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

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Online Appendix

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:

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

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:

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

Defining policies RST and $RSNT$ as "trading" and "no trading" and defining $Q^r_s \equiv \sum_i \sum_t q^r_{sit}$, this equation implies:

$$Carbon^{RST}_s + Carbon^{RST}_{s'} = Q^{RST}_s \sigma_s + Q^{RST}_{s'} \sigma_{s'}$$

which can be rewritten as:

$$Carbon^{RST}_s + Carbon^{RST}_{s'} = \frac{Q^{RST}_s}{Q^{RSNT}_s} Carbon^{RSNT}_s + \frac{Q^{RST}_{s'}}{Q^{RSNT}_{s'}} Carbon^{RSNT}_{s'}.$$

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, $FMC^{CAT}_{si} = c_i + \beta_i p_{cs}$. Since $FMC^{CAT}_{si} \geq c_i = FMC^{BAU}_{si}$ for every s and i the electriciy price is higher under CATs than under no regulation.

Since $FMC^{RS}_{si} = c_i + (\beta_i - \sigma_s) p_{cs}$, it follows that $FMC^{RS}_{si} \leq FMC^{CAT}_{si}$ 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 $q^{CAT}_{sit} > q^{RS}_{sit}$ for some s, i, and t. First consider the case where $p^{CAT}_t > c_i + \beta_i \tau$. 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.[39]

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.[40]

[39] 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.

[40] This result could be stated more precisely.

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 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.[41] 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

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

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.[42] 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 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 $15\sigma_{B'}\tau - c_G - \beta_G\tau + c_C + \beta_C\tau$.[43]

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.[44]

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: $\pi_{sC}^{CAT} - \pi_{sC}^{E} = 2[(\beta_O - \beta_C)\tau - (c_G - c_C)]$. 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

[42]Generation is efficident in all other hours.

[43]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.

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

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 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.[45]

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.[46] 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

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

[46] 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.

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 incentives in Table D7 would look quite different.[47]

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,

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

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 $Bill^{CAT} = 15(c_O + \beta_O\tau) + 11(c_C + \beta_C\tau) + 7(c_G + \beta_G\tau) + 3(c_N + \beta_N\tau)$.

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 $\pi_{sN}^{CAT} = 2[c_O + \beta_O\tau + c_C + \beta_C\tau + c_G + \beta_G\tau - 3(c_N + \beta_N\tau)]$.[48]

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 $\pi_{sn}^{RS} = \pi_{sn}^{CAT}$.[49] These profits are illustrated in Table D3.

[48]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.

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

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 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 $c_C + (\beta_C - \sigma_B)\tau < c_G + \beta_G\tau < c_C + \beta_C\tau$.[50] 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

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

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 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 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 $\pi_{Ag}^{Mix} = \pi_{sg}^{CAT} - \sigma_B\tau - (c_C + \beta_C\tau - (c_G + \beta_G\tau))$. 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 $\pi_{An}^{Mix} = \pi_{sn}^{CAT} - 3\sigma_B\tau$.

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 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 $\pi_{Bo}^{Mix} = \sigma_B\tau$. 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 $\pi_{Bc}^{Mix} = \pi_{sc}^{CAT} + 3\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$. 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 $\pi_{Bg}^{Mix} = \pi_{sg}^{CAT} + 3\sigma_B\tau$. Finally, the nuclear generation is inframarginal in seven hours and in four of those hours a CAT generator is marginal so the price is higher by $\sigma_B\tau$. So the profit is $\pi_{Bn}^{Mix} = \pi_{sn}^{CAT} + 4\sigma_B\tau$.

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.[51] 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 $\pi \equiv \pi_O^{CAT} + \pi_G^{CAT} + \pi_C^{CAT} + \pi_N^{CAT} = \pi_O^{RS} + \pi_G^{RS} + \pi_C^{RS} + \pi_N^{RS}$. 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:

$$W_A^{Mix} + W_B^{Mix} = \pi_A^{Mix} + \pi_B^{Mix} + TR_A^{Mix} - Bill^{Mix} - (Carbon_A^{Mix} + Carbon_B^{Mix})\tau$$

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

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

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

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 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:

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

For state B, there is no tax revenue, so

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

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 percent 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.[52]

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.[53]

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

[52]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.

[53]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.

"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 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.[54]

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.[55] 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

[54]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.

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

region network consisting primarily of the 4 major subregions.[56] Figure E3 illustrates the areas covered by these regions. The states in white, plus California, constitute the U.S. participants in the WECC.

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 percent 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

[56]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.

generation within the set of modeled plants.[57]

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 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 percent of the load and of the non-CEMS generation is allocated to the AZNMNV sub-region, with the remaining 25 percent 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 nuclear 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

[57]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.

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	+ $0.92	+ $1.04	+ $2.55	+ $1.87	+ $1.94	+ $1.75	+ $1.04	+ $0.95
OR	$4.40	+ $0.16	+ $0.17	+ $0.21	+ $0.17	+ $0.18	+ $0.17	+ $0.13	+ $0.14
WA	$8.27	+ $0.31	+ $0.25	+ $0.28	+ $0.22	+ $0.31	+ $0.29	+ $0.21	+ $0.24
Coastal Total	$28.80	+ $1.40	+ $1.46	+ $3.04	+ $2.26	+ $2.44	+ $2.21	+ $1.38	+ $1.32
AZ	$6.94	+ $0.70	+ $0.36	+ $0.03	- $0.16	+ $0.06	- $0.21	+ $0.33	+ $0.29
CO	$3.40	- $0.27	+ $0.04	- $0.06	- $0.06	- $0.06	- $0.08	- $0.16	- $0.16
ID	$1.65	- $0.01	+ $0.07	+ $0.22	+ $0.24	+ $0.22	+ $0.23	+ $0.06	+ $0.05
MT	$1.70	+ $0.02	- $0.08	- $0.22	- $0.17	- $0.21	- $0.17	- $0.04	- $0.04
NM	$1.79	- $0.04	- $0.02	- $0.21	- $0.14	- $0.20	- $0.15	- $0.11	- $0.11
NV	$2.51	+ $0.03	+ $0.06	+ $0.15	+ $0.11	+ $0.17	+ $0.10	+ $0.02	+ $0.01
UT	$2.28	+ $0.17	+ $0.01	- $0.21	- $0.07	- $0.17	- $0.08	+ $0.09	+ $0.08
WY	$2.15	- $0.09	- $0.15	- $0.67	- $0.56	- $0.64	- $0.55	- $0.17	- $0.14
Inland Total	$22.41	+ $0.51	+ $0.28	- $0.97	- $0.81	- $0.82	- $0.91	+ $0.02	- $0.01
Transmission Profits	$0.18	+ $0.02	- $0.03	- $0.00	+ $0.14	+ $0.10	+ $0.12	- $0.09	- $0.08
Total	$51.39	+ $1.93	+ $1.71	+ $2.06	+ $1.58	+ $1.72	+ $1.42	+ $1.30	+ $1.23

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	+ $0.80	+ $0.95	- $0.61	- $0.74	- $0.87	- $0.88	+ $0.48	+ $0.43
OR	$1.99	+ $0.03	- $0.02	- $0.44	- $0.53	- $0.48	- $0.50	- $0.02	+ $0.01
WA	$4.02	+ $0.14	+ $0.03	- $0.86	- $1.01	- $0.85	- $0.90	- $0.05	+ $0.02
Coastal Total	$12.10	+ $0.96	+ $0.96	- $1.91	- $2.28	- $2.19	- $2.28	+ $0.41	+ $0.45
AZ	$2.77	+ $0.10	- $0.18	- $0.34	- $0.58	- $0.32	- $0.66	- $0.43	- $0.47
CO	$1.32	- $0.83	- $0.77	- $0.94	- $0.77	- $0.94	- $0.79	- $0.81	- $0.81
ID	$0.41	+ $0.03	+ $0.03	- $0.08	- $0.09	- $0.09	- $0.09	- $0.01	- $0.01
MT	$0.88	- $0.29	- $0.36	- $0.42	- $0.39	- $0.41	- $0.38	- $0.38	- $0.37
NM	$0.63	- $0.31	- $0.34	- $0.33	- $0.27	- $0.31	- $0.28	- $0.40	- $0.41
NV	$0.58	- $0.02	- $0.06	- $0.09	- $0.16	- $0.08	- $0.17	- $0.16	- $0.16
UT	$1.02	- $0.57	- $0.74	- $0.61	- $0.49	- $0.57	- $0.48	- $0.70	- $0.69
WY	$1.32	- $0.81	- $0.89	- $0.89	- $0.74	- $0.87	- $0.73	- $0.89	- $0.88
Inland Total	$8.92	- $2.70	- $3.31	- $3.70	- $3.48	- $3.59	- $3.59	- $3.78	- $3.80
Total	$21.02	- $1.73	- $2.35	- $5.60	- $5.76	- $5.77	- $5.87	- $3.37	- $3.34

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		Inland: Rate	
Coastal	CAT	+ $1.40	+ $0.51	+ $2.44	- $0.82
	Rate	+ $1.38	+ $0.02	+ $3.04	- $0.97

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		Inland: Rate	
Coastal	CAT	- $0.48	- $3.31	- $0.68	- $3.15
	Rate	+ $0.09	- $4.06	- $0.47	- $3.32

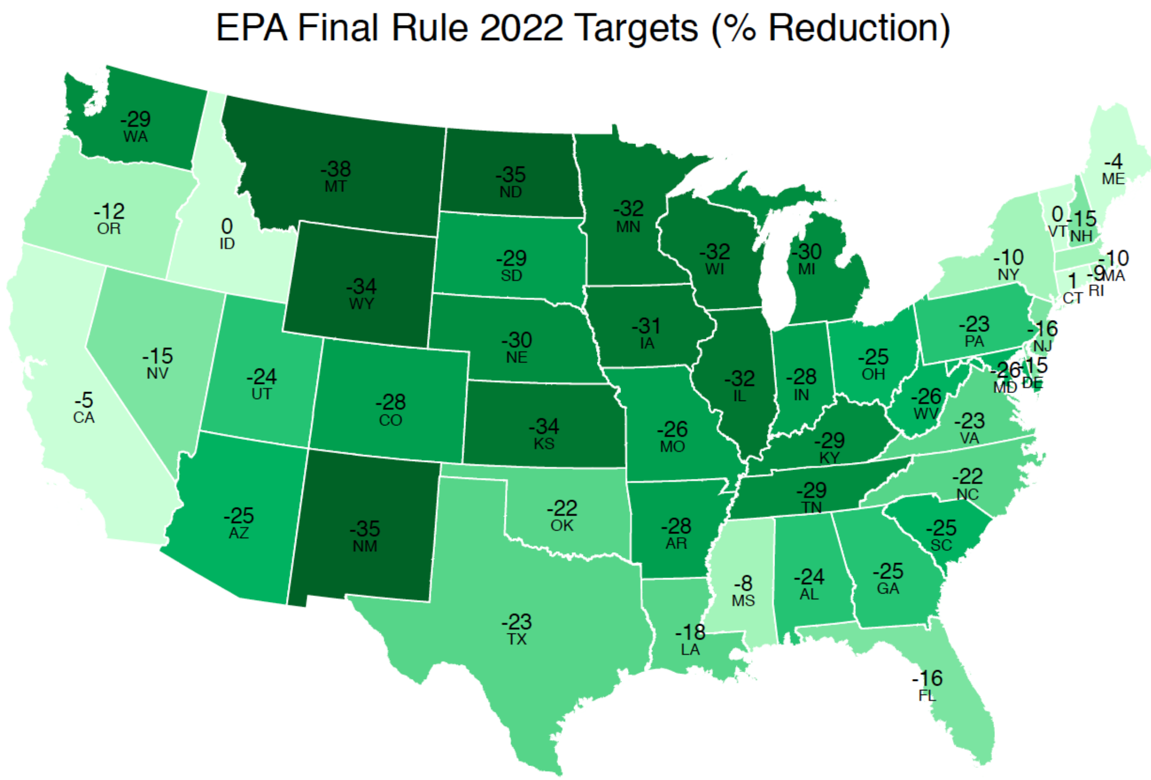
Notes: Profit is measured relative to business as usual (Scenario 0) in $ billion. "+" indicates an increase and "-" indicates a decrease.

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

		Inland: CAT		Inland: Rate	
Coastal	CAT	+ $1.44	+ $0.62	- $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.

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.

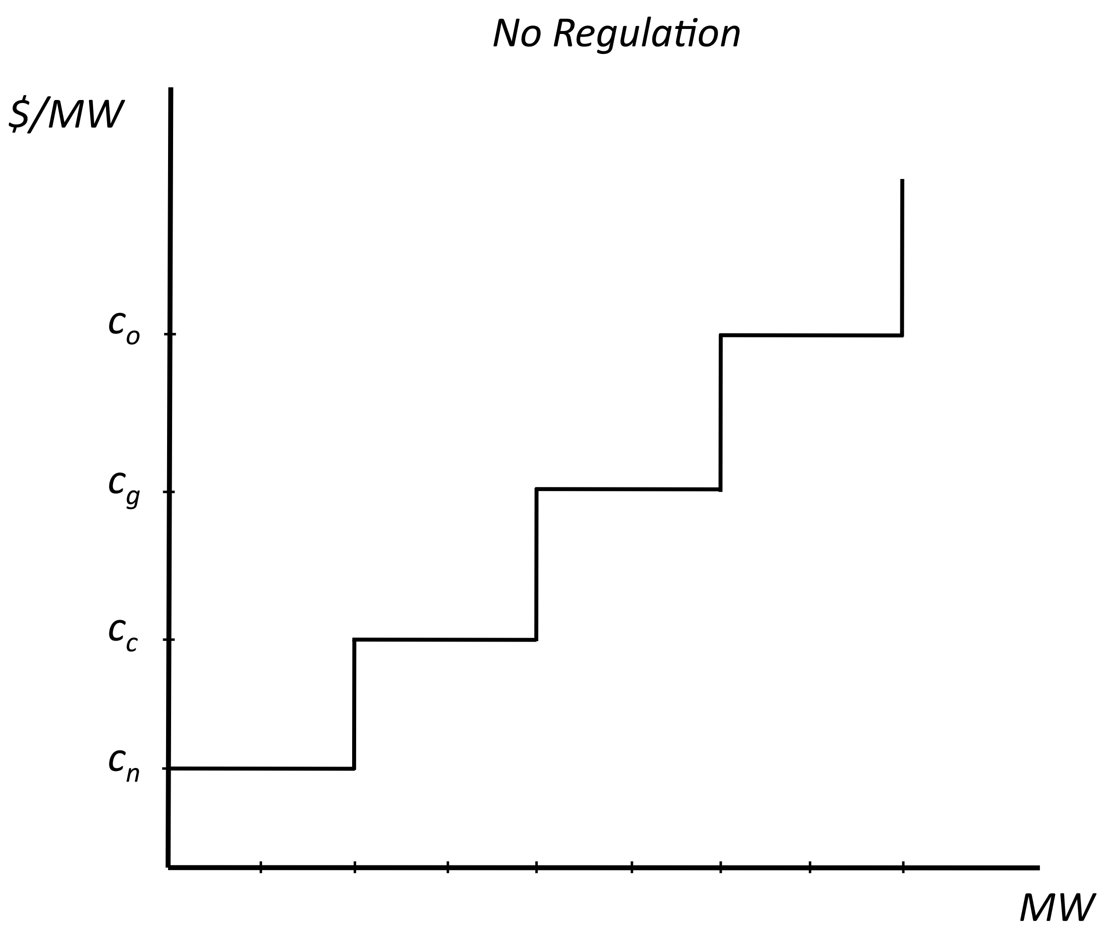


Figure E3. : Western regional electricity network and transmission constraints.

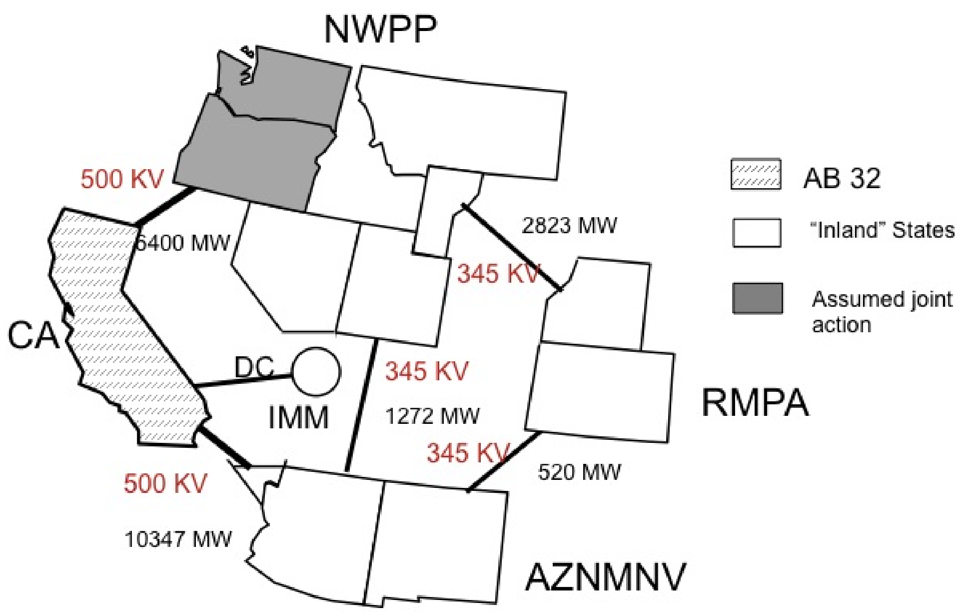
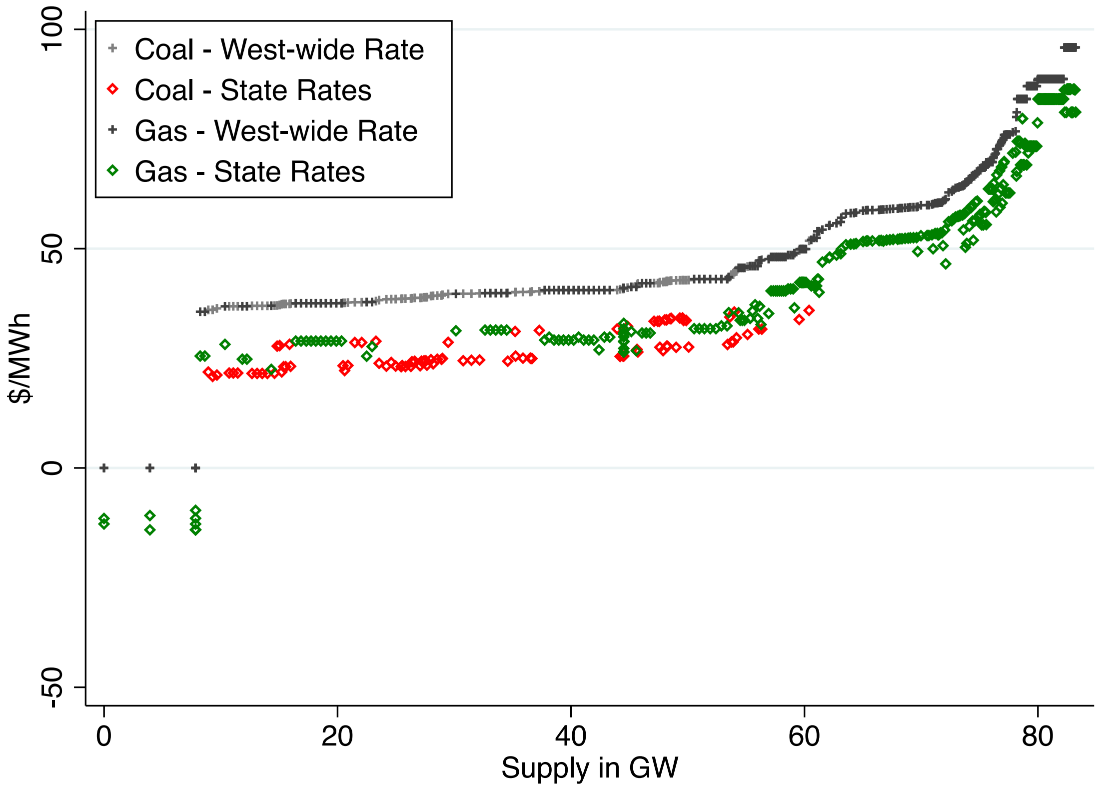


Figure E4. : Merit order under different regulations: West-wide rate standard and state-by-state rate standards.



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