Strategic Policy Choice in State-Level Regulation: The EPA's Clean Power Plan

By JAMES B. BUSHNELL,[1,5] STEPHEN P. HOLLAND,[2,5] JONATHAN E. HUGHES,[3] CHRISTOPHER R. KNITTEL,[4,5*]

The EPA's Clean Power Plan sets state-level 2030 goals for CO_2 *emission rate reductions that vary substantially across states. States can choose the regulatory mechanism they use and whether or not to join with other states in implementing their goals. We analyze incentives to adopt rate standards versus cap-and-trade with theory and simulation. We show conditions where adoption of inefficient rate standards is a dominant strategy from both consumers' and generators' perspectives. Numerical simulations of the Western electricity system highlight incentives for uncoordinated policies that lower welfare and increase emissions relative to coordination.*

Within the United States, state-by-state variation in regulatory approaches has been more of the norm than an exception. Within the utility industries, individual state regulatory commissions have used substantially different variations on the rate-of-return regulatory framework, for example, while some states have chosen to rely on wholesale power markets instead of vertically integrated utilities. In the environmental realm, the US Environmental Protection Agency (EPA) has often deferred to state or local air quality regulators to develop specific implementation plans to achieve the EPA's environmental mandates. The Clean Air Act, one of the dominant environmental regulatory instruments, requires the EPA leave regulatory decisions up to individual states.

In electricity markets, the regulatory actions of states, or even local communities, often affect the market outcomes in surrounding areas because electricity flows throughout regional networks. In the climate change policy arena, California and states in the northeastern U.S. have faced this issue with their unilateral adoption of cap-and-trade programs limiting carbon emissions from in-state sources. In both instances, there have been concerns that such actions could spur "leakage" of both emissions and of beneficial economic activity to the neighboring uncapped regions; specifically, while emissions may decrease within the regulatory jurisdictions, emissions may *increase* elsewhere as output increases from unregulated power plants.[1]

A more subtle form of economic spillovers can arise when individual states respond to regulatory requirements with different instruments. The choice of instrument affects each power plant's opportunity cost of selling electricity. Therefore, certain policies may provide a competitive advantage to power plants within a particular state, and this advantage will depend on the policies adopted in other states. In the face of these incentives, it is not clear the equilibrium outcome will yield the efficient mix of policies.

Recent actions by the EPA to address greenhouse gas emissions create a similar dynamic. In this case however, the stakes are much higher than the examples above. The EPA's Clean Power Plan

---

[*] The authors thank seminar participants at the Energy Institute at Haas, the Massachusetts Institute of Technology, the University of California at Berkeley and the University of North Carolina Greensboro.

[1]Department of Economics, University of California at Davis. [2]Department of Economics, University of North Carolina Greensboro. [3]Department of Economics, University of Colorado at Boulder. [4]William Barton Rogers Professor of Energy Economics, Sloan School of Management and Director, Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology. [5]National Bureau of Economic Research.

[1] See Fowlie (2009) and Chen (2009).

(CPP) proposes major reductions in carbon emissions from electricity generators in the United States. Focusing on the electricity sector, the CPP uses existing provisions of the Clean Air Act to regulate a substantial share of carbon emissions. Due in part to inaction at the federal level, recent US climate policy has been driven almost exclusively by state and regional initiatives. This has raised concerns over inefficiencies from uncoordinated policies (Bushnell, Peterman and Wolfram (2008)). A national framework holds the potential to decrease inefficiencies created by the patchwork of state and regional policies and could improve US standing in international climate negotiations (Newell, Pizer and Raimi (2012), Stavins (2008)).

We analyze the potential effects of the CPP in terms of electricity market outcomes and state adoption incentives using a general theoretical model and numerical simulation. The CPP establishes state-level targets for carbon emissions *rates* in lbs of carbon dioxide per megawatt hour of electricity generated (lbs per MWh). States can adopt the default rate standard or can instead adopt a "mass-based" regulation *i.e.*, a cap-and-trade (CAT) system. Further, states can form coalitions by adopting either a CAT regulation or rate standard, or by trading "emissions rate credits" across states. The effects on consumers and producers within a state depend on both the type of regulation adopted by each state and regulations adopted by its electricity trading partners. Furthermore, the states' private incentives may be at odds with those of a national social planner.

We have five main results. First, we show industry supply, i.e., the merit order, can be efficient under a CAT regulation, rate standard, or mixed regulation. However, supply efficiency requires stringent conditions for rate standards or for mixed regulation. Moreover, supply efficiency is necessary but not sufficient for efficiency. Echoing earlier results in the literature, e.g., Helfand (1991), Holland, Hughes and Knittel (2009), we show that in general only CAT can be efficient.

Second, we illustrate important differences in the incentives of a unified coalition of states versus the incentives of a single state or of various stakeholders. For the coalition of states, adoption of CAT is best from an efficiency perspective. However, for an individual state or for stakeholders the incentives are more nuanced and may result in an inefficient policy as a dominant strategy.

Third, we explore our theoretical predictions using a simulation model of the Western interconnection of the U.S. electricity grid. Relative to business as usual, we find that a West-wide CAT implementing the Clean Power Plan increases social welfare by \$2 billion; decreases carbon emissions by 74 million metric tons (MMT), about 22%; and has reasonable marginal abatement costs of \$21 per metric ton (MT). Failure to coordinate policies results in a merit order which can be "scrambled" quite dramatically and in substantial deadweight loss. State-by-state CAT standards reduce social welfare by approximately \$200 million relative to a West-wide CAT. The inefficiency is even worse under state-by-state rate standards. Mixed regulation creates the possibility of additional scrambling of the merit order as well as of emissions leakage, thereby introducing additional inefficiencies.

Fourth, we simulate the incentives of stakeholders and show that various stakeholders have an incentive to deviate from a coordinated policy regime. From a private surplus perspective, the coastal states would have an incentive to deviate from a West-wide CAT, and the inland states would have an incentives to deviate from a West-wide rate standard. Overall, these strategic interactions tend to result in uncoordinated policies across the regions.

Finally, we analyze how the design of CAT regulations affects entry incentives under the CPP. New generation may or may not be included in emissions caps for states that adopt CAT regulations. This creates the potential for emissions leakage via investment in new fossil generation outside of the cap.

This work contributes to several literatures. Our findings echo concerns about environmental and economic spillovers from local climate policies. First, environmental targets can be undermined if production is able to shift away from the jurisdictional reach of the regulator through either leakage or reshuffling of production sources.[2] Second, local regulatory programs are unlikely to lead to the efficient allocation of abatement across regions as marginal abatement costs are not equal. Third, regulatory action in one area may put firms in that region at a competitive disadvantage relative to firms in unregulated regions. These concerns have been a challenge for regional climate initiatives in the US. More generally, concerns over leakage have been a challenge for international climate agreements. In crafting the European CO_2 market, as well as the now defunct Waxman-Markey bill that would have established a national cap in the United States, much attention was paid to the "competitiveness" question, which is fundamentally related to how vulnerable domestic producers are to leakage from imports.

Our theoretical model is most closely related to Fischer (2003). Fischer analyzes carbon trading between CAT and rate standards and finds trading raises emissions. We extend this work by analyzing two components necessary for understanding the CPP. First, we explicitly model trading in the product market, electricity, that crucially affects the interactions of the states' policy choices. Second, we analyze states' adoption incentives for CAT and rate standards. Burtraw et al. (2015) also simulate electricity system outcomes under the CPP. They show the choice of allocation policy can mitigate some of the perverse effects of inconsistent state regulatory choices. However, as we show here, states may not find it in their interest to mitigate those effects. Finally, our work also contributes to the literature on rate-based environmental regulation.[3]

Section I discusses the Clean Power Plan in more detail and provides policy background. Section II develops the theoretical model and derives the theoretical results. Section III presents the simulation model and Section IV describes the results. Section V concludes.

I. The Clean Power Plan: GHG Regulation under the Clean Air Act

Since the landmark 2007 decision by the U.S. Supreme Court in *Massachusetts v. EPA*, the EPA has taken several steps to limit GHG emissions under the Clean Air Act (CAA). A significant milestone occurred on August 3, 2015 when the Obama administration released the Clean Power Plan (CPP) regulating GHG emissions from existing power plants. Rather than following the usual permitting process, the CPP instead uses provisions in Section 111 of the CAA. Section 111 provides a flexible framework for regulation, but also imposes constraints on the types of policies that may be implemented under the CPP. Regulation under Section 111 requires that the EPA establish "standards of performance" which are defined as "a standard for emissions of air pollutants which reflects the degree of emission limitation achievable through the application of the best system of emission reduction." The text also requires state-level implementation of the standards.

To estimate the best system of emissions reduction, the Clean Power Plan uses three "building blocks."[4] The first building block focuses on emissions reduction from fossil steam generation through heat rate (efficiency) improvements. The second building block focuses on shifting generation from relatively dirty coal-fired plants to relatively cleaner gas-fired plants. The third building block requires increased generation from low emissions or zero-emissions generation (e.g., renewables). Based on these building blocks, EPA allows states to choose between rate standards, CAT regulation, and "state measures."[5]

Rate standards can be based on national or state-blended rates. National rates (in lbs CO_2 per MWh) for fossil steam and natural gas combined cycle generation are based on the best system of

---

[2] See Bushnell, Peterman and Wolfram (2008), Fowlie (2009), and Chen (2009).

[3] See also Huang et al. (2013), Pizer (2005) and Zilberman et al. (2013).

[4] The initial CPP proposal included a fourth building block for energy efficiency. While energy efficiency measures are not used to calculate the rate standards in the final rule, coverered generators can still use energy efficiency programs to generate emission rate credits and can use to credits to meet CPP targets.

[5] The CPP defines "rate-based standards" and "mass-based standards". We simply refer to "rate standards" and "CAT" throughout.

emissions reduction.[6] The EPA calculates rates separately for the Eastern and Western electricity interconnections as well as for the Electric Reliability Council of Texas. The national rates for each technology are the highest of the three calculated regional rates, *i.e.* the most lenient. State-blended rates are calculated as the generation-weighted average of the national rates based on each state's 2012 generation (MWh) from fossil steam and natural gas combined cycle units. State-blended rates vary from a 0% reduction in the emissions rates for Connecticut, Idaho and Vermont to more than a 38% reduction in the emissions rate for Montana. Figure E1 shows the rate reductions states must achieve, on average, over the period from 2022 to 2029.

CAT standards can either include or exclude emissions from new generation. When new generation is excluded, CAT standards are calculated by multiplying the state's rate standard target by the sum of the state's 2012 generation and twice EPA's projected growth in renewable generation. When emissions from new generation are included, the CPP specifies alternate CAT targets. These standards allow for extra emissions called "new source complements." This provides an incentive for states to include emissions from new generation under their caps. The average state-level increase from new source complements is about 2.4%.

Finally, under a "state-measures" approach, states can implement alternate regulations, and not federal CPP rules, so long as the emissions reductions under the state rules are greater than the federal requirements. State-measures could include existing market-based policies, such as California's cap-and-trade law or the Regional Greenhouse Gas Initiative in the northeast. Alternatively, these rules could take the form of more prescriptive renewable energy or energy efficiency policies.

To provide additional compliance flexibility, the CPP creates tradeable "emission rate credits." A regulated generator earns emission rate credits when emissions reductions exceed the rate standard.[7] Emission rate credits are also earned from increased generation using zero carbon sources or through energy efficiency measures that reduce total load.

Based on one of the standards above, the individual states must adopt compliance plans, either alone or as part of a coalition of states. The CPP neither compels states to adopt a CAT nor compels states to follow a regional approach. This flexibility could allow states to tailor their regulations to better fit their unique circumstances. Alternatively, the flexibility could lead states to adopt inefficient regulations that benefit some stakeholders at the expense of others and lead to significant impacts in other states.

Our analysis below focuses on the two main compliance paths, rate standards and CAT regulation. While the state-measures approach does allow for alternate prescriptive policies, most states will likely adopt one of the market-based policies, which are the subject of our analysis. To the extent prescriptive policies change the implicit or explicit costs of clean and carbon-intensive generation, our analysis captures many of the forces at work in less market-oriented policies. Further, since prescriptive policies are likely less-efficient than the market-based policies we study here, our results represent an upper-bound on welfare gains under the CPP.

II. The model

Consider a model of electricity generation and consumption in multiple states (regions). Let s index the states. Since electricity cannot be economically stored, prices vary across time if demand varies. Let t index hours and assume electricity flows freely across the states so that the electricity price in hour t is p_t and is common across all the states.[8] Total demand at time t is given by $D_t(p_t)$

---

[6] Fossil steam includes coal, oil and natural gas steam generation units. Covered units at those capable of selling at least 25 MW of electricity to a utility power distribution system.

[7] Using our notation, the number of emission rate credits (ERCs) generated is given by: $ERC_i = q_i \times \frac{\sigma_s - \beta_i}{\sigma_s}$

[8] In the simulations, we extend the model to include transmission constraints. Other transmission costs, such as system costs and losses, are assumed to not vary by regulatory scenario.

and (net) consumer surplus by CS.[9,10]

Supply in the model comes from a variety of generating units each with a constant marginal cost of generation and a limited capacity. Since the generating units may be regulated differently across states, we differentiate generating units by their location. Let i index the technologies (e.g., coal-fired, combustion turbine, etc.) and s index the states. Assume c_i is the marginal cost of generating from technology i; $\bar{q}_{si}$ is the installed capacity in state s of technology i; and β_i is the carbon emissions rate of technology i.

Under a market-based carbon regulation, costs also include carbon costs. Let τ be the social cost of carbon, and let $r \in \{BAU, CAT, RS\}$ index the carbon regulations: "business as usual," "cap-and-trade," and "rate standards."

Define the *full marginal cost*, FMC^r_{si}, as the sum of the marginal generation cost plus generators' (private) carbon cost, *i.e.* the cost of any carbon permits.[11] Below we define the full marginal cost for CAT and rate standards. In the absence of carbon regulation, *i.e.,* in BAU, private carbon costs are zero and $FMC^{BAU}_{si} = c_i$. We also define the *full marginal social cost* as the marginal generation plus social carbon costs, i.e., $c_i + \beta_i \tau$.[12] Welfare, W^r, under regulation r is defined as the gross consumer surplus less full social costs, or, equivalently, the sum of net consumer surplus, generator profit, and any carbon market revenue minus carbon damages.

The supply from each technology is determined by comparing the electricity price with the full marginal cost. Generators supply at capacity if the electricity price exceeds their full marginal cost, supply nothing if the price is below their full marginal cost, and supply any amount up to capacity if the price equals their full marginal cost.

The market supply is determined by aggregating the supply from each generation technology. The resulting market supply is a non-decreasing step function which orders the technologies by their full marginal cost. The order of the technologies along the supply curve determines the order in which generation units would be called into service as demand increases and is called the *merit order.*

The equilibrium electricity price in hour t is found from the intersection of hour t demand and market supply. Specifically, under carbon regulation r, the price in hour t is given by:

$$p^r_t = \min\{p : D_t(p) \leq \sum_s \sum_i \Phi(FMC^r_{si} \leq p)\bar{q}_{si}\}, \tag{1}$$

where Φ is an indicator function which takes the value one if the argument is true and zero otherwise. Thus $\Phi(FMC^r_{si} \leq p)$ is one if $FMC^r_{si} \leq p$, i.e., if technology i is willing to supply at price p and is zero otherwise. The set defined in Eq. 1 is the set of prices for which there is excess supply. The minimum of this set will either be a price at which demand exactly equals market supply when all inframarginal generators supply at capacity (i.e., on a vertical portion of the supply curve) or will be a price at which any smaller price would have excess demand (i.e., on a horizontal portion of the supply curve).

Based on these equilibrium prices, we can now characterize the equilibrium generation and profits of each technology. If q^r_{sit} is equilibrium generation in state s from technology i in hour t under regu-

---

[9] CS is found by integrating under the demand curve and above the price and summing over t. To analyze the distribution of consumer surplus, CS_s, across the states, we assume that each state's share of demand is a constant fraction of total demand. We do not account for programmatic investments that would shift the demand curve.

[10] Our definition of consumer surplus is surplus in wholesale markets. Implicitly we assume that wholesale prices are (eventually) passed through to end consumers. Modeling the intricacies of regulated retail rates, e.g., increasing block rates, two-part tariffs, etc. is beyond the scope of this paper. (See Borenstein and Holland (2005) and Borenstein (2012)).

[11] We use "private" carbon costs to denote the portion of generators' compliance costs from carbon permit purchases. This is to distinguish these costs from "social carbon costs," *i.e.,* externalities from carbon emissions.

[12] The full marginal social cost does not depend on the state or the carbon regulation.

lation r, then profits are defined as $\pi^r_{si} \equiv \sum_t (p^r_t - FMC^r_{si}) q^r_{sit}$ for technology i in state s under carbon regulation r.[13] Finally, we define equilibrium carbon emissions as $Carbon^r = \sum_s \sum_i \sum_t \beta_i q^r_{sit}$.

A. *Cap-and-trade (CAT) regulation*

We now turn to equilibrium under a cap-and-trade (CAT) regulation limiting total carbon emissions. Let E_s be allowable emissions in state s and p_{cs} be the price of tradeable certificates for one unit of carbon emissions in state s. It is well known that such a cap-and-trade program raises costs of generators in proportion to their carbon emissions, and thus the full marginal cost of technology i is $FMC^{CAT}_{si} = c_i + \beta_i p_{cs}$ in state s.

These full marginal costs are illustrated in panel (a) of Fig. 1. The figure shows the marginal costs of four technologies: nuclear (c_N), coal (c_C), gas (c_G), and oil (c_O). As illustrated, the unregulated merit order would be first nuclear, then coal, then gas, and finally oil because $c_N < c_C < c_G < c_O$. If the emissions rates are such that $\beta_O > \beta_C > \beta_G > \beta_N = 0$, the carbon regulation increases the full marginal costs of coal-fired generation more than of gas-fired generation due to coal's higher carbon emissions. Thus as illustrated the CAT regulation switches the merit order of coal- and gas-fired generation. Market supply would be found from Fig. 1 by re-ordering the technologies according to their full marginal costs.

If all states adopt CAT regulations, the equilibrium electricity price in hour t is characterized by Eq. 1 with this full marginal cost. Generator profits are given by $\pi^{CAT}_{si} \equiv \sum_t (p^{CAT}_t - FMC^{CAT}_{si}) q^{CAT}_{sit} = \sum_t (p^{CAT}_t - c_i - \beta_i p_{cs}) q^{CAT}_{sit}$. Thus generator profits do not include carbon market revenue, e.g., permits are auctioned not grandfathered, and welfare calculations must account for the carbon market revenue separately.

To complete the characterization of the CAT equilibrium, we describe equilibrium in the market for carbon certificates. Since the supply of permits is fixed at E_s, demand equals supply in state s when $\sum_i \sum_t \beta_i q^{CAT}_{sit} = E_s$. Note that a higher carbon price p_{cs} decreases carbon emissions, so there exists a carbon price which clears the carbon market.

The above characterization of the market equilibrium under CAT assumes each state has its own independent regulation. The model is extended to allow carbon trading between states. If two states allow carbon trading, then the price of carbon certificates is equal across both states, and the carbon market equilibrium is characterized by emissions equal to the aggregate cap. It is well known that allowing trading across cap-and-trade programs reduces the cost of achieving the aggregate emissions target. Furthermore, the equilibrium is invariant to the distribution of the cap across the states, i.e., only the aggregate cap is relevant.

B. *Rate standard regulation*

Next we characterize equilibrium under a rate standard. A rate standard limits the aggregate carbon emissions per MWh of electricity and can be tradeable (see Holland, Hughes and Knittel (2009)). Let σ_s be allowed emissions per MWh in state s. Any technology whose emissions rate, β_i, exceeds the standard would be required to purchase certificates per MWh based on the amount by which its emissions rate exceeds the standard. Conversely, any technology whose emissions rate is below the standard could sell certificates based on the difference between their emissions rate and the standard. Let p_{cs} be the price of tradeable certificates for one unit of carbon emissions. Thus the rate standard changes the full marginal cost of generators based on whether they are buying or

---

[13] The equilibrium supply has three cases. If price is above marginal cost, then generation is at capacity. If price is below marginal cost, then generation is zero. If price is equal to marginal cost, we assume that each generator supplies the same fraction of their capacity α^r_{sit}, where $0 < \alpha^R_{sit} < 1$. With a carbon policy α^r_{sit} may need to be redefined such that the carbon market clears.

selling permits. In particular, the rate standard changes the full marginal cost of technology i in state s from c_i to $c_i + (\beta_i - \sigma_s)p_{cs}$. Note that full marginal costs may be higher or lower than BAU depending on whether $\beta_i - \sigma_s$ is positive or negative, i.e., depending on whether a technology buys or sells certificates.

These full marginal costs are illustrated in panel (b) of Fig. 1 for the four technologies. As illustrated, the rate standard reduces the full marginal costs of (i.e., subsidizes) nuclear- and gas-fired generation, but increases the full marginal costs of coal- and oil-fired generation. As with the CAT, the merit order under rate standards as illustrated switches gas and coal, i.e., gas-fired generation is used before coal-fired generation as demand increases.

Intuitively, the rate standard is equivalent to a tax of $\beta_i p_{cs}$ combined with a subsidy of $\sigma_s p_{cs}$. Whether the rate standard implicitly taxes or subsidizes generation depends on comparing the emissions rate with the standard. The implicit output subsidy has an efficiency cost (see Holland, Hughes and Knittel (2009)) but can also serve as a defensive mechanism to prevent leakage.[14]

If all states adopt rate standards, the equilibrium electricity price in hour t is characterized by Eq. 1 with these full marginal costs. Profits are $\pi_{si}^{RS} \equiv \sum_t (p_t^{RS} - FMC_{si}^{RS}) q_{sit}^{RS} = \sum_t (p_t^{RS} - c_i - (\beta_i - \sigma_s)p_{cs}) q_{sit}^{RS}$. As above we assume that generators are not given permits. However generators with relatively cleaner technologies, for which $\beta_i < \sigma_s$, create permits by generating electricity. In this case, the term $-(\beta_i - \sigma_s)$ is positive and captures the revenue which would arise from selling carbon credits. Thus the profits capture all revenue streams and there is no carbon market revenue to be accounted for separately.

To complete the characterization of the equilibrium, we describe the market for carbon certificates. The demand for carbon certificates is determined by the amount each technology exceeds the standard and by how much electricity is generated from each technology. For example, demand for certificates in state s from technology i is $\sum_t (\beta_i - \sigma_s) q_{sit}^{RS}$ if $\beta_i > \sigma_s$. Similarly, supply in state s from technology i is $\sum_t (\sigma_s - \beta_i) q_{sit}^{RS}$ if $\beta_i < \sigma_s$. Because demand less supply equals zero in equilibrium, the carbon market equilibrium is characterized by $\sum_i \sum_t (\beta_i - \sigma_s) q_{sit}^{RS} = 0$. Note that a higher carbon price p_{cs} decreases demand and increases supply for carbon certificates, so there exists a carbon price which clears the carbon market. Note also that the equilibrium condition can be written to show that the aggregate carbon emissions rate exactly equals the rate standard in equilibrium.

The model can be readily extended to analyze two states who combine their rate standards through carbon trading. Suppose the states s and s' allow carbon certificates to be freely traded between the states. Then the prices of the certificates are equal, i.e., $p_{cs} = p_{cs'}$, and the equilibrium condition is that demand across both states equals supply across both states. Setting demand minus supply equal to zero, we can characterize the carbon market equilibrium by $\sum_i \sum_t (\beta_i - \sigma_s) q_{sit}^{RS} + \sum_i \sum_t (\beta_i - \sigma_{s'}) q_{s'it}^{RS} = 0$. This equilibrium condition can be written to show that the aggregate carbon emissions rate equals a weighted average of the allowed emissions rates across the states where the weights depend on generation.

In addition to trading carbon, which equates the carbon prices, states may also wish to harmonize their rate standards, i.e., to set $\sigma_s = \sigma_{s'}$. Note that if states do *not* harmonize their rate standards, then the full marginal costs of identical generators can be different across states even if carbon prices are the same. In order to avoid this additional inefficiency, states would need to harmonize their rate standards as well as to allow carbon trading.

Combining rate standards across states does not have the efficiency justification of combining CAT regulations. Combining CATs across states allows the same aggregate emissions target to be attained at lower cost. Combining rate standards across states does reduce costs, but it also means that the emissions target changes: both the aggregate emissions and the aggregate emissions rate

---

[14] Output-based allocations are a similar defensive mechanism to prevent leakage; see Fischer (2001).

are changed by combining rate standards in two states.

C. *Mixed CATs and rate regulation*

Finally, we consider the case of *mixed regulation* in which some states adopt CATs and other states adopt rate standards. Under the Clean Power Plan proposals, states can choose what type of regulation to adopt and a mixture of CATs and rate standards could result. The model is readily extended to mixed regulation. In particular, the equilibrium electricity price is found from the set defined in Eq. 1 where the full marginal costs are $c_i + \beta_i p_{cs}$ in a CAT state and $c_i + (\beta_i - \sigma_s)p_{cs}$ in a rate standard state.

In theory, states could allow carbon trading across CATs and rate standards.[15] Generating one MWh from any relatively clean plant under a rate standard creates $\sigma_s - \beta_i$ permits, which are simply tons of carbon. These permits can then be purchased by relatively dirty generators under a rate standard or any generator under a CAT. If state s has a CAT and state s' has a rate standard, trading equates the price of carbon in each state, i.e., sets $p_{cs} = p_{cs'}$. Setting the difference between aggregate certificate demand and supply equal to zero implies that the equilibrium certificate price is characterized by $\sum_i \sum_t \beta_i q_{sit}^{RS} - E_s + \sum_i \sum_t (\beta_i - \sigma_{s'}) q_{s'it}^{RS} = 0$. This condition does not have a clear interpretation either as a cap or a emissions rate constraint.

D. *Theoretical results*

We first compare the merit orders under the different regulations. We define *efficient supply* as the merit order which minimizes full social costs for any given level of generation. Note that efficient supply may not result in efficiency if the level of generation is inefficient. Our first result describes efficient supply; we then address efficiency in a corollary. All proofs are in the appendix.

RESULT 1: **Efficient Supply:** *The merit order is efficient (full social costs are minimized):*
(i): if all states adopt CATs and p_{cs} *is sufficiently close to* τ *for all* s*;*
(ii): if all states adopt rate standards, p_{cs} *is sufficiently close to* τ *for all* s*, and* σ_s *is sufficiently close to* σ *for all* s*; or*
(iii): if there is mixed regulation, p_{cs} *is sufficiently close to* τ *for all* s*,* σ_s *is sufficiently close to* σ *for all* s*, and* $|c_i + \beta_i\tau - c_j - \beta_j\tau| > \sigma\tau$ *for all* i *and* j*.*

This result shows sufficient conditions for the efficiency of supply. Importantly, the sufficient conditions become increasingly stringent across the regulations.

For CATs, supply is efficient if the carbon price equals (or is close to) the social cost of carbon. Intuitively, the CAT can implement Pigouvian pricing if the cap is sufficiently stringent, but not too stringent.

For rate standards, supply can also be efficient. For a given carbon price, the CAT and rate standard induce the same merit order since $c_i + (\beta_i - \sigma_s)p_{cs} < c_{i'} + (\beta_{i'} - \sigma_s)p_{cs}$ if and only if $c_i + \beta_i p_{cs} < c_{i'} + \beta_{i'} p_{cs}$ Intuitively, the rate standard can induce the correct relative prices across the technologies because it simply shifts the full marginal costs down by a constant. However, supply efficiency for a rate standard requires that carbon prices equal the social cost of carbon *and* that the rate standards be equal across states. Note that these sufficient conditions will not be ensured by carbon trading alone but would also require explicit harmonization of the rate standards across states. Thus the sufficient conditions are more strict for rate standards than for CAT.

Surprisingly, Result 1 (*iii*) shows that mixed regulation can also attain the efficient supply but only under more stringent conditions. This result is illustrated in panel (c) of Fig. 1 for four

---

[15] The Clean Power Plan discourages trading across regimes and none of our simulations model carbon trading across regimes.

technologies where some of each technology is subject to a CAT and some is subject to a rate standard of σ and the carbon price is τ. Note that within each technology, the implicit subsidy of the rate standard lowers the full marginal cost by $\sigma\tau$, so the rate-standard technology is dispatched first, e.g., gas under the rate standard is dispatched before gas under the CAT. As illustrated, the merit order is efficient, because all the gas-fired generation is used before the coal-fired generation as demand increases.

However, the efficiency of supply only occurs because the full marginal costs are sufficiently different. If the full marginal costs are close, i.e., if $|c_C + \beta_C\tau - c_G - \beta_G\tau| < \sigma\tau$, then the merit order is not efficient. As illustrated in panel (d) of Fig. 1 the full marginal costs are sufficiently close that the merit order is rate-standard gas, followed by rate-standard coal, then CAT gas, and then CAT coal. This merit order is "scrambled," i.e., inefficient, because the full marginal social cost of gas-fired generation is less than the full marginal social cost of coal.[16]

Result 1 also highlights the importance of coordination across states. For CATs, all carbon prices need to be sufficiently close to τ, which can be ensured by carbon trading and a correct overall cap. Note that with carbon trading the distribution of the cap across states is irrelevant for efficiency of supply. With rate standards, trading can also ensure that carbon prices are equal across states. However, now the standards must be set equally across states in order for the merit order to be efficient, i.e., the distribution of the rate standards across the states is crucial. The result also shows an additional inefficiency if states fail to coordinate on a CAT or a rate standard.

This result also emphasizes the importance of carbon prices. Importantly, efficient supply depends on the carbon price being sufficiently close to τ, but does not depend on the target emissions level or the target emissions rate. Thus, to attain efficient supply, the regulator would need to adjust the emissions cap or target emissions rate to maintain the carbon price equal to τ. Unfortunately, the Clean Power Plan specifies emissions rate targets rather than carbon price targets.

Although efficient supply is necessary for the overall efficiency of a regulation, it is not sufficient as the following corollary makes clear:

COROLLARY 1: **Efficiency:** *If demand is perfectly inelastic, then CATs, rate standards, or mixed regulation achieve efficiency if the merit order is efficient.*

If demand is not perfectly inelastic, then CAT regulations achieve efficiency if $p_{cs} = \tau$ *for all* s. *Rate standards and mixed regulation do not achieve efficiency.*

This corollary, which demonstrates the superiority of CAT, echoes earlier results in the literature (e.g., see Helfand (1991), Kwoka (1983), Holland, Hughes and Knittel (2009)). If demand is perfectly inelastic, then there is no consumption inefficiency and efficiency only requires efficient supply. However, if demand is not perfectly inelastic, then only a CAT regulation with a carbon price of τ can attain the first best.[17]

Given the importance of equal carbon prices in Result 1, the next result addresses the benefits from carbon trading, which equates carbon prices across regions.

RESULT 2: **Carbon Trading:** *Trading carbon between states reduces costs. Trading between states with CATs holds aggregate emissions constant. Trading between states with rate standards may cause aggregate emissions to increase or decrease.*

This result shows that although carbon trading does reduce costs, it may not have clear efficiency benefits. It is well known that under CAT aggregate emissions are held constant and thus a reduction in costs leads to a clear efficiency gain, i.e., CAT is cost effective.

---

[16] This inefficiency from mixed regulation is limited, because it only arises if full marginal costs are sufficiently close, i.e., if costs are small from the wrong merit order.

[17] Holland (2012) shows that rate standards can attain the first best if they are coupled with an electricity tax of $\sigma\tau$. Furthermore, he shows that in a second-best setting all these policies may fail to attain efficiency and the best policy is not theoretically clear.

Under rate standards, Holland, Hughes and Knittel (2009) show aggregate emissions could increase or decrease, and thus the welfare effects of carbon trading are indeterminate. For example, consider a state with an inelastic supply of relatively clean generation but elastic supply of dirty generation. This state will primarily respond by reducing dirty generation, which would lower overall emissions. If this state trades carbon with a state with an elastic supply of relatively clean (but not zero carbon) generation, then the resulting increase in relatively clean generation could lead to an overall increase in emissions. The welfare effects would need to compare any cost savings from carbon trading with this increase in emissions and hence are ambiguous.

We next compare the equilibrium outcomes across policies in which all states adopt the same policy. We analyze electricity prices, consumer surplus, and profits to "uncovered generators," namely, generators which are not covered by the regulation, e.g., renewables or distributed generation.

RESULT 3: **Prices, Consumer Surplus, and Uncovered Generator Profits:** *For a given carbon price* $p_{cs} > 0$*,*

(i) electricity prices are higher under CATs than under either rate standards or no regulation, i.e., $p_t^{CAT} \geq p_t^{RS}$ *and* $p_t^{CAT} \geq p_t^{BAU}$*, and electricity prices under rate standards or under mixed regulation can be either higher or lower than under no regulation;*

(ii) consumer surplus is lower under CATs than under either rate standards or no regulation, i.e., $CS^{CAT} \leq CS^{RS}$ *and* $CS^{CAT} \leq CS^{BAU}$*, and consumer surplus under rate standards or under mixed regulation can be either higher or lower than under no regulation; and*

(iii) profits for uncovered generation are higher under CATs than under either rate standards or no regulation, and profits for uncovered generation under rate standards or under mixed regulation can be either higher or lower than under no regulation.

This result shows that a rate standard will generally be preferred by consumers, but that uncovered generators will generally prefer a CAT. The intuition follows directly from the electricity prices. For a given carbon price, the result shows that electricity prices are higher under a CAT but can be higher or lower than BAU prices under rate standards. These price comparisons follow from a comparison of the full marginal costs under the policies. Since full marginal costs are higher under CAT than under rate standards or BAU, the electricity price is higher. Similarly, since the full marginal costs under rate standards can be higher or lower than under BAU, the electricity prices are similarly higher or lower. The results on consumer surplus and profits of uncovered generation follow directly from the result on prices.

The result on uncovered generation is important since significant generation capacity may not be covered by the Clean Power Plan, e.g., hydro, nuclear, and some combined heat and power. The result shows that these uncovered generators will prefer CAT regulation because they would benefit from the higher electricity prices. The effect is somewhat different for "dirty" and "clean" uncovered generators. For dirty uncovered generators, the benefit arises from the higher electricity prices and because the lack of carbon regulation does not increase their costs. For clean uncovered generators, the difference arises from the higher electricity prices and because the lack of carbon regulation does not *decrease* their costs under rate standards. The inability to sell carbon credits under a rate standard implies that uncovered clean generation prefers CAT. Note that this result also implies that incentives are strongest under CAT for new clean generation and for efficiency improvements both of which might be uncovered by the Clean Power Plan.

The result also has important implications for investment incentives. Investment will occur in the most profitable locations. New fossil-fuel fired generation may be "uncovered" since it is subject to other regulations, e.g., Section 111(b), and may not be subject to the Clean Power Plan. Small combined heat and power will also likely not be covered by the Clean Power Plan. Efficiency improvements may also not be covered. The result implies that there would be more investment in uncovered generation under CAT regulation than under rate standards.

We next analyze the incentives for states to adopt either CATs or rate standards by analyzing the outcomes if states coordinate on either a single CAT or a single rate standard. To focus the analysis, we assume additionally that carbon prices equal τ and rate standards are equal across states, i.e., we assume efficient supply.

RESULT 4: **Adoption Incentives of a Coalition:** *Suppose that all states adopt the same regulation, i.e., all states have a unified CAT or unified rate standard. Suppose further that the CAT or rate standard results in a carbon price equal to the social cost of carbon across both regimes and across all states, i.e.,* $p_{cs} = \tau$ *for all* s*, and that rate standards are equal across states, i.e.,* $\sigma_s = \sigma$ *for every* s*.*

(i): $p_t^{CAT} \leq p_t^{RS} + \sigma\tau$ *for all* t*;*

(ii): $q_{sit}^{CAT} \leq q_{sit}^{RS}$ *for all* s*,* i*, and* t*;*

(iii): $\pi_{si}^{CAT} \leq \pi_{si}^{RS}$ *for all* s *and* i*;*

(iv): $W^{CAT} \geq W^{RS}$*; and*

(v): $TR^{CAT} + \tau(Carbon^{RS} - Carbon^{CAT}) \geq (CS^{RS} - CS^{CAT}) + (\pi^{RS} - \pi^{CAT})$*.*

If additionally we assume that demand is perfectly inelastic, then each of the weak inequalities above is an equality.

When states act in a coalition, this result shows that although welfare is maximized under CAT instead of a rate standard, the direct revenue from carbon permit sales may not be enough to compensate consumers and producers for lost surplus and profit. The intuition follows from noting that under these assumptions the merit order is unchanged and full marginal costs are lower by $\sigma\tau$ under the rate standard, which implies that the market supply is simply shifted down by $\sigma\tau$. If demand were perfectly inelastic, equilibrium prices would fall by exactly this amount. If demand is not perfectly inelastic, then a price which is lower by $\sigma\tau$ could result in excess demand. Thus the price difference between the CAT and rate standard is at most $\sigma\tau$.

Because the market supply shifts down, generation must be (weakly) higher under the rate standard for each generator for each hour (Result 4 (*ii*)). This has additional implications for carbon emissions and generation costs, which are both higher under the rate standard.

The comparison of profits in Result 4 (*iii*) follows because the market supply shifts down by $\sigma\tau$ and the price falls by at most $\sigma\tau$. Thus producer surplus (i.e., generator profit) is higher under the rate standard for each generator.

The inefficiency of rate standards, described in Corollary 1, implies the result on welfare in Result 4 (*iv*). Rewriting this in Result 4 (*v*) shows that the sum of carbon market revenue and the increase in carbon market damages exceeds the sum of the increases in consumer surplus and profit under rate standards.

With perfectly inelastic demand this equality becomes $CS^{CAT} + TR^{CAT} = CS^{RS}$, which shows that the gain in consumer surplus from a rate standard is exactly the foregone carbon market revenue TR^{CAT}. In this case, the carbon market revenue is exactly sufficient to compensate consumers for the lost consumer surplus under CATs.

If demand is not perfectly inelastic, the inequality in (*vii*) is less informative about the ability of carbon market revenue to compensate consumers and producers for their losses under the CAT. In particular, it shows that carbon market revenue plus the additional carbon damages would be sufficient to compensate both producers and consumers for their losses under the CAT. However, the result suggests that it is an empirical question whether or not carbon market revenue by itself will be sufficient to compensate both producers and consumers for their losses under CAT.

E. Incentives for Regulatory Choice

We now turn to the adoption incentives of an individual state. In particular the question of how a state's choice interacts with other states' choices to influence economic outcomes. This question could be directly addressed by the previous results if carbon prices were exogenous to the specific mechanism, for example, if states adjusted the CATs or rate standards so that the carbon prices always equaled the social cost of carbon.

For exogenous carbon prices, Result 4 is a good guide to the adoption incentives of a single state.[18] As in Result 4 (i), if the state adopted a rate standard instead of a CAT, electricity prices would be lower in any hour in which that state's generators were marginal, but the electricity price would be lower by at most $\sigma_s\tau$. Since generators' costs would be lower by $\sigma_s\tau$, generators' profits would be higher under the rate standard. With lower electricity prices, consumer surplus would also be higher under a rate standard. Thus consumers and covered generators would prefer that their state adopt the rate standard regardless of what other states do. In other words, adoption of a rate standard would be a dominant strategy from the perspective of covered generators or consumers. On the other hand, carbon market revenue and higher electricity prices from CAT imply that CAT adoption would be a dominant strategy from the perspective of government revenues and of uncovered generators. Thus, with fixed carbon prices, some perspectives would have a dominant strategy for adoption of a CAT but others would have a dominant strategy for adoption of a rate standard.

Since the Clean Power Plan specifies emissions and emissions rates rather than carbon price targets, carbon prices are likely endogenous to the regulatory choices of neighboring states. This complicates a single state's adoption decision. We assess these incentives more thoroughly in our numerical simulations; however, a few examples illustrate the possibilities. Suppose a state were to consider a CAT when all its neighbors adopt a rate standard. Without a carbon price response, the full marginal costs would be higher under the CAT and thus the state's generators would be dispatched less frequently, and there would be an excess supply of carbon permits. This implies that the state's carbon price would be lower if it adopted a CAT instead of an equivalent rate standard thereby making CAT more attractive from some perspectives.[19] On the other hand, a state choosing a rate standard when its neighbors are under CAT could experience either an increase or decrease in its carbon price, depending upon the mix of available supply in that state. For example if the rate state had excess "clean" generation capacity (e.g. gas generation with an emissions rate below the state's standard) then increasing exports from those clean sources would relax the rate standard constraint and hence lower carbon prices. Finally, we can construct an example where adoption of mixed regulations lowers carbon prices for both CAT and rate states. Compliance costs and electricity prices would then be lower compared to a uniform CAT scheme.

A state's adoption incentives will hence involve a combination of carbon price effects in addition to the effects outlined in Result 4. To assess the direction and magnitude of these effects, we turn to a numerical simulation model.

III. Numerical simulations

The theoretical model describes the inefficiencies which can result when states choose CAT regulation or rate standards across an integrated product market. As described above, there are several additional considerations to the actual Clean Power Plan that are difficult to capture in a theoretical model, including the heterogeneity of both supply technologies and emissions limits across states,

---

[18] Result 5 in Supplementary Appendix A extends Result 4 to analyze the adoption incentives of a single state assuming carbon prices are fixed at τ.

[19] Intuitively, the state can achieve compliance through importing.

and importantly, the endogeneity of carbon prices to a market's choice of regulatory mechanism. We approach this richer set of issues using numerical simulation methods applied in the context of the electricity market in the Western US.[20] In this section, we present the simulation model and the data used to parameterize the model. Additional details on the numerical simulation are in Online Appendix C

A. Optimization model and constraints

Because we assume firms act in a manner consistent with perfect competition in both the electricity and emissions permit markets, market equilibrium is equivalent to the solution of a social planner's problem. Our social planner's problem maximizes gross consumer surplus less generation costs subject to various operating constraints. Using the notation developed above, the planner's objective is thus:[21]

$$\max_{q_{sit}} CS + \sum_{s} \sum_{i} \sum_{t} (p_t - c_i) q_{sit}. \tag{2}$$

The generation costs in Equation 2 are comprised of the marginal operating costs for existing and new generation (taken from sources described in the appendix) and annualized capital costs for new generation capacity. Maximization of Equation 2 is subject to generation, transmission, and policy constraints. Generation constraints reflect installed capacity adjusted proportionally for the probability of a forced outage of each unit from the generator availability data system.

The model allows for market-based investment in new natural gas and wind generation capacity. The availability of a new wind resource is subject to an hourly generation profile that is specific to each region and taken from data sources described in the appendix. For both technologies, the objective function in Equation 2 includes an annualized per-MW cost of capital, and the hourly output and marginal cost of new units. The resulting equilibrium condition equates the capital cost to the net operating profit of a technology, or $C_i * K_i = \sum_t q_{it} * (p_t - FMC_{si})$, where i is a technology with capital cost C_i and full marginal cost (including carbon) FMC_{si}, and $q_{it} \leq K_i * avail_t$ is the output of technology i, which is constrained to not exceed the installed capacity (adjusted for availability).

Our transmission constraints replicate centralized locational marginal pricing (LMP). Any LMP price differences are arbitraged away subject to the constraints of the transmission network. Optimization of Equation 2 is therefore subject to constraints on the flows between five transmission regions represented in our model. These constraints are governed by existing line capacities. See Supplemental Appendix C.C3 for more detail on our modeling of transmission constraints. Transmission fees and line loses are implicitly captured by our BAU simulation and assumed to be constant across the different policy scenarios.

The carbon policies are modeled with additional constraints. BAU is modeled by optimizing Equation 2 subject to the generation and transmission constraints. Under CAT regulation in state s, total emissions in the state must also be less than allowed emissions, i.e., the policy constraint is $\sum_i \sum_t \beta_i q_{sit} \leq E_s$. If two states harmonize their CAT regulations through emissions trading, aggregate emissions across the two states must be less than total allowed emissions. The shadow values of the constraints are the carbon prices that would result from implementation with market mechanisms. Similarly, if state s adopts a rate standard, then the emissions rate in the state

---

[20] We utilize an electricity transmission and supply model similar to that used in Bushnell and Chen (2012) and Bushnell, Chen and Zaragoza-Watkins (2014).

[21] The objective does not consider carbon damages, which are addressed through the constraints.

must be less than the allowed emissions rate. If two states harmonize their rate standards, then the constraint is on the aggregate emissions rate. Note that this is equivalent to allowing carbon trading *plus* harmonizing the allowed emissions rates. The shadow values are again the carbon prices.[22] In cases where both rate and CAT standards co-exist we assume no trading of emissions credits across regimes.

B. Data Sources and Assumptions

The model uses cost and market data from the year 2007. Electricity demand levels and market prices for each region and hour are taken from public data sources described in Appendix C. For tractability, hourly data are aggregated into representative periods which are weighted to calibrate market outcomes in terms of annual statistics. We assume linear demand where the intercept in each time period is determined by the mean actual hourly electricity price and consumption level during that time period.[23] Because electricity demand is extremely inelastic, we utilize an extremely low value for the slopes of the linear demand curve.[24] The slope of the demand curve is set so that the median elasticity in each region is -.05.[25] Consumer surplus is, as usual, the area under the demand and above the price.[26]

We explicitly model all fossil-fired generation monitored by the EPA's continuous emissions monitoring system (CEMS). These constitute almost all the units whose emissions would be regulated under the Clean Power Plan, *i.e.* covered generation. The marginal cost of a modeled generation unit is assumed to be the sum of its fuel and variable operation and maintenance (VO&M) costs, taken from data sources described in Appendix C. We calculate fuel costs for each unit as a constant heat-rate (mmBtu/MWh) multiplied by regional average fuel price, up to the capacity of the unit. We use unit average heat-rates and regional average fuel prices taken from the Platts PowerDat dataset. Emissions rates, measured as tons CO_2/MWh, are based upon the fuel-efficiency (heat-rate) of a plant and the CO_2 intensity of the fuel burned by that plant.

We first use natural gas prices from 2007 to establish if the simulation reasonably captures generation and emissions totals over Western states. Because we separately calibrate demand and supply before aggregating demand, our simulation does not exactly replicate 2007 market outcomes. Appendix Table D9 shows that our predicted uncovered generation, covered generation, and emissions each match actual 2007 levels to within 2%. The results reported here utilize natural gas prices that are, on average \$2.00/mcf lower, to better capture current fuel price conditions.

Investment in our simulations is based on information from the National Renewable Energy Laboratory. We assume the annualized capital cost of new natural gas combined-cycle units is \$100 KW-yr. Operating costs for the combined-cycle gas c_{st} depend on natural gas prices and are assumed to be \$48/MWh under 2007 gas prices and \$32/MWh under current gas prices. The annualized capital cost of a new wind turbine is \$200 KW-yr. We assume that wind turbines have no marginal operating costs, but their output is constrained by wind availability. We use data on projected capacity factors of new wind plants taken from a WECC data set used in Bushnell

---

[22] We write the rate standard constraints as $\sum_i \sum_t \beta_i q_{sit} \leq \sigma_s \sum_i \sum_t q_{sit}$ so that the shadow value is in dollars per ton of carbon.

[23] The intercept is the sum of mean consumption and the product of the mean price and demand slope.

[24] The inelasticity of demand reflects in part the imperfect pass-through of wholesale prices to end-use electricity consumers.

[25] The low elasticity is chosen in part to reflect the imperfect pass-through of wholesale prices to retail rates. Because the market is modeled as perfectly competitive, the results are relatively insensitive to the elasticity assumption, as price is set at the marginal cost of system generation and the range of prices is relatively modest. We discuss this assumption in the appendix.

[26] Inelastic linear demand implies unrealistically large consumer surplus triangles, which we arbitrarily truncate above \$100 per MWh. Because we are mainly interested in changes in consumer surplus relative to BAU, this assumption is unimportant. For state-level demand and consumer surplus calculations, we use EIA data on annual consumption by state to calculate the fraction of a region's demand that is attributable to a given state. This approximation assumes that the hourly distribution of regional demand amongst states is the same as the annual average.

(2011). These capacity factors, which capture the intermittency of wind generation, vary by every hour and subregion in the simulation. The average capacity factor for a new wind plant is about 35%. The capacity factors vary considerably by region, approaching 40% in the Rocky Mountains but averaging only 28% in the Southwest.

Unfortunately, we lack data on the hourly generation from some other sources, namely, renewable resources, hydro-electric resources, nuclear, combined heat and power, and other small thermal resources. We infer aggregate hourly generation from these sources from the difference between regional hourly demand and fossil-fired generation after accounting for net imports. These sources, which primarily have very low or zero marginal costs, are assumed to have the same hourly generation in all of our simulations. We do not observe state imports for a given hour. Instead net imports are aggregated to the regional level within the Western interconnection (WECC) and approximated from data on the hourly flow over key transmission lines between regions.

In some results we disaggregate the outcomes for supply between generation sources covered under the Clean Power Plan and "uncovered" sources. Covered sources include all modeled fossil generation. For the CPP, the EPA has proposed a complex formula that gives partial credit for output from nuclear plants as well as credits for non-hydro renewable generation and energy efficiency. Such sources may be eligible to earn emissions credit payments by virtue of their emissions rates being below the emissions rate standard. However because of our data limitations we include all non-thermal sources in our "uncovered" category in the results below.

To model CO_2 regulation under the CPP, we convert EPA's interim goals for 2022-2029 into the equivalent rate and CAT standards for our simulation. To do this we assume that the carbon reductions would be equivalent if the electricity quantities were the same. In other words, we establish a baseline emissions quantity and MWh output for each state, which converts into a baseline emissions rate by dividing the former by the latter. We apply the EPA's mandated reduction percentage to this baseline emissions rate and calculate the rate standard for each state. For example, Arizona's emissions rate is required to be reduced to 75.6% of its baseline emissions rate, so Arizona's rate standard is $0.756\times(1.3\times10^{11}$ lbs. $CO_2)/(8.6\times10^{7}$ MWh).

The equivalent CAT regulation is the baseline emissions reduced by the same percentage. Our main scenarios assume new generation is included under the CAT regulation. To be consistent with the EPA's calculations for new source complements, we increase the cap described above by an additional 2.4%, which is the average increase allowed. For example, Arizona's cap is $0.756\times(1.3\times10^{11}$ lbs. $CO_2)\times1.024$.

C. Caveats and Limitations

Our simulations capture many of the key elements that influence state choices and outcomes under the Clean Power Plan, such as short-run generation costs, transmission constraints, and investment in natural gas and wind generation. That said, there are some limitations to the model. We do not explicitly consider the opportunities for abatement from increasing the efficiency of coal-fired power plants or from state investments in energy efficiency. Further, we do not explicitly model other state level policies, such as renewable portfolio standards, that might influence the specific compliance strategy of a state. Finally, the generation mix has changed somewhat since 2007, primarily through investment in new gas-fired generation. To the extent that these factors reduce the need for relatively dirty generation, they lower compliance costs. However, the relative effects on costs across the policies are less clear.

We also make several simplifying assumptions in reporting our simulation results. To calculate carbon damages, we use a social cost of carbon equal to \$43/MT, consistent with EPA regulatory filings. We do not include damages from other co-pollutants. Including co-benefits would increase welfare relative to the status quo in all policy scenarios and could change the scenario rankings.

Next, while we separately report producer and consumer surplus, the division of surplus likely depends on whether generation in a given state falls under rate regulation. In regulated states, producer surplus may largely accrue to consumers. Consumer surplus is calculated and reported for the wholesale electricity markets. This implicitly assumes wholesale prices are eventually passed through to end users but diluted to some extent by the regulation of retail rates. The dilution of wholesale price fluctuations is one reason we utilize a relatively low demand elasticity. We also do not model the myriad inefficiencies of retail electricity pricing. For instance, if retail prices are inefficiently high, a rate standard that does not increase electricity prices as much may be less inefficient. Finally, our calculations abstract away from tax interaction effects and double-dividend style benefits (Goulder, Parry and Burtraw, 1997), which may be larger under CAT compared to rate standards. To get a sense of the size of the potential double-dividend, we separately report carbon market revenue, which could in principle be given to generators, consumers or taxpayers.

IV. Simulation results

We present simulation results from scenarios that span the states' policy options under the CPP, e.g., rate standard v. CAT regulation and coordinated v. mixed regulation. To reduce the number of possible policy combinations, some results collect states into possible regional groups. We consider a group of "Coastal" states, (California, Oregon and Washington) and "Inland" states: Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, Wyoming and Utah. This division is somewhat reflective of current policy discussions.[27]

Following the theory model, we first discuss the supply-side effects of regulations on the generation merit order. Then, we analyze equilibrium outcomes under each policy and incentives to form coalitions. Finally, we explore incentives for investment in new capacity under different regulations.

A. Supply-side effects

Figures 2-5 illustrate how various policies options affect the full marginal costs and how the merit order can be scrambled. Figure 2 compares the full marginal costs of existing fossil-fuel generation units under West-wide CAT and rate standards to the market supply under BAU (i.e., the generating units are sorted along the x-axis by BAU marginal costs). The generating units to the left of 23 GW are primarily coal-fired and the generating units to the right of 23 GW are gas-fired. The West-wide CAT increases the full marginal costs of the units in proportion to their carbon emissions. Because coal is dirtier than gas, this changes the merit order, and some gas-fired generation is now cheaper than coal-fired generation and would be used first as demand increases.

The West-wide rate standard also increases costs in proportion to carbon emissions, but includes an implicit output subsidy. The net effect increases the full marginal costs of the coal-fired generation but *decreases* the full marginal costs of gas-fired generation with emissions rates below the standard. Both the West-wide CAT and rate standard achieve approximately the same relative ordering of generation. This is consistent with theoretical Result 1 that both policies can eliminate the supply-side inefficiency. However, full marginal costs are too low under the rate standard.[28]

Figure 3 compares the coal and gas full marginal costs under state-by-state CAT standards with the supply curve for a West-wide CAT. The state-by-state CATs lead to full marginal costs that are too high in some states (those with tight caps) and too low in other states (those with loose caps). This heterogeneity "scrambles" the merit order and is an additional source of inefficiency.[29]

---

[27] California, Oregon, and Washington and Oregon are currently members of the Pacific Coast Collaborative, which seeks cooperative action in mitigating greenhouse gas emissions. They are the only WECC states participating in this initiative.

[28] Our CAT simulation yields a permit price below the social cost of carbon. Under the rate standard, full marginal costs are lower than those under CAT and are often less than the unregulated case where carbon emissions are unpriced.

[29] Appendix Figure E4 shows a similar "scrambling" of the merit order due to state-by-state rate standards.

Practically speaking, this can lead to very different dispatch ordering of similar generating units, which is clearly inefficient.

Figure 4 compares the full marginal cost when regional coalitions fail to coordinate policies with the supply curve for a West-wide CAT. If Coastal states adopt a CAT standard and Inland states adopt a rate standard, the carbon prices are too low in both regions. The resulting merit order which is not only scrambled, but the full marginal costs are also too low. This suggests the possibility of additional inefficiencies from mixed regulation, which we explore further below.

Finally, Figure 5 compares market supply under the West-wide CAT, West-wide rate standard, and BAU. Because wind capacity varies throughout the year, we plot a representative peak summer hour. Two features are worth noting. First, both CAT and the rate standard increase investment in wind generation, the leftmost portion of each curve, shifting out supply by about 8 GW relative to the no regulation case. Second, since CAT increases the full marginal cost of all fossil generation, costs are higher than BAU for almost all generation levels despite the substantial investment in wind capacity. Because the rate-standard decreases the full marginal cost of some gas generation and induces substantial wind investment, costs are often lower than BAU.

B. *Equilibrium market impacts*

These scrambled merit orders indicate the potential for inefficiency. To assess the magnitudes of any inefficiencies, Table 1 compares equilibrium outcomes from eight policy scenarios to BAU ("No Reg" or Scenario 0). Scenarios 1 through 8 vary which states or regions operate under CAT and rate standards and whether regulations are harmonized. Online Appendix C.C8 presents a subset of outcomes for individual states.

First, consider the two West-wide policies: a West-wide CAT (Scenario 1) and a West-wide rate standard (Scenario 3). Consistent with theory, average electricity prices relative to BAU are higher under CAT and lower under a rate standard. As expected, electricity consumption relative to BAU is lower under CAT but higher under the rate standard. These electricity prices and consumption, translate into effects on consumer surplus and generator profits that are also consistent with the theoretical results. The difference in consumer surplus between the scenarios is mostly accounted for by the carbon market revenue and higher profits to uncovered generators, thus the private surplus loss (or abatement cost) is quite similar across the two policies (-\$1.19 v. \$1.32 billion relative to BAU).

To compare the efficiency of these two scenarios, first note that the carbon prices (marginal abatement costs) are quite similar (\$21.45 v. \$21.80 per MT), so any supply-side inefficiencies should be modest (as suggested by Figure 2). Moreover, these carbon prices are well below the social cost of carbon (\$43 per MT), so both policies are reducing carbon less than would be efficient.[30] Due to the new source complements in the parameterization of the CAT, emissions reductions are actually smaller under the West-wide CAT (74.34 MMT, about 22%) than under the West-wide rate standard (78.27 MMT, about 24%). Because the emissions reduction is more modest and because the policy can be efficient, the West-wide CAT has the lowest average abatement cost of all the policies. The West-wide rate standard, by reducing carbon emissions more, actually results in the highest welfare gain (\$2.04 billion relative to BAU).[31]

Relaxing the West-wide CAT by including new source complements was intended to prevent leakage to new capacity. However, loosening the cap has an efficiency cost. Modeling "No New Source Complements" shows that a West-wide CAT, which achieves the same emissions reduction

---

[30] In an earlier version of this paper, our simulations did not allow for the option of building new wind capacity. In that case, compliance costs were \$30 per ton of CO_2 and electricity prices were nearly \$20 per MWh higher, despite less aggressive carbon reductions.

[31] Our assumption of inelastic demand also minimizes the inefficiency of the West-wide rate standard.

as the West-wide rate standard, would result in even larger gains in Social Welfare ($2.14 billion relative to BAU). This illustrates the inefficiency of the West-wide rate standard.

We next turn to cases where states fail to harmonize regulations. In particular, Scenario 2 shows state-by-state CATs and Scenario 4 shows state-by-state rate standards. Due to the idiosyncracies of the state-level targets in the CPP, failure to harmonize policies results in substantial inefficiencies. Compared to the West-wide policies, state-by-state policies have higher average abatement costs ($18.69 v. $15.98 per MT, about 17% higher and $18.55 v. $16.88 per MT, about 10% higher) despite the state-by-state rate standard having a smaller carbon reduction. These high abatement costs translate directly into lower social welfare gains, which illustrates the efficiency costs of the failure to harmonize regulations.

Scenarios 5 through 8 investigate mixed regulation under which some states adopt CATs and some states adopt rate standards. First consider Scenario 5 ("CAT Rate" in which the Coastal region adopts a harmonized CAT and the Inland region adopts a harmonized rate standard) and Scenario 7 ("Rate CAT" in which the policies are reversed).[32] The mixed regulations introduce the possibility for emissions to "leak" to the rate standard region. In Scenario 5, leakage is so severe that the carbon price in the Coastal CAT is zero, i.e., the cap is non-binding, and emissions reductions are much smaller.[33] In Scenario 7, leakage is not so severe as to result in a zero carbon price, however, emissions reductions are quite small (55 MMT) and welfare gains are eroded to $1.34 billion. Overall, average abatement costs are between 5 and 21 percent higher compared to a West-wide CAT.

Scenarios 6 and 8, illustrate policy failures across two dimensions: mixed regulation and a failure to harmonize rate standards. Not surprisingly, these scenarios result in the highest average abatement costs and lowest social welfare gains of all the scenarios.

Finally, our results suggest investment in renewable energy will be an important compliance option. In an earlier version of this work (Bushnell et al., 2015), we analyze compliance without investment. Relative to those results, investment reduces the disparity between marginal compliance costs in the state-by-state scenarios, reflecting the common option of wind investment available to all states. More importantly, the addition of new investment greatly magnifies the potential leakage that could be experienced under the "uncoordinated" regulations when one region adopts a cap and another adopts a rate standard. The addition of a zero carbon investment option also greatly depresses power prices in regions adopting rate standards. This has important implications for consumers and profits for incumbent generation, particularly nuclear.

C. Incentives to form a West-wide coalition

Our simulations suggest efficiency is enhanced when states form regional trading markets. A natural question, then, is whether states will have the incentive to join such a coalition? To address this question, we focus on outcomes if the Coastal or the Inland states either join or unilaterally depart from a West-wide coalition. The game-theoretic "normal form" is a useful way to summarize payoffs holding fixed the actions of others. Because the incentives of stakeholders within each region may not necessarily align, Table 2 presents normal forms for four main outcomes: private surplus; consumer surplus; profits; and emissions.

---

[32] Given that California currently has a cap-and-trade system in place, we do not believe scenarios 7 and 8 are realistic. However, they provide the basis for understanding the complete set of incentives.

[33] Given that California currently has in place a mass-based greenhouse gas law for electricity generators and Inland states are currently unregulated, one may worry adoption of a rate standard by the Inland states would magnify leakage from the Coast to the Inland region. In unreported results, available upon request, we simulate a Coastal CAT and unregulated Inland region. Imports to the Coastal region do increase relative to our BAU scenario, however these imports from the Inland region to the Coast are smaller than under scenarios 5 and 6. Therefore the rate standard applied to the Inland states does indeed exacerbate the problem of emissions leakage.

Private surplus—the first panel of Table 2—is the sum of consumer surplus, producer surplus, and carbon market revenue and thus captures the perspective of a regional planner focused on abatement costs. Under a West-wide CAT (Scenario 1) the private surplus (i.e., abatement cost) is \$1.2 billion less than BAU. However, this panel shows that this cost is not shared equally between the two regions, but rather that more is borne by the Coastal region (\$0.7 billion) than the Inland region (\$0.5 billion). This division of the burden means that the Coastal region has an incentive to deviate from a West-wide CAT. Conversely, the burden of the West-wide rate standard (Scenario 3 with cost of \$1.3 billion) is borne more heavily by the Inland region, who then have an incentive to unilaterally adopt a CAT. Thus neither a West-wide CAT nor a West-wide rate standard is a stable coalition. In fact, the only stable policy, from a private surplus perspective, is a mixed policy where the Coastal region adopts a rate standard and the Inland region adopts a CAT. As we saw in Table 1, this stable policy (Scenario 7) has substantial efficiency costs.

Consumer surplus—the second panel of Table 2—also casts doubt on the prospects for a West-wide coalition. Since CAT regulation results in high electricity prices, both regions would have an incentive to unilaterally deviate from a West-wide CAT. If carbon prices were fixed, Result 2 suggests that rate standards would yield the highest consumer surplus. However, when carbon prices are endogenous, the simulations show a West-wide rate standard is not a stable policy, because Coastal consumers would have an incentive to unilaterally deviate by adopting a CAT. The only stable policy from the consumer's perspective, "CAT Rate" (Scenario 5) results in substantial emissions leakage, a zero carbon price, and substantial inefficiency.

Generator profits—the third panel of Table 2—is the only perspective in which West-wide coordination results in stable policies. However, this is somewhat deceptive in that generator incentives do not necessarily align. Appendix Table D13 shows that covered generator prefer rate standards and hence would have an incentive to unilaterally deviate from a West-wide CAT. Conversely, Appendix Table D14 shows that uncovered generators prefer CAT, so would have an incentive to unilaterally deviate from a West-wide rate standard.

Emissions—the final panel of Table 2—can be thought of as the environmental perspective. Alternatively, the normal form shows the substantial leakage that results under mixed regulation. With a West-wide CAT or rate standard, total emissions and emissions for each region are similar. However, if the Coastal region unilaterally switches to a rate standard, their emissions increase by almost 20 MMT. Since Inland emissions would remain capped, this increase in emissions is not offset, and aggregate emissions increase substantially. Leakage similarly results in a substantial increase in emissions (over 15 MMT) for the mixed regulation where the Inland region unilaterally adopts the rate standard (Scenario 5). This illustrates the leakage that results when a West-wide coalition fails to form.

D. Entry incentives

The treatment of newly constructed fossil power plants in state compliance plans affects adoption incentives and efficiency. Technically, Section 111d of the Clean Air Act covers only existing sources. New sources are regulated separately and will have to comply with a source-specific CO_2 emissions rate standard. Therefore, new natural gas capacity can safely be excluded from rate standard regulation under the CPP. However if states adopt CAT regulation, excluding new fossil generation may create substantial scope for leakage. Because of this concern, EPA is encouraging states who opt for CAT regulations to implement measures to limit leakage to new fossil generation.

Table 3 analyzes investment in combined-cycle natural gas and wind capacity under different regulatory policies toward new generation. The first row breaks out the new capacity results in Table 1 for Scenarios 1, 3, 5, and 7 by region. When new generation is included in the state compliance plans (as our main results assume), there is substantial investment in wind capacity

(9,000 to 17,000 MWs mostly Inland), but virtually no investment in natural gas (the 2,017 MW of natural gas that would have been constructed Inland in BAU is not constructed).

If new natural gas is excluded from a West-wide CAT regulation, Table 3 shows that over 9,000 MW of additional natural gas capacity is constructed, much of it occuring in the Coastal region. This additional natural gas capacity comes at the expense of wind capacity which is almost 10,000 MW lower. This huge, inefficient investment in natural gas capacity (over 10% of total capacity) illustrates the importance of including new capacity in a CAT regulation. In fact, we estimate that excluding new capacity leads to approximately 30 MMT (9%) more emissions relative to CAT where new capacity is included.

By assumption, excluding new capacity has no effect on the West-wide rate standard, but it can have substantial effects on mixed regulation. Excluding new capacity from the CPP has no effect when there is a Coastal CAT and Inland rate standard (Scenario 5), but this is because the CAT carbon price is zero in this scenario. In Scenario 7 (Coastal Rate & Inland CAT), excluding the new capacity results in substantial shifts in the location of the new natural gas capacity: about 1000 MW is constructed in the Inland CAT region but not in the Coastal region. However, overall investment is largely unaffected by the decisions to include or exclude new capacity from the CAT regulation. Thus the inefficiencies of mixed regulation seem to outweigh the leakage inefficiency from excluding new capacity under the CAT regulation. However, excluding new capacity from CAT regulation could substantially change investment patterns and potentially undermine the environmental effectiveness of the policy, especially the West-wide CAT.

V. Conclusion

There are many contexts in which environmental regulation and trade can interact to undermine the efficiency of both. The EPA's Clean Power Plan is a clear and timely example of these interactions. The CPP proposes major reductions in carbon emissions from generators of electricity, a good that is perfectly substitutable across neighboring states. The CPP establishes state-level targets for carbon emissions rates in lbs of carbon dioxide per megawatt hour of electricity generated. States have a great deal of flexibility in how to achieve these goals. Because this flexibility creates different incentives, effects on consumers and producers within a state could be quite different depending on the type of regulation adopted both in that particular state as well as in other states because electricity is traded regionally across state lines. Furthermore, the states' private incentives may be at odds with those of a social planner.

In this paper we have focused on the two likely market-based regulatory approaches that could be adopted by states, a mass-based (CAT) approach, and a rate standard. Our theoretical findings imply that efficiency is most likely achieved under CAT, and that a mix of CAT and rate standards is likely to create an inefficient "ordering" of generation resources. Further we find that, while consumers in each state may prefer to coordinate on rate standards, producers can prefer to coordinate on inconsistent regulations, where different states adopt different approaches.

We investigate the importance of our theoretical findings using numerical simulations of the electricity market in the Western United States. We find lack of coordination, when states independently pursue their own emissions targets without regard to electricity trading partners, leads to large inefficiencies. For example under state-specific caps, average abatement costs are 17% higher than under a West-wide CAT. Under state-specific rate standards, average abatement costs are 10% higher relative to a West-wide rate standard. Regional cooperation may not mitigate these concerns. When two regions of the West coordinate internally, but adopt different instruments, average abatement costs are between 5 and 21% higher than costs under a West-wide CAT. While generator incentives favor coordination, this may or may not lead to adoption of a West-wide CAT.

One unresolved aspect of the CPP is whether new natural gas generation is included under compliance plans when states adopt mass-based regulations. We examine the implications of the CPP on the construction of new natural gas and wind generation under a medium-term outlook where demand grows by 10% relative to 2007 levels. Whether new plants are covered under the CPP can dramatically change where new plants are built. When new plants are excluded from CPP compliance, new gas plants are built in place of new wind generation. Under mixed regulation, including new plants can shift new generation out of CAT regions toward rate regions.

Overall, our findings indicate that despite the *opportunities* the CPP provides for states to coordinate and implement compliance plans that can efficiently achieve their joint targets, the incentives of individual states to participate in those plans are conflicted. Indeed, there can easily be circumstances when states find it in their own interest to adopt a regulatory approach that is contrary to those of its neighbors.

REFERENCES

Borenstein, Severin. 2012. “The Redistributional Impact of Nonlinear Electricity Pricing.” *American Economic Journal: Economic Policy*, 4(3): 56–90.

Borenstein, Severin, and Stephen Holland. 2005. “On the Efficiency of Competitive Electricity Markets with Time-Invariant Retail Prices.” *RAND Journal of Economics*, 469–493.

Burtraw, Dallas, Karen L. Palmer, Sophie Pan, , and Anthony Paul. 2015. “A Proximate Mirror: Greenhouse Gas Rules and Strategic Behavior under the US Clean Air Act.” Resources for the Future.

Bushnell, James, and Yihsu Chen. 2012. “Allocation and leakage in regional cap-and-trade markets for CO2.” *Resources and Energy Economics*, 34(4): 647–668.

Bushnell, James B., Stephen P. Holland, Jonathan E. Hughes, and Christopher R. Knittel. 2015. “Strategic Policy Choice in State-Level Regulation: The EPA’s Clean Power Plan.” National Bureau of Economic Research Working Paper 21259.

Bushnell, James, Carla Peterman, and Catherine Wolfram. 2008. “Local Solutions to Global Problems: Climate Change Policies and Regulatory Jurisdiction.” *Review of Environmental Economics and Policy*, 2(2): 175–193.

Bushnell, James, Yihsu Chen, and Matthew Zaragoza-Watkins. 2014. “Downstream regulation of CO2 emissions in California’s electricity sector.” *Energy Policy*, 64: 313–323.

Chen, Yihsu. 2009. “Does a regional greenhouse gas policy make sense? A case study of carbon leakage and emissions spillover.” *Energy Economics*, 31(5): 667–675.

Fischer, Carolyn. 2001. “Rebating Environmental Policy Revenues: Output-based Allocations and Tradable Performance Standards.” *Resources for the Future Discussion Paper*, 01-22.

Fischer, Carolyn. 2003. “Combining rate-based and cap-and-trade emissions policies.” *Climate Policy*, 3(S2): S89–S103.

Fowlie, Meredith L. 2009. “Incomplete environmental regulation, imperfect competition, and emissions leakage.” *American Economic Journal: Economic Policy*, 1(2): 72–112.

Goulder, Lawrence H., Ian W.H. Parry, and Dallas Burtraw. 1997. “Revenue-Raising versus Other Approaches to Environmental Protection: The Critical Significance of Preexisting Tax Distortions.” *RAND Journal of Economics*, 28(4): 708–731.

Helfand, Gloria E. 1991. "Standards versus Standards: The Effects of Different Pollution Restrictions." *The American Economic Review*, 81(3): 622–634.

Holland, Stephen P. 2012. "Emissions taxes versus intensity standards: Second-best environmental policies with incomplete regulation." *Journal of Environmental Economics and Management*, 63(3): 375 – 387.

Holland, Stephen P., Jonathan E. Hughes, and Christopher R. Knittel. 2009. "Greenhouse Gas Reductions under Low Carbon Fuel Standards?" *American Economic Journal: Economic Policy*, 1(1): 106–46.

Huang, Haixiao, Madhu Khanna, Hayri Onal, and Xiaoguang Chen. 2013. "Stacking low carbon policies on the renewable fuels standard: Economic and greenhouse gas implications." *Energy Policy*, 56(0): 5 – 15.

Ito, Koichiro. 2014. "Do Consumers Respond to Marginal or Average Price? Evidence from Nonlinear Electricity Pricing." *American Economic Review*, 104(2): 537–63.

Kamerschen, David R, and David V Porter. 2004. "The demand for residential, industrial and total electricity, 1973–1998." *Energy Economics*, 26(1): 87–100.

Kwoka, John E., Jr. 1983. "The Limits of Market-Oriented Regulatory Techniques: The Case of Automotive Fuel Economy." *The Quarterly Journal of Economics*, 98(4): 695–704.

Newell, Richard G, William A. Pizer, and Daniel Raimi. 2012. "Carbon Markets: Past, Present, and Future." National Bureau of Economic Research.

Pizer, William A. 2005. "The case for intensity targets." *Climate Policy*, 5(4): 455–462.

Reiss, Peter C, and Matthew W White. 2005. "Household electricity demand, revisited." *The Review of Economic Studies*, 72(3): 853–883.

Stavins, Robert N. 2008. "Meaningful US Cap-and-Trade System to Address Climate Change, A." *Harv. Envtl. L. Rev.*, 32: 293.

Taylor, Lester D. 1975. "The demand for electricity: a survey." *The Bell Journal of Economics*, 74–110.

Zilberman, David, Gal Hochman, Deepak Rajagopal, Steve Sexton, and Govinda Timilsina. 2013. "The Impact of Biofuels on Commodity Food Prices: Assessment of Findings." *American Journal of Agricultural Economics*, 95(2): 275–281.

Tables

Table 1—: Equilibrium outcomes for business as usual and eight policy scenarios.

	0 No Reg	1 CAT	2 CATs	3 Rate	4 Rates	5 CAT Rate	6 CAT Rates	7 Rate CAT	8 Rates CAT
Electricity Price ($/MWh)	$ 41.83	$ 48.14	$ 47.43	$ 36.43	$ 36.05	$ 35.90	$ 35.67	$ 43.81	$ 43.79
Electricity Quantity (GWh)	787,472	-4,252	-3,972	+3,786	+3,975	+3,987	+4,107	-1,386	-1,417
New Natural Gas Gen. Cap. (MW)	2,017	-2,017	-214	-2,017	-2,017	-2,017	-2,017	+229	+1,045
New Wind Gen. Cap. (MW)	875	+14,984	+11,275	+17,191	+18,826	+16,950	+17,602	+9,043	+8,213
Emissions (MMT)	330.79	-74.34	-74.34	-78.27	-64.15	-64.75	-56.48	-55.34	-53.33
CAT Permit Price ($/MT)		$ 21.45	$ 20.21			$ 0.00	$ 0.00	$ 19.68	$ 19.60
Rate Permit Price ($/MT)				$ 21.80	$ 22.48	$ 20.90	$ 20.81	$ 9.22	$ 9.56
Consumer Surplus ($ bn.)	$ 44.41	- $4.96	- $4.39	+ $4.27	+ $4.44	+ $4.55	+ $4.74	- $1.38	- $1.40
Covered Generator Profits ($ bn.)	$ 7.12	- $3.83	- $4.31	- $3.79	- $3.82	- $3.80	- $3.84	- $3.99	- $3.99
Uncovered Generator Profits ($ bn.)	$ 13.90	+ $2.09	+ $1.90	- $1.81	- $1.94	- $1.95	- $2.06	+ $0.59	+ $0.62
Transmission Profits ($ bn.)	$ 0.18	+ $0.02	- $0.03	+ $0.01	+ $0.14	+ $0.10	+ $0.13	- $0.10	- $0.08
Generation Costs ($ bn.)	$ 11.91	+ $1.00	+ $1.23	+ $1.46	+ $1.34	+ $1.24	+ $1.19	+ $1.00	+ $0.99
Carbon Market Rev. ($ bn.)		+ $5.50	+ $5.44			+ $0.00	+ $0.00	+ $3.84	+ $3.83
Abatement Cost ($ bn.)		- $1.19	- $1.39	- $1.32	- $1.19	- $1.09	- $1.03	- $1.04	- $1.03
Avg. Abatement Cost ($/MT)		+ $15.98	+ $18.69	+ $16.88	+ $18.55	+ $16.84	+ $18.18	+ $18.74	+ $19.32
Carbon Damages ($ bn.)	$ 14.22	- $3.20	- $3.20	- $3.37	- $2.76	- $2.78	- $2.43	- $2.38	- $2.29
Social Welfare ($ bn.)	$51.39	+ $2.01	+ $1.81	+ $2.04	+ $1.57	+ $1.69	+ $1.40	+ $1.34	+ $1.26
No New Source Source Complements	$51.39	+ $2.14	+ $1.94	+ $2.04	+ $1.57	+ $1.69	+ $1.40	+ $1.42	+ $1.34

Notes: Results from Scenarios 1-8 are reported as changes relative to Scenario 0. “+” indicates an increase and “-” indicates a decrease. “Abatement Cost” is the sum of consumer surplus, profits (covered, uncovered, and transmission), and carbon market revenue. Consumer surplus calculated using a choke price of $100/MWh. Carbon damages assume a social cost of carbon equal to $43.

Table 2—: Adoption incentives in the Coastal and Inland west.

Private surplus

		Inland	
		CAT	Rate
Coastal	CAT	- $0.70 , - $0.51	+ $0.50 , - $1.70
	Rate	- $0.20 , - $0.75	+ $0.71 , - $2.04

Generator profits

		Inland	
		CAT	Rate
Coastal	CAT	+ $0.97 , - $2.72	- $2.18 , - $3.56
	Rate	+ $0.40 , - $3.80	- $1.91 , - $3.70

Consumer surplus

		Inland	
		CAT	Rate
Coastal	CAT	- $2.97 , - $1.99	+ $2.69 , + $1.86
	Rate	- $0.60 , - $0.78	+ $2.62 , + $1.66

Emissions

		Inland	
		CAT	Rate
Coastal	CAT	- 6.91 , - 67.43	- 13.69 , - 51.06
	Rate	+ 12.75 , - 68.09	- 6.87 , - 71.40

Notes: "Private surplus" is the sum of consumer surplus, generator profits (covered and uncovered), and carbon market revenue and is measured in $ billion. Private surplus in Table 1 is the sum of regional private surplus and transmission profits. The figures above exclude transmission profits. Generator profits (covered and uncovered) and consumer surplus are measured in in $ billion. Emissions are measured in million metric tons (MMT). All values are measured relative to business as usual (Scenario 0). "+" indicates an increase and "-" indicates a decrease. Consumer surplus calculated using a choke price of $100/MWh.

Table 3—: New capacity under four policy scenarios when new natural gas combined cycle investment is included and *not* included under mass-based regulation.

New Capacity (MW)	1 - CAT (Mass-Based)			3 - Rate Standard			5 - Coast CAT & Inland Rate			7 - Coast Rate & Inland CAT		
	Coast	Inland	Total	Coast	Inland	Total	Coast	Inland	Total	Coast	Inland	Total
Included												
Natural Gas	+0	-2,017	-2,017	+0	-2,017	-2,017	+0	-2,017	-2,017	+2,245	-2,017	+229
Wind	+0	+14,984	+14,984	+1,239	+15,952	+17,191	+0	+16,950	+16,950	+4,130	+4,913	+9,043
Excluded												
Natural Gas	+5,003	+2,094	+7,097	+0	-2,017	-2,017	+0	-2,017	-2,017	+1,643	-1,093	+550
Wind	+0	+4,430	+4,430	+1,241	+15,952	+17,193	+0	+16,950	+16,950	+4,147	+5,368	+9,515

Note: Results are reported as changes relative to new capacity built under business as usual. ``+" indicates an increase and ``-" indicates a decrease. ``Included" means emissions from new generation are regulated under a mass-based cap. ``Excluded" means emissions from new generation are unregulated. Scenarios assume 10% load growth from 2006 levels.

Figures

Figure 1. : Full marginal costs under different regulatory regimes.

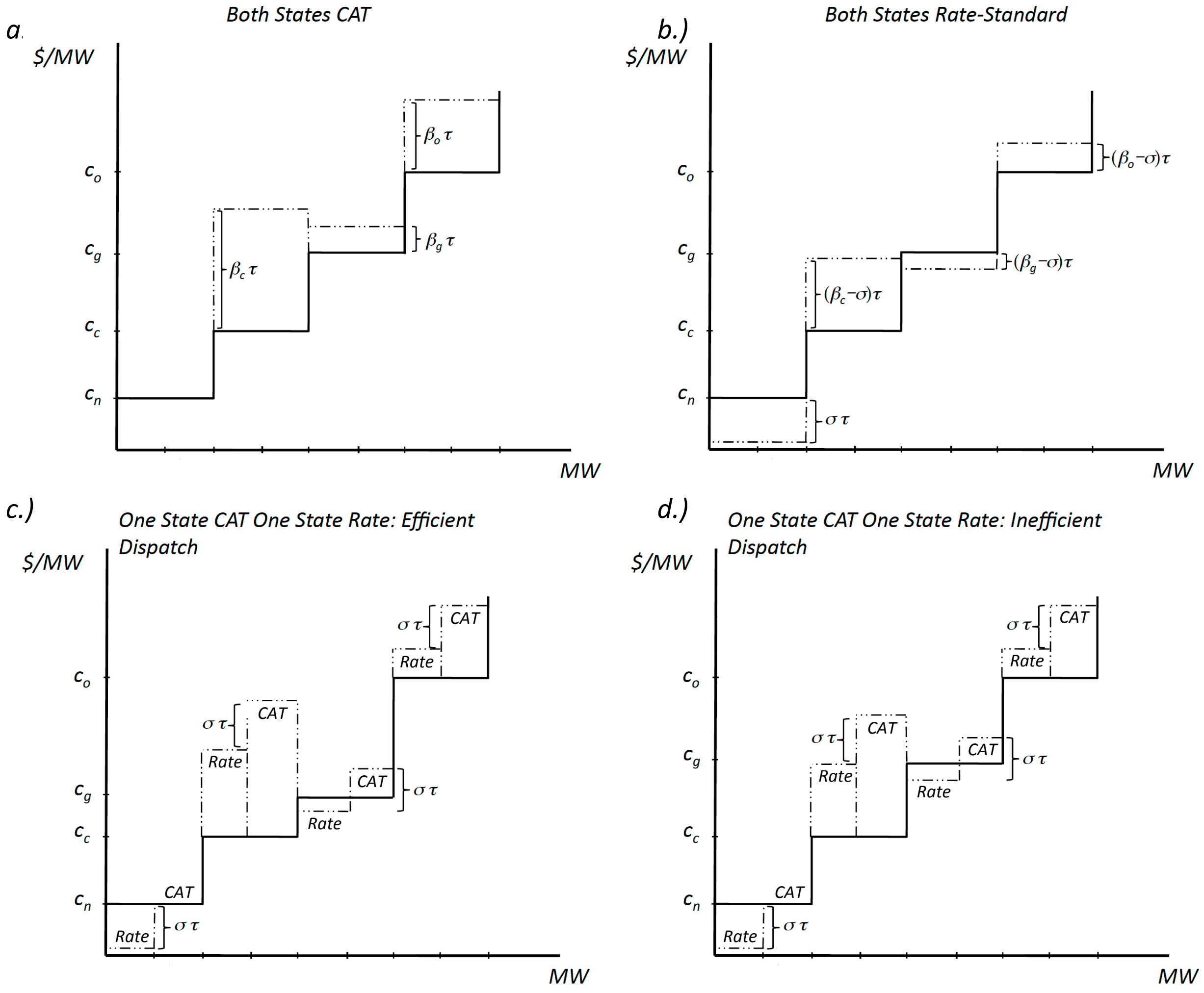
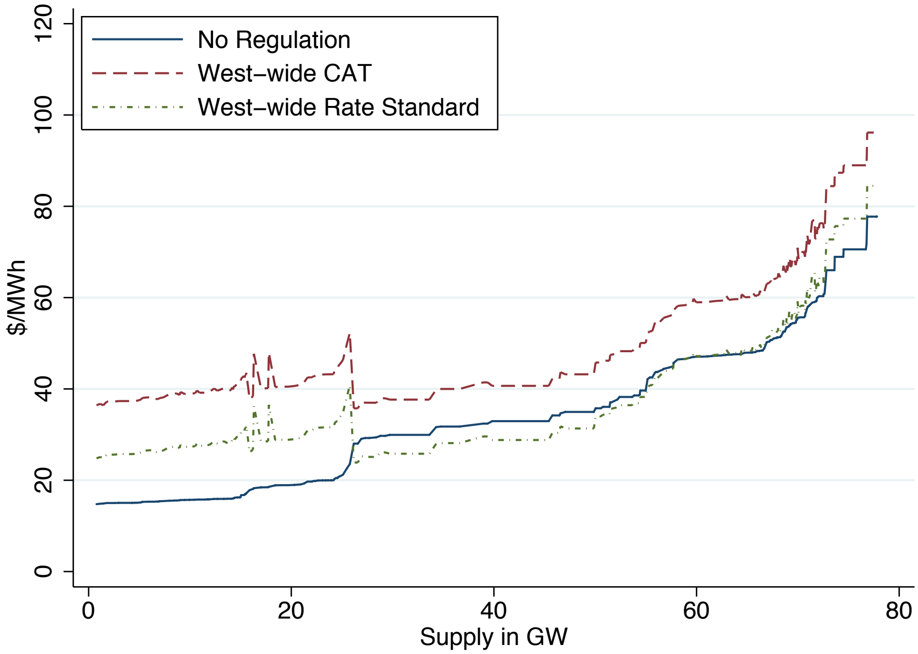
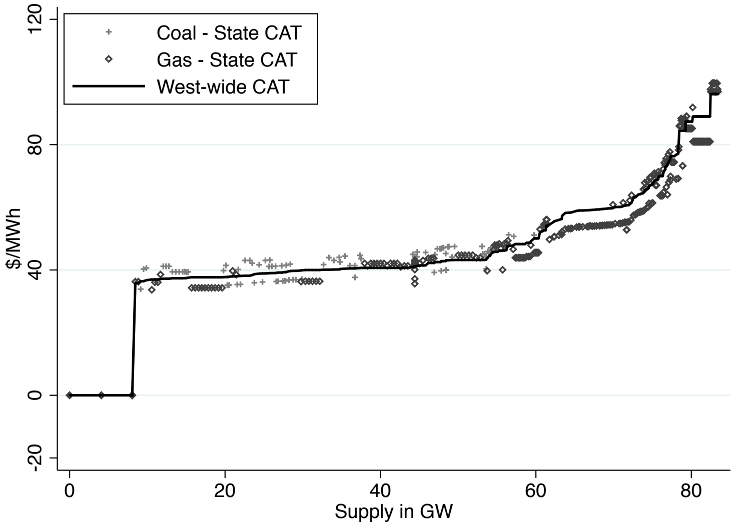


Figure 2. : Full marginal costs: BAU and West-wide CAT and rate standards.



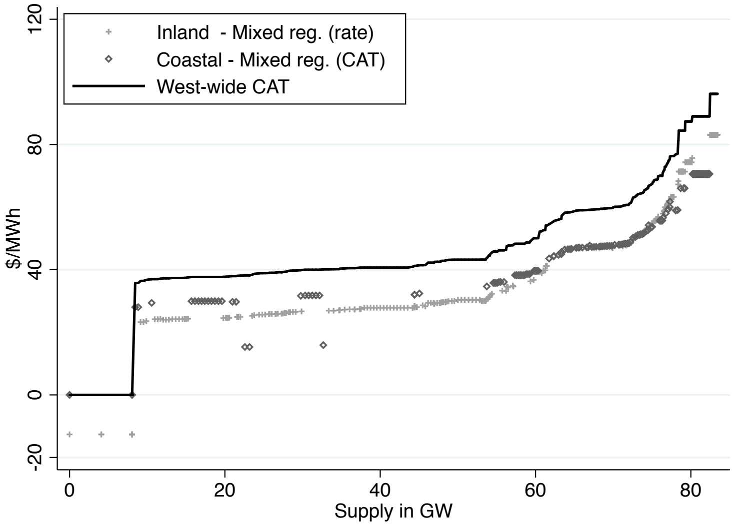
Note: Generating units sorted on x-axis by marginal costs under BAU (Scenario 0).

Figure 3. : Full marginal costs: West-wide CAT standards and state-by-state CAT standards.



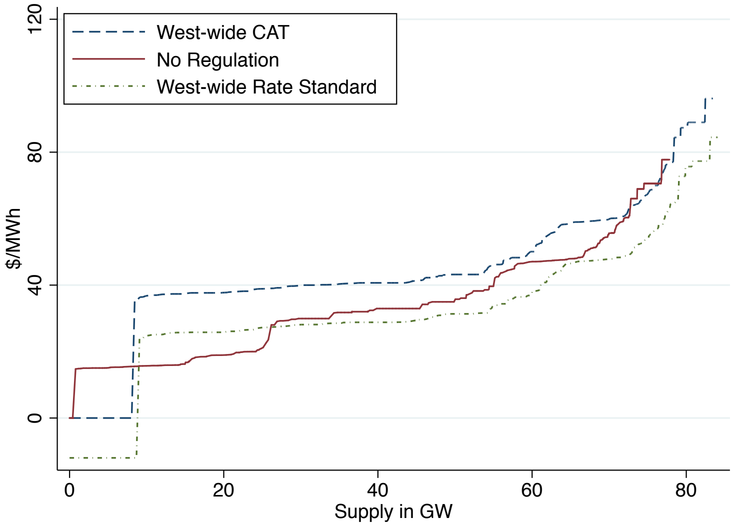
Note: Generating units sorted on x-axis by full-marginal costs under West-wide CAT standards (Scenario 1).

Figure 4. : Full marginal costs: West-wide CAT standards and mixed regulation.



Note: Generating units sorted on x-axis by full-marginal costs under West-wide CAT standards (Scenario 1). Mixed regulation has Coastal CAT standard and Inland rate standard.

Figure 5. : Market supply with new investment: West-wide CAT standards and West-wide rate standards.



Note: Generating units sorted on x-axis by full-marginal costs under each policy: CAT; no regulation; or rate standard.

Supplementary Appendices for Web Publication

Proofs of Results

A1. Proof of Result 1

The merit order is efficient for regulation r if $FMC^{r}_{si} < FMC^{r}_{s'i'}$ iff $c_i + \beta_i\tau < c_{i'} + \beta_{i'}\tau$.

Result 1 (i) follows because for CATs $FMC^{CAT}_{si} = c_i + \beta_i p_{cs}$. Clearly this merit order is efficient if $p_{cs} = \tau$ for every s. The result also holds if $p_{cs} \neq \tau$ and $|p_{cs} - \tau| \leq \min_{i,j}|\frac{c_i - c_j}{\beta_j - \beta_i} - \tau|$, i.e., if p_{cs} is sufficiently close to τ.

To see this, assume, without loss of generality, that $\beta_j > \beta_i$. First consider the case in which $c_i + \beta_i\tau < c_j + \beta_j\tau$, i.e., in which $\tau - \frac{c_i - c_j}{\beta_j - \beta_i} > 0$. Then $c_i + \beta_i p_{cs} < c_j + \beta_j p_{cs}$ iff $\frac{c_i - c_j}{\beta_j - \beta_i} < p_{cs}$ iff $\tau - \frac{c_i - c_j}{\beta_j - \beta_i} > \tau - p_{cs}$. But this last condition clearly holds because p_{cs} is sufficiently close to τ.

Next consider the case in which $c_i + \beta_i\tau > c_j + \beta_j\tau$, i.e., in which $\frac{c_i - c_j}{\beta_j - \beta_i} - \tau > 0$. Then $c_i + \beta_i p_{cs} > c_j + \beta_j p_{cs}$ iff $\frac{c_i - c_j}{\beta_j - \beta_i} > p_{cs}$ iff $\frac{c_i - c_j}{\beta_j - \beta_i} - \tau > p_{cs} - \tau$. But this last condition clearly holds because p_{cs} is sufficiently close to τ.

Result 1 (ii) follows because for rate standards $FMC^{RS}_{si} = c_i + (\beta_i - \sigma_s)p_{cs}$. If the carbon price is τ and rate standard is σ in all states, $FMC^{RS}_{si} < FMC^{RS}_{s'i'}$ iff $c_i + (\beta_i - \sigma)\tau < c_{i'} + (\beta_{i'} - \sigma)\tau$ iff $c_i + \beta_i\tau < c_{i'} + \beta_{i'}\tau$. Clearly, this result can still hold if p_{cs} is sufficiently close to τ and σ_s is sufficiently close to σ for every s.

To demonstrate Result 1 (iii), assume without loss of generality that $c_i + \beta_i\tau < c_{i'} + \beta_{i'}\tau$ so that the sufficient condition is $c_{i'} + \beta_{i'}\tau - c_i + \beta_i\tau > \sigma\tau$. First, let state s have a rate standard and state s' have a CAT. Then $FMC^{RS}_{si} = c_i + (\beta_i - \sigma)\tau < c_i + \beta_i\tau < c_{i'} + \beta_{i'}\tau = FMC^{CAT}_{s'i'}$, i.e., the merit order is efficient. Next, let state s have a rate standard and state s' have a CAT. Then $FMC^{CAT}_{si} = c_i + \beta_i\tau < c_{i'} + (\beta_{i'} - \sigma_{s'})\tau = FMC^{RS}_{s'i'}$ where the inequality follows from the sufficient condition.

Proof of Corollary 1

If demand is perfectly inelastic, then consumption cannot be inefficient, and efficiency of the regulation merely requires efficiency of supply.

If demand is not perfectly inelastic, then consumption is only efficient if the electriciy price reflects the full marginal social cost. The only regulation in which the electricity price equals the full marginal social cost is a CAT with carbon price τ.

A2. Proof of Result 2

Carbon trading reduces costs since firms would only undertake mutually beneficial trades if costs are reduced.

Trading between states with CATs holds aggregate emissions constant because the equilibrium in the carbon market is determined by $\sum_t\sum_i \beta_i q^{CAT}_{sit} + \sum_t\sum_i \beta_i q^{CAT}_{s'it} = E_s + E_{s'}$. which holds aggregate emissions constant at $E_s + E_{s'}$.

Trading between states with rate standards may cause aggregate emissions to increase or decrease. Setting demand minus supply equal to zero, we can characterize the carbon market equilibrium by $\sum_i\sum_t(\beta_i - \sigma_s)q^{RS}_{sit} + \sum_i\sum_t(\beta_i - \sigma_{s'})q^{RS}_{s'it} = 0$. This equilibrium condition can be written:

$$\frac{\sum_i\sum_t \beta_i(q^{RS}_{sit} + q^{RS}_{s'it})}{\sum_i\sum_t(q^{RS}_{sit} + q^{RS}_{s'it})} = \frac{\sum_i\sum_t q^{RS}_{sit}}{\sum_i\sum_t(q^{RS}_{sit} + q^{RS}_{s'it})}\sigma_s + \frac{\sum_i\sum_t q^{RS}_{s'it}}{\sum_i\sum_t(q^{RS}_{sit} + q^{RS}_{s'it})}\sigma_{s'}, \tag{A1}$$

This shows that carbon trading across states with rate standards results in a carbon intensity which is a weighted average of the intensity standards of the two states. Rewriting Eq. A1, shows that

$$\sum_i \sum_t \beta_i (q_{sit}^{RS} + q_{s'it}^{RS}) = \sum_i \sum_t q_{sit}^{RS} \sigma_s + \sum_i \sum_t q_{s'it}^{RS} \sigma_{s'}.$$

Defining policies RST and $RSNT$ as "trading" and "no trading" and defining $Q_s^r \equiv \sum_i \sum_t q_{sit}^r$, this equation implies:

$$Carbon_s^{RST} + Carbon_{s'}^{RST} = Q_s^{RST} \sigma_s + Q_{s'}^{RST} \sigma_{s'}$$

which can be rewritten as

$$Carbon_s^{RST} + Carbon_{s'}^{RST} = \frac{Q_s^{RST}}{Q_s^{RSNT}} Carbon_s^{RSNT} + \frac{Q_{s'}^{RST}}{Q_{s'}^{RSNT}} Carbon_{s'}^{RSNT}.$$

This equation relates carbon emissions with trading to carbon emissions without trading and shows that carbon trading has an ambiguous affect on aggregate carbon emissions.

A3. Proof of Result 3

Result 3 (*i*) follows from a comparison of the full marginal costs. Under CATs, $FMC_{si}^{CAT} = c_i + \beta_i p_{cs}$. Since $FMC_{si}^{CAT} \geq c_i = FMC_{si}^{BAU}$ for every s and i the electriciy price is higher under CATs than under no regulation.

Since $FMC_{si}^{RS} = c_i + (\beta_i - \sigma_s) p_{cs}$, it follows that $FMC_{si}^{RS} \leq FMC_{si}^{CAT}$ for every s and i and thus the electricity price is lower under rate standards than under CATs.

Moreover, since $(\beta_i - \sigma_s)$ can be positive or negative, it follows that the electricity price under rate standards can be higher or lower than under no regulation.

Result 3 (*ii*) follows directly from the comparison of electricity prices in Result 3 (*i*) because higher electricity prices result in lower consumer surplus from electricity consumption.

Result 3 (*iii*) also follows directly from the comparison of electricity prices in Result 3 (*i*). For an uncovered generator, their costs are unaffected by the regulations. Thus regulations only affect their profit through the electricity prices and higher electricity prices imply higher profit.

A4. Proof of Result 4

Result 4 (*i*) follows by comparing full marginal costs under CAT and rate standards. Because full marginal costs are $c_i + \beta_i \tau$ under CAT but are $c_i + (\beta_i - \sigma)\tau$ under a rate standard, the merit order is identical under CAT or rate standards but the full marginal cost is lower by $\sigma\tau$ for every s and i. Because full marginal costs are lower by $\sigma\tau$ under rate standards, prices are also lower by exactly this amount if demand is perfectly inelastic. If demand is not perfectly inelastic, then a price which is lower by $\sigma\tau$ could result in excess demand. Thus the price difference is at most $\sigma\tau$.

Result 4 (*ii*). Suppose not, i.e., suppose $q_{sit}^{CAT} > q_{sit}^{RS}$ for some s, i, and t. First consider the case where $p_t^{CAT} > c_i + \beta_i \tau$. In this case, generator i is dispatched at capacity under CAT, so it must not be dispatched at capacity under the rate standard, which implies $p_t^{RS} \leq c_i + (\beta_i - \sigma)\tau$. But this implies that $p_t^{CAT} - p_t^{RS} > c_i + \beta_i \tau - (c_i + (\beta_i - \sigma)\tau = \sigma\tau$ which contradicts the result in (*i*). In the case where $p_t^{CAT} < c_i + \beta_i \tau$, $q_{sit}^{CAT} = 0$ which contradicts the supposition. Finally if $p_t^{CAT} = c_i + \beta_i \tau$, the result in (*i*) implies that $p_t^{RS} + \sigma\tau \geq p_t^{CAT} = c_i + \beta_i \tau$, which implies that $p_t^{RS} \geq c_i + (\beta_i - \sigma)\tau$. If this inequality is strict, then the generator is dispatched at capacity, which contradicts the suppostion. Alternatively, if this is an equality, then both conditions hold with equality, i.e., price equals full marginal cost under both the CAT and the rate standard. Because $p_t^{RS} < p_t^{CAT}$ and by the assumption of proportional generation when price equals full marginal cost, we have $q_{sit}^{RS} > q_{sit}^{CAT}$ which contradicts the supposition.

With perfectly inelastic demand, $p_t^{CAT} = p_t^{RS} + \sigma\tau$ so $p_t^{CAT} > c_i + \beta_i\tau$ iff $p_t^{RS} > c_i + (\beta_i - \sigma)\tau$. Thus $q_{sit}^{CAT} = q_{sit}^{RS}$.

Result 4 (*iii*) follows by noting that $\pi_{si}^{CAT} = \sum_t (p_t^{CAT} - c_i - \beta_i\tau)q_{sit}^{CAT} \leq \sum_t (p_t^{RS} + \sigma\tau - c_i - \beta_i\tau)q_{sit}^{RS} = \pi_{si}^{RS}$.

Result 4 (*iv*) is a direct corollary of Result 1.

Result 4 (*v*) follows directly from Result 4 (*iv*) since $W^{CAT} = CS^{CAT} + \pi^{CAT} + TR^{CAT} - \tau Carbon^{CAT}$ and $W^{RS} = CS^{RS} + \pi^{RS} - \tau Carbon^{RS}$.

A5. Result 5: Adoption Incentives of a State

In this appendix, we address the adoption incentives of individual states. In particular, we state, discuss, and prove a result which is similar to Result 4, but focuses on a single state (or region) rather than the coalition of all states. As in Result 4, we assume here that carbon prices are independent of the adoption choices of states. While carbon prices may be independent of the choice of the coalition of states, they are unlikely to be independent of the choice of an individual state. Thus, this result provides only a partial analysis of the adoption incentives of individual states.

RESULT 5: **Adoption Incentives of a State:** *Consider two scenarios of mixed regulation. In one scenario, RSx, state s has a rate standard, and in the other scenario, CATx, state s has a CAT. Regulation of each other state is unchanged across the scenarios, and carbon prices equal τ in all scenarios.*

(i) $p_t^{CATx} \geq p_t^{RSx} \geq p_t^{CATx} - \sigma_s\tau$ *for every t*

(ii) $\pi_{is}^{CATx} \leq \pi_{is}^{RSx}$ *for every i*

(iii) $CS^{CATx} \leq CS^{RSx}$.

(iv) $TR_s^{CATx} > TR_s^{RSx} = 0$.

(v) $CS_s^{CATx} + TR_s^{CATx} + \sum_i \pi_{is}^{CATx}$ *can be greater or less than* $CS_s^{RSx} + \sum_i \pi_{is}^{RSx}$

This result shows the strong incentives for a state to adopt an inefficient rate standard. Under these assumptions, a rate standard is a dominant strategy from the perspective both of consumers and of covered generators' profits. In other words, both consumers and covered generators are better off if their state adopts a rate standard no matter what other states are doing.

Intuitively, adoption of a rate standard causes electricity prices to fall, which benefits consumers. However, prices fall by at most $\sigma_s\tau$ as shown in Result 5 (*i*). But because costs fall by $\sigma_s\tau$, covered generator profits increase.

This result implies that adopting a rate standard is a dominant strategy from the perspective of profit to the regulated generators, because profits are higher no matter what policies the other states adopt. Importantly, if the coalition of states were to adopt a CAT, generators in any single state would have an incentive to lobby for adoption of a rate standard in their own state. Moreover, there remains an incentive for generators to lobby for adoption of a rate standard in their own state no matter how many other states adopt rate standards. In fact, the only outcome, which is stable from the perspective of generator profits, is the coalition in which all states adopt rate standards.

Result 5 (*i*) also implies that adoption of a rate standard in state *s* decreases generator profits in other states. This follows since the electricity price falls, which decreases margins. Since the merit order can also change, generators in other states may also generate less, so profits decrease. This implies that defection by state s from the coalition in which all states adopt CATs *increases* the incentive for other states to also defect from the coalition.

Result 5 (*iii*) shows that consumers are better off under rate standards. Our assumption that each state accounts for a constant share of consumer surplus implies that consumers in each state have an incentive to lobby for adoption of rate standards in their state and in other states as well. In fact, because we assume that carbon market revenue benefits consumers within a state, this result implies that consumers have a stronger incentive to lobby for *other* states to adopt rate standards.

Despite the strong incentive to adopt rate standards from the perspective of both consumers and generators, there is an efficiency cost to rate standards. Result 5 (*iv*) and (*v*) show that states may or may not have sufficient carbon market revenue to compensate consumers and generators such that everyone prefers CATs. The result is weaker than Result 4 (*vii*) which showed that compensation might require monetizing carbon damages. Here since welfare may increase when a single state adopts a rate standard, it may not be efficient (or desirable!) to compensate consumers and generators so that they would be willing to support a CAT.[34]

Result 5 (*v*) shows that there may or may not be sufficient carbon market revenue to compensate consumers and generators so that adoption of a CAT is preferred. Since theory is indeterminate, we will return to this question in our simulations analysis.

Proof:

Result 5 (*i*) follows from noting that if state s adopts a rate standard, the full marginal costs of all generators in state s decrease by $\sigma_s \tau$, but the full marginal costs of generators in other states are unchanged. Thus the electricity price in hour t falls by $\sigma_s \tau$ if a generator in state s is marginal in that hour under both the CAT and the rate standard, i.e., $p_t^{RSx} = p_t^{CATx} - \sigma_s \tau$. Alternatively if a generator from state s is not on the margin in hour t, the price is unchanged, i.e., $p_t^{CATx} = p_t^{RSx}$. Finally, for all other situations (e.g., if a generator in state s goes from being marginal to non-marginal) the electricity price falls by at most $\sigma_s \tau$.

Result 5 (*ii*) follows directly from (*i*). If state s switches to a rate standard, the full marginal costs of generators in state s fall by $\sigma\tau$, but the price falls by at most $\sigma\tau$, so margins increase. Since generation does not decrease profits increase.

Result 5 (*iii*) follows directly from (*i*), because electriciy prices are lower if state s switches to a rate standard.

Result 5 (*iv*) follows since carbon market revenue is positive under a CAT but is zero under a rate standard.

Result 5 (*v*) follows because welfare can increase or decrease with one state switching from a CAT to a rate standard. The results in Table **??** show that welfare can increase with adoption of a rate standard, which implies that $CS_s^{CATx} + TR_s^{CATx} + \sum_i \pi_{is}^{CATx} < CS_s^{RSx} + \sum_i \pi_{is}^{RSx}$. The other inequality holds if welfare decreases.[35]

The four technology model

In this appendix, we illustrate the general model in Section II with four technologies. The stronger assumptions allow us to draw sharper contrasts between the policies. The advantage of this approach is that we obtain simple expressions for prices, costs, profits and welfare, which we use to analyze incentives for adopting the different policies.

The model has four generating technologies, two states (A and B), and eight hours. Demand for electricity is perfectly inelastic and is 1, 2, 3, 4, 5, 6, 7 or 8 MWhs in the corresponding hours

---

[34] To illustrate, suppose there are two states and perfectly inelastic demand and the full marginal social costs are sufficiently close. Then adoption of a rate standard by one state would decrease efficiency (since the merit order would be inefficient) but adoption by the second state would *increase* efficiency (since the merit order would then be efficient.

[35] This result could be stated more precisely.

1 through 8. Thus, the total electricity consumption in the model is 36 MWhs. Assume that the consumers are distributed equally between the two states. Further, assume no transmission constraints so that electricity flows freely between the two states, and there is a single price of electricity for each hour.

Assume there are eight MWs of competitively supplied generation with two MWs of each technology one of which is located in each state. The four technologies are N, C, G, and O (nuclear (or renewables), coal, gas, and oil) with $c_N < c_C < c_G < c_O$. This supply curve (merit order) is illustrated in Appendix Figure E2. Assume further that the carbon emissions rates are $0 = \beta_N < \beta_G < \beta_C < \beta_O$. Thus coal is dirtier than gas but has lower marginal generation costs. We assume further that $c_G + \beta_G\tau < c_C + \beta_C\tau$ so that the marginal social cost (generation cost plus carbon damages) of gas-fired generation is less than that of coal, i.e., gas should be dispatched before coal. However, in the unregulated model, the coal-fired generation will be dispatched first since $c_C < c_G$.

Because demand is perfectly inelastic, efficiency in the model is determined solely by the generation costs and carbon costs. To determine consumer benefits, we focus on the electricity bill since the total electricity consumed is identical under all policies. To determine producer benefits and the incentive to invest in additional generation capacity, we focus on generator profits per MW of capacity.

To study the incentives to adopt a CAT or a rate standard, we analyze three separate scenarios: both states adopt CATs, both states adopt rate standards, and mixed regulation in which one state adopts a CAT and the other state adopts a rate standard. Throughout, we assume that the standards are set such that the carbon price equals the social cost of carbon (τ), so that there are no additional inefficiencies from incorrect carbon pricing. For purposes of comparison, we also present results for the unregulated equilibrium. The full marginal costs are presented in Figure 1, panels a-d.

The electricity prices in each scenario are determined by the intersection of the supply curve and the (perfectly inelastic) demand in each hour as in Eq. 1. Table D1 shows these electricity prices as electricity consumption increases from one to eight MWs. With the first three scenarios the merit order is efficient, so dispatch is identical across the three scenarios. However, the full marginal cost of the marginal generator is different across the scenarios, and hence prices are different. If both states adopt rate standards, the full marginal costs are $\sigma\tau$ lower than the full marginal costs under CATs, and the price is lower by $\sigma\tau$ in each hour. With mixed regulation and efficient dispatch, the full marginal costs of the marginal generator (and hence electricity prices) are reduced in four hours by $\sigma\tau$ relative to the CAT prices.[36] With mixed regulation and *inefficient* dispatch, the prices when consumption is four or five MWs are switched relative to the efficient dispatch since coal under the rate standard is dispatched before gas under the CAT.

The generation costs, carbon emissions, electricity bills and carbon tax revenue under the four scenarios are shown in Table D2. Since dispatch is efficient in the first three scenarios, the generation costs and carbon emissions are identical across these three scenarios. In the mixed regulation scenario with inefficient dispatch, coal under the rate standard is dispatched before gas under the rate standard. Thus one MW of coal is dispatched instead of one MW of gas when demand is four MW.[37] This lowers the generation costs by $c_G - c_C$, but increases the carbon emissions by $\beta_C - \beta_G$, which is inefficient.

We can compare the electricity bills across the scenarios, by looking at the prices in Table D1. Comparing the rate standards with the CATs, we see that under the rate standards each of the 36 MWhs is purchased at a price which is lower by $\sigma\tau$. Because $\sigma = Carbon^{CAT}/36$, the electricity bill

---

[36] Alternatively, the prices are *increased* in four hours by $\sigma\tau$ relative to the rate standard prices.

[37] Generation is efficident in all other hours.

is reduced by exactly the amount of carbon tax revenue which could have been collected under the CAT. Similarly, comparing the prices for the scernario with mixed regulation and efficient dispatch with the CATs, we see lower prices in four hours which implies an electricity bill that is lower by $16\sigma_B\tau$. Finally comparing the prices for the scenario with mixed regulation and inefficient dispatch with the CATs, we see lower prices in three hours and a different price when consumption is four and five MWhs. Thus the bill is reduced by $15\sigma_{B'}\tau - c_G - \beta_G\tau + c_C + \beta_C\tau$.[38]

Table D2 also shows the carbon tax revenue generated under the scenarios. A CAT generates carbon market revenue (e.g., through auctioning carbon permits) which the political process can distribute as it sees fit. This revenue can be used to compensate consumers or generators who may be harmed by the regulation, e.g., to make a potential Pareto improvement an actual Pareto improvement. A rate standard generates no carbon revenue for the political process to distribute because carbon permits are created by generating electricity below the allowed level and hence accrue to the generators. Under mixed regulation, the state with a CAT has carbon market revenue, but the state with rate standard has no carbon market revenue.[39]

Table D3 shows the profits per MW of capacity to each technology under the four scenarios. Under CATs, oil is never inframarginal hence profits are zero. Coal is marginal in two hours and inframarginal in two hours, so profits are greater than zero. Similarly, gas is inframarginal in four hours and nuclear is inframarginal in six hours. Thus $\pi_N > \pi_G > \pi_C > \pi_O = 0$.

Note that technologies can earn higher, lower, or the same profits under a CAT relative to no regulation. This follows since costs are higher (costs now include carbon costs) but electricity prices are also higher (the marginal generator must cover their full marginal costs). For example, nuclear profits are clearly higher since $\beta_N = 0$ implies they have no carbon costs but benefit from the higher electricity prices. On the other hand, oil profits are unchanged at zero. Coal profits could increase or decrease. The difference is coal profits is given by: $\pi^{CAT}_{sC} - \pi^{E}_{sC} = 2[(\beta_O - \beta_C)\tau - (c_G - c_C)]$. The first term in this difference reflects the higher electricity price when oil is on the margin and is positive because $\beta_O > \beta_C$, i.e., the CAT increases the carbon costs of oil more than of coal. The second term in this difference is negative and reflects the lost margin that coal would have earned by being dispatched before gas in the absence of carbon regulation. Finally, gas profits increase under CATs, because gas is dispatched more and because its carbon costs are less than the electricity price increases when coal or oil is marginal.

Comparing generator profits under rate standards and under CATs, we see that the dispatch is identical and that although the price in each hour is lower by $\sigma_s\tau$, the full marginal costs are also lower by $\sigma_s\tau$. Thus profit is identical under both scenarios.

Generator profits under mixed regulation (columns four and five of Table D3) depend on the state. Assume that state A adopts a CAT but state B adopts a rate standard. Within a technology the generation in state B always has a lower full marginal cost and hence is dispatched first and earns higher profits. For example, oil in state A earns zero profit, but oil in state B is inframarginal in one hour and hence earns positive profit equal to $\sigma_B\tau$.

Under efficient dispatch, generator profits can be directly compared to profits under a CAT or a rate standard. In state A, each technology is inframarginal in exactly the same hours as under CATs. However, the electricity price is lower by $\sigma_B\tau$ whenever a rate standard technology is marginal. Thus coal, gas and nuclear lose $\sigma_B\tau$, $2\sigma_B\tau$, and $3\sigma_B\tau$ in profits relative to the CAT scenario. In state B, each technology is inframarginal in one additional hour relative to the scenario with rate standards. In addition, the electricity price is higher by $\sigma_B\tau$ whenever a CAT technology is marginal. Thus oil, coal, gas and nuclear gain $\sigma_B\tau$, $2\sigma_B\tau$, $3\sigma_B\tau$, and $4\sigma_B\tau$ in profits relative to

---

[38] The allowed emissions rate varies across the policies, but are set consistently such that the price of carbon (i.e., the shadow value of the constraint) is τ.

[39] The carbon tax revenue is slightly larger in the scenario with efficient dispatch since carbon emissions in the CAT state are higher.

the rate standard scenario (which is equivalent to the CAT scenario).

With inefficient dispatch, the profits of coal in state B and gas in state A are additionally affected. Relative to the scenario with efficient dispatch, coal in state B is dispatched in an additional hour and earns the additional margin $c_G + \beta_G\tau - (c_C + (\beta_C - \sigma_{B'})\tau$. Gas generation is dispatched in one fewer hour, so it loses the margin $c_C + (\beta_C - \sigma_{B'})\tau - c_G - \beta_G\tau$ relative to the scenario with efficient dispatch.

We can now analyze the incentives for adoption of a CAT or a rate standard. We begin with the adoption incentives from the perspective of social surplus including carbon emissions. The social surplus to each state is the sum of the state's generator profits and any tax revene less half the electricity bill and half the carbon damages. The distribution of social surplus for the three scenarios is shown in Table D4 for the efficient dispatch scenario and in Table D5 for inefficient dispatch. For efficient dispatch, our assumption of inelastic demand implies that all three scenarios yield the same total social surplus: $2W_s$. However, the distribution of the surplus across the states leads to different incentives for the states. For the scenarios in which both states adopt CATs or rate standards, the total surplus is simply split equally between the two states. However if one state adopts a rate standard when the other state adopts a CAT, then the state with the rate standard gains the additional surplus $(\frac{4}{5}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2$ which is positive. Thus if a state thinks another state will adopt a CAT, then it has an incentive to adopt a rate standard to gain the additional surplus. Note that this additional surplus is zero sum (i.e., a pure transfer between the states). This implies that if a state thinks another state will adopt a *rate standard*, then it has an incentive to also adopt a rate standard (to avoid losing the additional surplus). Thus each state has an incentive to adopt a rate standard no matter what the other state is adopting, i.e., adopting a rate standard is a dominant strategy.[40]

With inefficient dispatch, the incentives, shown in Table D5, are similar. Now, in addition to the distributional effect $(\frac{16}{21}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2$ which is again positive there is an efficiency effect $-(c_C + \beta_C\tau - c_G - \beta_G\tau)/2$ which is clearly negative. Thus the game is no longer zero sum, and total social surplus is lower in the scenario with mixed regulation. $(\frac{16}{21}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2 - (c_C + \beta_C\tau - c_G - \beta_G\tau)/2 > 0$ because the efficiency effect must be small under inefficient dispatch. This implies that as above each state has an incentive to adopt a rate standard no matter what the other state is adopting, i.e., adopting a rate standard is a dominant strategy.

The story is quite similar from the perspective of generator profit as shown in Tables D6 and D7. Again adopting a rate standard is better from a generator's perspective no matter what the other state adopts, i.e., a rate standard is a dominant strategy.[41] Thus we could expect generators to lobby for rate standards within their state.

The fact that the distributional effect is not zero sum for the generators adds an interesting twist. Because total generator profit is highest under mixed regulation, if a firm derived profit from generation in both states it might have an incentive to lobby for a CAT in one state and a rate standard in the other state. Alternatively, a firm in one state might offer side payments to a firm in another state. Since the distributional effect is not zero sum, profits are sufficient that one generator could sufficiently compensate the other for any lost profits.

From a consumer's perspective, as illustrated in Table D2, the electricity bills are clearly lowest under a rate standard. However, from the perspective of tax revenue, a CAT is clearly preferred, since the rate standard raises no revenue. This tax revenue is very valuable since it could be used strategically to alter support for the policies. For example, if the tax revenue were given to the firms (for example, through a cap and trade program with free allocation of permits) then the

---

[40] This implies that the game has a unique Nash equilibrium in which both states adopt rate standards.

[41] This holds even with inefficient dispatch since the efficiency effect is small, i.e., $c_C + \beta_C\tau - c_G - \beta_G\tau < \sigma_{B'}\tau$ by assumption.

incentives in Table D7 would look quite different.[42]

RESULT 6: *Consider the normal form of adoption in the four technology model. From the perspective of generator profits, adoption of a rate standard is a dominant strategy. The game is not zero sum, and generator profits would be higher if one state adopted a CAT and the other adopted a rate standard.*

From the perspective of social welfare, adoption of a rate standard is a dominant strategy. With efficient dispatch, the game is zero sum. With inefficient dispatch the game is not zero sum and there is an efficiency penalty if states fail to coordinate.

Here we provide additional details on the four technology model developed in Section B. Specifically, we discuss in detail the calculations for prices, generation costs, generator profits and electricity bills paid by consumers under the unregulated, CAT, rate standard, and mixed scenarios. As before, Figure 1, panels a-d of the main text illustrates the intuition behind these calculations.

B1. The unregulated equilibrium

In the absence of carbon regulation, the supply curve is illustrated in Figure E2, and the electricity price in each hour is determined by Eq. 1. In the two low demand hours, the nuclear capacity is marginal and the electricity price is c_N. If demand is 3 or 4 MWhs, coal-fired generation is marginal, the electricity price is c_C, and the nuclear generation is inframarginal. If demand is 5 or 6 MWhs, gas-fired generation is marginal, the electricity price is c_G, and coal-fired and nuclear generation are inframarginal. If demand is 7 or 8 MWhs, oil-fired generation is marginal; the electricity price is c_O; and gas-fired, coal-fired, and nuclear generation are inframarginal.

The total cost of generating electricity is $Cost^E = 3c_O + 7c_G + 11c_C + 15c_N$ because each generation technology generates three MWhs during the two hours it is marginal and two MWhs in each hour it is inframarginal, e.g., nuclear is marginal in two hours and inframarginal in six hours for a total generation of 15 MWh. Similarly, total carbon emissions are $Carbon^E = 3\beta_O + 7\beta_G + 11\beta_C + 15\beta_N$.

The electricity bill paid by consumers is $Bill^E = 15c_O + 11c_G + 7c_C + 3c_N$, because in the highest demand hours, 8 and 7 MWhs are purchased at a price of c_O, etc. Profits to the generators per MW of capacity are $\pi^E_{sO} = 0$, $\pi^E_{sG} = 2(c_O - c_G)$, $\pi^E_{sC} = 2(c_O - c_C) + 2(c_G - c_C)$, and $\pi^E_{sN} = 2(c_O - c_N) + 2(c_G - c_N) + 2(c_C - c_N)$. Oil-fired generation earns no profit since it is never inframarginal. Natural gas is inframarginal in two hours and coal is inframarginal in four hours. Each MW of nuclear generation is inframarginal in six hours and earns positive profit in these six hours.

B2. Both states adopt CAT regulation

Assume now that generators in both states are subject to a CAT. As before assume that the CAT is set such that the carbon price equals the social cost of carbon τ, i.e., the carbon price changes the merit order if it is efficient to change the merit order. Under the assumptions of the model, the CAT will change the merit order so that gas-fired generation is dispatched before coal-fired generation. The new merit order is illustrated in Figure 1, panel a.

The electricity price is now set by Eq. 1, and the prices for each hour are shown in Table D1. Note that the electricity price allows the marginal generator to cover both their generation and carbon costs. The total electricity bill paid by consumers can be readily calculated from these prices and is $Bill^{CAT} = 15(c_O + \beta_O\tau) + 11(c_C + \beta_C\tau) + 7(c_G + \beta_G\tau) + 3(c_N + \beta_N\tau)$.

---

[42] Would CAT be a dominant strategy if the firms got all the revenue? What if tax revenue went to both consumers and firms?

The total cost of generating electricity is $Cost^{CAT} = 3c_O + 7c_C + 11c_G + 15c_N$. Note that generation costs relative to the unregulated equilibrium increase by $Cost^{CAT} - Cost^{E} = 4(c_G - c_C)$ since gas is dispatched more and coal is dispatched less. However total carbon emissions are now $Carbon^{CAT} = 3\beta_O + 7\beta_C + 11\beta_G + 15\beta_N$. Note that carbon emissions decreased by $Carbon^{E} - Carbon^{CAT} = 4(\beta_C - \beta_G)$. The benefit of this carbon reduction, $4(\beta_C - \beta_G)\tau$, is greater than the abatement cost $4(c_G - c_C)$ by assumption, so reducing carbon emissions is efficient. The CAT also generates revenue to the carbon certificate holders. This revenue is $TR^{CAT} = \tau Carbon^{CAT}$.

We next turn to profit per MW. Oil is always marginal so $\pi_{sO}^{CAT} = 0$. Coal is inframarginal in two hours so $\pi_{sC}^{CAT} = 2[c_O + \beta_O\tau - (c_C + \beta_C\tau)]$. Gas is inframarginal in four hours so profit is $\pi_{sG}^{CAT} = 2[c_O + \beta_O\tau + c_C + \beta_C\tau - 2(c_G + \beta_G\tau)]$, and nuclear is inframarginal in six hours so profits are $\pi_{sN}^{CAT} = 2[c_O + \beta_O\tau + c_C + \beta_C\tau + c_G + \beta_G\tau - 3(c_N + \beta_N\tau)]$.[43]

B3. *Both states adopt rate standards*

Now assume that both states are subject to a rate standard. As above, assume that the rate standard is set such that the carbon price is τ, so the rate standard dispatches gas-fired generation before coal-fired generation. The new merit order is illustrated in Figure 1, panel b. Note that since demand is perfectly inelastic, the rate standard will be efficient.

The electricity price is now set by the marginal generator to cover generation costs and carbon costs where the carbon costs are based on emissions relative to the rate standard. Importantly, this reduces carbon costs for all technologies. The electricity prices for each hour are found from Eq. 1 and are shown in Table D1.

Because the merit order under the rate standard is identical to the merit order under the CAT and because demand is perfectly inelastic, the rate standard results in the same carbon emissions and electricity generation as the CAT. Thus $Carbon^{RS} = Carbon^{CAT}$ and $Cost^{RS} = Cost^{CAT}$, i.e., the abatement costs and carbon reductions are identical when both states adopt CAT or rate standards.

The electricity bill can be calculated by examining the electricity prices in Table D1. In each hour, the electricity price is $\sigma_s\tau$ lower than it is under the CAT. Thus the electricity bill is $Bill^{RS} = Bill^{CAT} - 36\sigma_s\tau$ because each of the 36 MWhs is purchased at a lower price. Note that since $\sigma_s = Carbon^{RS}/36$, this implies that $Bill^{RS} = Bill^{CAT} - TR^{CAT}$. The electricity bills and the tax revenue (if any) for the different policies are compared in Table D2.

Since carbon certificates for the rate standard are created by generators with emissions rates below the standard, we include any carbon market revenue directly in the generator's profits. As above, we note that the electricity price in each period is reduced by $\sigma_s\tau$ relative to the CAT. However, the generator's carbon costs are also reduced by $\sigma_s\tau$ relative to the CAT. Thus: $\pi_{so}^{RS} = \pi_{so}^{CAT} = 0$, $\pi_{sc}^{RS} = \pi_{sc}^{CAT}$, $\pi_{sg}^{RS} = \pi_{sg}^{CAT}$, and $\pi_{sn}^{RS} = \pi_{sn}^{CAT}$.[44] These profits are illustrated in Table D3.

B4. *Mixed adoption of CAT and rate standards*

Now assume that state A adopts a CAT and state B adopts a rate standard. As above, assume both standards are set such that the carbon price is τ. These carbon prices insure that the merit order is correct within each state. However, they do not insure that the merit order is correct across the states. Note that the carbon costs for technology i are $\beta_i\tau$ in state A and $(\beta_i - \sigma_B)\tau$ in state B. This difference in carbon prices across the states can lead to an inefficient merit order. Recall from

---

[43] These profits do not include revenue from carbon certificates. If generators were grandfathered certificates, then profits would be higher depending on the allocation scheme. We analyze certificate revenue separately from generator profits.

[44] For example, profits to coal-fired generation are $\pi_{sc}^{RS} = 2[c_O + (\beta_O - \sigma_s)\tau - (c_C + (\beta_C - \sigma_s)\tau)] = 2[c_O + \beta_O\tau - (c_C + \beta_C\tau)] = \pi_{sc}^{CAT}$.

Section B, if $c_C + (\beta_C - \sigma_B)\tau < c_G + \beta_G\tau < c_C + \beta_C\tau$ rate standard coal is dispatched before CAT gas and the merit order is no longer efficient. Therefore, we analyze two cases: *efficient* dispatch where $c_C + \beta_C\tau - (c_G + \beta_G\tau) > \sigma_B\tau$ and *inefficient* dispatch where $c_C + \beta_C\tau - (c_G + \beta_G\tau) < \sigma_B\tau$ i.

Efficient dispatch. — We assume here that the difference between the full costs of coal and gas is large, i.e., we assume $c_C + \beta_C\tau - (c_G + \beta_G\tau) > \sigma_B\tau$ so that $c_C + (\beta_C - \sigma_B)\tau > c_G + \beta_G\tau$. The new merit order is illustrated in Figure 1, panel c. Note in particular, that the merit order is efficient since gas is dispatched before coal.

As above, the electricity price is set by the marginal generator to cover generation costs and carbon costs where the carbon costs depend on the state of the generator. Although the merit order is efficient, the full marginal costs are not equal across the states and the CAT technology is always dispatched before the rate-standard technology.

The electricity generation cost can be determined directly from the merit order. Since the merit order is efficient, the costs are equal to the costs if both states had CATs or rate standards. However, the electricity generation, generation costs, and carbon emissions are no longer equal across the two states. Only 16 MWhs are generated in state A and 20 MWhs are generated in state B. The total cost of generation in state A is $Cost_A^{Mix'} = 7c_N + 5c_G + 3c_C + c_O$ and in state B is $Cost_B^{Mix'} = 8c_N + 6c_G + 4c_C + 2c_O$. Similarly, the carbon emissions are $Carbon_A^{Mix'} = 7\beta_N + 5\beta_G + 3\beta_C + \beta_O$ and $Carbon_B^{Mix'} = 8\beta_N + 6\beta_G + 4\beta_C + 2\beta_O$.

The electricity prices allow us to calculate the consumer's total electricity bill. Comparing to the CAT prices, we see the consumers purchase 11 MWhs at a discount of $\sigma_{B'}\tau$ when oil, gas, and nuclear generation subject to rate standards are on the margin. Thus $Bill^{Mix'} = Bill^{CAT} - 16\sigma_{B'}\tau$.

We next turn to the generator profits. The profit for the generators in state A can be found by comparing their profit with that of generators if both states had CATs. The oil-fired generation is never inframarginal and hence $\pi_{Ao}^{Mix'} = 0$. The coal-fired generation is only inframarginal in the two hours in which oil is marginal. In one of these two hours, the marginal oil-fired generator is subject to a CAT, but in the other hour the marginal oil-fired generator is subject to a rate standard so the price is lower in this hour by $\sigma_{B'}\tau$. Thus the profits are lower by $\sigma_{B'}\tau$ relative to the CAT profit, i.e., $\pi_{Ac}^{Mix'} = \pi_{sc}^{CAT} - \sigma_{B'}\tau$. The gas-fired generator is inframarginal in four hours. In two of these hours the marginal generator is subject to a rate standard, so the price is lower by $\sigma_{B'}\tau$. Thus the gas-fired generator's profits are $\pi_{Ag}^{Mix'} = \pi_{sg}^{CAT} - 2\sigma_{B'}\tau$. The nuclear generator in state A is inframarginal in six hours, and in three of those hours the marginal generator is subject to a rate standard, so the profits are $\pi_{An}^{Mix'} = \pi_{sn}^{CAT} - 3\sigma_{B'}\tau$.

Now consider the generators in state B subject to a rate standard. Again, we can compare them to profits when both states adopt CAT or rate standards since these two profits are equal. First consider the oil-fired generation. Now the generator is inframarginal in one hour and earns profit $\pi_{Bo}^{Mix'} = \sigma_{B'}\tau$. Next consider the coal-fired generation. It is inframarginal in three hours: In one of those hours it earns no additional profit since the rate-standard oil fired generation is on the margin; and in two of the hours it earns additional profit of $\sigma_{B'}\tau$ since a CAT generator is on the margin and the price is higher. Thus the profits are $\pi_{Bc}^{Mix'} = \pi_{sc}^{CAT} + 2\sigma_{B'}\tau$. Next turn to the gas-fired generator. This generator is inframarginal in five hours. In three of those hours, a CAT generator is marginal so the price is higher by $\sigma_{B'}\tau$. So the profit is $\pi_{Bg}^{Mix'} = \pi_{sg}^{CAT} + 3\sigma_{B'}\tau$. Finally, the nuclear generation is inframarginal in seven hours and in four of those hours a CAT generator is marginal so the profit is $\pi_{Bn}^{Mix'} = \pi_{sn}^{CAT} + 4\sigma_{B'}\tau$.

We now turn to the distribution of the welfare across the two states. For state A which is subject to a CAT, welfare is the sum of profit and tax revenue less its electricity bill and carbon damages.

Thus we have:

$$W_A^{Mix'} = \pi - 6\sigma_{B'}\tau + TR_A^{Mix'} - (Bill^{CAT} - 16\sigma_{B'}\tau)/2 - (Carbon_A^{Mix'} + Carbon_B^{Mix'})\tau/2$$

$$= W_s + 2\sigma_{B'}\tau + (Carbon_A^{Mix'} - Carbon_B^{Mix'})\tau/2$$

$$= W_s + (Carbon_A^{Mix'} - \frac{4}{5}Carbon_B^{Mix'})\tau/2.$$

For state B, there is no tax revenue, so

$$W_B^{Mix'} = \pi + 10\sigma_{B'}\tau - (Bill^{CAT} - 15\sigma_{B'}\tau)/2 - (Carbon_A^{Mix'} + Carbon_B^{Mix'})\tau/2$$

$$= W_s + 18\sigma_{B'}\tau - (Carbon_A^{Mix'} + Carbon_B^{Mix'})\tau/2$$

$$= W_s + (-Carbon_A^{Mix'} + \frac{4}{5}Carbon_B^{Mix'})\tau/2.$$

The distribution of welfare for the policies is reported in Table D4.

Whether the welfare exceeds W_s, depends on the sign of $Carbon_A^{Mix'} - \frac{4}{5}Carbon_B^{Mix'}$ which can be written as $(7-\frac{4}{5}8)\beta_N + (5-\frac{4}{5}6)\beta_G + (3-\frac{4}{5}4)\beta_C + (1-\frac{4}{5}2)\beta_O$. These coefficients are 0.6, 0.2, -0.2, and -0.6. Since $\beta_N < \beta_G < \beta_C < \beta_O$, this weighted average is negative and $Carbon_A^{Mix'} - \frac{4}{5}Carbon_B^{Mix'}$ is negative. Note also that $W_A^{Mix'} + W_B^{Mix'} = 2W_s$, since dispatch is efficient.

INEFFICIENT DISPATCH. — We assume here that the difference between the full costs of coal and gas is small, i.e., we assume $c_C + \beta_C\tau - (c_G + \beta_G\tau) < \sigma_B\tau$ so that $c_C + (\beta_C - \sigma_B)\tau < c_G + \beta_G\tau < c_C + \beta_C\tau$.[45] The new merit order is illustrated in Figure 1, panel d. Note in particular, that the merit order is no longer efficient since rate-standard coal is dispatched before CAT gas.

As above, the electricity price is set by the marginal generator to cover generation costs and carbon costs. However, now the the carbon costs depend on the state of the generator. These electricity prices (from Eq. 1 or Eq. 1) are illustrated in Table D1.

The electricity generation cost can be determined directly from the merit order. In particular, since the mixed merit order dispatches one MW of coal before one MW of gas (relative to the efficient merit order), the generation costs decrease by $c_C - c_G$ but carbon emissions increase by $\beta_C - \beta_G$. Note also that the electricity generation, generation costs, and carbon emissions are no longer equal across the two states. Note that only 15 MWhs are generated in state A and 21 MWhs are generated in state B. The total cost of generation in state A is $Cost_A^{Mix} = 7c_N + 4c_G + 3c_C + c_O$ and in state B is $Cost_B^{Mix} = 8c_N + 6c_G + 5c_C + 2c_O$. Similarly, the carbon emissions are $Carbon_A^{Mix} = 7\beta_N + 4\beta_G + 3\beta_C + \beta_O$ and $Carbon_B^{Mix} = 8\beta_N + 6\beta_G + 5\beta_C + 2\beta_O$.

The electricity prices allow us to calculate the consumer's total electricity bill. We can either compare the prices to the rate-standard prices or the CAT prices. Comparing to the CAT prices, we see the consumers purchase 11 MWhs at a discount of $\sigma_B\tau$ when oil, gas, and nuclear generation subject to rate standards are on the margin. When rate-standard coal is on the margin the electricity bill is lower by $4(\sigma_B\tau - c_C - \beta_C\tau + c_G + \beta_G\tau)$ and when CAT gas is on the margin the electricity bill is higher by $5(c_G + \beta_G\tau - c_C - \beta_C\tau)$. (See Table D1.) Thus $Bill^{Mix} = Bill^{CAT} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$.

We next turn to the generator profits, which are listed in Table D3. The profit for the generators in state A can be found by comparing their profit with that of generators if both states had CATs. The oil-fired generation is never inframarginal and hence $\pi_{Ao}^{Mix} = 0$. The coal-fired generation is only inframarginal in the two hours in which oil is marginal. In one of these two hours, the

---

[45] If we assume a smaller carbon price, this condition will hold.

marginal oil-fired generator is subject to a CAT, but in the other hour the marginal oil-fired generator is subject to a rate standard so the price is lower in this hour by $\sigma_B\tau$. Thus the profits are lower by $\sigma_B\tau$ relative to the CAT profit, i.e., $\pi^{Mix}_{Ac} = \pi^{CAT}_{sc} - \sigma_B\tau$. The gas-fired generator is inframarginal in three hours. In one of these hours the marginal generator is subject to a rate standard, so the price is lower by $\sigma_B\tau$. However, the gas-fired generator also would have been inframarginal four hours if both states had a CAT. Thus the gas-fired generator's profits are $\pi^{Mix}_{Ag} = \pi^{CAT}_{sg} - \sigma_B\tau - (c_C + \beta_C\tau - (c_G + \beta_G\tau))$. The nuclear generator in state A is inframarginal in six hours, and in three of those hours the marginal generator is subject to a rate standard, so the profits are $\pi^{Mix}_{An} = \pi^{CAT}_{sn} - 3\sigma_B\tau$.

Now consider the generators in state B subject to a rate standard. Again, we can compare them to profits when both states adopt CAT or rate standards because total profits are equal in these cases. First, consider the oil-fired generation. Under mixed regulation, the generator is inframarginal in one hour and earns profit $\pi^{Mix}_{Bo} = \sigma_B\tau$. Next, consider the coal-fired generation. It is now inframarginal in four hours: In one of those hours it earns no additional profit since the rate-standard oil-fired generation is on the margin; in two of the hours it earns additional profit of $\sigma_B\tau$ since a CAT generator is on the margin and the price is higher; and in one hour the gas-fired CAT plant is on the margin so additional profits are $c_G + \beta_G\tau - (c_C + (\beta_C - \sigma_B)\tau)$. Thus the profits are $\pi^{Mix}_{Bc} = \pi^{CAT}_{sc} + 3\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$. Next turn to the gas-fired generator. This generator is inframarginal in five hours. In three of those hours, a CAT generator is marginal so the price is higher by $\sigma_B\tau$. So the profit is $\pi^{Mix}_{Bg} = \pi^{CAT}_{sg} + 3\sigma_B\tau$. Finally, the nuclear generation is inframarginal in seven hours and in four of those hours a CAT generator is marginal so the price is higher by $\sigma_B\tau$. So the profit is $\pi^{Mix}_{Bn} = \pi^{CAT}_{sn} + 4\sigma_B\tau$.

Before turning to the distribution of surplus across the policies, we first analyze total welfare. We define a state's *welfare*, W as the sum of producer surplus and consumer surplus plus any tax revenue less half of carbon damages.[46] Because demand is here perfectly inelastic, gross consumer surplus is undefined in this model. However, gross consumer surplus is always the same, since the same amount of electricity is consumed. Thus the state's welfare is the sum of profits and tax revenue less the electricity bill and carbon damages. If both states adopt either a CAT or a rate standard, then welfare is equal across states and across policies, since electricity generation and carbon emissions are identical across the policies. In either of these cases, welfare for each state equals $W_s \equiv \pi^{CAT} - Bill^{CAT}/2$ where $\pi \equiv \pi^{CAT}_O + \pi^{CAT}_G + \pi^{CAT}_C + \pi^{CAT}_N = \pi^{RS}_O + \pi^{RS}_G + \pi^{RS}_C + \pi^{RS}_N$. Note that for the CAT, the tax revenue exactly offsets the carbon damanges and for the rate standard, the reduced electricity bill exactly offsets the carbon damages.

Under mixed regulation, Table D3 shows that total profits exceed profits under a CAT or rate standards by $6\sigma_B\tau + 2(c_G + \beta_G\tau - c_C - \beta_C\tau)$. We also showed above that $Bill^{Mix} = Bill^{CAT} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$. This implies that:

$$W^{Mix}_A + W^{Mix}_B = \pi^{Mix}_A + \pi^{Mix}_B + TR^{Mix}_A - Bill^{Mix} - (Carbon^{Mix}_A + Carbon^{Mix}_B)\tau$$

$$= 2\pi + 6\sigma_B\tau + 2(c_G + \beta_G\tau - c_C - \beta_C\tau) - Carbon^{Mix}_B\tau - [Bill^{CAT} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau]$$

$$= 2\pi + 21\sigma_B\tau - Carbon^{Mix}_B\tau - Bill^{CAT} + c_G + \beta_G\tau - c_C - \beta_C\tau$$

$$= 2\pi - Bill^{CAT} + c_G + \beta_G\tau - c_C - \beta_C\tau$$

$$= 2W_s + c_G + \beta_G\tau - c_C - \beta_C\tau$$

That welfare decreases by $c_C + \beta_C\tau - c_G - \beta_G\tau$ under the mixed regulation is quite intuitive. Under the mixed regulation, more electricity is generated from the coal-fired technology and less is

---

[46] Intuitively, we spread carbon damages equally across the two states.

generated from the gas-fired technology. This results in lower generation costs, but higher carbon costs and, hence, lower welfare.

We now turn to the distribution of the welfare across the two states. For state A which is subject to a CAT, welfare is the sum of profit and tax revenue less its electricity bill and carbon damages. Thus we have:

$$\begin{aligned}W_A^{Mix} &= \pi - 5\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau + TR_A^{Mix} - (Bill^{CAT} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau)/2 \\ &\qquad - (Carbon_A^{Mix} + Carbon_B^{Mix})\tau/2 \\ &= W_s + \frac{5}{2}\sigma_B\tau + (c_G + \beta_G\tau - c_C - \beta_C\tau)/2 + (Carbon_A^{Mix} - Carbon_B^{Mix})\tau/2 \\ &= W_s + (c_G + \beta_G\tau - c_C - \beta_C\tau)/2 + (Carbon_A^{Mix} - \frac{16}{21}Carbon_B^{Mix})\tau/2.\end{aligned}$$

For state B, there is no tax revenue, so

$$\begin{aligned}W_B^{Mix} &= \pi + 11\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau - (Bill^{CAT} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau)/2 \\ &\qquad - (Carbon_A^{Mix} + Carbon_B^{Mix})\tau/2 \\ &= W_s + \frac{37}{2}\sigma_B\tau + (c_G + \beta_G\tau - c_C - \beta_C\tau)/2 - (Carbon_A^{Mix} + Carbon_B^{Mix})\tau/2 \\ &= W_s + (c_G + \beta_G\tau - c_C - \beta_C\tau)/2 + (-Carbon_A^{Mix} + \frac{16}{21}Carbon_B^{Mix})\tau/2.\end{aligned}$$

The distribution of welfare for the policies is reported in Table D5.

Whether the welfare exceeds W_s, depends on $Carbon_A^{Mix} - \frac{16}{21}Carbon_B^{Mix}$ which can be written as $(7 - \frac{16}{21}8)\beta_N + (4 - \frac{16}{21}6)\beta_G + (3 - \frac{16}{21}5)\beta_C + (1 - \frac{16}{21}2)\beta_O$. Since $\beta_N = 0$ and all the other coefficients are negative, $Carbon_A^{Mix} - \frac{16}{21}Carbon_B^{Mix}$ is clearly negative.

DETAILS OF NUMERICAL SIMULATIONS

Investment in new conventional and renewable capacity

In our simulations we consider a medium-term time horizon where there is entry of new generation that supplements existing capacity. This new entry is market driven, and in equilibrium requires sufficient market revenues to cover the (annualized) capital costs of new generation. Formally, hourly generation from conventional generation plant i is constrained to not exceed the installed capacity of that plant.

$$q_{sit} \leq CAP_{si} \forall i, t.$$

For some technologies we consider new investment, which in equilibrium equates annual operating profits to annualized capital costs. In those scenarios the annualized capital cost of each new MW of capacity is an additional cost that is present in the objective function that maximizes social welfare.

For investment in wind resources, we need to consider the intermittent availability of the resource. From the WECC we have data on projected hourly wind output for resources in each region under a hypothetical WECC-wide 20% renewable portfolio standard (see Bushnell, 2011). These hourly generation profiles are aggregated to the same subregion level that other market variables have been aggregated to. The result is an hourly capacity factor, CF_{st} for new wind facilities that is expressed as a fraction of the overall new capacity that is built by the model. For wind plant j in state s, output in time t would constrained such that

$$q_{sjt} \leq CAP_{sj} * CF_{st} \forall j, t$$

.

C1. Market demand

To construct our demand functions, we assume linear demand that passes through the mean price and quantity for each representative time period and region. End-use consumption, as defined above, in each region is represented by the demand function $Q_{r,t} = \alpha_{r,t} - \beta_r p_{r,t}$, yielding an inverse demand curve defined as

$$p_{rt} = \frac{\alpha_{r,t} - \sum_i q_{rit} - y_{i,t}}{\beta_r}$$

where $y_{r,t}$ is the aggregate net imports into region r.

The parameter α_{rt} is calibrated so that, for a given β_r, $Q^{actual}_{r,t} = \alpha_{r,t} - \beta_r p^{actual}_{r,t}$. In other words, the demand curve is shifted so that it passes through the average of the observed price quantity pairs for that collection of hours. To derive actual demand, FERC form 714 provides hourly total end-use consumption by control-area which we aggregate to the North American Electric Reliability Commission (NERC) sub-region level. We utilize the full data on all regions of the West. We consolidate the 8760 individual hours of the year into a more tractable 80 hours of representative demand levels by grouping similar hours into a single representative one. The choice of bins is based upon the division of California load for each season into 20 equal sized bins of load. Actual demand in each Western region is then averaged over those same hours to create a representative hour for that bin. For example, there were nine hours in the highest demand bin for the winter of 2007. These include 5 hours from October 24 and 4 from December 12, essentially the two peak days in that season. All the relevant statistics for each NERC subregion are averaged over those 9 hours to create a single peak hour in the simulation.[47]

For electricity prices, we use hourly market prices in California and monthly average prices taken from the Intercontinental Exchange (ICE) for the non-market regions.[48]

We utilize an extremely low value for the slopes of the linear demand curve. We assume a low end-use elasticity with respect to our prices for several reasons. First, the "prices our model is capturing are hourly varying wholesale power prices. For almost all customers in the Western U.S. the regulatory process strongly dilutes the fluctuations in these prices in their flow through to retail prices. It is extremely difficult to capture all the complexities of the relationship between wholesale and retail prices, but our choice of a low elasticity is partly in recognition of this dilution. Second, as discussed elsewhere, retail rates include charges not related to generation costs or prices. This again dilutes the effect of a wholesale energy price change on an end-use bill. Last, estimates of "mid-term elasticities (annual or bi-annual changes) have for the most part produced relatively low values For example, in an early review article Taylor (1975) finds short-run price elasticities of electricity demand for residential consumers on the order of 0.15 with some estimates as high as 0.90. Commercial and industrial demand elasticities are estimated at 0.17 and 0.22 in the short-run. More recently, Kamerschen and Porter (2004) estimate total electricity demand elasticities in the range of 0.13 to 0.15 using US annual data from 1978 to 2008. Reiss and White (2005) estimate a

---

[47] Note that this does not force each region to peak during this time, only that our simulation hour 80 would have a demand level for, say, the Rocky Mountains that reflects that average in WY and CO during those same 9 hours.

[48] To obtain hourly prices in regions outside of California, we calculate the mean difference by season between the California prices and prices in other regions. This mean difference is then applied to the hourly California price to obtain an hourly regional price for states outside of California. Because demand in the model is very inelastic, the results are not very sensitive to this benchmark price method.

mean elasticity of 0.39 for households in California while Ito (2014) estimates values consistently less than 0.10. Because the CPP affects the price of energy and approximately half of consumers' rate is related to non-energy charges, such as transmission, the response of consumers to changes in wholesale energy prices is likely even smaller. Therefore, the slope of the demand curve is set so that the median elasticity in each region is -.05.[49]

C2. Fossil-fired generation costs and emissions

We explicitly model the major fossil-fired thermal units in each electric system. Because of the legacy of cost-of-service regulation, relatively reliable data on the generation costs of thermal generation units are available. The cost of fuel comprises the major component of the marginal cost of thermal generation. The marginal cost of a modeled generation unit is estimated to be the sum of its direct fuel, CO_2, and variable operation and maintenance (VO&M) costs. Fuel costs can be calculated by multiplying the price of fuel, which varies by region, by a unit's 'heat rate,' a measure of its fuel-efficiency.

The capacity of a generating unit is reduced to reflect the probability of a forced outage of each unit. The available capacity of generation unit i, is taken to be $(1 - fof_i) * cap_i$, where cap_i is the summer-rated capacity of the unit and fof_i is the forced outage factor reflecting the probability of the unit being completely down at any given time.[50] Unit forced outage factors are taken from the generator availability data system (GADS) data that are collected by the North American Reliability Councils. These data aggregate generator outage performance by technology, age, and region. State-level derated fossil generation capacity is shown in Table D8.

Figure 2 illustrates the merit order, including carbon costs, for all simulated (large fossil) plants included in the simulation. The location of a specific plant on the horizontal axis corresponds to its social marginal cost based upon a carbon cost of \$35/ton. Coal generation is represented by red + symbols while gas generation is represented by green x symbols. The lower solid line displays the private marginal costs of the same units. One can see how the \$35 carbon price shifts some low-cost gas generation to the base of the supply order, displacing low cost coal, which after applying carbon costs shift to the middle of the supply order.

C3. Transmission network

Our regional markets are highly aggregated geographically. The region we model is the electricity market contained within the U.S. portion of the Western Electricity Coordinating Council (WECC). The WECC is the organization responsible for coordinating the planning investment, and general operating procedures of electricity networks in most states west of the Mississippi. The multiple sub-networks, or control areas, contained within this region are aggregated into four "sub-regions." Between (and within) these regions are over 50 major transmission interfaces, or paths. Due to both computational and data considerations, we have aggregated this network into a simplified 5 region network consisting primarily of the 4 major subregions.[51] Figure E3 illustrates the areas covered by these regions. The states in white, plus California, constitute the U.S. participants in the WECC.

---

[49] Because the market is modeled as perfectly competitive, the results are relatively insensitive to the elasticity assumption, as price is set at the marginal cost of system generation and the range of prices is relatively modest.

[50] This approach to modeling unit availability is similar to Wolfram (1999) and Bushnell, Mansur and Saravia (2008).

[51] The final "node" in the network consists of the Intermountain power plant in Utah. This plant is connected to southern California by a high-capacity DC line, and is often considered to be electrically part of California. However under some regulatory scenarios, it would not in fact be part of California for GHG purposes, it is represented as a separate location that connects directly to California.

Mathematically, we adopt an approach utilized by Metzler, et al. (2003), to represent the transmission arbitrage conditions as another set of constraints. Under the assumptions of a direct-current (DC) load-flow model, the transmission 'flow' induced by a marginal injection of power at location l can be represented by a power transfer distribution factor, $PTDF_{lk}$, which maps injections at locations, l, to flows over individual transmission paths k. Within this framework, the arbitrage condition will implicitly inject and consume power, $y_{l,t}$, to maximize available and feasible arbitrage profits as defined by

Transmission models such as these utilize a "swing hub" from which other marginal changes in the network are measured relative to. We use the California region as this hub. In other words, an injection of power, $y_{l,t} \geq 0$, at location l is assumed to be withdrawn in California. The welfare maximization objective function is therefore subject to the flow limits on the transmission network, particularly the line capacities, T_k:

$$-\overline{T}_k \leq PTDF_{l,k} \cdot y_{l,t} \leq \overline{T}_k.$$

Given the aggregated level of the network, we model the relative impedance of each set of major pathways as roughly inverse to their voltage levels. The network connecting AZNM and the NWPP to CA is higher voltage (500 KV) than the predominantly 345 KV network connecting the other regions. For our purposes, we assume that these lower voltage paths yield 5/3 the impedance of the direct paths to CA. Flow capacities over these interfaces are based upon WECC data, and aggregate the available capacities of aggregate transmission paths between regions.

The congestion pricing model described above captures regional transmission congestion costs (in the form of locationally varying prices). System charges (e.g. fixed or volumetric access fees) are not explicitly modeled but are implicitly present through the calibration of the base case with 2007 outcomes. Our underlying assumption is that these charges would not be dependent upon the specific environmental regulation adopted by the state. The same is true for transmission losses. The level of transmission represented here is the very high voltage interconnections between regions, where losses are modest (3% for 500 kV) relative to more local lower voltage networks. To the extent that some scenarios lead to increased flows, losses would increase somewhat and we are understating costs, but we think these differences are relatively modest.

C4. Hydro, renewable and other generation

Generation capacity and annual energy production for each of our regions is reported by technology type in Tables D8 and D9. We lack data on the hourly generation quantities for the production from renewable resources, hydro-electric resources, combined heat and power, and small thermal resources that comprise the "non-CEMS" category. By construction, the aggregate generation from these resources will be the difference between market demand in a given hour, and the amount of generation from large thermal (CEMS) units in that hour. In effect we are assuming that, under our CO_2 regulation counter-factual, the operations of non-modeled generation (e.g., renewable and hydro) plants would not have changed. This is equivalent to assuming that compliance with the CO_2 reduction goals of a cap-and-trade program will be achieved through the reallocation of generation within the set of modeled plants.[52]

Non-CEMS generation is derived by aggregating CEMS generation by NERC sub-region, and calculating the difference for each region between hourly demand, hourly net-imports, and hourly

---

[52] We believe that this is a reasonable assumption for two reasons. First the vast majority of the CO_2 emissions from this sector come from these modeled resources. Indeed, data availability is tied to emissions levels since the data are reported through environmental compliance to existing regulations. Second, the total generation from "clean" sources is unlikely to change in the short-run. The generation of low carbon electricity is driven by natural resource availability (e.g., rain, wind, solar) or, in the case of combined heat and power (CHP), to non-electricity generation decisions.

CEMS generation for that sub-region. Since the hourly demand data, which come from FERC 714, is aggregated to the sub-regional level, both those data and non-CEMS generation, which is derived in part from the load data must be allocated to individual states for purposes of calculating the state-level impacts of different policies. This is done by calculating a state's share of total electricity consumption, and of non CHP fossil generation, for allocating load and generation, respectively. We take these data from the Energy Information Administration Detailed State Data section (http://www.eia.gov/electricity/data/state/). The original source of the load data is EIA form 861 and of the generation data is EIA form 860. Most states are assigned completely to on NERC sub-region, with the exception of Nevada, where 75% of the load and of the non-CEMS generation is allocated to the AZNMNV sub-region, with the remaining 25% being allocated to the NWPP sub-region.

C5. Decomposition of benefits and costs

The choice of regulatory instrument carries very different implications for different stakeholders in each state. One key division is between electricity consumers and producers. We calculate producer surplus in the conventional way, but it is worth noting that in some states much of the generation remains regulated. In these states, one could consider the producer surplus as accruing to ratepayers (e.g. consumers).

Another distinction is between sources that will be covered (regulated) under the clean power plan and those that are not (unregulated). All generation sources are assumed to earn the market clearing wholesale electricity price for their region. Only the covered sources are exposed to the costs and incentives created by the CO_2 regulation.

For this analysis we make the assumption that all regulated sources are included in our dataset and that the difference between hourly measured output from CEMS and measured demand is comprised of generation from non-regulated sources such as large hydro electric, renewable, and renewable generation. Current EPA proposals apply a more complex formula to renewable and nuclear generation, so this assumption is an approximation. From our data we can calculate an estimate of hourly regional non-CEMS, *i.e.* uncovered generation. Recall that our measure of non-CEMS generation was derived by taking the difference between regional demand less CEMS generation less net imports into a region.

C6. Additional results on supply side effects

Appendix Figure E4 illustrates the merit order that arises if states fail to harmonize their *rate-standards.* The figure plots the supply curve for a rate standard (West-wide Rate) and compares it with state-by-state rate standards (State Rates). As in the case of state-level CATs, Figure 3, the state-by-state rates "scramble" the merit order and are an additional source of inefficiency. An additional complication arises with state-level rate standards compared to state-level CAT standards. If states adopt, state-level CAT standards, but allow for trading across states, then the inefficiency will no longer exist; trading equalizes the shadow value of the CAT constraints across the states. Allowing for trading within state-specific rate standards does not eliminate the inefficiency. Trading across states will equate the shadow value of the state-specific constraints, but as long as the rate targets vary across states, the merit order will still be scrambled.

C7. Additional results on equilibrium market impacts

Table D10 calculates social welfare changes for each state, as well as the two blocks of states discussed in the main text, under each of the scenarios. We assume carbon-market revenues are returned to consumers and producers in a lump-sum fashion. State carbon damages are population-weighted and are based on a social cost of carbon of $43 per MT. This table makes clear the divergent incentives of Coastal and Inland states. The Coastal states prefer a single rate standard, Scenario 3, while Inland states are most harmed by such a standard. The intuition for this result is that Coastal generation sources are, on average, cleaner than Inland generators. Therefore under a single rate standard, more Coastal generators are implicitly subsidized, while more Inland generators are taxed, giving Coastal power plants a competitive advantage when the market operates under a rate standard. On the other hand, Inland states prefer a West-wide CAT standard, scenario 1. This result is driven in part by AZ where profits for uncovered generation are higher under CAT.

Table D11 focuses on changes in producer surplus. Here the incentives across states are more aligned, since producer surplus depends heavily on equilibrium electricity prices. Producers in both Coastal and Inland states prefer CAT standards, which as we have shown, lead to large increases in the price of electricity. Across Scenarios 5 through 8, each block of states prefers to face rate standards. Intuitively, a rate standard in the generator's region makes compliance less costly but a CAT in the neighboring region yields higher electricity prices there, and increases profits from exports. Further, we find Coastal generators benefit, relative to business-as-usual scenarios, when the Coast has a rate standard and the Inland region has a CAT.

C8. Additional results on incentives to form a West-wide coalition

Here were present several different normal form representations of the incentives to form coalitions and to adopt either coordinate or uncoordinated regulation. While the main text presents incentives for regulators and key stakeholder groups, the results presented here provide additional insight into the potential forces at work in policy deliberations. We first discuss social welfare effects.

As discussed in the previous section, social welfare is highest for Coastal states under a West-wide rate standard and welfare is highest for Inland states under a West-wide CAT. The normal form representation in Table D12 provides a more nuanced interpretation. From a social welfare perspective, the Coastal coalition prefers a CAT when Inland adopts a CAT but prefers a rate-standard when the Inland region adopts a rate. However, the Inland region prefers a CAT whether the Coast adopts a CAT or rate-standard. Therefore, CAT/CAT is a Nash equilibrium from a social welfare perspective.

We can better understand the profit results of the previous section by looking at the effects separately for covered and un-covered generators. Covered generators always prefer rate standards. On the Coast, covered generator profits are higher under a rate-standard regardless of whether Inland adopts a CAT or a rate. Similarly, Inland generator profits decrease less under a rate than under a CAT standard. Therefore, from the perspective of covered generators a West-wide rate is preferred. On the other hand, uncovered generators are not subject to regulation and prefer the higher electricity prices under CAT standards. As the last panel of Table D12 shows, CAT/CAT is the Nash equilibrium from the perspective of covered generators. As in the main text, these results show the incentives of stakeholder groups may not support formation of the efficient West-wide CAT coalition.

*

Appendix Tables

Table D1—: Prices in different hours under the four scenarios.

MW	CAT	Rate standard	Mixed regulation: efficient dispatch	Mixed regulation: inefficient dispatch
1	$c_N + \beta_N \tau$	$c_N + (\beta_N - \sigma_s)\tau$	$c_N + (\beta_N - \sigma_B)\tau$	$c_N + (\beta_N - \sigma_{B'})\tau$
2	$c_N + \beta_N \tau$	$c_N + (\beta_N - \sigma_s)\tau$	$c_N + \beta_N \tau$	$c_N + \beta_N \tau$
3	$c_G + \beta_G \tau$	$c_G + (\beta_G - \sigma_s)\tau$	$c_G + (\beta_G - \sigma_B)\tau$	$c_G + (\beta_G - \sigma_{B'})\tau$
4	$c_G + \beta_G \tau$	$c_G + (\beta_G - \sigma_s)\tau$	$c_G + \beta_G \tau$	$c_C + (\beta_C - \sigma_{B'})\tau$
5	$c_C + \beta_C \tau$	$c_C + (\beta_C - \sigma_s)\tau$	$c_C + (\beta_C - \sigma_B)\tau$	$c_G + \beta_G \tau$
6	$c_C + \beta_C \tau$	$c_C + (\beta_C - \sigma_s)\tau$	$c_C + \beta_C \tau$	$c_C + \beta_C \tau$
7	$c_O + \beta_O \tau$	$c_O + (\beta_O - \sigma_s)\tau$	$c_O + (\beta_O - \sigma_B)\tau$	$c_O + (\beta_O - \sigma_{B'})\tau$
8	$c_O + \beta_O \tau$	$c_O + (\beta_O - \sigma_s)\tau$	$c_O + \beta_O \tau$	$c_O + \beta_O \tau$

Table D2—: Generation costs, carbon emissions, electricity bills, and carbon tax revenue under the four scenarios.

	CAT	Rate standard	Mixed regulation: efficient dispatch	Mixed regulation: inefficient dispatch
Cost	$Cost^{CAT}$	$Cost^{CAT}$	$Cost^{CAT}$	$Cost^{CAT} - (c_G - c_C)$
Carbon	$Carbon^{CAT}$	$Carbon^{CAT}$	$Carbon^{CAT}$	$Carbon^{CAT} + (\beta_C - \beta_G)$
Bill	$Bill^{CAT}$	$Bill^{CAT} - TR^{CAT}$	$Bill^{CAT} - 16\sigma_B \tau$	$Bill^{CAT} - 15\sigma_{B'}\tau + c_G + \beta_G \tau - c_C - \beta_C \tau$
TR	TR^{CAT}	0	$TR^{Mix}, 0$	$TR^{Mix'}, 0$

Table D3—: Profits for the four technologies in the two states for the four scenarios.

State-technology	CAT	Rate standard	Mixed regulation efficient dispatch	Mixed regulation inefficient dispatch
A-oil	$\pi_O = 0$	$\pi_O = 0$	$\pi_O = 0$	$\pi_O = 0$
B-oil	$\pi_O = 0$	$\pi_O = 0$	$\pi_O + \sigma_B\tau$	$\pi_O + \sigma_{B'}\tau$
A-coal	π_C	π_C	$\pi_C - \sigma_B\tau$	$\pi_C - \sigma_{B'}\tau$
B-coal	π_C	π_C	$\pi_C + 2\sigma_B\tau$	$\pi_C + 3\sigma_{B'}\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$
A-gas	π_G	π_G	$\pi_G - 2\sigma_B\tau$	$\pi_G - \sigma_{B'}\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$
B-gas	π_G	π_G	$\pi_G + 3\sigma_B\tau$	$\pi_G + 3\sigma_{B'}\tau$
A-nuke	π_N	π_N	$\pi_N - 3\sigma_B\tau$	$\pi_N - 3\sigma_{B'}\tau$
B-nuke	π_N	π_N	$\pi_N + 4\sigma_B\tau$	$\pi_N + 4\sigma_{B'}\tau$

Note: In the scenarios with mixed regulation, State A adopts a CAT and State B adopts a rate standard.

Table D4—: Comparison of welfare in each state across the policies: efficient dispatch.

	CAT	Rate standard
CAT	W_s W_s	. .
Rate standard	$W_s + (\frac{4}{5}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2$ $W_s - (\frac{4}{5}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2$	W_s W_s

Table D5—: Comparison of welfare in each state across the policies: inefficient dispatch.

	CAT	Rate standard
CAT	W_s W_s	. .
Rate standard	$W_s + (\frac{16}{21}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2 - (c_C + \beta_C\tau - c_G - \beta_G\tau)/2$ $W_s - (\frac{16}{21}Carbon_B^{Mix} - Carbon_A^{Mix})\tau/2 - (c_C + \beta_C\tau - c_G - \beta_G\tau)/2$	W_s W_s

Table D6—: Comparison of each state's profit across the policies: efficient dispatch.

	CAT	Rate Standard
CAT	π π	. .
Rate standard	$\pi + 10\sigma_B\tau$ $\pi - 6\sigma_B\tau$	π π

Table D7—: Comparison of each state's profit across the policies: inefficient dispatch.

	CAT	Rate standard
CAT	π π	. .
Rate standard	$\pi + 11\sigma_{B'}\tau - (c_C + \beta_C\tau - c_G - \beta_G\tau)$ $\pi - 5\sigma_{B'}\tau - (c_C + \beta_C\tau - c_G - \beta_G\tau)$	π π

Table D8—: Derated CEMS (Fossil) Generation Capacity (MW) by State and Fuel Type

State	Coal	CCGT	Gas St	Gas CT	Oil	Total
AZ	4833	7875	1009	528	0	14244
CA	0	11015	12534	2728	496	26773
CO	4049	1476	96	1569	0	7190
ID	222	335	0	0	0	556
MT	1984	0	0	0	0	1984
NM	3312	496	337	383	0	4528
NV	950	2943	476	517	0	4887
OR	484	1967	88	0	0	2539
UT	3762	884	206	319	0	5171
WA	1184	1358	107	0	0	2649
WY	4810	60	0	0	0	4870
Total	25591	28409	14853	6044	496	75392

Table D9—: Actual and Simulated Output and Emissions by State

	Actual (EIA)			Simulated Baseline		
State	Uncovered Gen (GWh)	Covered Gen (GWh)	Emissions MMTon	Uncovered Gen (GWh)	Covered Gen (GWh)	Emissions MMTon
AZ	35.85	77.49	54.90	54.81	75.60	55.71
CA	127.68	83.16	37.20	123.03	86.99	35.23
CO	4.73	49.18	42.10	13.63	44.09	41.94
ID	9.97	1.52	0.62	7.75	1.34	0.66
MT	10.46	18.47	19.60	8.14	17.38	19.78
NM	2.21	33.78	31.60	3.38	31.27	33.10
NV	5.97	26.70	15.60	8.01	26.36	15.74
OR	42.48	12.60	7.42	33.03	18.71	10.43
UT	1.66	43.71	37.70	1.29	39.18	36.57
WA	92.83	14.16	11.40	72.19	18.83	14.73
WY	2.51	43.13	44.80	7.23	42.14	45.55
Totals	336.35	403.90	302.93	332.48	401.90	309.45

Table D10—: Social welfare gains across regions relative to business as usual under eight policy scenarios.

	0 No Reg	1 CAT	2 CATs	3 Rate	4 Rates	5 CAT Rate	6 CAT Rates	7 Rate CAT	8 Rates CAT
Social Welfare ($ bn.)									
CA	$16.12	+ $0.99	+ $1.11	+ $2.53	+ $1.85	+ $1.92	+ $1.73	+ $1.08	+ $0.99
OR	$4.40	+ $0.17	+ $0.17	+ $0.21	+ $0.17	+ $0.18	+ $0.17	+ $0.13	+ $0.14
WA	$8.27	+ $0.33	+ $0.26	+ $0.27	+ $0.22	+ $0.31	+ $0.29	+ $0.22	+ $0.24
Coastal Total	$28.80	+ $1.49	+ $1.54	+ $3.01	+ $2.24	+ $2.41	+ $2.19	+ $1.43	+ $1.37
AZ	$6.94	+ $0.74	+ $0.38	+ $0.03	- $0.14	+ $0.07	- $0.20	+ $0.35	+ $0.31
CO	$3.40	- $0.28	+ $0.04	- $0.06	- $0.06	- $0.06	- $0.09	- $0.17	- $0.16
ID	$1.65	- $0.00	+ $0.07	+ $0.22	+ $0.24	+ $0.22	+ $0.23	+ $0.06	+ $0.05
MT	$1.70	+ $0.01	- $0.08	- $0.22	- $0.17	- $0.21	- $0.17	- $0.04	- $0.04
NM	$1.79	- $0.05	- $0.02	- $0.21	- $0.14	- $0.19	- $0.15	- $0.12	- $0.11
NV	$2.51	+ $0.02	+ $0.06	+ $0.15	+ $0.11	+ $0.17	+ $0.10	+ $0.01	+ $0.00
UT	$2.28	+ $0.17	+ $0.00	- $0.21	- $0.07	- $0.17	- $0.08	+ $0.09	+ $0.08
WY	$2.15	- $0.10	- $0.15	- $0.67	- $0.56	- $0.64	- $0.55	- $0.18	- $0.15
Inland Total	$22.41	+ $0.50	+ $0.30	- $0.98	- $0.81	- $0.82	- $0.91	+ $0.01	- $0.03
Transmission Profits	$0.18	+ $0.02	- $0.03	+ $0.01	+ $0.14	+ $0.10	+ $0.13	- $0.10	- $0.08
Total	$51.39	+ $2.01	+ $1.81	+ $2.04	+ $1.57	+ $1.69	+ $1.40	+ $1.34	+ $1.26

Notes: Results from Scenarios 1-8 are reported as changes relative to Scenario 0. "+" indicates an increase and "-" indicates a decrease. Carbon damages assume a social cost of carbon equal to $35.10. Carbon damages are allocated across states based on population.

Table D11—: Generator profits across regions for all generation (covered and uncovered) under business as usual and eight policy scenarios.

	0 No Reg	1 CAT	2 CATs	3 Rate	4 Rates	5 CAT Rate	6 CAT Rates	7 Rate CAT	8 Rates CAT
CA	$6.09	+ $0.82	+ $0.93	- $0.61	- $0.74	- $0.86	- $0.89	+ $0.48	+ $0.42
OR	$1.99	+ $0.02	- $0.03	- $0.44	- $0.53	- $0.47	- $0.50	- $0.02	+ $0.01
WA	$4.02	+ $0.13	+ $0.02	- $0.86	- $1.01	- $0.85	- $0.90	- $0.06	+ $0.02
Coastal Total	$12.10	+ $0.97	+ $0.92	- $1.91	- $2.29	- $2.18	- $2.29	+ $0.40	+ $0.45
AZ	$2.77	+ $0.12	- $0.18	- $0.34	- $0.57	- $0.31	- $0.66	- $0.44	- $0.48
CO	$1.32	- $0.84	- $0.77	- $0.94	- $0.77	- $0.94	- $0.79	- $0.82	- $0.82
ID	$0.41	+ $0.03	+ $0.03	- $0.08	- $0.09	- $0.09	- $0.09	- $0.01	- $0.01
MT	$0.88	- $0.30	- $0.36	- $0.42	- $0.39	- $0.41	- $0.38	- $0.38	- $0.37
NM	$0.63	- $0.31	- $0.35	- $0.33	- $0.27	- $0.31	- $0.29	- $0.40	- $0.41
NV	$0.58	- $0.02	- $0.06	- $0.09	- $0.16	- $0.08	- $0.18	- $0.16	- $0.16
UT	$1.02	- $0.58	- $0.74	- $0.60	- $0.49	- $0.56	- $0.48	- $0.70	- $0.69
WY	$1.32	- $0.83	- $0.90	- $0.89	- $0.74	- $0.87	- $0.73	- $0.89	- $0.88
Inland Total	$8.92	- $2.72	- $3.33	- $3.70	- $3.48	- $3.56	- $3.61	- $3.80	- $3.82
Total	$21.02	- $1.74	- $2.40	- $5.60	- $5.77	- $5.74	- $5.90	- $3.40	- $3.38

Notes: Results from Scenarios 1-8 are reported as changes relative to Scenario 0. "+" indicates an increase and "-" indicates a decrease. Profits in $ billion.

Table D12—: Social welfare incentives in the Coastal and Inland West.

		Inland	
		CAT	Rate
Coastal	CAT	+ $1.49 , + $0.50	+ $2.41 , - $0.82
	Rate	+ $1.43 , + $0.01	+ $3.01 , - $0.98

Notes: Profit is measured relative to business as usual (Scenario 0) in $ billion. “+” indicates an increase and “-” indicates a decrease.

Table D13—: Profit incentives for covered generation in the Coastal and Inland West.

		Inland	
		CAT	Rate
Coastal	CAT	- $0.49 , - $3.35	- $0.68 , - $3.12
	Rate	+ $0.08 , - $4.08	- $0.47 , - $3.32

Notes: Profit is measured relative to business as usual (Scenario 0) in $ billion. “+” indicates an increase and “-” indicates a decrease.

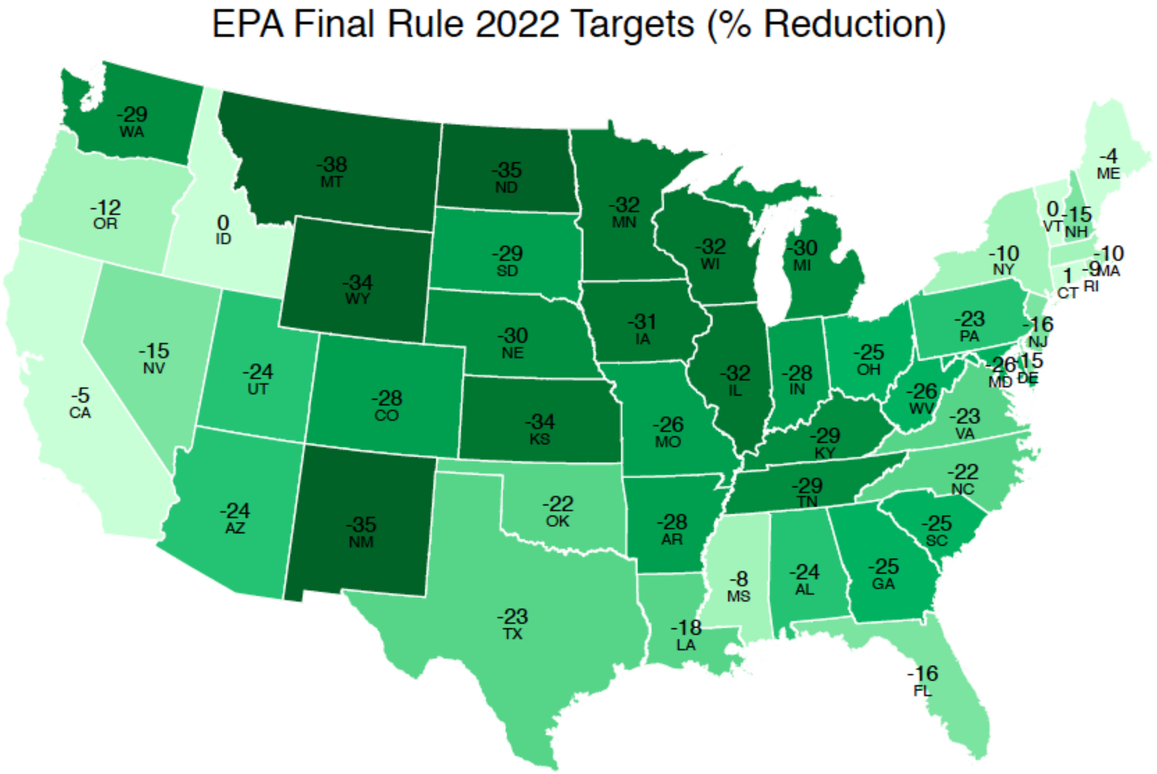
Table D14—: Profit incentives for uncovered generation in the Coastal and Inland West.

		Inland	
		CAT	Rate
Coastal	CAT	+ $1.46 , + $0.63	- $1.51 , - $0.44
	Rate	+ $0.32 , + $0.28	- $1.43 , - $0.38

Notes: Profit is measured relative to business as usual (Scenario 0) in $ billion. “+” indicates an increase and “-” indicates a decrease.

Appendix Figures

Figure E1. : EPA Clean Power Plan target reductions for 2022-2029.



Note: Percentage reduction in lbs per MWh.

Figure E2. : Merit order in the 4 technology model without regulation.

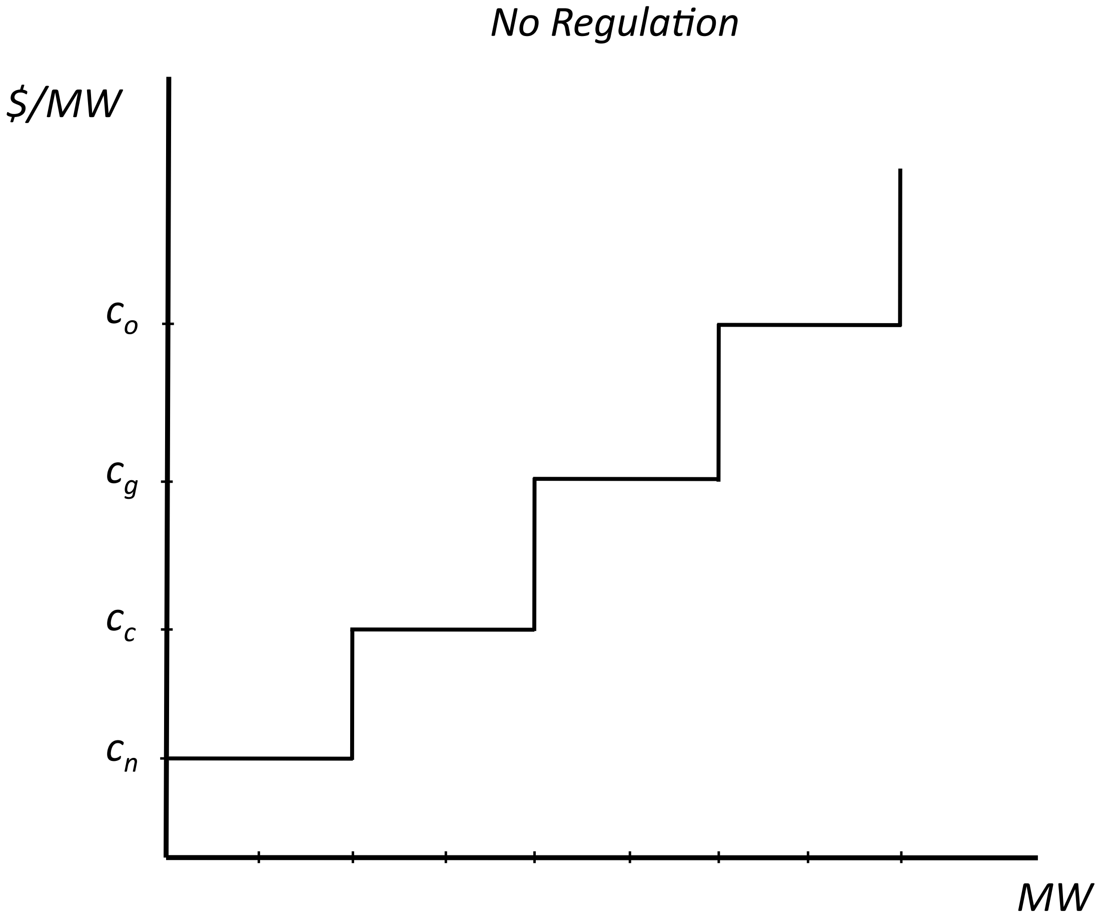


Figure E3. : Western regional electricity network and transmission constraints.

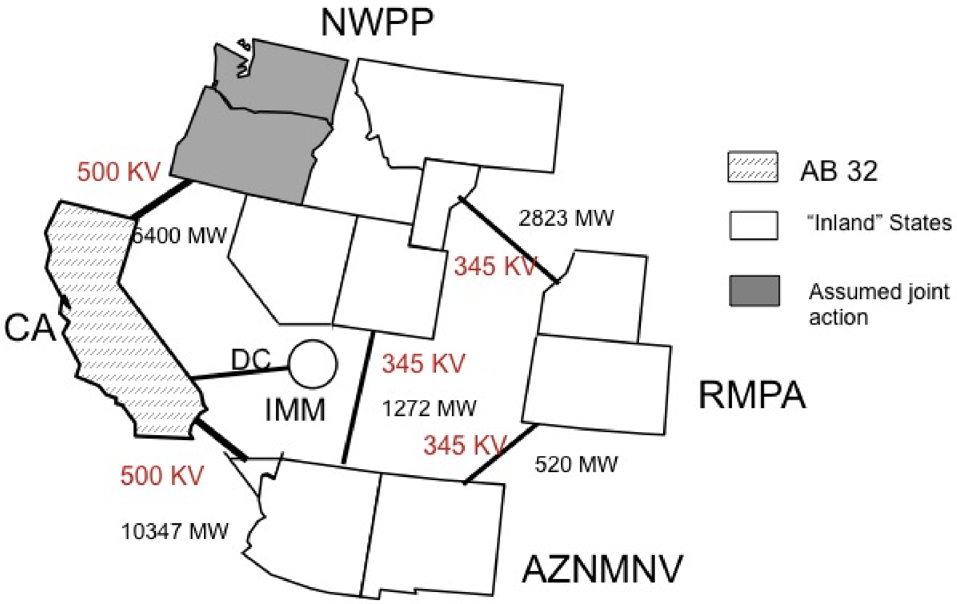
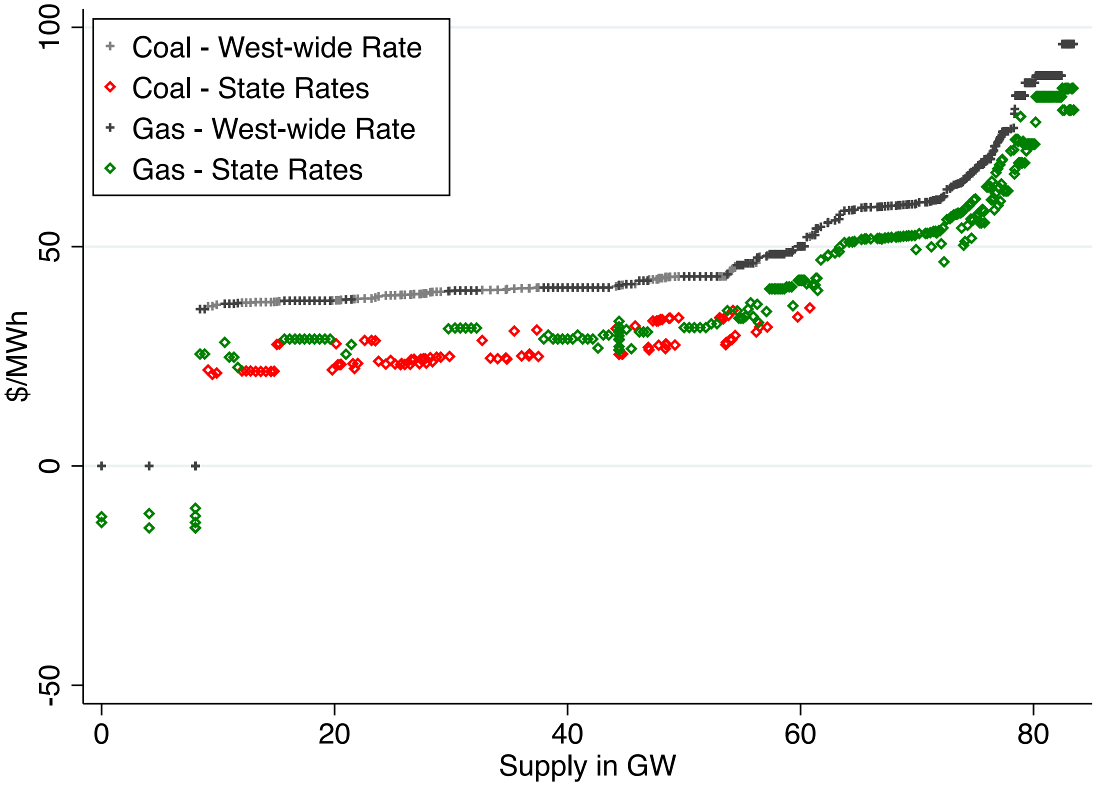


Figure E4. : Merit order under different regulations: West-wide rate standard and state-by-state rate standards.



Note: Generating units sorted on x-axis by full-marginal costs under West-wide rate standard (Scenario 3).