Supplementary Appendices for Web Publication

A Proofs of Results

A.1 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.

A.2 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 $\sum_t \sum_i \beta_i q_{sit}^{CAT} + \sum_t \sum_i \beta_i q_{s'it}^{CAT} = E_s + E_{s'}$. which holds aggregate emissions constant at $E_s + E_{s'}$.

Trading between states with rate standards may cause aggregate emissions to increase or decrease. As shown in Eq. 2, 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. 2, 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.

A.3 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.

A.4 Proof of Result 4

Result 4 (*i*) follows by comparing full marginal costs under CAT and rate standards. Since the merit order is the same across the two scenarios, 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*) follows readily by noting that prices are lower under rate standards and hence equilibrium electricity generation is higher. If demand is prefectly inelastic, equilibrium electricity generation is unchanged.

Result 4 (*iii*) follows by noting that in the case of perfectly inelastic demand, prices and full marginal costs both differ in the two scenarios by exactly $\sigma\tau$; i.e., margins are equal. Because quantities are fixed and margins are identical across the scenarios, profits are equal across the scenarios for each technology. If demand is not perfectly inelastic, costs are lower by $\sigma\tau$ but prices are lower by at most $\sigma\tau$ under rate standards. Thus margins are higher under rate standards. Because quantities are also greater, profits cannot fall.

Result 4 (*iv*), (*v*), and (*vi*) follow because equal carbon prices and equal rate standards across the scenarios ensure that the merit order is identical across the scenarios. Fixed quantities under perfectly inelastic demand, then ensure that costs, carbon emissions, and welfare are identical across the scenarios. If demand is not perfectly inelastic, the higher quantities imply that quantities and costs are higher. The inefficiency of rate standards when demand is not perfectly inelastic, described in Corollary 1, implies that welfare is weakly greater under CATs.

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

A.5 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, becasue 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.[44]

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

[44]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.

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.[45]

B The four technology model

In this appendix, we illustrate the general model in Section 3 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 A.2. 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

[45]This result could be stated more precisely.

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 A.1 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.[46] 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 A.2. 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

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

of gas when demand is four MW.[47] 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 A.1. 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 scernario 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 $15\sigma_{B'}\tau - c_G - \beta_G\tau + c_C + \beta_C\tau$.[48]

Table A.2 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.[49]

Table A.3 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

[47]Generation is efficient in all other hours.

[48]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.

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

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 A.3) 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 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 A.4 for the efficient dispatch scenario and in Table A.5 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.[50]

With inefficient dispatch, the incentives, shown in Table A.5, 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 A.6 and A.7. 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.[51] 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

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

[51] 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.

profits.

From a consumer's perspective, as illustrated in Table A.2, 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 A.7 would look quite different.[52]

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.

B.1 The unregulated equilibrium

In the absence of carbon regulation, the supply curve is illustrated in Figure A.2, 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

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

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.

B.2 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 A.1. 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 $\pi^{CAT}_{sO} = 0$. Coal is inframarginal in two hours so $\pi^{CAT}_{sC} = 2[c_O + \beta_O\tau - (c_C + \beta_C\tau)]$. 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 $\pi_{sN}^{CAT} = 2[c_O + \beta_O\tau + c_C + \beta_C\tau + c_G + \beta_G\tau - 3(c_N + \beta_N\tau)]$.[53]

B.3 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 A.1.

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 A.1. 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 A.2.

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 $\pi_{sn}^{RS} = \pi_{sn}^{CAT}$.[54] These profits are illustrated in Table A.3.

[53] 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.

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

B.4 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.

B.4.1 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 A.4.

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.

B.4.2 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 $c_C + (\beta_C - \sigma_B)\tau < c_G + \beta_G\tau < c_C + \beta_C\tau$.[55] 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 A.1.

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 A.1.) Thus $Bill^{Mix} = Bill^{CAT} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$.

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

We next turn to the generator profits, which are listed in Table A.3. 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.[56] 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

[56] Intuitively, we spread carbon damages equally across the two 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 A.3 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:

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

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

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

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

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

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 A.5.

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.

C Details of numerical simulations

Investment in new capacity

In some scenarios we consider a medium-term time horizon where there is entry of new generation entry 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 production from 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.

C.1 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.[57] 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.[58]

C.2 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 production 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.[59] 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 A.8.

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

[57] Average values for demand by sub-region are given in Table ??.

[58] 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.

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

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.

C.3 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.[60] Figure A.3 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

[60] 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.

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 resulting PTDFs for our aggregated network is summarized in the appendix.

C.4 Hydro, renewable and other generation

Generation capacity and annual energy production for each of our regions is reported by technology type in Tables A.8 and A.9. We lack data on the hourly production 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 production 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 production within the set of modeled plants.[61]

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

[61] 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 production from "clean" sources is unlikely to change in the short-run. The production 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 production decisions.

of Nevada, where 75% of the load and of the non-CEMS production is allocated to the AZNMNV sub-region, with the remaining 25% being allocated to the NWPP sub-region.

C.5 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. Another is the distinction 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.

C.6 Additional results on supply side effects

Appendix Figure A.4 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, this merit order will be scrambled.

Appendix Tables

Table A.1: 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 A.2: 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	$Bill^{CAT}$	$Bill^{CAT} - TR^{CAT}$	$Bill^{CAT} - 16\sigma_B \tau$	$Bill^{CAT} - 15\sigma_{B'}\tau + c_G + \beta_G \tau - c_C - \beta_C$
TR	TR^{CAT}	0	$TR^{Mix}, 0$	$TR^{Mix'}, 0$

Table A.3: 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 A.4: 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 A.5: 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 A.6: 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 A.7: 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 A.8: 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 A.9: 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 A.10: Profit incentives for covered generation in the coastal and inland west.

		Inland	
		CAT	Rate
Coastal	CAT	+ $0.26 , - $2.74	- $0.26 , + $2.50
	Rate	+ $2.35 , - $1.50	+ $1.09 , - $2.19

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

Table A.11: Profit incentives for uncovered generation in the coastal and inland west.

		Inland	
		CAT	Rate
Coastal	CAT	+ $4.62 , + $1.74	+ $3.43 , + $1.11
	Rate	+ $5.36 , + $1.73	+ $0.03 , + $0.11

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

Table A.12: Future equilibrium outcomes with investment for business as usual and eight policy scenarios where new NGCC investment is included under the CPP.

	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)	$ 43.10	$ 59.57	$ 59.31	$ 38.05	$ 45.33	$ 36.59	$ 42.43	$ 50.66	$ 51.20
Electricity Quantity (GWh)	483,169	-11,278	-11,135	+3,365	-2,200	+4,178	+97	-4,966	-6,604
Emissions (MMT)	345.10	-51.21	-51.21	-49.17	-36.35	-29.61	-26.38	-32.12	-28.60
CAT Permit Price ($/MT)		$ 35.01	$ 34.88			$ 0.00	$ 9.62	$ 19.34	$ 18.81
Rate Permit Price ($/MT)				$ 35.80	$ 92.67	$ 32.70	$ 23.91	$ 236.75	$ 215.62
Consumer Surplus ($ bn.)	$ 501.42	- $13.03	- $12.89	+ $4.41	- $3.71	+ $5.18	+ $0.22	- $6.06	- $8.45
Covered Generator Profits ($ bn.)	$ 7.70	- $3.72	- $3.79	- $3.83	- $0.25	- $4.03	- $1.76	- $2.04	- $1.69
Uncovered Generator Profits ($ bn.)	$ 14.23	+ $5.38	+ $5.31	- $1.75	+ $1.23	- $2.15	- $0.04	+ $2.54	+ $3.25
Transmission Profits ($ bn.)	$ 0.22	- $0.18	- $0.12	- $0.18	+ $1.31	+ $0.14	+ $0.16	- $0.12	+ $1.24
Production Costs ($ bn.)	$ 16.18	+ $0.89	+ $0.88	+ $1.70	+ $0.91	+ $0.79	+ $0.74	+ $0.23	+ $0.12
Carbon Market Rev. ($ bn.)		+ $10.29	+ $10.21			+ $0.00	+ $0.56	+ $4.55	+ $4.42
Abatement Cost ($ bn.)		- $1.26	- $1.29	- $1.35	- $1.42	- $0.86	- $0.87	- $1.13	- $1.23
Avg. Abatement Cost ($/MT)		+ $24.62	+ $25.13	+ $27.42	+ $39.16	+ $29.00	+ $32.87	+ $35.25	+ $42.87
New Capacity (MW)	+4,517	+3,716	+4,108	+5,977	+9,046	+6,081	+5,087	+9,095	+10,333

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.

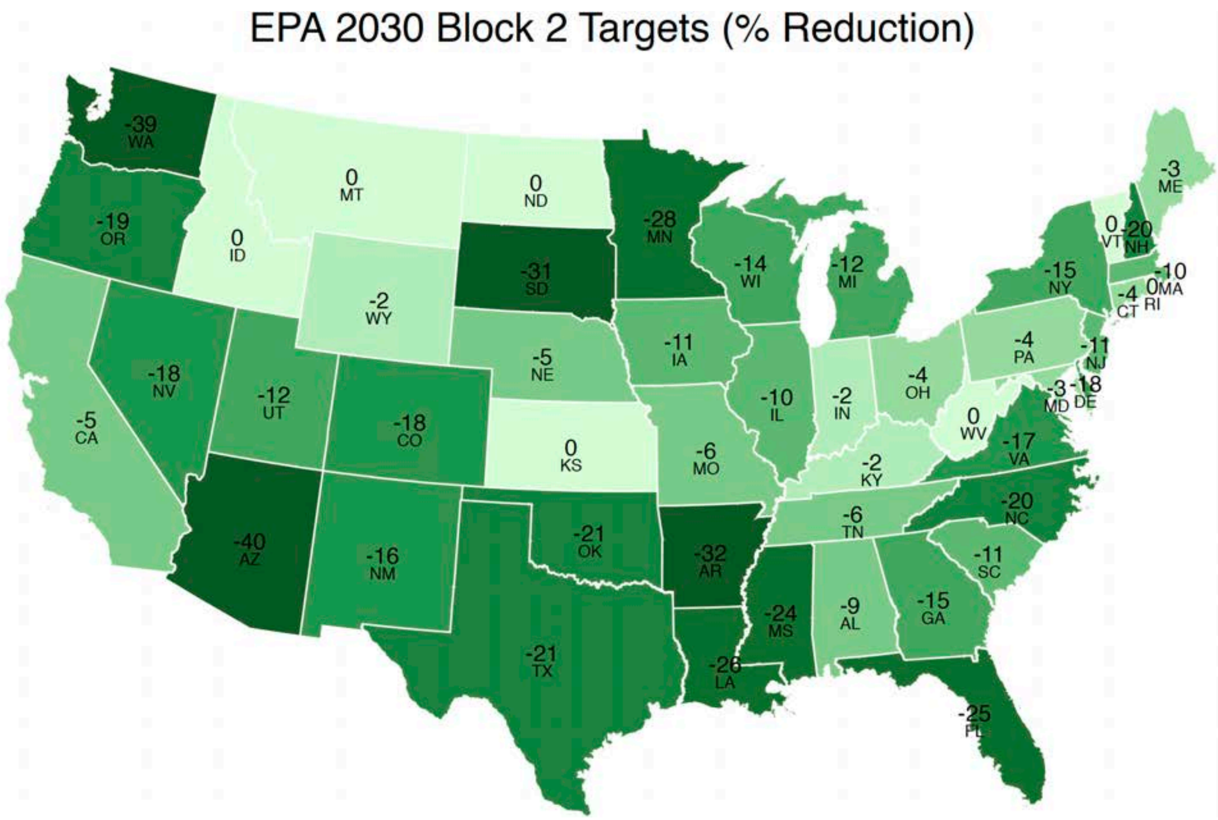
Table A.13: Future equilibrium outcomes with investment for business as usual and eight policy scenarios where new NGCC investment is *not* included under the CPP.

	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)	$ 43.10	$ 44.66	$ 44.40	$ 44.33	$ 44.81	$ 44.31	$ 44.49	$ 44.74	$ 45.04
Electricity Quantity (GWh)	483,169	-1,039	-1,034	-1,024	-1,040	-1,044	-1,045	-1,043	-1,034
Emissions (MMT)	345.10	-10.46	-16.20	-66.08	-68.44	-69.60	-59.22	-20.85	-19.47
CAT Permit Price ($/MT)		$ 16.20	$ 13.83			$ 11.52	$ 10.99	$ 16.24	$ 14.57
Rate Permit Price ($/MT)				$ 54.79	$ 86.80	$ 69.60	$ 84.46	$ 63.95	$ 111.48
Consumer Surplus ($ bn.)	$ 501.42	- $0.97	- $0.79	- $0.74	- $1.04	- $0.70	- $0.81	- $1.03	- $1.27
Covered Generator Profits ($ bn.)	$ 7.70	- $5.07	- $4.83	- $0.72	- $1.26	- $1.22	- $1.69	- $4.18	- $3.88
Uncovered Generator Profits ($ bn.)	$ 14.23	+ $0.40	+ $0.36	+ $0.35	+ $0.40	+ $0.34	+ $0.36	+ $0.42	+ $0.49
Transmission Profits ($ bn.)	$ 0.22	- $0.16	- $0.17	- $0.95	- $0.41	- $1.50	- $0.66	- $0.08	+ $0.18
Production Costs ($ bn.)	$ 16.18	- $0.42	+ $0.05	+ $2.82	+ $2.34	+ $2.23	+ $1.97	+ $0.08	- $0.03
Carbon Market Rev. ($ bn.)		+ $5.42	+ $4.94			+ $0.93	+ $0.87	+ $4.16	+ $3.71
Abatement Cost ($ bn.)		- $0.37	- $0.49	- $2.05	- $2.30	- $2.15	- $1.93	- $0.72	- $0.77
Avg. Abatement Cost ($/MT)		+ $35.60	+ $30.12	+ $31.07	+ $33.67	+ $30.91	+ $32.59	+ $34.33	+ $39.74
New Capacity (MW)	+4,517	+6,353	+4,822	+4,520	+10,600	+9,471	+8,671	+6,979	+8,229

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.

Appendix Figures

Figure A.1: EPA Clean Power Plan target reductions for 2030 from Building Block 2.



Note: Percentage reduction in lbs per MWh.

Figure A.2: Merit order in the 4 technology model without regulation.

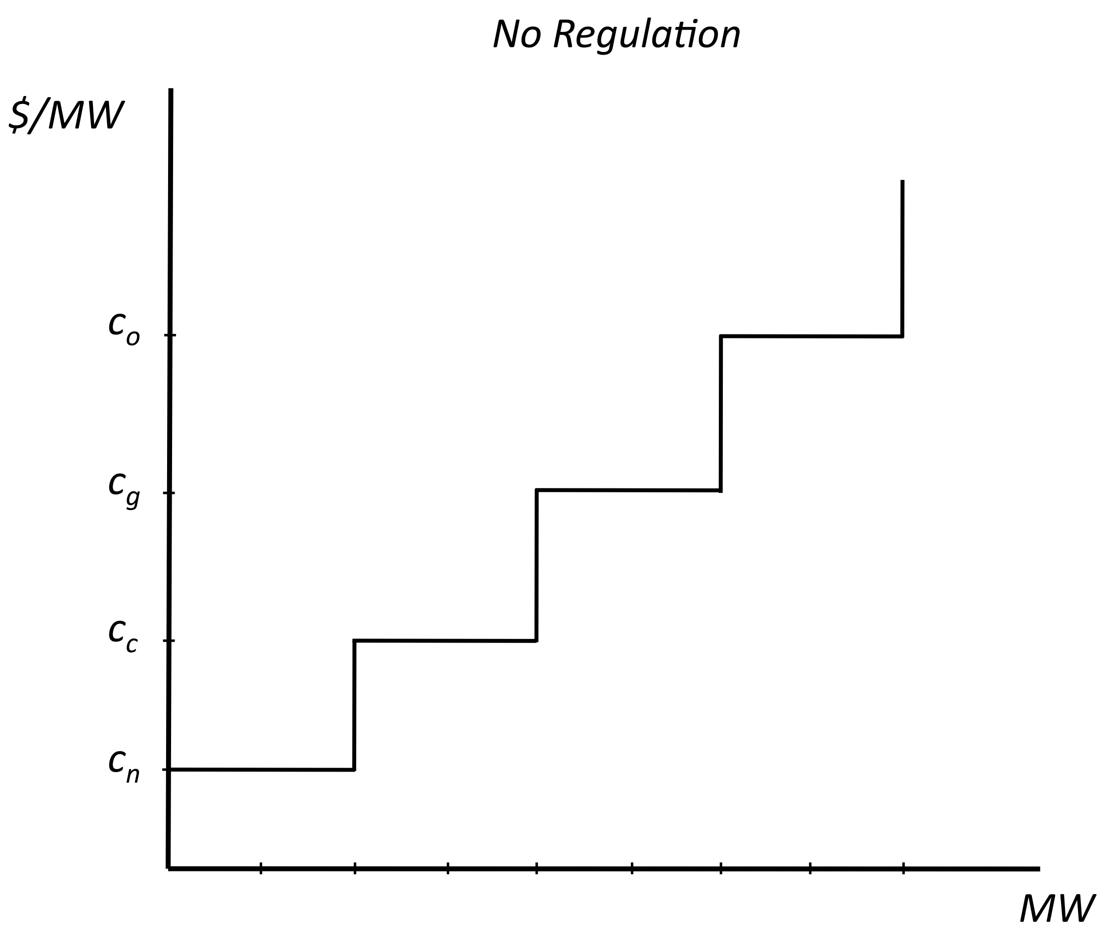


Figure A.3: Western regional electricity network and transmission constraints.

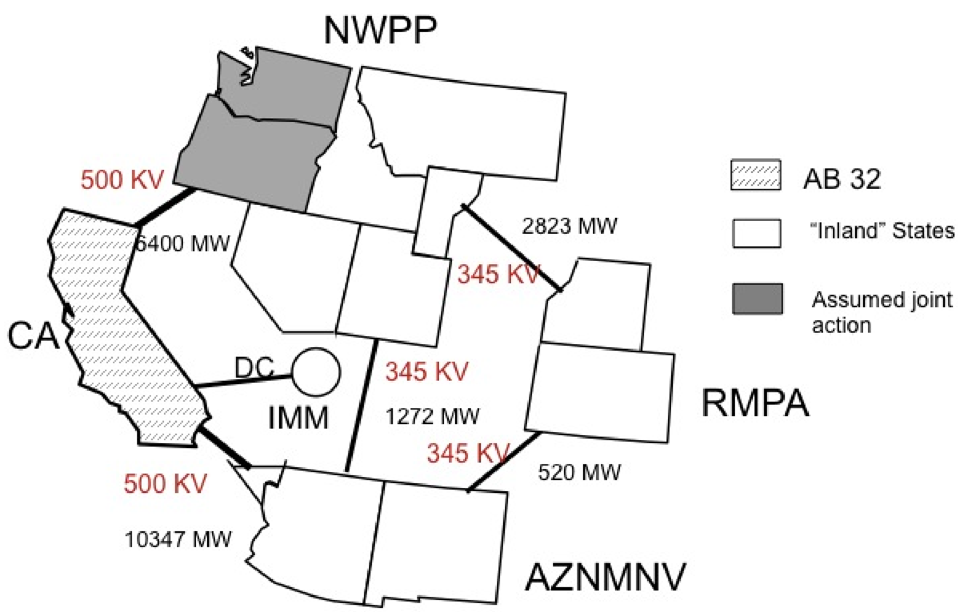
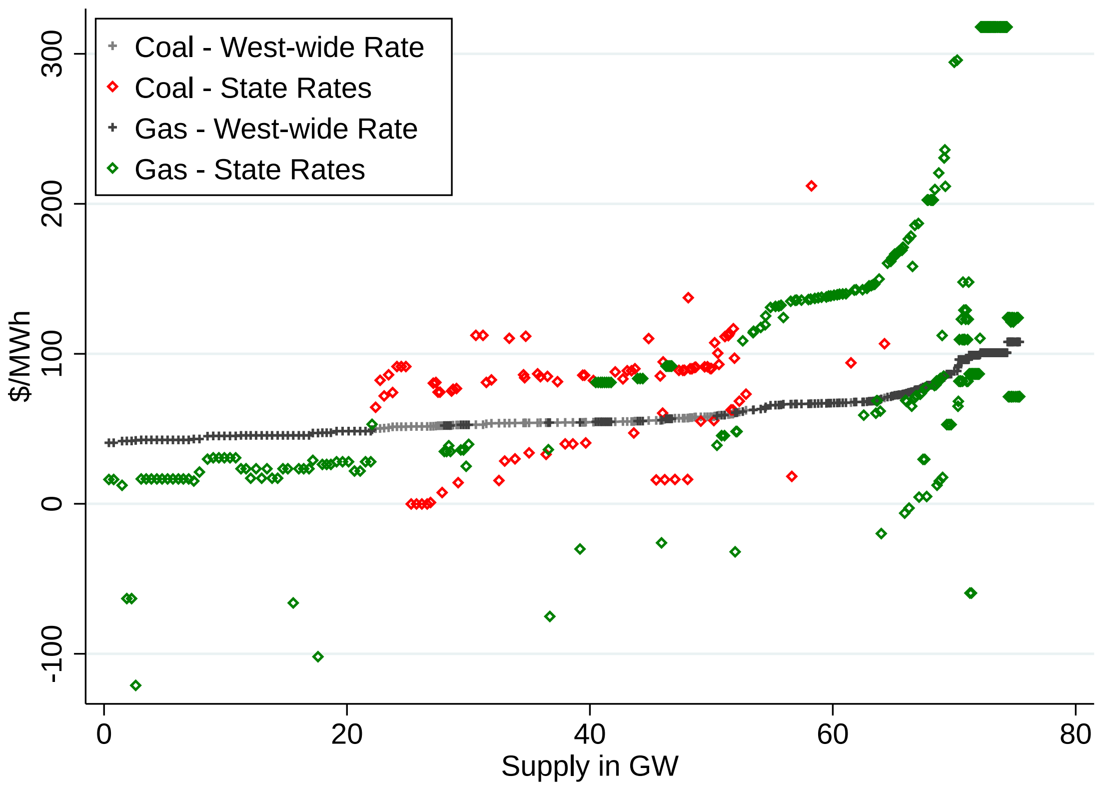
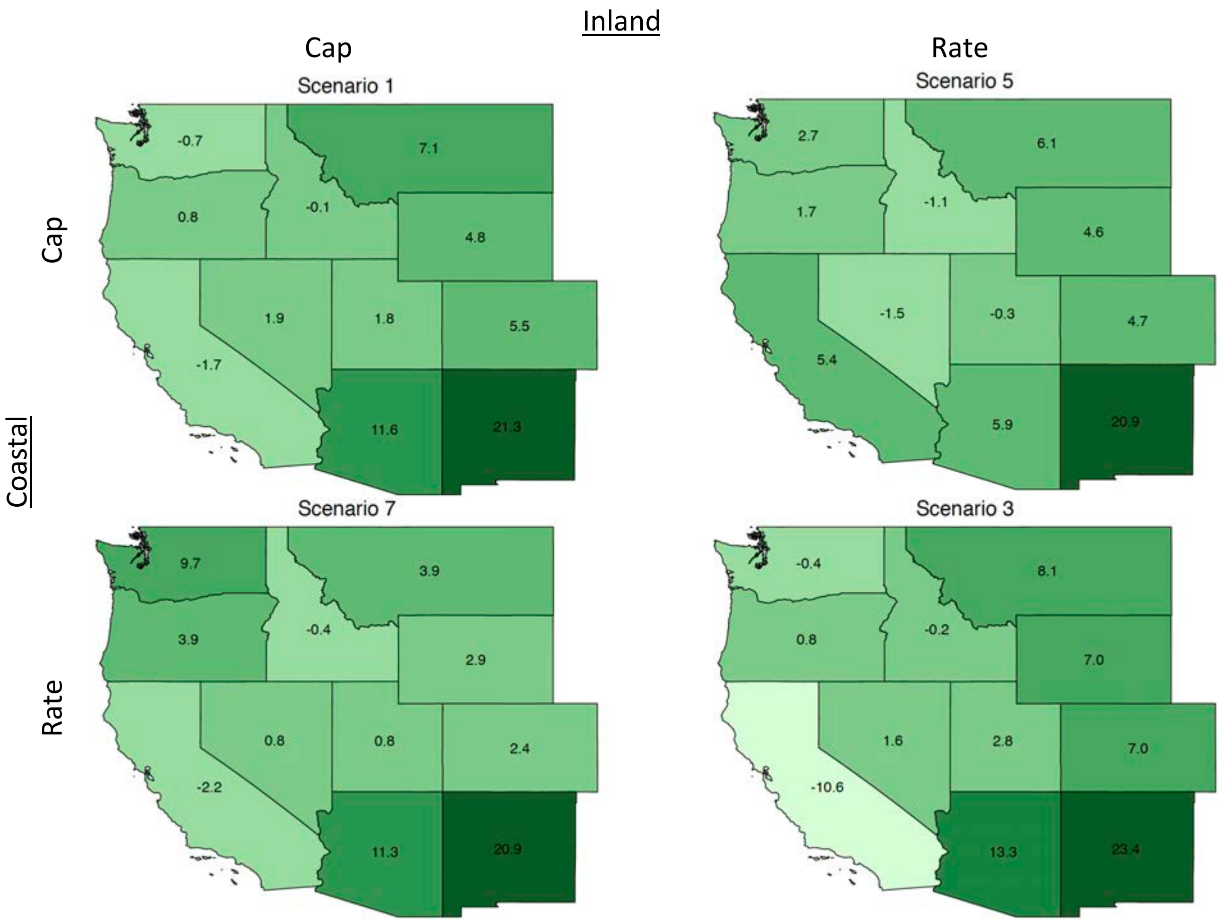


Figure A.4: Merit order under different regulations: west-wide rate standard and state-by-state rate standards.



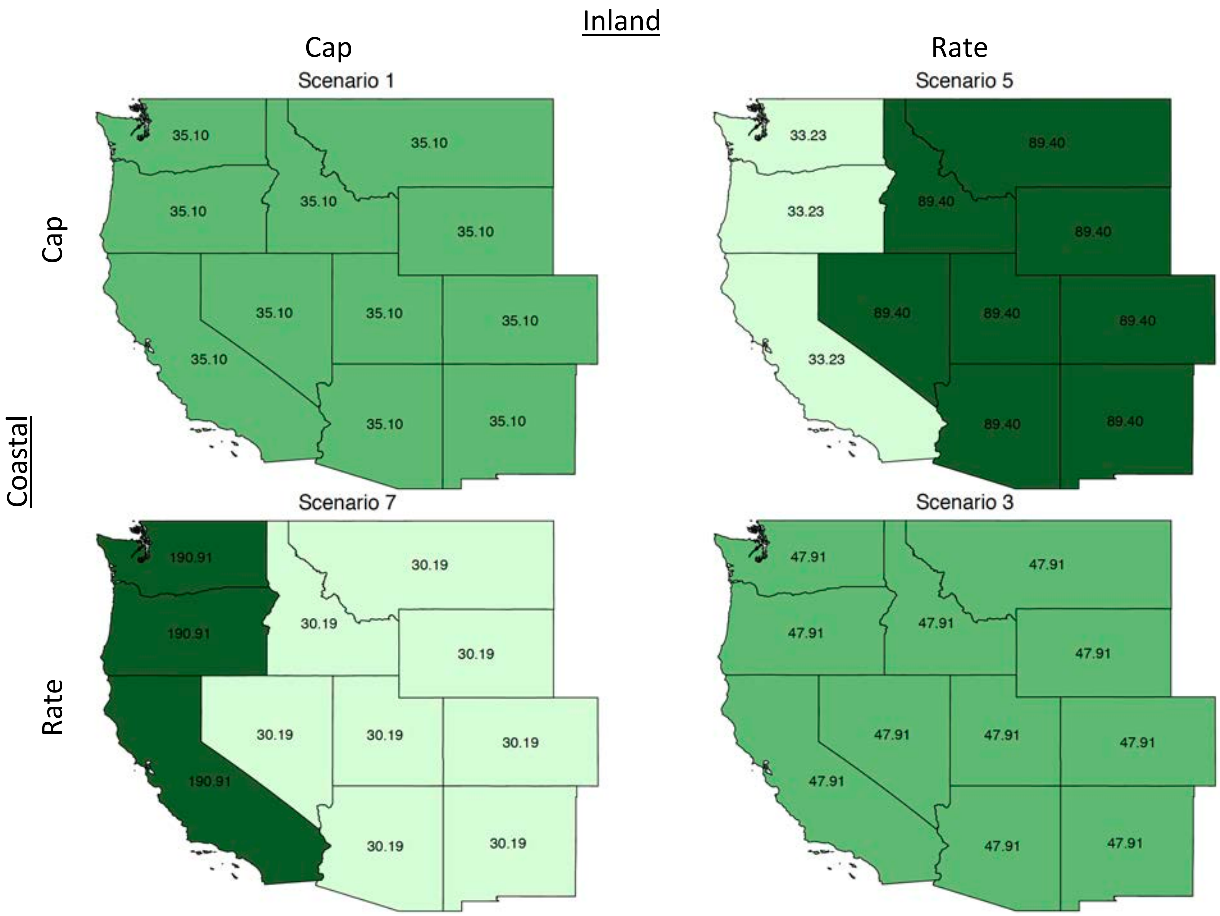
Note: Generating units sorted on x-axis by full-marginal costs under west-wide rate standard (Scenario 3).

Figure A.5: Carbon abatement under uniform and mixed regulation.



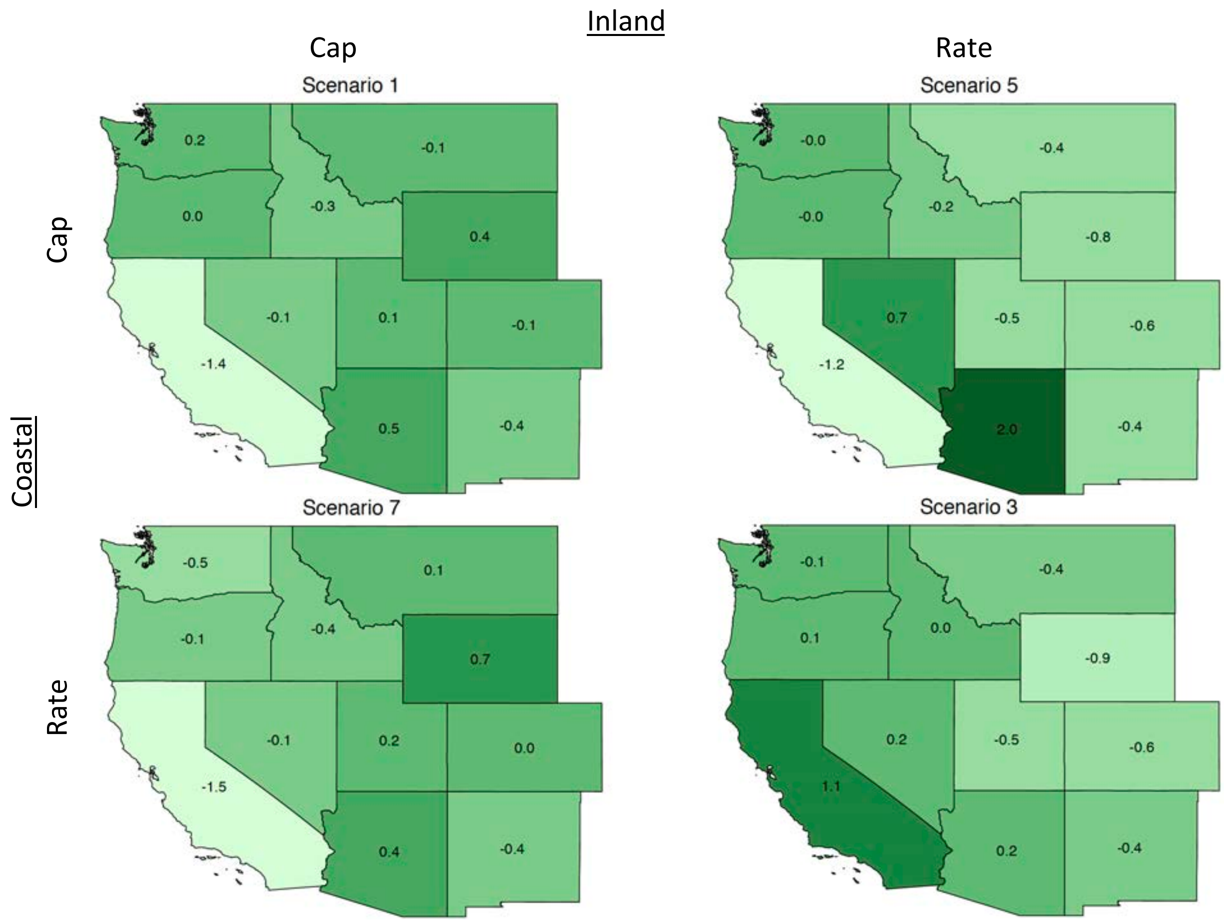
Note: Carbon abatement in million metric tons.

Figure A.6: Carbon prices under uniform and mixed regulation.



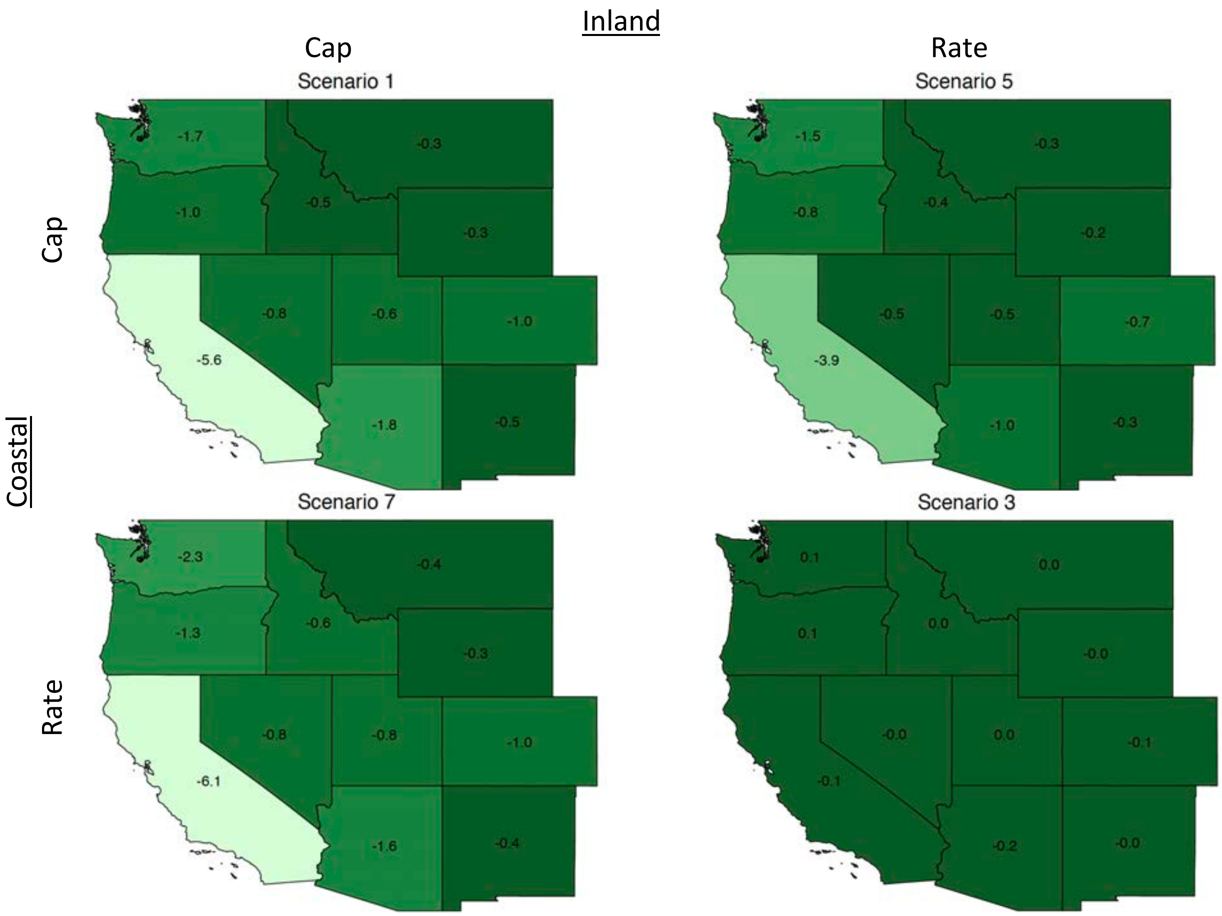
Note: Carbon prices in $ per ton.

Figure A.7: Abatement cost under uniform and mixed regulation.



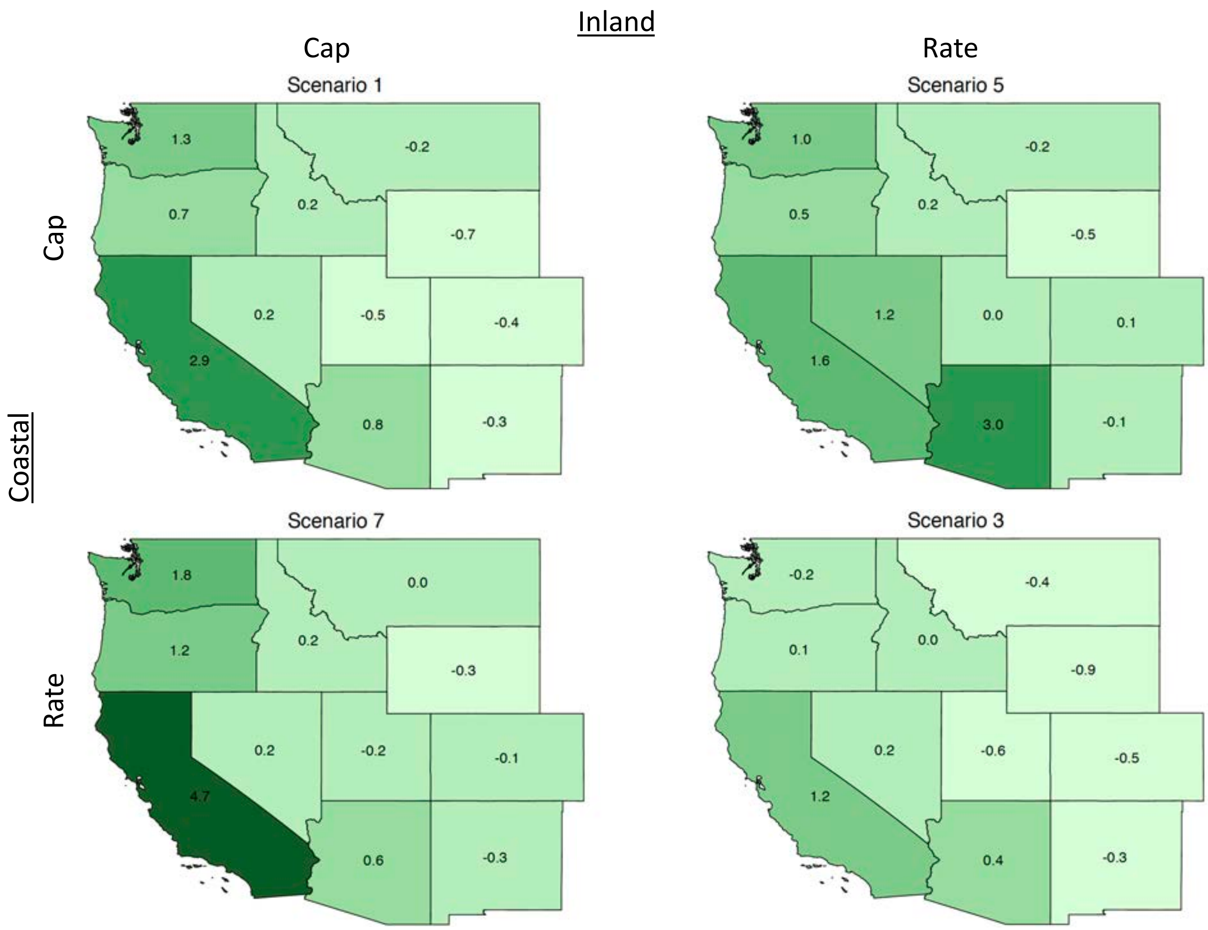
Note: Abatement cost in $ billion relative to BAU.

Figure A.8: Consumer surplus incentives under uniform and mixed regulation.



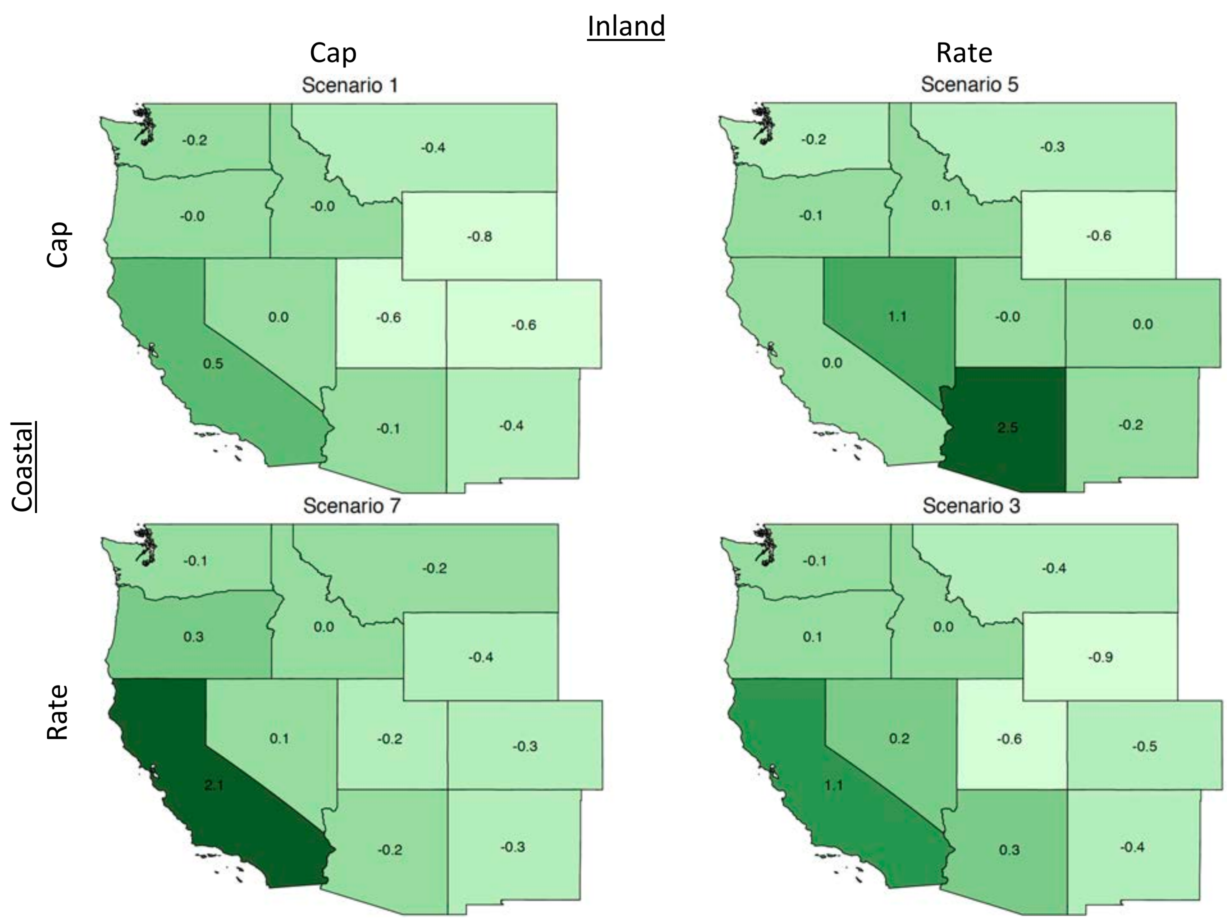
Note: Consumer surplus changes in $ billion relative to BAU.

Figure A.9: Profit incentives for all generation (covered and uncovered) under uniform and mixed regulation.



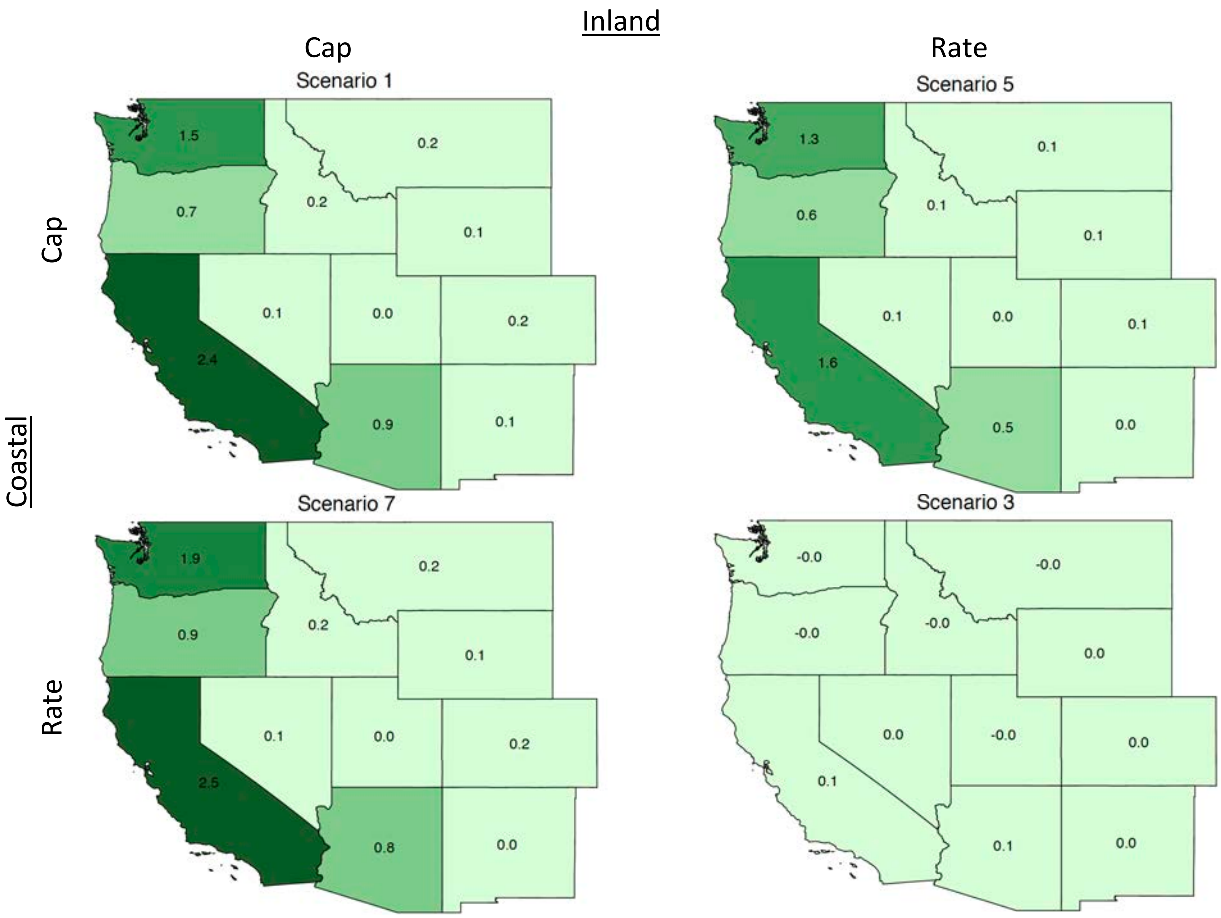
Note: Profit changes in $ billion relative to BAU.

Figure A.10: Profit incentives for covered generation under uniform and mixed regulation.



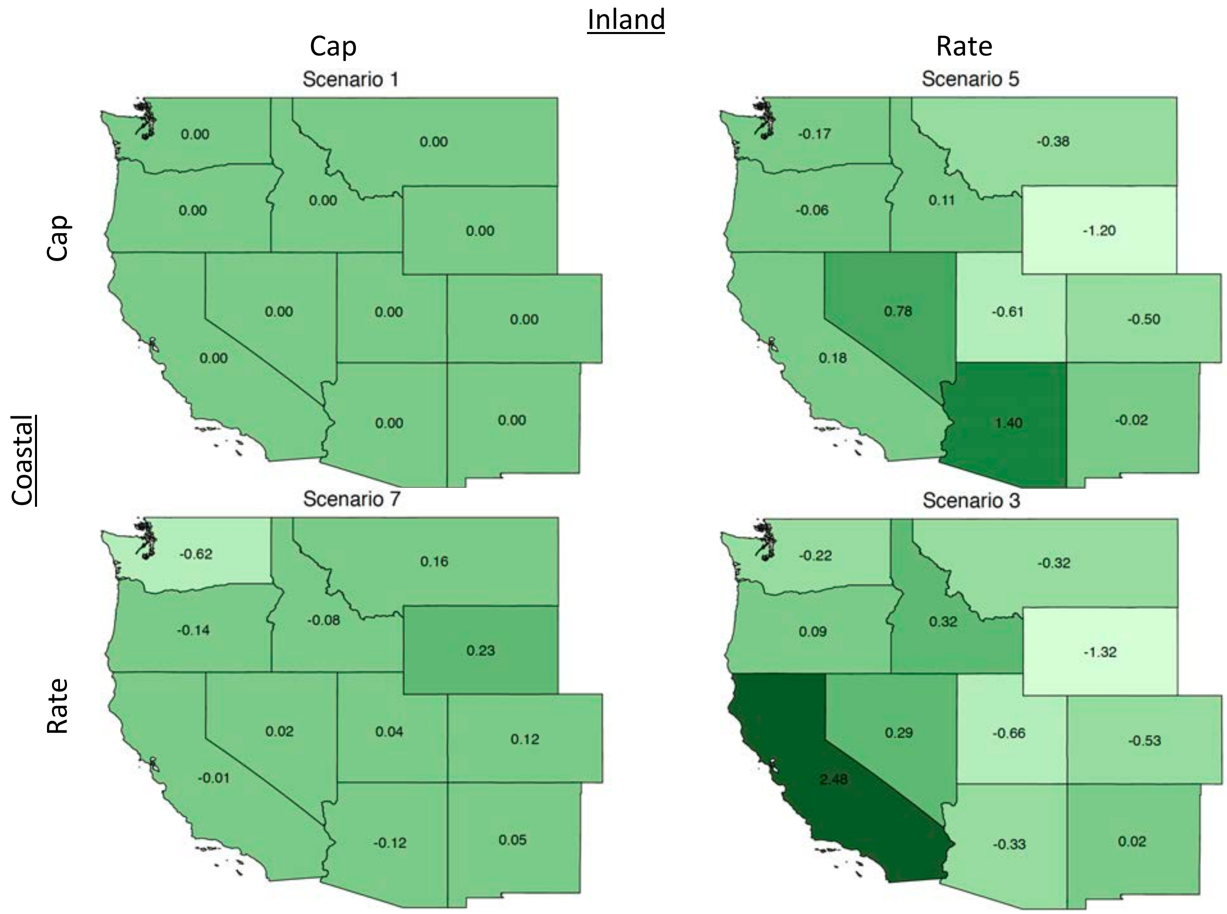
Note: Profit changes in $ billion relative to BAU.

Figure A.11: Profit incentives for uncovered generation under uniform and mixed regulation.



Note: Profit changes in $ billion relative to BAU.

Figure A.12: Deadweight loss under uniform and mixed regulation.



Note: Deadweight loss in $ billion relative to uniform CAT with carbon permit price and social cost of carbon equal to $35 per ton.