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

(Appendix B)

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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 Figure 1. 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 mass- or rate-based standards, we analyze three separate scenarios: both states adopt mass-based standards, both states adopt rate-based standards, and mixed regulation in which one state adopts a mass-based standard and the other state adopts a rate-based 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 Figures 1-6.

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 [1]. Table A.1 shows these electriciy 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-based standards, the full marginal costs are $\sigma\tau$ lower than the full marginal costs under mass-based standards, 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 mass-based prices.[35] 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-based standard is dispatched before gas under the mass-based standard.

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-based standard is dispatched before gas under the rate based standard. Thus one MW of coal is dispatched instead of one MW of gas when demand is four MW.[36] 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-based standards with the mass-based standards, we see that under the rate-based standards each of the 36 MWhs is purchased at a price which is lower by $\sigma\tau$. Because $\sigma = Carbon^{MB}/36$, the electricity bill is reduced by exactly the amount of carbon tax revenue which could have been collected under the mass-based standard. Similarly, comparing the prices for the scernario with mixed regulation and efficient dispatch with the mass-based standards, 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 mass-based standards, we see lower prices in three hours and a different price when consumption is four and five MWhs. Thus the bill is reduced by $15\sigma_{B'}\tau - c_G - \beta_G\tau + c_C + \beta_C\tau$.[37]

Table A.2 also shows the carbon tax revenue generated under the scenarios. A mass-based standard 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

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

[36] Generation is efficient in all other hours.

[37] 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.

Pareto improvement an actual Pareto improvement. A rate-based 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 mass-based standard has carbon market revenue, but the state with rate-based standard has no carbon market revenue.[38]

Table A.3 shows the profits per MW of capacity to each technology under the four scenarios. Under mass-based standards, 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 mass-based standard 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: $\pi_{sC}^{MB} - \pi_{sC}^{E} = 2[(\beta_O - \beta_C)\tau - (c_G - c_C)]$. 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 mass-based standard 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 mass-based standards, 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-based standards and under mass-based standards, 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 mass-based standard but state B adopts a rate-based 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 $\sigma_B\tau$.

[38] The carbon tax revenue is slightly larger in the scenario with efficient dispatch since carbon emissions in the mass-based state are higher.

Under efficient dispatch, generator profits can be directly compared to profits under mass- or rate-based standards. In state A, each technology is inframarginal in exactly the same hours as under mass-based standards. However, the electricity price is lower by $\sigma_B\tau$ whenever a rate-based 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 mass-based scenario. In state B, each technology is inframarginal in one additional hour relative to the scenario with rate-based standards. In addition, the electricity price is higher by $\sigma_B\tau$ whenever a mass-based 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-based scenario (which is equivalent to the mass-based 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 mass-based or rate based standards. 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 mass- or rate-based standards, the total surplus is simply split equally between the two states. However if one state adopts a rate-based standard when the other state adopts a mass-based standard, then the state with the rate-based 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 mass-based standard, then it has an incentive to adopt a rate-based 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*-based standard, then it has an incentive to also adopt a rate-based standard (to avoid losing the additional surplus). Thus each state has an incentive to adopt a rate-based standard no matter what the other state is adopting, i.e., adopting a rate-based standard is a dominant strategy.[39]

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

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-based standard no matter what the other state is adopting, i.e., adopting a rate-based 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-based standard is better from a generator's perspective no matter what the other state adopts, i.e., a rate-based standard is a dominant strategy.[40] Thus we could expect generators to lobby for rate-based 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 mass-based standard in one state and a rate-based standard in the other state. Alternatively, a firm in one state might offer side payments to a firm in another state. Since the distributional effect is not zero sum, profits are sufficient that one generator could sufficiently compensate the other for any lost profits.

From a consumer's perspective, as illustrated in Table A.2, the electricity bills are clearly lowest under a rate-based standard. However, from the perspective of tax revenue, a mass-based standard is clearly preferred, since the rate-based 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.[41]

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

From the perspective of social welfare, adoption of a rate-based standard is a dominant

[40] 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.

[41] Would mass-based by a dominant strategy if the firms got all the revenue? What if tax revenue went to both consumers and firms?

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, mass-based, rate-based and mixed scenarios. As before, Figures 1-6 of the main text illustrate the intuition behind these calculations.

B.1 The Unregulated Equilibrium

In the absence of carbon regulation, the supply curve is illustrated in Figure 1, and the electricity price in each hour is determined by [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.

B.2 Both States Adopt Mass-Based Regulation

Assume now that generators in both states are subject to a mass-based standard. As before assume that the mass-based standard 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 mass-based standard will change the merit order so that gas-fired generation is dispatched before coal-fired generation. The new merit order is illustrated in Figure 3.

The electricity price is now set by [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 $Bill^{MB} = 15(c_O + \beta_O\tau) + 11(c_C + \beta_C\tau) + 7(c_G + \beta_G\tau) + 3(c_N + \beta_N\tau)$.

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

We next turn to profit per MW. Oil is always marginal so $\pi_{sO}^{MB} = 0$. Coal is inframarginal in two hours so $\pi_{sC}^{MB} = 2[c_O + \beta_O\tau - (c_C + \beta_C\tau)]$. Gas is inframarginal in four hours so profit is $\pi_{sG}^{MB} = 2[c_O + \beta_O\tau + c_C + \beta_C\tau - 2(c_G + \beta_G\tau)]$, and nuclear is inframarginal in six hours so profits are $\pi_{sN}^{MB} = 2[c_O + \beta_O\tau + c_C + \beta_C\tau + c_G + \beta_G\tau - 3(c_N + \beta_N\tau)]$.[42]

B.3 Both States Adopt Rate-Based Regulation

Now assume that both states are subject to a rate-based standard. As above, assume that the rate-based standard is set such that the carbon price is τ, so the rate-based standard dispatches gas-fired generation before coal-fired generation. The new merit order is illustrated in Figure 4. Note that since demand is perfectly inelastic, the rate-based 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-based standard. Importantly, this reduces carbon costs for all technologies. The electricity prices for each hour are found from [1] and are shown in Table A.1.

[42] 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.

Because the merit order under the rate-based standard is identical to the merit order under the mass-based standard and because demand is perfectly inelastic, the rate-based standard results in the same carbon emissions and electricity generation as the mass-based standard. Thus $Carbon^{RB} = Carbon^{MB}$ and $Cost^{RB} = Cost^{MB}$, i.e., the abatement costs and carbon reductions are identical when both states adopt rate-based or mass-based 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 mass-based standard. Thus the electricity bill is $Bill^{RB} = Bill^{MB} - 36\sigma_s \tau$ because each of the 36 MWhs is purchased at a lower price. Note that since $\sigma_s = Carbon^{RB}/36$, this implies that $Bill^{RB} = Bill^{MB} - TR^{MB}$. 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-based 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 mass-based standard. However, the generator's carbon costs are also reduced by $\sigma_s \tau$ relative to the mass-based standard. Thus: $\pi_{so}^{RB} = \pi_{so}^{MB} = 0$, $\pi_{sc}^{RB} = \pi_{sc}^{MB}$, $\pi_{sg}^{RB} = \pi_{sg}^{MB}$, and $\pi_{sn}^{RB} = \pi_{sn}^{MB}$.[43] These profits are illustrated in Table A.3.

B.4 Mixed Adoption of Mass- and Rate-Based Regulation

Now assume that state A adopts a mass-based standard and state B adopts a rate-based 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-based coal is dispatched before mass-based 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.

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

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 $c_C + (\beta_C - \sigma_B)\tau > c_G + \beta_G\tau$. Note in particular, that the merit order is no longer efficient since all coal is dispatched after all gas.

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 mass-based technology is always dispatched before the rate-based 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 mass- or rate-based 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 mass-based prices, we see the consumers purchase 11 MWhs at a discount of $\sigma_{B'}\tau$ when oil, gas, and nuclear generation subject to rate-based regulation are on the margin. Thus $Bill^{Mix'} = Bill^{MB} - 16\sigma_{B'}\tau$.

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 mass-based standards. 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 mass-based standard, but in the other hour the marginal oil-fired generator is subject to a rate-based 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 mass-based profit, i.e., $\pi_{Ac}^{Mix'} = \pi_{sc}^{MB} - \sigma_{B'}\tau$. The gas-fired generator is inframarginal in four hours. In two of these hours the marginal generator is subject to a rate-base standard, so the price is lower by $\sigma_{B'}\tau$. Thus the gas-fired generator's profits are $\pi_{Ag}^{Mix'} = \pi_{sg}^{MB} - 2\sigma_{B'}\tau$. 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-base standard, so the profits are $\pi_{An}^{Mix'} = \pi_{sn}^{MB} - 3\sigma_{B'}\tau$.

Now consider the generators in state B subject to rate-based regulation. Again, we can compare them to profits when both states adopt mass- or rate-based regulation 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-based oil fired generation is on the margin; and in two of the hours it earns additional profit of $\sigma_{B'}\tau$ since a mass-based generator is on the margin and the price is higher. Thus the profits are $\pi_{Bc}^{Mix'} = \pi_{sc}^{MB} + 2\sigma_{B'}\tau$. Next turn to the gas-fired generator. This generator is inframarginal in five hours. In three of those hours, a mass-based generator is marginal so the price is higher by $\sigma_{B'}\tau$. So the profit is $\pi_{Bg}^{Mix'} = \pi_{sg}^{MB} + 3\sigma_{B'}\tau$. Finally, the nuclear generation is inframarginal in seven hours and in four of those hours a mass-based generator is marginal so the profit is $\pi_{Bn}^{Mix'} = \pi_{sn}^{MB} + 4\sigma_{B'}\tau$.

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

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

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

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

For state B, there is no tax revenue, so

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

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

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

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 $c_C + (\beta_C - \sigma_B)\tau < c_G + \beta_G\tau < c_C + \beta_C\tau$.[44] The new merit order is illustrated in Figure 6. Note in particular, that the merit order is no longer efficient since rate-based coal is dispatched before mass-based 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 [1] or [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-based prices or the mass-based prices. Comparing to the mass-based prices, we see the consumers purchase 11 MWhs at a discount of $\sigma_B\tau$ when oil, gas, and nuclear generation subject to rate-based regulation are on the margin. When rate-based 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 mass-based 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 $Bill^{Mix} = Bill^{MB} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$.

We next turn to the generator profits, which are listed in Table 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 mass-based standards. 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 mass-based standard, but in the other hour the marginal oil-fired generator is subject to a rate-based 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 mass-based profit, i.e., $\pi_{Ac}^{Mix} = \pi_{sc}^{MB} - \sigma_B\tau$. The gas-fired generator is inframarginal in three hours. In one of these hours the marginal generator is subject to

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

a rate-base 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 mass-based standard. Thus the gas-fired generator's profits are $\pi^{Mix}_{Ag} = \pi^{MB}_{sg} - \sigma_B\tau - (c_C + \beta_C\tau - (c_G + \beta_G\tau))$. The nuclear generator in state A is inframarginal in six hours, and in three of those hours the marginal generator is subject to a rate-base standard, so the profits are $\pi^{Mix}_{An} = \pi^{MB}_{sn} - 3\sigma_B\tau$.

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

Before turning to the distribution of surplus across the policies, we first analyze total welfare. We define a state's *welfare*, W as the sum of producer surplus and consumer surplus plus any tax revenue less half of carbon damages.[45] 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 mass-based or a rate-based 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 $W_s \equiv \pi^{MB} - Bill^{MB}/2$ where $\pi \equiv \pi^{MB}_O + \pi^{MB}_G + \pi^{MB}_C + \pi^{MB}_N = \pi^{RB}_O + \pi^{RB}_G + \pi^{RB}_C + \pi^{RB}_N$. Note that for the mass-based standard, the tax revenue exactly offsets the carbon damanges and for the rate-based standard, the reduced electricity bill exactly offsets the carbon damages.

Under mixed regulation, Table A.3 shows that total profits exceed profits under mass- or rate-based standards by $6\sigma_B\tau + 2(c_G + \beta_G\tau - c_C - \beta_C\tau)$. We also showed above that

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

$Bill^{Mix} = Bill^{MB} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau$. This implies that:

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

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

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

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

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

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 mass-based regulation, welfare is the sum of profit and tax revenue less its electricity bill and carbon damages. Thus we have:

$$W_A^{Mix} = \pi - 5\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau + TR_A^{Mix} - (Bill^{MB} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau)/2$$

$$- (Carbon_A^{Mix} + Carbon_B^{Mix})\tau/2$$

$$= W_s + \frac{5}{2}\sigma_B\tau + (c_G + \beta_G\tau - c_C - \beta_C\tau)/2 + (Carbon_A^{Mix} - Carbon_B^{Mix})\tau/2$$

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

For state B, there is no tax revenue, so

$$W_B^{Mix} = \pi + 11\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau - (Bill^{MB} - 15\sigma_B\tau + c_G + \beta_G\tau - c_C - \beta_C\tau)/2$$

$$- (Carbon_A^{Mix} + Carbon_B^{Mix})\tau/2$$

$$= W_s + \frac{37}{2}\sigma_B\tau + (c_G + \beta_G\tau - c_C - \beta_C\tau)/2 - (Carbon_A^{Mix} + Carbon_B^{Mix})\tau/2$$

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

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.

Appendix Tables

Table A.1: Prices in different hours under the four scenarios.

MW	Mass-based standards	Rate-based standards	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.

	Mass-based standards	Rate-based standards	Mixed regulation: efficient dispatch	Mixed regulation: inefficient dispatch
Cost	$Cost^{MB}$	$Cost^{MB}$	$Cost^{MB}$	$Cost^{MB} - (c_G - c_C)$
Carbon	$Carbon^{MB}$	$Carbon^{MB}$	$Carbon^{MB}$	$Carbon^{MB} + (\beta_C - \beta_G)$
Bill	$Bill^{MB}$	$Bill^{MB} - TR^{MB}$	$Bill^{MB} - 16\sigma_B \tau$	$Bill^{MB} - 15\sigma_{B'}\tau + c_G + \beta_G \tau - c_C - \beta_C \tau$
TR	TR^{MB}	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	Mass-based standards	Rate-based standards	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 mass-based standard and State B adopts a rate-based standard.

Table A.4: Comparison of welfare in each state across the policies: efficient dispatch.

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

Table A.5: Comparison of welfare in each state across the policies: inefficient dispatch.

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

Table A.6: Comparison of each state's profit across the policies: efficient dispatch.

	Mass-based	Rate-based
Mass-based	π π	. .
Rate-based	$\pi + 10\sigma_B\tau$ $\pi - 6\sigma_B\tau$	π π

Table A.7: Comparison of each state's profit across the policies: inefficient dispatch.

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