

Online Appendix:
Federal Coal Program Reform, the Clean Power Plan,
and the Interaction of Upstream and Downstream Climate Policies

TODD D. GERARDEN, W. SPENCER REEDER, JAMES H. STOCK

Appendix A

This appendix presents the analytical results behind the comparative statics presented graphically in Section 3. The treatment of Section 3 is expanded to four fuels: federal coal (*FC*), non-federal coal (*NFC*), other covered sources (*O*), and uncovered generation (*U*) that is not covered by emissions regulation. We consider a royalty surcharge r on federal coal under (a) mass-based cap-and-trade and (b) rate-based regulation with tradable allowances. We also show that a quantity cap on federal coal yields outcomes equivalent to a royalty surcharge in this simple static model. An expanded treatment, including special cases, welfare results, and the optimal level of the royalty surcharge, appears in the working paper version of this paper (Gerarden, Reeder, and Stock 2016).

We model production decisions by a representative firm that takes prices and maximizes profits.¹ We assume that: generation costs from each source are additively separable, increasing, and convex in production; marginal cost curves are weakly increasing in output; electricity demand curves weakly slope down; and all quantities are positive in equilibrium.

Federal and non-federal coal are assumed to have the same CO₂ emissions rate per MWh of generation; *O* is assumed to have a lower emissions rate which is a fraction λ of the emissions rate of coal (as is the case for natural gas). Uncovered generation (*U*) has an emissions rate λ_U that is lower than coal but not necessarily the same as the other covered sources. Units of the royalty surcharge and tradable allowance prices are the units of p (\$/MWh). Units of emissions is the amount of CO₂ emitted to generate one MWh by coal.

¹ This approach is similar to that taken by Holland et al. (2009) in the context of a low carbon fuel standard. Fischer and Newell (2008) use this approach in the context of multiple policy instruments and fuels with different carbon intensities. We also took an alternative approach, deriving comparative statics from “reduced-form” inverse demand and supply curves as is common in public finance for studying tax incidence. Horowitz and Linn (2015) employ this alternative approach to study the effects of technological change under rate-based regulation. See the Appendix of Gerarden, Reeder, and Stock (2016) for details.

A.1. Mass-Based Regulation with Uncovered Sources

Because U is uncovered, its emissions do not count towards the mass cap. Thus the mass cap constraint is,

$$q_{FC} + q_{NFC} + \lambda q_O \leq \bar{E}. \quad (1)$$

The representative firm maximizes profits subject to the constraint (1). The firm has revenue pQ , cost $C_i(q_i)$ for generation source i , and pays royalties $r q_{FC}$ on generation from federal coal. Thus the firm's constrained maximization problem is,

$$\max_{q_{FC}, q_{NFC}, q_O, q_U, t} pQ - \sum_i C_i(q_i) - r q_{FC} - t(q_{FC} + q_{NFC} + \lambda q_O - \bar{E}), \quad (2)$$

where the summation extends over all four sources. We consider the case that the mass cap is binding, so the price of the tradable allowance is t .

Quantity and price effects.—The firm's four first order conditions (with respect to q_{FC} , q_{NFC} , q_O , and q_U) determine equilibrium quantities and allowance prices given r when the cap is binding. It is shown at the end of this section that differentiating that system of equations with respect to r yields the following comparative statics results:

$$\frac{dp}{dr} = \frac{\lambda(1-\lambda)C''_{NFC}C''_U p'}{\Delta} \leq 0 \quad (3)$$

$$\frac{dt}{dr} = \left[\frac{(1-\lambda)C''_U p' - C''_O(C''_U - p')}{\lambda(1-\lambda)C''_U p'} \right] \frac{dp}{dr} \leq 0 \quad (4)$$

$$\frac{dq_{FC}}{dr} = \left[\frac{(1-\lambda)^2 C''_U p' - (C''_O + \lambda^2 C''_{NFC})(C''_U - p')}{\lambda(1-\lambda)C''_{NFC}C''_U p'} \right] \frac{dp}{dr} \leq 0 \quad (5)$$

$$\frac{dq_{NFC}}{dr} = \left[\frac{C''_O(C''_U - p') - (1-\lambda)^2 C''_U p'}{\lambda(1-\lambda)C''_{NFC}C''_U p'} \right] \frac{dp}{dr} \geq 0 \quad (6)$$

$$\frac{dq_O}{dr} = \left[\frac{C''_U - p'}{(1-\lambda)C''_U p'} \right] \frac{dp}{dr} \geq 0 \quad (7)$$

$$\frac{dq_U}{dr} = \frac{1}{C''_U} \frac{dp}{dr} \leq 0 \quad (8)$$

$$\frac{dQ}{dr} = \frac{1}{p'} \frac{dp}{dr} \geq 0, \quad (9)$$

where $p' = dp/dQ$ (the slope of the demand curve), $C'_{FC} = dC_{FC}(q_{FC})/dq_{FC}$ and so forth, and $\Delta = (C''_{FC}C''_O + C''_{NFC}C''_O + \lambda^2 C''_{FC}C''_{NFC})(C''_U - p') - (1 - \lambda)^2 (C''_{FC} + C''_{NFC})C''_U p' \geq 0$.

The price and quantity effects in (3) - (9) generalize those in Figure 3c to multiple fuels and uncovered sources. The increase in the relative price of coal shifts generation to non-federal coal and other, so the total generation from covered sources increases because the emissions constraint is binding and generation is from a cleaner mix. Thus, the prices of electricity and tradable allowances fall. With a lower allowance price, both non-federal coal generation and other generation increase even though the price of electricity declines. The lower electricity price provides less reward for uncovered generation (which gets no benefit from the decline in the tradable permit price), so uncovered generation falls. On net, total generation increases.

Emissions effects.—Total emissions include all sources:

$$E = q_{FC} + q_{NFC} + \lambda q_O + \lambda_U q_U. \quad (10)$$

Although emissions from covered sources are subject to a binding cap and thus do not change with r , emissions from uncovered sources change as r changes:

$$\frac{dE}{dr} = \frac{dq_{FC}}{dr} + \frac{dq_{NFC}}{dr} + \lambda \frac{dq_O}{dr} + \lambda_U \frac{dq_U}{dr} = \lambda_U \frac{dq_U}{dr} \leq 0, \quad (11)$$

where the second equality in (11) follows from the fact that the cap fixes total emissions from covered sources. The change in emissions from all sources depends only on the response of uncovered sources. The decline in the price of electricity reduces uncovered generation, so emissions decline. In effect, increasing the royalty surcharge reduces leakage under a partial mass cap.

Derivation of (3) - (9). Let \dot{p} denote dp/dr , etc. Differentiating with respect to r the four first order conditions for the constrained maximization (2), the binding emissions constraint (1), the demand curve $p = p(Q)$, and the identity $Q = q_{FC} + q_{NFC} + q_O + q_U$ yields,

$$0 = \dot{p} - C''_{FC} \dot{q}_{FC} - \dot{t} - 1 \quad (12)$$

$$0 = \dot{p} - C''_{NFC} \dot{q}_{NFC} - \dot{t} \quad (13)$$

$$0 = \dot{p} - C''_O \dot{q}_O - \lambda \dot{t} \quad (14)$$

$$0 = \dot{p} - C''_U \dot{q}_U \quad (15)$$

$$0 = \dot{q}_{FC} + \dot{q}_{NFC} + \lambda \dot{q}_O \quad (16)$$

$$0 = \dot{p} - p' \dot{Q} \quad (17)$$

$$\dot{Q} = \dot{q}_{FC} + \dot{q}_{NFC} + \dot{q}_O + \dot{q}_U. \quad (18)$$

Equations (12) - (18) are a system of seven equations in seven unknowns. It is convenient to solve the system by reducing it to two equations in two unknowns, \dot{p} and \dot{i} . First, premultiply (12) – (15) respectively by $C''_{NFC} C''_O C''_U$, $C''_{FC} C''_O C''_U$, $C''_{FC} C''_{NFC} C''_U$, and $C''_{FC} C''_{NFC} C''_O$, sum the result, use the identity (18) to eliminate the individual quantities, then use (17) to eliminate \dot{Q} . Second, premultiply (12) – (14) respectively by $C''_{NFC} C''_O$, $C''_{FC} C''_O$, and $\lambda C''_{FC} C''_{NFC}$, sum the result, and use (16) to eliminate the individual quantities. The result is a pair of equations for \dot{p} and \dot{i} :

$$0 = (C''_{NFC} C''_O C''_U + C''_{FC} C''_O C''_U + C''_{FC} C''_{NFC} C''_U + C''_{FC} C''_{NFC} C''_O) \dot{p} - (C''_{NFC} C''_O C''_U + C''_{FC} C''_O C''_U + C''_{FC} C''_{NFC} C''_U + \lambda C''_{FC} C''_{NFC} C''_O) \dot{i} - C''_{NFC} C''_O C''_U \quad (19)$$

$$0 = (C''_{NFC} C''_O + C''_{FC} C''_O + \lambda C''_{FC} C''_{NFC}) \dot{p} - (C''_{NFC} C''_O + C''_{FC} C''_O + \lambda^2 C''_{FC} C''_{NFC}) \dot{i} - C''_{NFC} C''_O. \quad (20)$$

Equations (19) and (20) can be solved to yield (3) and (4). Equation (9) is equation (17). The derivatives for the individual quantities obtain by direct substitution, for example (5) obtains by substituting (3), (4), and (9) into (12).

A.2. Rate-Based Regulation with Uncovered Sources

A rate-based standard regulates the emissions rate or, equivalently, sets an emissions limit that is proportional to total generation by covered sources. Let R denote the rate standard, which we assume is set between the emission rates for coal and other so that $\lambda \leq R < 1$. The rate-based standard, which only includes covered sources, is thus $q_{FC} + q_{NFC} + \lambda q_O \leq R(q_{FC} + q_{NFC} + q_O)$. Rearranging this rate limit gives $(1-R)q_{FC} + (1-R)q_{NFC} + (\lambda-R)q_O \leq 0$ or,

$$q_{FC} + q_{NFC} + \tilde{\lambda} q_O \leq 0, \quad (21)$$

where $\tilde{\lambda} = (\lambda-R)/(1-R) \leq 0$. Thus in the case of two emission rates, coal and other, the rate standard mandates a fractional mix between generation by coal and by other.

The representative firm maximizes profits subject to (21):

$$\max_{q_{FC}, q_{NFC}, q_O, q_U} pQ - \sum_i C_i(q_i) - rq_{FC} - t(q_{FC} + q_{NFC} + \tilde{\lambda}q_O), \quad (22)$$

where the summation extends over all four fuels.

Mathematically, the only differences between the rate problem (22) and the mass problem (2) are that λ in (2) is replaced by $\tilde{\lambda}$ and that \bar{E} in (2) takes on the value of zero. Because \bar{E} does not enter the comparative statics expressions, the comparative statics results for the mass case with leakage apply directly to the rate case with leakage, with λ replaced by $\tilde{\lambda}$. Because λ and $\tilde{\lambda}$ have different signs, the signs of several of the comparative statics expressions change, so we summarize them here.

Quantity and price effects.—Substitution of $\tilde{\lambda}$ for λ in (3) – (18) yields,

$$\frac{dp}{dr} = \frac{\tilde{\lambda}(1-\tilde{\lambda})C''_{NFC}C''_U p'}{\tilde{\Delta}} \geq 0 \quad (23)$$

$$\frac{dt}{dr} = \left[\frac{(1-\tilde{\lambda})C''_U p' - C''_O(C''_U - p')}{\tilde{\lambda}(1-\tilde{\lambda})C''_U p'} \right] \frac{dp}{dr} \leq 0 \quad (24)$$

$$\frac{dq_{FC}}{dr} = \left[\frac{(1-\tilde{\lambda})^2 C''_U p' - (C''_O + \tilde{\lambda}^2 C''_{NFC})(C''_U - p')}{\tilde{\lambda}(1-\tilde{\lambda})C''_{NFC}C''_U p'} \right] \frac{dp}{dr} \leq 0 \quad (25)$$

$$\frac{dq_{NFC}}{dr} = \left[\frac{C''_O(C''_U - p') - (1-\tilde{\lambda})^2 C''_U p'}{\tilde{\lambda}(1-\tilde{\lambda})C''_{NFC}C''_U p'} \right] \frac{dp}{dr} \geq 0 \quad (26)$$

$$\frac{dq_O}{dr} = \left[\frac{C''_U - p'}{(1-\tilde{\lambda})C''_U p'} \right] \frac{dp}{dr} \leq 0 \quad (27)$$

$$\frac{dq_U}{dr} = \frac{1}{C''_U} \frac{dp}{dr} \geq 0 \quad (28)$$

$$\frac{dQ}{dr} = \frac{1}{p'} \frac{dp}{dr} \leq 0 \quad (29)$$

where $\tilde{\Delta} = (C''_{FC}C''_O + C''_{NFC}C''_O + \tilde{\lambda}^2 C''_{FC}C''_{NFC})(C''_U - p') - (1-\tilde{\lambda})^2 (C''_{FC} + C''_{NFC})C''_U p' \geq 0$.

The comparative statics follow the results in the two-fuel supply and demand discussion in Section 3. As in the mass-based case, an increase in the royalty surcharge makes federal coal more

expensive, inducing a shift to non-federal coal. As long as it binds, the rate standard fixes the ratio of coal to gas. The royalty surcharge increases the marginal cost of all coal and thus of electricity, so the price of electricity increases and production falls. The higher electricity price induces more uncovered generation. Because the marginal cost of coal increases, the price of the tradable permit falls.

Emissions effects.—Emissions are given by (10), which can be rewritten as $E = (1 - R)(q_{FC} + q_{NFC} + \tilde{\lambda}q_U) + RQ + (\lambda_U - R)q_U$. The first term in this expression is zero under the binding rate constraint (21). Thus the effect on emissions of a change in r is,

$$\frac{dE}{dr} = R \frac{dQ}{dr} + (\lambda_U - R) \frac{dq_U}{dr}. \quad (30)$$

The two terms in (30) represent the two channels whereby the royalty surcharge affects emissions under rate regulation with leakage. The first is the total demand effect, which is negative because $dQ/dr \leq 0$ by (29). The second is the effect on generation by uncovered sources. Because uncovered generation increases with r , this term leads to emissions reductions if the emissions rate of uncovered sources is less than the rate standard and vice versa.

A.3. Restrictions on the Quantity of Federal Coal Production

An alternative policy is to impose a quantity cap on the amount of coal that could be mined from federal lands through quantity restrictions on new federal coal leases. Modifying the analysis above for such a policy entails dropping the terms involving the royalty rate and adding the quantity constraint $q_{FC} \leq \bar{q}_{FC}$. In the simple setup here, price regulation and quantity regulation yield the same comparative statics. That is, $dp/d\bar{q}_{FC} = (dp/dr)/(dq_{FC}/dr)$, where $dp/d\bar{q}_{FC}$ is the price comparative statics under the quantity restriction case and the derivatives with respect to r are those derived above, and so forth for Q , t , and the individual fuel quantities.

Appendix B

Table B.1: IPM Results: Comparison of the Primary and Secondary Base Cases

	Primary Base Case			Secondary Base Case		
	No surcharge	20% SCC	100% SCC	No surcharge	20% SCC	100% SCC
	A. No CPP			A. No CPP		
Emissions (MMT)	2,010	1,956	1,750	2,289	2,236	1,890
Relative to No CPP, no surcharge (within base case)	-	-2.7%	-12.9%	-	-2.3%	-17.4%
PRB production (MST)	318	242	11	430	344	23
Total coal production (MST)	765	711	500	1113	1055	736
Wholesale electricity price (\$/MWh)	\$57.20	\$57.96	\$61.12	\$53.40	\$54.74	\$58.67
Allowance price						
North Central	-	-	-	-	-	-
South Central	-	-	-	-	-	-
Southeast	-	-	-	-	-	-
Generation (1000 GWh)						
Solar+Wind	378	382	394	244	245	270
New NGCC	334	383	638	352	415	856
	B. CPP mass-based			B. CPP mass-based		
Emissions (MMT)	1,652	1,642	1,562	1,657	1,649	1,582
Relative to No CPP, no surcharge (within base case)	-17.8%	-18.3%	-22.3%	-27.6%	-28.0%	-30.9%
PRB production (MST)	264	172	9	283	205	33
Total coal production (MST)	583	549	450	747	717	608
Wholesale electricity price (\$/MWh)	\$61.86	\$60.97	\$58.83	\$66.53	\$64.88	\$61.07
Allowance price						
North Central	\$17.92	\$11.38	\$0.00	\$27.53	\$20.18	\$0.00
South Central	\$23.48	\$18.19	\$0.27	\$28.51	\$20.22	\$0.00
Southeast	\$14.77	\$11.38	\$7.18	\$25.75	\$23.49	\$20.73
Generation (1000 GWh)						
Solar+Wind	410	402	388	308	291	263
New NGCC	254	265	402	561	585	765
	C. CPP rate-based			B. CPP rate-based		
Emissions (MMT)	1,660	1,621	1,534	1,673	1,660	1,574
Relative to No CPP, no surcharge (within base case)	-17.4%	-19.4%	-23.7%	-26.9%	-27.5%	-31.2%
PRB production (MST)	281	173	9	267	186	25
Total coal production (MST)	622	568	461	737	705	594
Wholesale electricity price (\$/MWh)	\$53.81	\$55.02	\$55.19	\$57.40	\$58.21	\$60.03
Allowance price						
North Central	\$21.43	\$15.64	\$0.00	\$41.82	\$36.35	\$33.26
South Central	\$21.58	\$15.75	\$0.00	\$42.11	\$36.60	\$27.18
Southeast	\$21.75	\$15.87	\$0.00	\$42.44	\$36.89	\$33.75
Generation (1000 GWh)						
Solar+Wind	460	445	430	337	321	293
New NGCC	113	166	333	283	326	554

Notes: All results are for 2030. Source: IPM simulations by ICF. See Section 4 for a discussion of the assumptions used in each base case.