results and Sect. 6 concludes.

## 2 Context

Technology-based standards are the most widely used type of policy for influencing environmental performance. The economics literature generally contrasts traditional inflexible standards with incentive-based approaches such as a cap-and-trade program or an emissions tax, which are shown to be the most efficient way to achieve a specific emissions reduction target (Baumol and Oates 1988). Incentive-based approaches also tend to provide greater incentives for firms to innovate to find less expensive ways to reduce emissions in the future by providing an incentive to exceed emission standards (Fischer et al. 2003; Downing and White 1986; Magat 1978; Milliman and Prince 1989; Zerbe 1970).

In practice, technology standards for environmental performance typically are not uniform across regulated sources and often differ by vintage (National Research Council 2006). Economic theory suggests that applying stricter environmental standards to new or modified facilities than apply to existing facilities will raise the cost of investing, limit the rate of capital turnover and extend the lives of existing, often dirty, facilities (Gruenspecht 1982). Consequently emissions may not fall, especially as compared to other policy instruments (Evans et al. 2008). The size of this disincentive to invest can be limited by phasing in levels of stringency, imposing less stringent standards on facilities that are constructed earlier and more stringent standards for later investment (Stavins 2006).

Empirical evidence supports the theory. Gruenspecht (1982) looks at the effects of corporate average fuel efficiency standards for new automobiles on the turnover of the existing automobile fleet and finds that they depressed sales of new automobiles by a few percentage points when they initially came into effect and actually resulted in a small increase in emissions of carbon monoxide in the early years, although this effect was undone over time. Maloney and Brady (1988) find that vintage-differentiated regulations decreased the rate of new plant investment in the electricity sector and led to an increase in $SO_2$ emission over the 70s and early 80s. Nelson et al. (1993) study the effect of new source regulations and find that differential regulations retard capital turnover in the electricity sector, but do not result in a significant increase in emissions. More recently, Bushnell and Wolfram (2006) find weak evidence that new source review increases the lifetimes of existing plants in areas with more stringent environmental regulations. Because new source review can be triggered by major investments at existing plants, some have suggested that it could accelerate the closure of existing plants that fail to make those necessary investments. List et al. (2004) studies this issue and find it retards the rate of alteration of existing plants, but they find little evidence that it accelerates the closure of existing plants.

The dilemma of how to design policies to promote new technology is especially acute in the electricity sector because many existing facilities have technology that is in use beyond its anticipated life. New investments are likely to be more efficient with lower emissions rates even in the absence of technology standards. Moreover, because new investments also are likely to have a long operating life effectively locking in their technology for decades, there is a motivation to make those investments as modern as possible. The long-term nature of investment in the electricity sector triggers special concern about the long-term problem of climate change. The electricity sector contributes roughly 40 percent of the U.S. domestic carbon dioxide ($CO_2$) emissions.

Despite state and federal policies to encourage development of non-emitting renewable generating technologies and federal policies to promote development of nuclear power, over 70 % of the electricity produced in this country is generated with fossil fuels and that figure is expected to remain above 60 % for the next 25 years (EIA 2010a).

Currently there is no national limit on $CO_2$ emissions. In the absence of legislative action on climate policy, and since the Supreme Court decision affirming the authority of the EPA to regulate greenhouse gases under the Clean Air Act (Massachusetts v. EPA 2007), regulatory approaches have assumed center stage in the development of climate policy. EPA has finalized a science-based finding of harm from greenhouse gases that compels regulatory action unless and until Congress moves to change the Act (Richardson et al. 2011). In 2011, in accordance with its obligation EPA revised its corporate average fuel economy standards for vehicles and enacted pre-construction permitting requirements (new source review) for new and modified stationary sources. With respect to the important issue of the operation of stationary sources including power plants, the EPA has indicated its preference for regulation under section 111, a section of the Act that would impose technology-based performance standards.

In April 2012, EPA proposed a technology-based performance standard that specifies a maximum $CO_2$ emissions rate for new electric steam boilers, similar to standards for sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$). Achieving the substantial reduction in $CO_2$ emission rates at coal plants required under the proposal would effectively require CCS. However, the high costs of carbon capture, the uncertainty surrounding the performance of the technology and the largely undeveloped physical and regulatory infrastructure for carbon transport and storage contribute to the reluctance of investors to make major investments in this technology. In the presence of a performance standard mandating this technology, even if coupled with a moderate $CO_2$ price, investors might hold off on investing in new facilities and extend the lives of existing units at least until costs come down and experience with the new technology builds.

The EPA anticipated the concern that CCS is not yet commercially mature by including in its proposed regulation an innovative provision to allow for 30-year emissions rate averaging. A new facility can either achieve the annual average emissions rate standard of 1,000 pounds $CO_2$ per MWh or it can emit at a higher rate in the first ten years and commit to reduce its emissions rate to 600 pounds $CO_2$ per MWh by year eleven so as to achieve a weighted-average emissions rate no greater than 1,000 lb/MWh over the first thirty years of operation.[4] This resembles the approach employed for phase-out of nuclear power in European countries that limited the total hours of operation for existing plants and gave industry the flexibility to achieve the phase out in a cost effective way. The disadvantage in both contexts is dynamic inconsistency; as the date of reckoning comes nearer, the incentive to revisit the commitment strengthens. Because the costs are back loaded, meaning that they would not be felt until new investments were required, policy reversal would seem plausible. In fact, in every country where nuclear phase-outs were proposed there was substantial subsequent backsliding (until the Fukushima Daiichi accident in March 2011), and the EPA's proposal for 30-year $CO_2$ emissions rate averaging might experience a similar fate.

[4] For illustration, a facility could achieve the 1,000 lb $CO_2$/MWh standard on a 30 year basis if it were to emit at 1,800 lb $CO_2$/MWh for the first ten years of operation, which is achievable with supercritical generation technology, and commit to reducing its emissions rate beginning in the eleventh year to 600 lb $CO_2$/MWh, which should be achievable with CCS.

The alternatives we investigate are an ACP—an emissions rate surcharge on new investments that exceed the emission rate standard—and secondly the holding of ACP revenues in escrow for potential use in offsetting some of the capital cost of later retrofit investment. An ACP at the federal level for performance standards affecting new sources would likely require legislative authorization, but precedent exists under the Clean Air Act.[5] However, performance standards regulating existing sources would be implemented at the state level, and an ACP at the state level most likely would face no obstacle under federal law (Richardson 2012). In fact, several states, including Massachusetts, New Jersey and Connecticut, have alternative compliance payments for their renewable portfolio standards (DSIRE 2012).

EPA's recent proposal comes in the context of several developments that suggest a future climate regulatory regime, if one takes shape, is likely to be multi-faceted. This would seem to be true even if a price-based policy were enacted. All nine bills in the 111th Congress that proposed some form of a national cap-and-trade or fee program suggested a level of stringency that was unlikely to provide sufficient incentive for development of CCS.[6] Consequently several of those bills, including Waxman-Markey (H.R.2454) that passed the House of Representatives in June 2009, included special provisions to incent CCS technology. Moreover, survey research on attitudes toward environmental and climate policy find the U.S. public has a clear preference for standards over cap and trade or taxes (Bannon et al. 2007). Even if the US were to introduce a price on $CO_2$ emissions, technology standards could be likely to remain in effect, as occurred previously with the introduction of emissions trading for $SO_2$ and $NO_x$. In this context, two major sources of uncertainty faced by investors in the electric power sector are the stringency of a price on $CO_2$ emissions and the level of natural gas prices in the future, both of which strongly influence the choice of technology for electricity generation.

## 3 Analytical framework

In this section we make precise the hypotheses suggested by the previous literature that we subsequently investigate in the simulation analysis. We describe the annual cost of operating an existing facility as constant annual production $v$ times the average (equal to marginal) production cost $w$ and if there is an emissions fee $o$, then also the cost of emissions $o\hat{e}$(where $\hat{e}$ denotes the plant's emissions per unit of output). The cost of installing and operating a new plant with new technology in year $t$ includes the levelized capital cost per unit of expected operation $c_t$ (with $c > 0$, $\partial c/\partial t \leq 0, \partial^2 c/\partial t^2 \leq 0$), the

[5] A noncompliance penalty (similar to an ACP) is currently authorized under the Act for heavy duty diesel engines, with revenues directed specifically to go to the general fund. Other programs also have financial penalties that could be interpreted as an ACP. Automobile manufacturers often have paid a penalty in lieu of compliance with CAFE.

[6] Estimates for a $CO_2$ price sufficient to justify investment in CCS range from \$28–\$30 (Sekar et al. 2007; Bergerson and Lave 2007), to \$40 (Patino-Echeverri et al. 2007) to \$50 (Reinelt and Keith 2007). Al-Juaied and Whitmore (2009) estimate first-of-a-kind plant is likely to have an abatement cost of \$100–150 per metric ton $CO_2$ avoided, while a mature technology plant is likely to have an abatement cost of \$30–50 per metric ton $CO_2$.

per unit annual operation and maintenance (O&M) costs $m$, and if there is an emissions fee, then also $oe$ (where $e$ denotes the plant's emissions per unit of output with the new technology). The present value of cost is calculated over the planning horizon through year $T$ using discount factor $d = 1/(1+r)$, where r is the rate of interest.

In the absence of a technology standard, a policy that we call the baseline, the decision to invest in a new technology would be made at time $t = \tau^{bsln}$ when the present discounted value of the existing facility is greater than the life-time cost with new technology. Ignoring the possibility of retrofitting with emissions control equipment at a future time, this investment timing is represented by:

$$\sum_{t=\tau}^{T} d^{(t-\tau)} \upsilon \left(w + \hat{e}o\right) \geq \upsilon c_{\tau} + \sum_{t=\tau}^{T} d^{(t-\tau)} \upsilon \left(m + eo\right) \qquad (1)$$

The left hand side of expression (1) is a constant. We assume that rate of change in the cost of capital for the new technology is less than the savings in generation and pollution costs: $c_{\tau} - dc_{\tau+1} < w + \hat{e}o - m + eo$. This implies the new technology is installed as soon as expression (1) is satisfied. In the baseline (no technology standard) the possibility of retrofitting with pollution control technology could only lower the right hand side of (1) and therefore it would accelerate the time of investment.

## 3.1 Traditional new source performance standard

A traditional (inflexible) performance standard would limit the emission rate at new sources to $s$ requiring any new facility to install additional pollution control technology in order to comply. Designate $t = \upsilon$ as the date when pollution control is built, so under a traditional standard this is the same date as when the production facility is built ($\tau^{std} \equiv \upsilon^{std}$). The per unit capital cost of the pollution control technology, $c_t^{pc}$(with $c^{pc} > 0$, $\partial c^{pc}/\partial t \leq 0, \partial^2 c^{pc}/\partial t^2 \leq 0$) would add to the capital cost of the new production facility. In addition, the per unit operating and maintenance costs would increase by the cost of operating the pollution control, $m^{pc}$.

As in the baseline, under the traditional performance standard an investor would invest in new production capacity at time $\tau^{std}$ to minimize the present discounted cost. In each year, the right-hand side of (1) would increase given the additional capital and operating expenses of pollution control, unless the prices of pollution justify the installation of pollution controls independent of the standard, in which case the pollution control is installed in the baseline. Hence, profits would not increase and could decrease. The investment in a new production facility will not happen earlier and may happen later than in the baseline, $\tau^{bsln} \leq \tau^{std}$. Because a new production facility is expected to have lower emissions than current uncontrolled technology even without pollution controls the delay in construction implies cumulative emissions between $\tau^{bsln}$ and $\tau^{std}$ may increase, but will not decrease. The effect on cumulative emissions over the entire planning horizon is ambiguous. Costs will not be lower and may increase, so profits will not increase and may fall in the short and consequently long run.

### 3.2 Flexible new source performance standard

A flexible performance standard would allow the investor to delay or avoid construction of pollution control by paying the ACP denoted $\beta$ (with units: \$/(tons/output)) on the difference between the new facility's emissions rate and the standard per unit of output. The ACP would be paid in addition to the cost of emissions if they have a positive per unit price, $o > 0$. The pollution-related cost is written: $oe + \beta \max\left[(e - s), 0\right]$. If pollution control is added after construction of the production facility plant, the capital cost of pollution control increases by a factor $z$ that represents the extra costs associated with a retrofit installation, and the emissions rate falls to $e^{pc}$, which we assume is less than $s$.

The time at which a new production facility would be built given that the investor could pay the ACP would be no later than $\tau^{std}$ because the investor could always opt to build a facility with pollution control technology at $\tau^{std}$ and avoid the ACP, i.e. $\tau^{flex} \leq \tau^{std}$. If a new generation facility is built at $\tau^{flex}$ without pollution control, the investor's decision about whether to subsequently retrofit the facility depends on whether it would be less expensive to install and operate pollution control than to continue to pay the ACP and the higher pollution costs associated with the emission fee for an uncontrolled level of emissions. The pollution control retrofit occurs at time $\upsilon = \upsilon^{flex}$ when the pollution-related costs associated with continued operation of the uncontrolled facility are greater than or equal to the costs associated with the retrofit, given by the right hand side of expression (2):

$$\sum_{t=\upsilon}^{T} d^{(t-\upsilon)} v\left(eo + (e - s)\beta\right) \geq v\,(1 + z)\,c_{\upsilon}^{pc} + \sum_{t=\upsilon}^{T} d^{(t-\upsilon)} v\left(m^{pc} + e^{pc} o\right) \quad (2)$$

An increase in the ACP increases the left hand side of expression (2) and thereby can move forward the time when retrofit occurs $\left(\partial \upsilon^{flex}/\partial\beta \leq 0\right)$. However, a high ACP has the potential of making the flexible new source performance standard equivalent to the traditional (inflexible) standard. Similarly, a low ACP may make the flexible new source performance standard equivalent to a business-as-usual policy with no technology standard. Therefore an effective ACP value is low enough to encourage investment in a new production facility before it would occur under a traditional standard, but high enough to create incentives for a pollution control retrofit to occur at the same time or before the production facility with pollution control would be built under a traditional standard[7].

Note that the effectiveness of a flexible emissions standard depends on two conditions; (a) the existence of a pollution control technology without prohibitive cost penalties for retrofit installations, and (b) the expectation that the capital costs of this technology will gradually come down. A retrofit installation will be profitable if and only if the gains from postponing the investment to take advantage of such reductions in capital costs are higher than the extra cost of a retrofit installation. Therefore the

[7] See Appendix 4 in the appendix for an estimation of the range of ACP values that allow a flexible performance standard to be effective.

CCS learning rate determines the maximum retrofit penalty that allows the flexible emissions standard to be superior to the inflexible standard.[8]

We define $\beta^*$ as the ACP value that would achieve investment in pollution control technology by the same time as would a traditional emission performance standard, that is $\tau^{std} \equiv \upsilon^{std} = \upsilon^{flex}$. The implication is that at $\beta^*$, even if a new uncontrolled production facility is built earlier than it would be under the traditional performance standard, $\tau^{flex} < \tau^{std}$, emissions would not rise before $\tau^{std}$ because emissions from the new uncontrolled technology are expected to be less than from existing technology. Furthermore, since construction of a new facility with pollution control at $\tau^{std}$ remains possible, we expect profits for the investor would not fall with the introduction of a flexible performance standard. However, the investor might choose a different technology, an issue we explore in the simulation.

Investment in new production capacity under a flexible standard will occur when the present value of costs of continued operation of an existing facility is greater than or equal to the present value of costs of a new facility. Given that retrofit of pollution controls occurs at time $\upsilon^{flex}$ the investment in new production capacity occurs at time $\tau = \tau^{flex}$:

$$\begin{aligned}\sum_{t=\tau}^{T} d^{(t-\tau)} v\left(w + \hat{e}o\right) \geq v c_\tau &+ \sum_{t=\tau}^{T} d^{(t-\tau)} v m \\ &+ \sum_{t=\tau}^{\upsilon^{flex}} d^{(t-\tau)} v\left(eo + \beta \max\left[(e-s), 0\right]\right) \\ &+ d^{(\upsilon^{flex}-\tau)} v(1+z) c_\upsilon^{pc} \\ &+ \sum_{t=\upsilon^{flex}}^{T} d^{(t-\upsilon^{flex})} v\left(m^{pc} + e^{pc} o\right)\end{aligned} \tag{3}$$

### 3.3 Flexible new source performance standard with an escrow fund

Heretofore we have not accounted for revenue from the ACP under the flexible policy. One alternative would be to allow the revenue to accumulate and earn interest at rate $\rho$. Under the flexible policy, if retrofit installation of pollution control at time $\upsilon^{flex}$ were to occur, the value of the fund (at time $\upsilon^{flex}$) would be $\sum_{t=\tau^{flex}}^{\upsilon^{flex}} (1+\rho)^{\upsilon^{flex}-t} v \max\left[(e-s), 0\right]\beta$.

Here we consider that those funds held in escrow are available to offset some or all of the capital costs of retrofitting a plant with pollution control. We assume $\rho$ is less than the market interest rate plus the rate of change in the cost of pollution control capital, $\rho < r + (\partial c^{pc}/\partial t)$, to avoid the incentive to delay investment beyond the time when retrofit is first profitable.

[8] See Appendix 5 in the appendix for a calculation of the upper bound of the retrofit penalty.

The availability of the funds accumulated in escrow may change the timing of pollution control retrofit. If the new production facility were built without pollution control one could expect retrofit to occur when the O&M costs, pollution fees and APC without pollution control is greater than the expected discounted value of the capital and O&M costs of pollution control technology plus the (reduced) pollution fees minus the funds from escrow:

$$\sum_{t=\upsilon}^{T} d^{(t-\upsilon)}\upsilon\,(eo+(e-s)\,\beta) \geq \upsilon\,(1+z)\,c_{\upsilon}^{pc}+\sum_{t=\upsilon}^{T} d^{(t-\upsilon)}\upsilon\left(m^{pc}+e^{pc}o\right)$$
$$-\sum_{t=\tau}^{\upsilon}(1+\rho)^{(\upsilon-t)}\,\upsilon\max\left[(e-s)\,,0\right]\beta \qquad (4)$$

The left-hand side of expression (4) is identical to expression (2) and the right hand-side differs only due to the subtraction of funds from the escrow. Therefore, the time when pollution control is installed under the escrow fund policy occurs no later than the time under the flexible performance standard $\left(\upsilon^{esc} \leq \upsilon^{flex}\right)$. This is true because after time $\upsilon^{flex}$ the going-forward cost of installing and operating pollution control is always less than the variable costs of not doing so, and the availability of the escrow fund strictly reduces further the cost of retrofit.

The introduction of the escrow account reduces the right hand side of expression (3) by:

$$-\,d^{(\upsilon-\tau)}\sum_{t=\tau}^{\upsilon}(1+\rho)^{(\upsilon-\tau)}\,\upsilon\max\left[(e-s)\,,0\right]\beta \qquad (5)$$

Consequently, the date of construction of new capacity with the escrow fund is expected to be no later and possibly earlier than under the flexible emission standard, i.e. ($\tau^{esc} \leq \tau^{flex}$). As a consequence, the ACP that leads to investment at the same time as occurs under the traditional performance standard should be less with an escrow account than occurs otherwise.

With the introduction of the escrow fund policy, given the expectation that new capacity displaces higher emitting existing capacity and is built no later, and that pollution control is installed no later, the escrow fund policy is unambiguously expected to not increase emissions. Finally, since construction of a new facility with pollution control at $\tau^{flex}$ remains an option, we expect profits for the investor would not fall with the introduction of the escrow fund.

This discussion provides intuition that increased flexibility coupled with economic incentives in the performance standard would lead to lower emissions, more timely achievement of investment in pollution control, and greater profits. The suggested hypotheses are summarized in Table 3 in the results section. Since the actual outcome is an empirical question we test the predictions with a simulation model as described in the next sections.

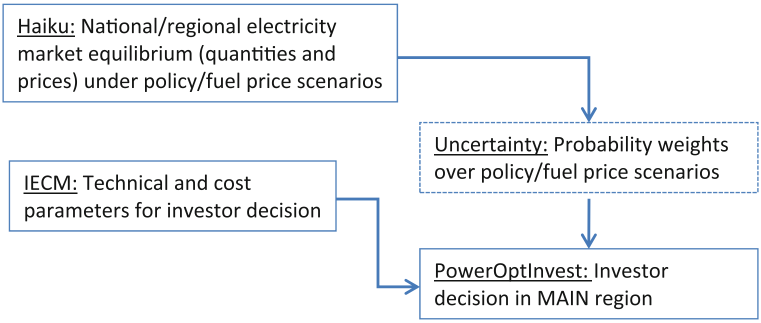


**Fig. 1** Model relationships

## 4 Simulation model

The reduction of greenhouse gas emissions from the power sector is a forefront technical challenge associated with mitigating climate change. EPA's recently proposed emissions rate standard for the power sector would effectively require CCS technology on new and modified steam boilers in the power sector. We use this concrete setting to evaluate the hypotheses generated above.

CCS involves the capture of $CO_2$ and its transportation and sequestration in a secure storage site. Commercialization of CCS would be particularly important in the Illinois Basin, a region that covers most of Illinois and western parts of Indiana and Kentucky and is a major producer of coal and of coal-fired electricity. The region is home to three types of geologic formations potentially suitable for storage: depleted oil and natural gas reservoirs, saline aquifers and deep coal mines that are inaccessible for mining. Transportation of carbon represents an important part of the cost of CCS and this could be minimized at plants in the region.

We integrate three models as illustrated in Fig. 1 to explore the incentives created under different policies.[9] The first is the Haiku model (Paul et al. 2009), which solves for electricity market equlibria in twenty regions of the US linked by transmission capability. Nine of the twenty regions have competitive pricing in place, including the region that covers Illinois, the location under study. The other eleven regions are modeled to have traditional cost-of-service regulation. The model solves for capacity investment and retirement and system operation accounting for three seasons and four time blocks, obtaining simultaneous compliance with a large set of constraints including regulations to control emissions of $NO_x$, $SO_2$, $CO_2$ and mercury from the electricity sector. Twelve scenarios reported in Table 1 describe potential future natural gas equilibrium price and a potential national price on $CO_2$.[10] These scenarios are

[9] More complete detail on these models and the simulation results is provided in Patino-Echeverri et al. (2012).

[10] In the business-as-usual baseline scenario there is no federal climate policy (labeled "0 %_L-M"). In the other three policy scenarios a federal climate policy is assumed to be in effect beginning in 2012 that specifies an emission cap with banking with an aggregate quantity of $CO_2$ emissions from the electricity sector that matches the quantity anticipated by the EIA in its analysis of S.280 (Lieberman-McCain)

**Table 1** Twelve scenarios developed in Haiku

| Natural gas price scenario | Climate policy scenario | | | |
|---|---|---|---|---|
| | 0 %_L-M | 50 %_L-M | 100 %_L-M | 150 %_L-M |
| Low NG price | low0 | low50 | low100 | low150 |
| Mid NG price | mid0 | mid50 | mid100 | mid150 |
| High NG price | high0 | high50 | high100 | high150 |

solved in the electricity market model assuming perfect foresight to generate projections of prices for fuel, electricity and emissions allowances, along with the expected reductions in capital and O&M costs for the various power generation technologies and emissions controls. These projections are then used as inputs for the decision-making process of an individual first-mover price-taking investor represented in PowerOptInvest.

The second model is the Carnegie Mellon University Integrated Environmental Control Model-Carbon Sequestration Edition, version 5.2.1(c) (referred to hereafter as IECM-cs)(Carnegie Mellon University 2010), which provides detail on the performance and cost of new coal and gas fired electricity-generating facilities and opportunities for applying CCS either at the time of initial construction or as a post-construction retrofit.[11] We consider five options for new generation investment including sub-critical pulverized coal, supercritical pulverized coal, ultra-supercritical pulverized coal, integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC). The detailed parameters are modified by information from Haiku about the evolution of capital cost, allowance prices, electricity and fuel prices over time under the twelve policy scenarios. Investment in CCS is assumed to be the first in the region and not to affect equilibrium prices.

For sub-critical pulverized coal, the efficiency penalty of CCS measured by the increase in net heat rate is close to 40 %, for a supercritical facility it is about 33 %, and it is close to 30 % for ultra-supercritical pulverized coal facilities. For IGCC, the heat rate penalty introduced by CCS is 20 %. The requisite increased energy use can have

Footnote 10 continued
(EIA 2007a). This policy was chosen because unlike H.R. 2450 (Waxman-Markey) there is no free allocation to local distribution companies. With banking, the allowance price rises at the opportunity cost of capital (the real interest rate) of 8 % over time. The two other climate policy scenarios simply take the price trajectory for $CO_2$ from this run and diminish it by roughly 50 % (labeled “50 %_L-M”) or increase it by 50 % (labeled “150 %_L-M”) to achieve a different aggregate level of emissions. In every case $CO_2$ allowances are distributed through auction.

The natural gas supply curves are fit to older data on the supply and prices of natural gas (EIA 2007b) to construct a supply curve for natural gas that reflects historic variability. In the low natural gas price case, the supply curve prices are reduced by 33 %; in the high natural gas price case, they are increased by 33 %. The price of natural gas is then solved endogenously, determined by the quantity demanded by gas-fueled electricity generators.

[11] The IECM model was 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. The database provided by the model is a later vintage of the same database that was used for the MIT coal study (MIT 2007).

implications for emissions of other pollutants (Rubin et al. 2007; MIT 2007, p. 28). Under specific assumptions about coal type in the region (Illinois # 6) CCS is least expensive on ultra-supercritical, then supercritical, and relatively more expensive for sub-critical. The initial cost of constructing advanced facilities is higher (per MW) than for a sub-critical pulverized coal facility, but this is somewhat offset by lower fuel consumption at the more advanced facilities. There are important uncertainties about the timing, mitigation potential, safety, regulatory framework, and overall costs of a national system to capture, transport and store large quantities of $CO_2$. To reflect these uncertainties we multiply by 2 the current estimates of CCS capital costs and linearly decrease this factor until it becomes 1 in the twelfth year of the model. We assume a retrofit penalty of 20 % for a pulverized coal plant and also for NGCC; for IGCC it is 30 %.

The third model is PowerOptInvest, which is a multi-stage stochastic optimization model used to find the investment decision from the perspective of the investor in the face of uncertainty. At each point in time the investor has the option to invest in any of the identified generation technologies, with CCS or without. If the investment does not include CCS the investor retains the option of retrofitting with CCS at a later date. Alternatively, in a given period the investor can delay the investment altogether thereby retaining the option to choose a different generation technology in the future.

To represent uncertainty, the scenarios in Table 1 are assigned equal probability weights that evolve toward resolution. Initially the investor holds priors of equal probability and over the first twelve years the investor updates her priors based on current observations, placing relatively greater probability on the likelihood that the current state of the world will govern in year twelve. At year $t$ the probability assigned to any of the twelve scenarios other than the current scenario $(j)$ is $p_t^{\hat{j}} = \frac{1}{12} \times \left(\frac{\text{Year 12}-\text{Year}t}{\text{Year 12}-\text{Year 1}}\right)$ and the probability assigned to scenario $j$ is $p_t^j = 1 - \frac{11}{12} \times \left(\frac{\text{Year 12}-\text{Year}t}{\text{Year 12}-\text{Year 1}}\right)$. In year twelve and over the remainder of the investment horizon the scenario is known for certain.

The possibility exists that the introduction of a performance standard, a flexible standard or an escrow fund would cause a different technology to be chosen. If the choice of technology varies, the timing of construction of the generation facility or the CCS technology could also vary. No matter what investments have been made in previous years, the investor can always choose to change technologies and build any new plant with or without CCS, but sunk capital investment costs are not recoverable.

## 5 Results

The modeling analysis compares investment decisions under the three different versions of the technology standard and a scenario with no technology policy. We first consider the twelve potential natural gas and federal climate policy scenarios in a context with perfect foresight. Subsequently we consider uncertainty.

### 5.1 Perfect foresight

The baseline results describe investment decisions in the absence of a technology policy. The dates that new generation capacity and CCS come into operation are presented in Table 2.

The full characterization of investment choices is presented in the appendix. For illustration, we offer a brief description of investment choices in the baseline. When natural gas prices are low, initially an NGCC plant is always the technology of choice. When there is no federal climate policy in place, NGCC is never retrofit with CCS, but it is finally replaced by IGCC without CCS. Under the weak climate policy (low50), the IGCC plant is built with CCS in 2046. Under the mid climate policy (low100) the IGCC with CCS comes online in 2041, and under strict climate policy (low150) in 2036.

With natural gas prices at their mid-level and no federal climate policy (mid0), an ultra-supercritical coal plant is chosen. With mid-level gas prices, under any type of federal climate policy NGCC is chosen. It is replaced by IGCC with CCS in years 2041 under weak climate policy (mid50), 2036 in the mid-case (mid100), and 2032 under strict climate policy (mid150).

For the scenarios with high natural gas prices, ultra-supercritical is chosen for all versions of federal climate policy except for the most stringent one. Under the weak climate policy (high50), it is replaced by IGCC with CCS in 2048, and under the mid-climate policy (high100) this occurs in 2036. For the most stringent climate policy (high150), an IGCC plant comes online with CCS installed in 2023, so in this case technology policy is expected to have no effect.

The introduction of an inflexible performance standard on new investments (NSPS) leads to delays in investment in generation capacity for all scenarios except where natural gas prices are high and climate policy is stringent (high150), in which case the initial investment includes CCS even in the absence of the technology policy. This is indicated by slant values in Table 2. However, it does not necessarily lead to a delay in operation of CCS. In eleven of twelve cases, operation of CCS occurs earlier, as indicated by the bold values in Table 2.

With a flexible standard (Flexible NSPS) an investor can build a new facility that does not strictly meet the technology standard but must pay the ACP on its emissions that are in excess of the standard. Introducing this type of policy raises the question of how to set the emissions surcharge. We denote $\beta^*$ as the minimum value of the ACP that must be paid for each ton in excess of the emissions standard so that investment in CCS under the flexible standard occurs at the same time (or earlier) than under the inflexible standard[12]. We always find a value of $\beta^*$ between \$0 and \$13 that leads to investment in CCS at least as soon as under the inflexible technology standard.[13]

[12] The original goal is to set the ACP that achieves investment in CCS at the same time under the inflexible and flexible standard. However achieving investment at the same time is not always possible so we choose the minimum ACP that causes investment at the same time or earlier. Another possibility is choosing an ACP value that achieves the same emissions level under the inflexible and flexible standard, or an ACP value that achieves the same profits for investors. Future work will explore these alternatives.

[13] When natural gas price is at its mid level and there is no federal climate policy (mid0) the inflexible NSPS policy causes investment to be indefinitely postponed (beyond 2052), so in this case the surcharge

**Table 2** Date when first investments in generation and CCS come into service

| Gas price | $CO_2$ tax | Baseline: no technology policy | | Inflexible NSPS | | Flexible NSPS (ACP) | | Flexible NSPS (ACP) with Escrow | |
|---|---|---|---|---|---|---|---|---|---|
| | | Certain | Uncertain | Certain | Uncertain | Certain | Uncertain | Certain | Uncertain |
| Date that Initial Investment in Generation Begins Operation | | | | | | | | | |
| Low | 0 % | 2017 | 2024 | *2046* | *2046* | **2018** | **2024** | 2018 | 2024 |
| Low | 50 % | 2014 | 2023 | *2023* | *2025* | **2019** | 2025 | **2016** | 2025 |
| Low | 100 % | 2012 | 2023 | *2023* | *2024* | **2013** | NA | 2013 | NA |
| Low | 150 % | 2012 | 2023 | *2023* | *2028* | **2012** | 2028 | 2012 | 2028 |
| Mid | 0 % | 2017 | 2024 | *Never* | *Never* | **2017** | **2024** | 2017 | 2024 |
| Mid | 50 % | 2014 | 2024 | *2030* | *2030* | 2030 | 2030 | **2015** | 2030 |
| Mid | 100 % | 2012 | 2024 | *2029* | *2029* | **2013** | 2029 | 2013 | 2029 |
| Mid | 150 % | 2012 | 2026 | *2023* | 2026 | **2013** | 2026 | **2012** | 2026 |
| High | 0 % | 2015 | 2024 | *2036* | *2036* | 2036 | 2036 | 2036 | 2036 |
| High | 50 % | 2013 | 2024 | *2033* | *2033* | 2033 | 2033 | 2033 | 2033 |
| High | 100 % | 2012 | 2027 | *2023* | **2024** | 2023 | NA | 2023 | NA |
| High | 150 % | 2023 | 2024 | *2023* | **2023** | 2023 | NA | 2023 | NA |
| Date that CCS begins operation | | | | | | | | | |
| Low | 0 % | Never | Never | **2046** | **2046** | 2046 | 2046 | 2046 | 2046 |
| Low | 50 % | 2046 | 2046 | **2023** | **2025** | 2023 | 2025 | *2025*[a] | 2025 |
| Low | 100 % | 2041 | 2041 | **2023** | **2024** | 2023 | NA | 2023 | NA |
| Low | 150 % | 2036 | 2036 | **2023** | **2028** | 2023 | 2028 | 2023 | 2028 |
| Mid | 0 % | Never | Never | Never[b] | Never[b] | NA | NA | NA | NA |
| Mid | 50 % | 2041 | 2041 | **2030** | **2030** | 2030 | 2030 | **2025** | 2030 |
| Mid | 100 % | 2036 | 2036 | **2029** | **2029** | **2027** | 2029 | **2024** | 2029 |
| Mid | 150 % | 2032 | 2026 | **2023** | 2026 | 2023 | 2026 | 2023 | 2026 |
| High | 0 % | Never | Never | **2036** | **2036** | 2036 | 2036 | 2036 | 2036 |
| High | 50 % | 2048 | 2048 | **2033** | **2033** | 2033 | 2033 | 2033 | 2033 |
| High | 100 % | 2036 | 2027 | **2023** | **2024** | 2023 | NA | 2023 | NA |
| High | 150 % | 2023 | 2024 | **2023** | **2023** | 2023 | NA | 2023 | NA |

*Slant* values indicate years later than policy to left with same information structure, *bold* values indicate years earlier than policy to left

[a] Investment occurs at the same time as under the inflexible policy but operation is delayed 2 years

[b] Due to some convergence tolerances in Haiku, electricity prices after 2030 in the Mid-0 % scenario are lower than under the Low-0 % scenario. With these lower electricity prices investors will prefer to buy electricity in the market instead of generating with an IGCC + CCS plant

We find an increase in the value of the ACP moves forward the time at which CCS technology is built.

Footnote 13 continued
value needed to replicate this result under a flexible NSPS policy is $0. Under perfect foresight and under the most strict federal climate policy, when natural gas prices are high (high150), no technology policy is necessary to get the IGCC with CCS to come on line, so again the surcharge value is $0.

The change in the timing and choice of generation technology can have an important effect on cumulative emissions. In many cases investment in newer technology, albeit absent CCS, comes years earlier than under the inflexible policy.

The escrow fund, comprised of accumulated alternative compliance payments, provides a source of funds that can be used to subsidize the cost of retrofitting a facility with CCS in the future.[14] The $\beta^*$ values of flexible policy with escrow are lower or the same as the $\beta^*$ values for flexible policy without escrow. There are two cases where the operation of an investment does not start when the plant is ready. With low natural gas prices and no climate policy (low0) there is one year when the NGCC plant is available and is not used because the investor finds it less expensive to buy electricity from the market[15]. Under low natural gas prices and weak climate policy (low50) a CCS retrofit is ready to operate in year 2023 (as under the inflexible policy), but the NGCC plant is operated without CCS for two years before carbon prices justify reducing $CO_2$ emissions[16].

### *5.1.1 Emissions*

Figure 2 shows cumulative $CO_2$ emissions over 43 years under the baseline situation and the three different policies analyzed. Under perfect foresight, the inflexible standard produces $CO_2$ emissions higher than those of the baseline for 8 out of 12 scenarios and equivalent in one scenario. The exceptions are the scenarios with high natural gas prices. The flexible standard with an ACP equal to $\beta^*$ produces cumulative $CO_2$ emissions that are lower or equal to the inflexible standard for every scenario. Moreover, $CO_2$ emissions of the flexible standard with escrow are the lowest or equal to lowest in every scenario.

In summary, under perfect foresight an inflexible standard tends to delay investment and produce cumulative $CO_2$ emissions that are higher than under the baseline. The introduction of flexibility tends to result in lower $CO_2$ emissions than under the inflexible policy. In nine scenarios the flexible standard leads to lower or equal emissions than in the baseline. In every scenario the flexible standard with an escrow leads to equal or lower emissions than with no technology policy.

[14] In the simulations, three rules are imposed to simplify the problem: the escrow fund does not earn intereset, the funds withdrawn cannot exceed the capital cost of CCS and funds can only be withdrawn once.

[15] This occurs because NG prices continuously rise even in the low NG price scenarios and in year 2045 it is more expensive to operate a NGCC plant than to buy electricity from the market. Anticipating high NG prices, the investor installs an IGCC+CCS plant in year 2044 but this plant is only ready for operation in 2046.

[16] The operation of the CCS retrofit begins in 2025, 2 years later than occurs under the flexible standard, but investment happens at the same time as under the flexible standard. The investment occurs because the ACP payment stops at the time of investment in CCS, but there is no constraint forcing investors to use such investment. This is the only case when a CCS investment is not used.

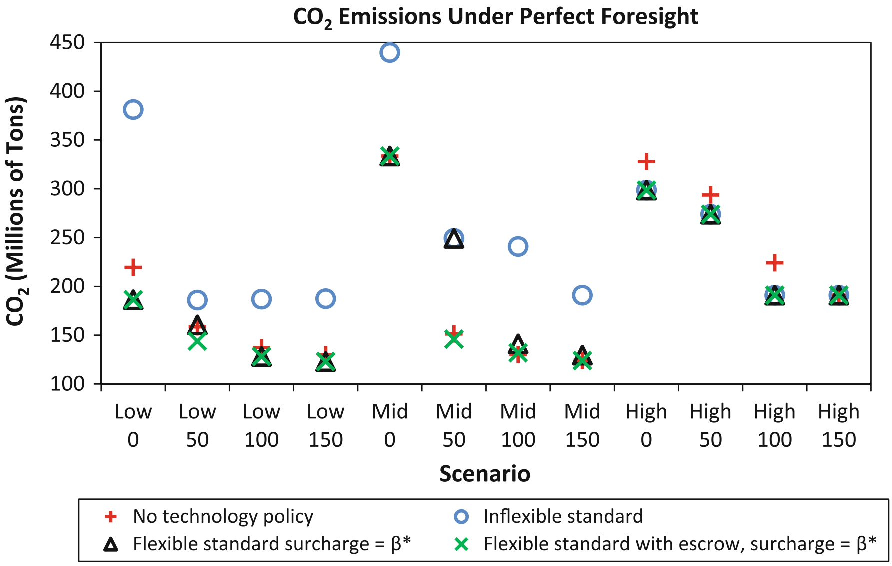


**Fig. 2** Cumulative $CO_2$ emissions with perfect foresight

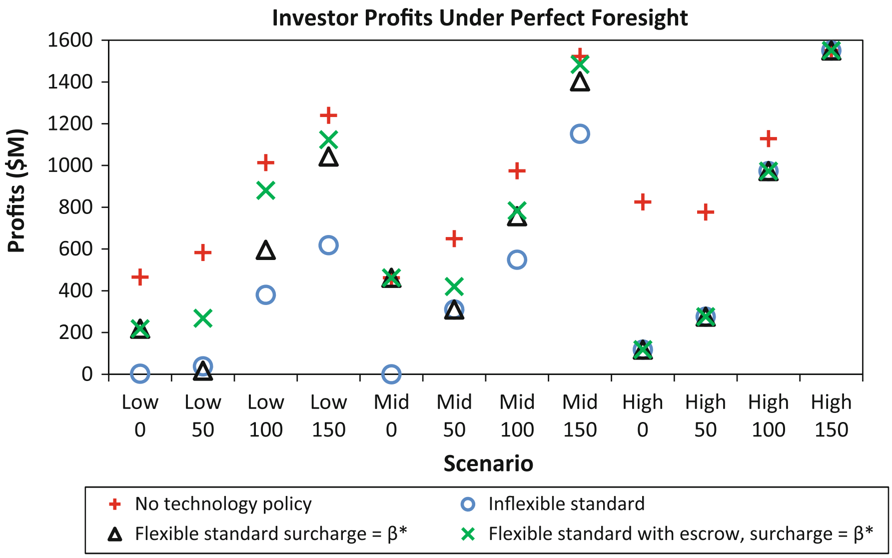


**Fig. 3** Investor's profits with perfect foresight

### *5.1.2 Profits*

Figure 3 shows the net present value of investor profits across the four policies under perfect foresight. In most scenarios profits are highest in the baseline. Profits are always lower under the inflexible standard than under no technology policy, with the exception of the scenario with high natural gas prices and stringent climate policy (high150) where the same investments occur. The introduction of a flexible policy always leads to profits that are at least as great as under the inflexible policy and often they are substantially greater. In turn, the introduction of an escrow fund leads to profits that are always as great as under the flexible policy without an escrow fund, and strictly greater in five scenarios.

### 5.2 Uncertainty

We again describe the investments in the baseline to illustrate the differences in investment with uncertainty. In the scenarios with low natural gas prices again investors choose to build an NGCC plant and subsequently replace it with IGCC. With no climate policy, the IGCC does not include CCS. As in the perfect foresight case, with increasing stringency of climate policy the IGCC facility with CCS comes online in years 2046, 2041 and 2036, respectively.

When natural gas prices are at the mid-level and there is no federal climate policy (mid0), an ultra-supercritical coal plant is chosen. With weak (mid50) or mid-case (mid100) climate policy, an NGCC is initially installed but later replaced by IGCC with CCS in 2041 or 2036. Under strong climate policy (mid150), an IGCC with CCS comes online in 2026. When natural gas prices are high, an ultra-supercritical plant without CCS is the investment of choice under no (high0) or weak (high50) climate policy. Under the weak climate policy, the plant is replaced with an IGCC with CCS plant in 2048. For the mid (high100) and stringent (high150) climate policies, an IGCC with CCS plant starts operating in 2027 and 2024, respectively. In these two scenarios technology policy is expected to have no effect because the CCS is a component of the initial investment.

In general, Table 2 shows the magnitude of delay for new generation to begin operation due to uncertainty is roughly comparable to the delay resulting from the introduction of the inflexible policy under perfect foresight. The delay in the operation of CCS due to uncertainty is always greater than the delay due to the inflexible policy.

The inflexible technology policy forces all investment to have CCS, but several different technology choices are made compared to the no-policy baseline. The investment in CCS happens earlier in 10 scenarios and stays the same in two. However, this inflexible standard causes initial investments to be delayed in 9 scenarios (slant values in Table 2), unaffected in one scenario, and sped up in two scenarios (bold values in Table 2).

Hence, comparison of no technology policy with an inflexible policy illustrates a contradiction of the first hypothesis of Sect. 3, developed in the context of perfect foresight, which suggested that an inflexible policy would never speed up investment but with uncertainty the result does not hold in two scenarios. The reason is that for the case with high natural gas prices, the only two power generation technologies that an investor would consider for an initial investment are an ultra-supercritical plant for the cases with no or weak climate policy (high0 or high50), or an IGCC plant for the mid or strong climate policy (high100 or high150). Assuming a scenario with high natural gas prices and a strong climate policy (High150), at year 2018, the investor sees a high probability of being in one of the stronger climate policies. For

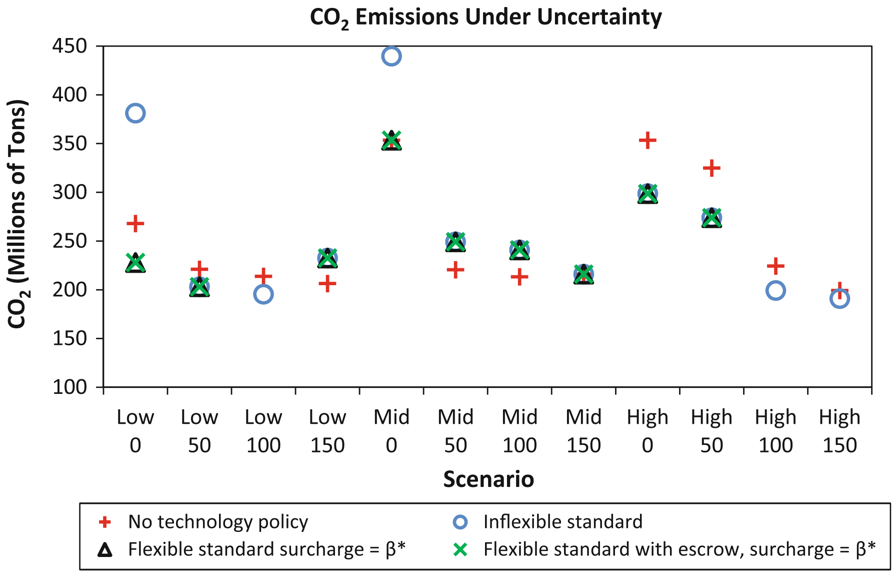


**Fig. 4** Cumulative $CO_2$ emissions with uncertainty

example, if scenario is high150, then at year 18 the probability of high150 = 0.7708, probability of high100 = 0.0208, probability of mid100 = 0.0208 and probability of mid150 = 0.0208 for a total 0.83 probability of being in a mid or strong climate policy scenario. Under no technology policy, it is optimal to wait one more year to get an updated probability for the climate policy scenarios and decide whether an ultra-supercritical (without CCS) or an IGCC with CCS should be installed. Under a strict technology standard, there is no value of waiting one more year because the choice of an ultra-supercritical without CCS is not available. In other words, the inflexible policy accelerates the investment in this case because it reduces the set of possible investments.

Under the flexible policy, there are three scenarios for which there is no surcharge value in the range of $\beta^* \leq 20$ that yields installation of CCS at the same time or before than the inflexible NSPS. Hence, although increasing $\beta$ does move forward the time of investment, in the range we studied we do not find results that are consistent with hypothesis 3 with respect to the timing of investments.

The timing and choice of investments with the flexible policy is identical to that with the escrow fund.

### *5.2.1 Emissions*

Figure 4 shows results with uncertainty, where emissions produced by the inflexible standard are higher than those of the baseline for five scenarios. The $CO_2$ emissions produced by the flexible standard are lower than or equal to emissions in the inflexible policy in all of the scenarios where $\beta^*$ is identified. With an escrow fund the cumulative emissions are the same as for the flexible standard because investments are identical.

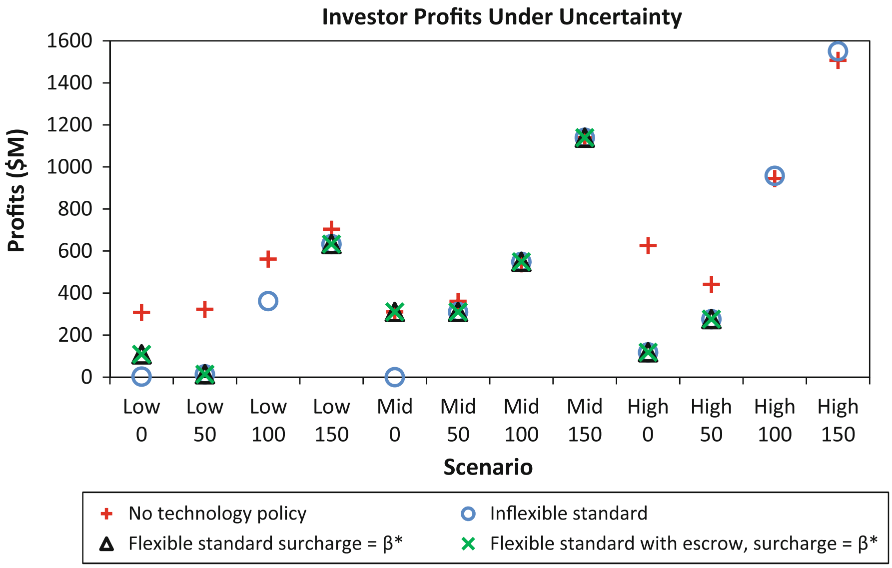


**Fig. 5** Investor's profits with uncertainty

### *5.2.2 Profits*

Figure 5 reports investor profits under uncertainty. Under all scenarios, profits are never higher with uncertainty. The introduction of the inflexible standard leads to lower profits than under the baseline in every case except with high natural gas prices and stringent climate policy (high150). The introduction of flexibility leads profits to be no lower than to the inflexible standard where $\beta^*$ is identified. Profits are the same with and without the escrow because the investment choices are the same under these policies.

The change in investor profits compared to the no technology policy provides a direct estimate of the cost of $CO_2$ emissions abatement because electricity consumption and price remain unchanged with respect to the individual investor's decision. In just more than half of the scenario and policy combinations the abatement cost is ill-defined because emissions increased (for example under the inflexible standard), the change in emissions was very small (dividing by a small number led to large and unstable cost estimate), a solution was not found ($\beta^*$ does not exist) or profits increased (in one case, when the inflexible policy forced an investment that proved profitable when uncertainty was resolved). In the other cases the cost compared to the no technology policy ranged from near \$0 to \$46 per ton in the certain context and near \$0 to \$17 in the uncertain context. (See Appendix 6 for details.)

## 5.3 Summary

The analytical framework in Sect. 3 provides hypotheses about the timing of investments, the value of the ACP and implications for cumulative emissions and profits under various technology policies. The hypotheses are shaped in a simple decision framework with a single production technology with perfect foresight about changing capital costs over time. The simulations provide a more complex and realistic decision framework with multiple technologies for production and pollution control and with evolution in fixed and variable costs that depends on equilibria in linked markets under the twelve scenarios concerning natural gas price and climate policy. The scenarios are considered under perfect foresight and uncertainty that is resolved over the first twelve years in a 43-year planning horizon. The predictions and simulation outcomes are listed in Table 3.

The first two columns of Table 3 list the hypotheses from the analytical framework and their implications. The third column reports the outcomes in the simulation model with perfect foresight. Every specific prediction is confirmed at least weakly. Under a traditional performance standard the prediction is that emissions will increase in the short run if there is a delay in investment but the effect on emissions in the long run is ambiguous. The simulations find that under low and mid natural gas prices cumulative emissions increase under the traditional performance standard. Under high natural gas prices, which provide a relatively greater incentive for investment in coal technology, the traditional performance standard leads long-run emissions to fall or be unchanged.

The fourth column reports the outcomes in the simulation model with uncertainty. The predictions are confirmed at least weakly for the flexible performance standard and for the flexible standard with escrow. The exception is especially informative, finding that the traditional performance standard can lead investment to occur earlier than it would with no technology policy because it reduces the set of possible investments and thereby reduces the option value of waiting to invest with uncertainty. The predicted effect on cumulative emissions is ambiguous and this is borne out as the change in emissions varies across scenarios in the simulations.

Looking across results in Figs. 2, 3, 4 and 5 another informative finding is the relative effect of flexibility and perfect foresight. Generally speaking, the introduction of flexibility in the performance standard accelerates the timing of investments and the introduction of uncertainty delays investments, and these two effects are of comparable magnitude. Under uncertainty, the effect of introducing flexibility is less potent than in a framework with perfect foresight.

## 6 Conclusion

This study examines policies to promote state-of-the art technologies on new investments to achieve environmental goals. Unfortunately, vintage-differentiated standards requiring a specific technology for new investments may slow the turnover of capital because they raise the cost of new investment. This delay would not only lower profits, but arguably can lead to an overall increase in emissions if the new investment absent a technology mandate would have led to lower emissions than the existing facility it might replace. Without detracting from the usual guidance that price-based policies can influence capital investment appropriately, we suppose that political barriers exist to the efficient introduction of an emissions price and that regulatory requirements

**Table 3** Hypotheses suggested in analytical framework and simulation outcomes

| Hypotheses | Implications | Confirmed with simulation under perfect foresight? | Confirmed with simulation under uncertainty? |
|---|---|---|---|
| Traditional (inflexible) performance standard: | | | |
| 1. Will not accelerate, may delay construction of new production facility: $\tau^{bsln} \leq \tau^{std}$ | | Yes. Investment is strictly delayed for 10 scenarios, no change in mid150 and high150 scenario under which CCS is chosen with no technology policy | No. Investment is strictly delayed for 9 scenarios, unchanged in 1, and accelerated in 2 (high100, high150). A traditional standard can accelerate investment if it reduces the set of possible investments and the option value of waiting |
| | 2. $\tau^{bsln} < \tau^{std}$ increases emissions in the short run. Long run effects are ambiguous | No. Emissions are higher for 8 scenarios, unchanged for 1 (high150) and reduced for 3 (high0, high50, high100) | Emissions are higher for 5 scenarios, unchanged for 1 (high150) and reduced for 6 (low50, low100, high0, high100, high150) |
| | 3. $\tau^{bsln} < \tau^{std}$ leads to an unambiguous decrease in profits | Yes. Over the entire horizon profits are lower under 11 scenarios and unchanged in one (high150) | Cumulative profits are lower for 8 scenarios and unchanged for 3 (mid100, mid150, high100) and greater for 1 (high150) |
| Flexible performance standard: | | | |
| 4. Will not delay and may accelerate construction of new production facility compared to traditional standard: $\tau^{flex} \leq \tau^{std}$ | | Yes. Investment is strictly accelerated for 7 scenarios, no change in 5 | Yes. Investment is accelerated for 2 scenarios, no change in 7. For low100, high100, and high150 we do not find $\beta^* < 20$ |
| 5. ACP value $\beta \geq \beta^*$ will not delay pollution control compared to a traditional standard: $\upsilon^{flex} \leq \upsilon^{std}$ (An increase in the ACP will not delay pollution control: $\partial \upsilon^{flex}/\partial \beta \leq 0$) | | Yes. Investment is strictly accelerated in 1 scenario, no change in others | Yes. No change in 9 scenarios. For 3 scenarios (low100, high100, and high150) we do not find $\beta^* < 20$ |

**Table 3** continued

| Hypotheses | Implications | Confirmed with simulation under perfect foresight? | Confirmed with simulation under uncertainty? |
|---|---|---|---|
| | 6. At $\beta \geq \beta^*$ emissions will not increase compared to traditional standard even if $\tau^{flex} < \tau^{std}$ | Yes. Emissions are strictly lower in 7 scenarios, unchanged in 5 | Yes. Emissions are strictly lower in 2 scenarios, unchanged in 7. For 3 scenarios (low100, high100, and high150) we do not find $\beta^* < 20$ and emissions are not calculated |
| | 7. At $\beta \geq \beta^*$ profits will not decrease compared to traditional standard | Yes. Profits are strictly higher in 6 scenarios, unchanged in 6 | Yes. Profits are strictly higher in 2 scenarios, unchanged in 7. For 3 scenarios (low100, high100, and high150) we do not find $\beta^* < 20$ and profits are not calculated |
| Flexible emissions standard with escrow: | | | |
| 8. Will not delay and may accelerate construction of new production facility compared to flexible standard: $\tau^{esc} \leq \tau^{flex}$ | | Yes. Investment is strictly accelerated in 3 scenarios, no change in others | Yes. Investment choices are identical under the flexible standards and the flexible standard with escrow |
| 9. An ACP value $\beta \geq \beta^*$ with escrow will not delay investment in pollution control: $\upsilon^{esc} \leq \upsilon^{std}$ | | Yes. Investment is strictly accelerated in 2 scenarios, unchanged in 10. In one scenario, operation is delayed two years | Yes. Investment choices are identical under the flexible standards and the flexible standard with escrow |
| 10. The escrow will cause the ACP value $\beta^*$ to be the same or lower | | Yes. $\beta^*$ with the escrow is lower for 6 scenarios, and equal for 6 | Yes. There is no change in $\beta^*$ |
| | 11. At $\beta \geq \beta^*$ emissions will not increase | Yes. Emissions are strictly lower in 2 scenarios, unchanged in 10 | Yes, weakly. There is no change in investments |
| | 12. At $\beta \geq \beta^*$ profits will not decrease | Yes. Profits are strictly greater in 5 scenarios, unchanged in 7 | Yes, weakly. There is no change in investments |

or political preference will promote the use of technology standards. The challenge that motivates this investigation is how to design standards that provide incentives to accelerate rather than delay the adoption of new technology.

We evaluate a traditional (inflexible) emissions performance standard and two alternatives. The first alternative would involve an ACP in the form of an emissions surcharge for investments that fail to meet the maximum emission rate standard. In a second alternative we propose that revenue from the ACP accumulate in an escrow fund and would be available to offset capital costs for subsequent retrofit if it occurs within ten years. We do not consider the question of whether this is the highest valued use of that revenue, but more narrowly consider only its effect on investments.

We use an analytical framework to formalize predictions about the policy alternatives. We then use a detailed simulation model with many more parameters and a richer choice set to evaluate the predictions in the specific context of policies to reduce $CO_2$ emissions in the electricity sector. These policies are examined under twelve scenarios that vary the level of natural gas prices and the stringency of a federally imposed price on $CO_2$. The analysis compares perfect foresight over the twelve scenarios with uncertainty.

With perfect foresight we find a traditional performance standard will delay investment, consistent with the hypothesis developed in the analytical framework. The introduction of the flexible policy with an appropriately chosen ACP will typically accelerate investment. The introduction of an escrow fund may further accelerate investment, although in one case we find operation of the CCS is delayed. Concurrently, total cumulative emissions are lower for the flexible policy, and lower still with the escrow fund, under most scenarios. Profits are no lower and sometimes higher with the flexible policy, and equal or higher still with the escrow fund.

The introduction of uncertainty introduces a substantial delay in investment in new generation that is comparable in magnitude to the delay caused by the introduction of a traditional performance standard. From this starting point, the inflexible policy has the expected effect of further delaying investment in generation capital in most scenarios, as occurs under perfect foresight, but the effect is muted considerably. Further, with uncertainty, there are exceptions where investment occurs earlier under an inflexible policy than under no technology policy because the inflexible policy interacts with the usual option value of waiting to invest by eliminating some investment alternatives. Nonetheless, with uncertainty as with perfect foresight, compared to a traditional performance standard the introduction of flexibility generally leads to the earlier investment, reductions in cumulative emissions and increased profits.

Several aspects of an ACP are unaddressed by this research. One is the identification of the level of the ACP when the regulator is uncertain about the future path of technology costs. A second is alternative ways that uncertainty may be resolved. A third is the influence of first-mover investments in new technology on the path of costs over time. Nonetheless, we find the ACP can lead to earlier investment, lower emissions and greater profits. An ACP coupled with an escrow fund is expected to amplify these effects. In addition, an ACP appears to be roughly dynamically consistent, that is, as a rule it introduces an endogenous incentive to make retrofit investments in pollution control as the cost of the technology falls over time.

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## Appendix: Technology choice and timing in the simulations

Table 4 illustrates the technology choice and timing of investments for the base case and the three versions of technology policy, for the twelve scenarios, both under perfect foresight and uncertainty. Table 5 provides a mapping from numeric labels to technologies. For additional supporting information see Patino-Echeverri et al. (2012).

Three options for new investment use solid coal: sub-critical (sub), supercritical (super) and ultra-supercritical (ultra). In addition we investigate integrated gasification combined cycle coal-fired (IGCC) and natural gas combined cycle (NGCC). Each of these would satisfy standards for new sources for emissions of $SO_2$, $NO_x$, mercury and particulates. Each could come with or without CCS, or with retrofit CCS sometime after initial construction, which results in 10 different generation technologies but a total of 15 different investment alternatives with associated costs and emissions as shown in Table 4.

### Appendix 1: effects of an inflexible performance standard

For each scenario under the base case and the inflexible performance standard, Table 4 presents the year when the first installation comes online Y1, the technology first installed T1, the year when a second installation (new plant or retrofit) comes online Y2, and the technology installed in the second installation T2.

When there is perfect foresight about the future natural gas price and climate policy, the introduction of an inflexible performance standard on new investments leads to delays in investment for all scenarios except where natural gas prices are high and climate policy is stringent (high150), where technology policy is not expected to have an effect because the initial investment includes CCS in the absence of the standard. When natural gas prices are at mid- level, and there is no federal climate policy (mid0), new investment never occurs.

When there is uncertainty about future natural gas prices and climate policy, compared to no technology policy, an inflexible performance standard causes investments to be delayed in 9 scenarios, unaffected in 1 scenario, and sped up in two scenarios. The acceleration of investment for the scenarios with high natural gas prices and stronger climate policy (high100 and high150) shows that under uncertainty the intuition that an inflexible standard would never speed up investment does not hold. In the case of scenario high150 the inflexible standard reduces uncertainty. For the

**Table 4** Year of investment and technology installed with ACP that produces investment in CCS at the same time as the inflexible standard

| Scenario | No technology policy | | | | | | | | Inflexible standard | | | | | | | | Flexible standard | | | | | | Flexible standard with Escrow | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Perfect foresight | | | | Uncertainty | | | | Perfect foresight | | | | Uncertainty | | | | Perfect foresight | | | Uncertainty | | | Perfect foresight | | | Uncertainty | | |
| | $Y1$ | $T1$ | $Y2$ | $T2$ | Y1 | $T1$ | $Y2$ | $T2$ | Y1 | T1 | $Y2$ | $T2$ | Y1 | T1 | $Y2$ | $T2$ | β* | $Y*$ | $T*$ | β* | Y* | $T*$ | β* | $Y*$ | $T*$ | β* | Y* | $T*$ |
| low0 | 6 | 13 | 35 | 10 | 13 | 13 | 35 | 10 | 35 | 11 | 0 | 0 | 35 | 11 | 0 | 0 | 3 | 35 | 11 | 3 | 35 | 11 | 3 | 35 | 11 | 3 | 35 | 11 |
| low50 | 3 | 13 | 35 | 11 | 12 | 13 | 35 | 11 | 12 | 14 | 36 | 11 | 14 | 14 | 36 | 11 | 13 | 12 | 15 | 9 | 14 | 14 | 7 | 12 | 15 | 9 | 14 | 14 |
| low100 | 1 | 13 | 30 | 11 | 12 | 13 | 30 | 11 | 12 | 14 | 31 | 11 | 13 | 14 | 31 | 11 | 10 | 12 | 15 | | | | 5 | 12 | 15 | | | |
| low150 | 1 | 13 | 25 | 11 | 12 | 13 | 25 | 11 | 12 | 14 | 29 | 11 | 17 | 11 | 0 | 0 | 6 | 12 | 15 | 3 | 17 | 11 | 3 | 12 | 15 | 3 | 17 | 11 |
| mid0 | 6 | 7 | 0 | 0 | 13 | 7 | 0 | 0 | | | | | | | | | 0 | 6 | 7 | 0 | 13 | 7 | 0 | 6 | 7 | 0 | 13 | 7 |
| mid50 | 3 | 13 | 30 | 11 | 13 | 13 | 30 | 11 | 19 | 11 | 0 | 0 | 19 | 11 | 0 | 0 | 9 | 19 | 11 | 2 | 19 | 11 | 6 | 14 | 15 | 2 | 19 | 11 |
| mid100 | 1 | 13 | 25 | 11 | 13 | 13 | 25 | 11 | 18 | 11 | 0 | 0 | 18 | 11 | 0 | 0 | 6 | 16 | 15 | 1 | 18 | 11 | 4 | 13 | 15 | 1 | 18 | 11 |
| mid150 | 1 | 13 | 21 | 11 | 15 | 11 | 0 | 0 | 12 | 11 | 0 | 0 | 15 | 11 | 0 | 0 | 6 | 12 | 15 | 0 | 15 | 11 | 3 | 12 | 15 | 0 | 15 | 11 |
| high0 | 4 | 7 | 0 | 0 | 13 | 7 | 0 | 0 | 25 | 11 | 0 | 0 | 25 | 11 | 0 | 0 | 4 | 25 | 11 | 3 | 25 | 11 | 4 | 25 | 11 | 3 | 25 | 11 |
| high50 | 2 | 7 | 37 | 11 | 13 | 7 | 37 | 11 | 22 | 11 | 0 | 0 | 22 | 11 | 0 | 0 | 4 | 22 | 11 | 2 | 22 | 11 | 4 | 22 | 11 | 2 | 22 | 11 |
| high100 | 1 | 7 | 25 | 11 | 16 | 11 | 0 | 0 | 12 | 11 | 0 | 0 | 13 | 11 | 0 | 0 | 3 | 12 | 11 | | | | 3 | 12 | 11 | | | |
| high150 | 12 | 11 | 0 | 0 | 13 | 11 | 0 | 0 | 12 | 11 | 0 | 0 | 12 | 11 | 0 | 0 | 0 | 12 | 11 | | | | 0 | 12 | 11 | | | |

Y1: year when the first installation comes online. T1: technology first installed. Y2: year when a second installation (new plant or retrofit) comes online. T2: technology installed after first installation (new plant or retrofit). Technology numbers correspond to the investment number provided in Table 5. The year numbers correspond to the number of years after year 2011 (e.g. Y1 = 1 means 2012). Blank cells occur when there is no investment under that scenario and policy combination

**Table 5** Cost and performance of investment alternatives

| (2004 dollars) | Sub | Sub +CCS/ CCS retrofit | Super | Super +CCS/ CCS retrofit | Ultra | Ultra +CCS/ CCS retrofit | IGCC | IGCC +CCS/ CCS retrofit | NGCC | NGCC +CCS/ CCS retrofit |
|---|---|---|---|---|---|---|---|---|---|---|
| Investment number | 1 | 2, 3 | 4 | 5, 6 | 7 | 8, 9 | 10 | 11, 12 | 13 | 14, 15 |
| Capacity (MW) | 1,358 | 1,358 | 1,359 | 1,359 | 1,359 | 1,359 | 1,359 | 1,359 | 1,266 | 1,266 |
| Capital cost (million$) | 1,480 | 2,049 | 1,541 | 2,048 | 1,529 | 2,003 | 2,239 | 3,003 | 795 | 1,119 |
| CCS Retrofit penalty (%)[a] | | 20 | | 20 | | 20 | | 30 | | 20 |
| Generation (GWh/yr)[b] | 8,929 | 6,403 | 8,935 | 6,667 | 8,935 | 6,877 | 8,935 | 7,903 | 8,324 | 7,108 |
| O&M ($/MWh)[c] | 7.98 | 32.25 | 7.76 | 28.66 | 7.45 | 25.91 | 7.28 | 12.69 | 1.66 | 3.95 |
| Net plant heat rate, HHV (Btu/kWh) | 9,786 | 9,786 | 8,791 | 8,791 | 7,981 | 7,981 | 9,856 | 9,856 | 6,803 | 6,803 |
| Emissions[d] | | | | | | | | | | |
| $CO_2$ | 9,144 | 916 | 8,220 | 823 | 7,463 | 747 | 8,789 | 742 | 3,369 | 337 |
| $SO_2$ | 27,030 | 30 | 24,300 | 27 | 22,061 | 24 | 5,539 | 603 | – | – |
| $NO_x$ | 6,553 | 6,470 | 5,891 | 5,817 | 5,349 | 535 | 857 | 846 | 849 | 838 |
| Particulate | 1,311 | 655 | 1,178 | 589 | 1,070 | 535 | 44 | 44 | – | – |
| Mercury | 55 | 55 | 49 | 49 | 45 | 45 | – | – | – | – |

[a] The retrofit penalty for CCS is applied only to the CCS capital cost
[b] The power loss involves reduced flow through turbines and power for CCS technology and other emission control devices
[c] O &M excludes fuel costs
[d] Emissions are tons/year except $CO_2$ (thousand tons/year) and Mercury (pounds/year)

scenarios with high natural gas prices, the only two power generation technologies that an investor would consider for an initial investment are an ultra-supercritical coal plant for the cases with no or weak climate policy (high0 or high50), or an IGCC plant for the mid or strong climate policy (high100 or high150). An NGCC plant is not competitive due to the high prices of the fuel, and the alternative of not installing any plant is not competitive because for these scenarios the expected electricity prices after 2020 are sufficiently high to motivate investment. Under no technology policy, it is optimal to wait one more year to have certainty about the climate policy scenario and decide whether an ultra-supercritical (without CCS) or an IGCC with CCS should be installed. Under an inflexible performance standard, there is no value of waiting one more year because the choice of an ultra-supercritical without CCS is not available.

## Appendix 2: effects of a flexible standard

For the flexible standard we present the minimum surcharge level that produces investment in CCS at the same time or before the inflexible standard, which is denoted by $\beta^*$. For this $\beta^*$, we present the corresponding year of installation $Y^*$ and CCS technology installed $T^*$. For some scenarios $T^*$ is different than the CCS technology installed for the first time under the inflexible standard.

The value of $\beta^*$ refers to the surcharge in $ per ton that must be paid for each ton in excess of the emissions standard. We assume $\beta^*$ increases every year at the same rate of discount used by the investor in the expected NPV calculations.

In each scenario, with perfect foresight, we identify a value of $\beta^*$ between $0 and $20 per ton of $CO_2$ that leads to investment in CCS at least as soon as under the inflexible performance standard. An increase in the value of the surcharge moves forward the time at which CCS technology is built. When natural gas prices are at mid- level and there is no federal climate policy (mid0) the inflexible standard causes investment to be indefinitely postponed (beyond 2052). In this case the surcharge value needed to replicate this result under a flexible performance standard is $0. Under perfect foresight and under the most strict federal climate policy, when natural gas prices are high (high150), no technology policy is necessary to get the IGCC with CCS to come on line, so the surcharge value is $0. For any other case under perfect foresight there is always a surcharge level $\beta^*$, for which investment in CCS will happen at the same time or before as under the inflexible standard.

The change in the timing and choice of generation technology can have an important effect on cumulative emissions. In three cases investment in newer technology, albeit absent CCS, comes years earlier than under the inflexible policy (low0, mid100, mid150). For the scenario with low natural gas prices and no federal climate policy (low0), a surcharge of $3 produces investment in IGCC with CCS the same year that it occurs under the inflexible NSPS policy. However, in the flexible case NGCC without CCS appears several years earlier and is subsequently replaced. For the scenarios with mid-level natural gas prices and mid- and stringent- level federal climate policy (mid100, mid150) a surcharge of $6 yields investment in a CCS retrofit for NGCC, subsequently replaced by IGCC with CCS, instead of the IGCC with CCS initially chosen under the inflexible standard. For these scenarios there is no surcharge value that would cause identical investment as under the inflexible standard.

When there is uncertainty about the future natural gas prices and federal climate policy, there are three scenarios (low100, high100, and high150) for which there is no surcharge value in the range of $\beta^* \leq 20$ that yields installation of CCS at the same time or before than the inflexible standard. In these scenarios and for the set of values we examine, installation happens one or more years later than under the inflexible standard. For the scenario with mid-level natural gas prices with no climate policy (mid0), and the scenario with mid-level natural gas prices and stringent climate policy (mid150), no surcharge is needed to yield identical investment (e.g. $\beta^* = 0$). For the remaining scenarios there is a surcharge level that yields an identical investment to the one produced by the inflexible standard.

## Appendix 3: effects of a flexible standard with escrow account

The escrow fund comprised of accumulated emission surcharge payments provides a source of funds that can be used to subsidize the cost of retrofitting a facility with CCS in the future. Thus the policy is most effective when the flexible policy by itself does not lead to CCS being installed with the initial investment. We have assumed the flexible performance standard with escrow fund operates with 3 rules that help destroy incentives for delaying CCS investment in the hopes for lower capital costs. The first rule specifies that the funds accumulated in the escrow account do not gain any interest. This makes delaying in CCS costly since the surcharge payment accumulates in an escrow fund that loses value with time. The second rule specifies that the maximum amount of funds withdrawn from the escrow cannot exceed the capital costs of the CCS investment (be it a CCS retrofit or a new plant with CCS included). This discourages accumulating funds in the escrow that exceed the capital costs of the needed CCS investment. The third rule specifies that funds from the escrow account can be withdrawn only once. This means that any funds not used for the first CCS investment (a retrofit or a new plant) are lost, which discourages accumulation of funds in the escrow and accelerates investment.

Under perfect foresight the $\beta^*$ values for the flexible standard with escrow are lower than without escrow for the 6 scenarios with climate policy and low or mid-natural gas prices (scenarios low50, low100, low150, mid50, mid100, mid150), and the same for the scenarios with no climate policy or high natural gas prices. For two of the scenarios (mid50 and mid100) the lower $\beta^*$ required to obtain CCS also causes earlier investment. Under low50 the flexible standard requires a $\beta^*$ of \$13 to cause an investment in NGCC plant subsequently retrofit in year 2023, while the standard with escrow requires a $\beta^*$ of only \$7 to produce earlier investment in NGCC and a CCS retrofit in 2023. In the mid50 scenario the flexible standard requires a $\beta^*$ of \$9 to produce the installation of an IGCC plant with CCS in year 2030, while the standard with escrow requires a $\beta^*$ of \$6 to cause an investment in NGCC subsequently retrofit in year 2025, and then replaced by IGCC with CCS. These results are consistent with a hypothesis suggesting that the introduction of an escrow account should not delay the timing of investment in CCS.

With uncertainty, the timing and choice of investments is identical to the flexible standard and there is no change in the $\beta^*$values, and as expected the fund does not delay investment in new generation or CCS.

## Appendix 4: ACP values required for an effective flexible standard

For a flexible policy to be effective the ACP must be low enough to allow installation of uncontrolled facilities when the capital costs of CCS are too high, but high enough to motivate a CCS retrofit at the same time or earlier than when a CCS plant would be installed under an inflexible technology policy.

An investment in a new uncontrolled plant will occur when the emissions costs of such plant (i.e. paying for a carbon tax + ACP) are lower than the capital and O&M costs of a CCS plant[17]:

$$\sum_{t=\tau}^{\tau+T} d^{(t-\tau)} v \left(eo + (e-s)\,\beta\right) \leq vc_{\tau}^{pc} + \sum_{t=\tau}^{\tau+T} d^{(t-\tau)} v \left(m^{pc} + e^{pc} o\right) \tag{6}$$

[17] Equation (8) assumes that the life-time of the retrofitted plant is always $T$.

Assuming a discount rate of zero (i.e. $d$=1), no carbon tax (i.e. $o$=0), and emissions from the CCS plant $e^{pc}$ being less than $s$we find the lower bound of the ACP as:

$$\beta \leq \frac{c_{\tau}^{pc}}{T(e-s)} + \frac{m^{pc}}{(e-s)} \tag{7}$$

Note that since $(e - s)$ represents the amount of emissions abated with CCS, Eq. 7 indicates that at the time of installation of the uncontrolled plant $t = \tau$ the ACP must be less than the per unit cost of emissions abatement (capital + O&M) from a CCS plant.

Similarly, an upper bound for the ACP is given by the per unit capital and O&M cost of abatement of a retrofitted plant at a time $t = \upsilon$:

$$\beta \geq \frac{(1+z)\, c_{\upsilon}^{pc}}{T(e-s)} + \frac{m^{pc}}{(e-s)} \tag{8}$$

In conclusion if the ACP is in the range indicated by 7 and 8 for $\tau^{\text{bsln}} \leq \tau \leq \upsilon \leq \tau^{\text{std}}$ the flexible standard will be effective. In the case where the flexible standard is complementing a carbon tax policy, the ACP value needs to be reduced by the carbon tax $o$, so that the new threshold is:

$$\frac{c_{\tau}^{pc}}{T(e-s)} + \frac{m^{pc}}{(e-s)} \geq \beta + o \geq \frac{(1+z)\, c_{\upsilon}^{pc}}{T(e-s)} + \frac{m^{pc}}{(e-s)} \tag{9}$$

## Appendix 5: effects of the retrofit penalty

As discussed in Sect. 3.2, the effectiveness of a flexible new source performance standard depends on the existence of a pollution control technology without prohibitive cost penalties for retrofit installations and the expectation that the capital costs of this technology will gradually come down. Under the flexible policy mechanism, investors will find that delaying the CCS installation is profitable if there is the expectation that sometime in the future the gains from postponing the investment to take advantage of reductions in capital costs are higher than the extra cost of a retrofit installation.

In this section we find a threshold for the retrofit penalty $z$ above which the flexibility of the emissions standard becomes irrelevant.

An investment in CCS (at the same time as the initial investment in the plant or as a retrofit) will occur if and only if the net present value of the reduction in emissions costs over the planning horizon exceeds the capital and O&M costs of the CCS equipment. If we assumed that the CCS retrofit extends the lifetime of the plant, then a retrofit will occur when Eq. (10) is satisfied[18]:

[18] Equation (10) is similar to Eq. (2) in the paper but it differs in that it is assumed that the life-time of the retrofitted plant is $T$.

**Table 6** Maximum value of the retrofit penalty factor $z(\%)$

| $l$:(learning rate %) | $\nu - \tau$: years between initial plant installation and retrofit | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 11 |
| 2 | 2 | 4 | 6 | 8 | 11 | 13 | 15 | 18 | 20 | 22 |
| 3 | 3 | 6 | 10 | 13 | 16 | 20 | 24 | 28 | 32 | 36 |
| 4 | 4 | 9 | 13 | 18 | 23 | 28 | 33 | 39 | 44 | 50 |
| 5 | 5 | 11 | 17 | 23 | 29 | 36 | 43 | 51 | 59 | 67 |
| 6 | 6 | 13 | 20 | 28 | 36 | 45 | 54 | 64 | 75 | 86 |
| 7 | 8 | 16 | 24 | 34 | 44 | 55 | 66 | 79 | 92 | 107 |
| 8 | 9 | 18 | 28 | 40 | 52 | 65 | 79 | 95 | 112 | 130 |
| 9 | 10 | 21 | 33 | 46 | 60 | 76 | 94 | 113 | 134 | 157 |
| 10 | 11 | 23 | 37 | 52 | 69 | 88 | 109 | 132 | 158 | 187 |

$$\sum_{t=\upsilon}^{\upsilon+T} d^{(t-\upsilon)} v \left(eo + (e-s)\,\beta\right) \geq v\,(1+z)\,c_{\upsilon}^{pc} + \sum_{t=\upsilon}^{\upsilon+T} d^{(t-\upsilon)} v \left(m^{pc} + e^{pc} o\right) \quad (10)$$

Under this assumption, retrofit will occur at or after a year $\nu > \tau$ such that:

$$(1+z)\,c_{\upsilon}^{pc} \leq c_{\tau}^{pc} \quad (11)$$

If capital costs of CCS decline by a factor $l$ such that the capital costs at a time t are given by:

$$c_t^{pc} = (1-l)^t\, c_0^{pc} \quad (12)$$

Then for a retrofit to occur at year $\nu$ after an initial installation of the base plant at year $\tau$, the retrofit penalty factor $z$ must be less than the cumulative reduction in capital costs due to learning by doing:

$$z \leq (1-l)^{\tau-\upsilon} - 1 \quad (13)$$

Table 5 shows the maximum value of the retrofit penalty factor for different combinations of the annual percentage reduction in CCS capital costs, and the number of years between the initial plant installation and the retrofit:

Note that if the lifetime of the retrofitted plant is determined by the age of the uncontrolled plant as stated in Eq. (2), then the upper bounds of the retrofit penalty are lower than those presented in Table 6, since investors will have less time to recover the capital costs of the CCS investment. However, in the simulation analysis we assume that the retrofit extends the lifetime of the CCS plants as in Eq. 6.

As discussed in the paper, the simulation assumes that current capital costs of CCS are twice what they will be in year 12 of the simulation. This implies an annual learning

**Table 7** Cost of $CO_2$ abatement ($/ton)

| | | Inflexible standard | | Flexible standard ($\beta$*) | | Flexible standard w/ escrow ($\beta$*) | |
|---|---|---|---|---|---|---|---|
| Gas price | $CO_2$ price | Certain | Uncertain | Certain | Uncertain | Certain | Uncertain |
| Low | BL | N/A[3] | N/A[3] | 7 | 5 | 7 | 5 |
| Low | 50 % | N/A[3] | 17 | N/A[1] | 17 | 22 | 17 |
| Low | 100 % | N/A[3] | 11 | 46 | N/A[2] | 15 | N/A[2] |
| Low | 150 % | N/A[3] | N/A[3] | 28 | N/A[3] | 17 | −3 |
| Med | BL | N/A[3] | N/A[3] | N/A[1] | N/A[1] | N/A[1] | N/A[1] |
| Med | 50 % | N/A[3] | N/A[3] | N/A[3] | N/A[3] | N/A[1] | N/A[3] |
| Med | 100 % | N/A[3] | 0 | N/A[a] | 0 | N/A[1] | 0 |
| Med | 150 % | N/A[3] | N/A[1] | N/A[1] | N/A[1] | N/A[1] | N/A[1] |
| High | BL | 24 | 9 | 24 | 9 | 24 | 9 |
| High | 50 % | 25 | 3 | 25 | 3 | 25 | 3 |
| High | 100 % | 5 | N/A[4] | 5 | N/A[2] | 5 | N/A[2] |
| High | 150 % | N/A[1] | N/A[1] | N/A[1] | N/A[2] | N/A[1] | N/A2 |

N/A[1]: Change in $CO_2$ < 5 percent
N/A[2]: $\beta$* does not exist
N/A[3]: $CO_2$ emissions are higher and profits lower than under No Technology Policy
N/A[4]: $CO_2$ emissions are lower and profits higher than under No Technology Policy
[a] $CO_2$ emissions are lower and profits higher than under Inflexible standard

rate $l$ of 5.6 percent. If we assumed that emissions costs are constant (i.e. $o$ and $b$ are constant as suggested by Eq. 6) and there are no other environmental benefits or costs (due to emissions costs of other pollutants such as $SO_2$, $NO_x$, and mercury) then from Table 6 it can be observed that as long as there are 3 or more years between the initial plant installation and the retrofit, penalties of 20 % as assumed for the Pulverized Coal plants are within the bounds of penalties that allow the Flexible Emissions Standard to have a positive effect. Similarly, for the IGCC, a CCS retrofit penalty of 30 % requires that there are at least 5 years between the base plant installation and the retrofit. Note however than in the simulation there are other factors such as economic benefits from reduced compliance costs for other air pollutants, affecting the profitability of initial investments and retrofits.

## Appendix 6: cost of $CO_2$ emissions abatement

Table 7 shows the cost of $CO_2$ emission abatement under the three technology policies considered. The cost is found by dividing the reduction in the net present value of the change in investors' profits by the reduction in cumulative $CO_2$ emissions over 43 years. Under perfect foresight, $CO_2$ emissions under the inflexible standard increase and profits decrease for the first 8 scenarios implying that compared to the baseline (i.e. no technology policy) the inflexible policy increases emissions while reducing investors' profits. In contrast, the flexible policies in general reduce emissions at a cost that range from near \$0 to \$46/ton of $CO_2$.[19] For the mid100 scenario the flexible policy has higher emissions and lower profits than under no technology policy, but profits are higher and emissions are lower than under the inflexible standard. Since the ACP for the flexible policies is set to achieve CCS installation at the same time or earlier than under the inflexible standard, it is unsurprising that the outcomes of these flexible policies are not always superior to those with no technology policy.

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19 In four scenarios emissions reductions are almost negligible and this causes a higher cost of abatement if the difference in profits is positive. We have omitted the value calculations for these cases because in the presence of a negligible change in emissions the abatement cost is meaningless.

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