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The relationship between policy choice and the size of the policy region: Why small jurisdictions may prefer renewable energy policies to reduce CO_2 emissions

Megan H. Accordino[*] and Deepak Rajagopal[†][‡]

Abstract

We analyze how the size of the policy jurisdiction affects policy choice for the goal of reducing carbon dioxide (CO_2) emissions from electric power generation. We compare three policies, a CO_2 tax, a clean energy standard (CES) and a renewable portfolio standard (RPS). For emissions reduction targets achievable under all three policies, a CO_2 tax is the most cost-effective policy, while an RPS is the least cost-effective. However, when the policy region does not cover the entire market, an RPS can achieve larger reductions in CO_2 emissions than can a CES or CO_2 tax. The smaller the policy region, the larger the difference between the maximum emissions reduction achievable by an RPS and that achievable by a CES or CO_2 tax. For a sufficiently small policy region, only a renewables-based policy reduces global emissions. This provides one rationale for small jurisdictions to prefer a renewables-based policy over a pollution-based policy.

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1 Introduction

Electric power generation is the single largest source of carbon dioxide (CO_2) emissions in the U.S., accounting for 40 percent of CO_2 emissions in 2010 (EPA, 2012, Table 2-1). Furthermore, several studies show that it is cost-effective to first target CO_2 emission reduction in the electricity sector (EPA, 2008; EIA, 2009). As a result, this sector is often the focus of efforts aimed at reducing CO_2 emissions.

The economists' prescription is to price pollution either directly using a CO_2 tax or indirectly using tradable pollution permits, commonly referred to as a cap-and-trade policy (Fischer and Newell, 2008). A cap-and-trade program sets a politically-chosen cap on the quantity of CO_2 emissions and allocates tradable permits amounting to the cap to polluters. A regulated firm is allowed to pollute up to the quantity of permits it holds. Prominent examples of such policies include the European Union's (EU) Emission Trading System (ETS)[1], the Regional Greenhouse Gas Initiative implemented by Northeastern and Mid-Atlantic states in the U.S., and California's Global Warming Solutions Act (EIA, 2012).

The popular approach both in the U.S. and elsewhere, however, is to mandate renewable energy. Such policies, which are called renewable portfolio standards (RPS), mandate a share of electricity that must be generated by qualified renewable resources. In the U.S., twenty-nine states, the District of Columbia, and two U.S. territories have implemented mandatory RPS goals, and an additional eight states and two territories have voluntary RPS goals.[2] Globally, RPS policies have been adopted in several countries and by several state or provincial governments.[3] A limitation of an RPS is that constraining pollution reduction strategies to increasing the share of renewable en-

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[1] This policy targets CO_2 emissions from 11 industrial sectors including power generation, http://ec.europa.eu/clima/policies/ets/index_en.htm

[2] Database of State Incentives for Renewables & Efficiency, http://www.dsireusa.org

[3] Renewable Energy Policy Network, http://www.ren21.net

ergy excludes options such as fuel-switching between fossil fuels of varying CO_2 intensity, which studies show is relatively cheaper (CBO, 2011; Fischer and Newell, 2008). This is of particular significance, given recent developments in the natural gas sector, which have lowered the cost of natural gas relative to other fuels (C2ES, 2010; Yergin and Inesin, 2009).

An alternative type of policy is a clean energy standard (CES) (Mignone et al., 2012; CBO, 2011). A CES mandates an upper-bound on the emissions intensity of electricity, defined as CO_2 emissions per MWh of electricity produced. Similar to an RPS and cap-and-trade program, a CES can permit trading of credits, which would be linked to the emissions intensity of each fuel. When increasing production using natural gas is more cost-effective than increasing production from renewable resources, the cost of reducing CO_2 emissions will be lower under a CES than under an RPS.

Several studies have explored how various CO_2 emissions reduction policies perform. Fischer and Newell (2008) found that a CO_2 tax is the most efficient means of achieving a given emissions reduction target, that a CES is the second most cost-effective, and an RPS is the least cost-effective of the three policies. Fischer (2010) analyzes the impact of an RPS on electricity prices and finds that when the mandated share of renewables is small, electricity prices may decline, but the direction and magnitude of the change depends also on the relative elasticity of supply from renewable and non-renewable resources. Burtraw et al. (2012) compare the effect of requiring individual generation facilities to meet strict environmental performance standards versus allowing a collection of facilities to meet the standards on average. They find that the latter approach results in a significant cost savings for a given emissions reduction target.

Mignone et al. (2012) evaluate the cost-effectiveness and distribution of resources under a national CES with various methods of compensating nuclear and hydroelectric power under the policy. Fully crediting existing nuclear and hydropower for their lack of CO_2 emissions increases the cost of the policy to consumers for a given reduction in CO_2 emissions as these resources would receive a subsidy equivalent to that received by other renewable resources but would operate whether they receive the subsidy or not. Reducing the credit received by nuclear and hydropower limits the windfall profit these producers would receive, thereby reducing the cost to consumers of the policy per ton of CO_2 eliminated. The Congressional Budget Office's 2011 report, *The Effects of Renewable or Clean Energy Standards*, compares the results of 7 separate analyses of the effects of a national RPS or CES policy.

A major concern with environmental regulations is the unintended consequence of increasing pollution in unregulated markets, which is referred to as leakage. As electricity markets are often sub-continental or regional in scale, a state-level policy may simply shift the distribution of resources between in-state and rest of the market, without affecting total emissions or may increase total emissions. Leakage especially undermines greenhouse gas (GHG) policies, for GHGs are global pollutants.

Several recent articles have analyzed the impact of leakage under nested federal and state regulations. Goulder and Stavins (2011), and Goulder et al. (2012) find that 100 percent leakage may occur when states enact policies that are more stringent relative to a national quota or standard. However, under a federal policy that taxes emissions, a higher emissions tax in an individual state causes only 'economic' leakage, though there is a loss in efficiency. McGuinness and Ellerman (2008) and Burtraw and Shobe (2009), in earlier working papers, find similar results regarding federal cap-and-trade policies.

Our paper contributes to the literature by illustrating how leakage may differ under different policies and how this depends on the market share of the policy jurisdiction. Our findings indicate that when the policy region covers the full market, a CO_2 tax is the cost-effective policy while an RPS is the least cost-effective policy. The CES produces a reduction in market surplus that is similar to the CO_2 tax, but the distribution of gains and losses across consumers and producers differs from that produced by the CO_2 tax. As the size of the policy region relative to the market shrinks, the ordering of the policies does not change, but the difference between the outcomes of each policy decreases. When the policy region does not cover the entire market, however, an RPS can achieve larger reductions in CO_2 emissions than can a CES or CO_2 tax. The smaller the policy region, the larger the difference between the maximum emissions reduction achievable by an RPS and that achievable by a CES or CO_2 tax. In fact, for a sufficiently small policy region, an RPS is the only one of the three policies that can induce a reduction in CO_2 emissions.

The rest of the paper is as follows. Section 2 describes the formulation of the model and presents analytical results that do not depend on functional form. Section 3 explains the numerical simulation exercise and data used therein. Section 4 details the results of the numerical simulations.

2 Model

We analyze the RPS, CES, and CO_2 tax policies in a static, partial-equilibrium setting. Our model builds on Fischer (2010) and has two regions: home or the policy region and a rest-of-the-market or no-policy region. We model electricity supply from four sources: coal, natural gas, renewable resources, and a fourth category, which represent nuclear and large hydroelectric power. Nuclear and large hydro generation are not treated as qualifying renewables under the RPS policies of most states. Given the significant environmental and regulatory hurdles to building new nuclear or large hydro generation capacity in addition to their high capital cost (CBO, 2011), we assume that the capacity of these two resources is fixed.

We now describe the mathematical formulation of the three policies. Let p denote price, q denote quantity of electricity and the subscripts c, g, r, and nh denote coal, gas, qualifying renewables, and nuclear and hydro resources respectively.

2.1 Renewable Portfolio Standard

A renewable portfolio standard (RPS) dictates that qualifying renewable generation must be a specified share of total generation, α. The RPS requirement is represented by:

$$\frac{q_r}{q_c + q_g + q_{nh} + q_r} \geq \alpha$$

This can be rearranged such that $q_r \geq A(q_c + q_g + q_{nh})$ where $A = \frac{\alpha}{1-\alpha}$.

With an RPS, suppliers of electricity from qualifying renewables generate one renewable energy credit (REC) for each megawatt-hour (MWh) of electricity produced. These suppliers then sell the RECs to load serving entities (LSEs), the companies that distribute electricity to consumers, who must demonstrate to state regulators that at least α percent of the electricity sold to end-users was generated from qualifying renewable resources. Thus, for each MWh of electricity purchased from conventional suppliers (coal, gas, or nuclear and hydro in our model), an LSE must purchase $A = \frac{\alpha}{1-\alpha}$ MWh of renewable resources or A RECs. The price of the REC is represented by s. A supplier of electricity from renewable resources receives the price of electricity plus s, while a supplier of electricity from conventional resources receives the price of electricity less As.

A representative consumer in each region, r, maximizes his utility, $u^r(q^r)$, subject to his budget constraint, $p^r q^r = B^r$. Here $u^r(\cdot)$ is the consumer's utility function in region r for electricity consumption, assumed to be continuous, increasing, and strictly concave, q^r is the quantity of electricity consumed in region r, p^r is the price of electricity in the consumer's region, and B^r is the consumer's budget. The policy region is assumed to be a fractional portion of the full market, and the no-policy region, the remaining portion of the market. A policy region that consists of $\rho \in (0, 1)$ of the market, therefore consumes ρ of the electricity pre-policy, which will be reflected in the preferences of the representative consumers. This yields the first order condition:

$$u^{r\prime}(q^r) = p^r \tag{1}$$

Each producer seeks to maximize profit, which is defined as the sum of the revenue from electricity sold in each region less the cost of generating the electricity:

$$\max_{q_f^p, q_f^n} \quad (p^p + x)q_f^p + p^n q_f^n - c_f(q_f^p + q_f^n)$$

$$\text{s.t. } q_f^p \geq 0,\, q_f^n \geq 0$$

f indicates the fuel utilized by the producer (coal, natural gas, qualifying renewables, nuclear, or hydro). The superscript p indicates the policy region, and the superscript n indicates the no-policy region. p^p+x is the price received by the producer in the policy region for the electricity sold, q_f^p. p^p represents the price of electricity in the policy region, and x represents the adjustment to the price in the policy region due to the policy. For producers using coal, natural gas, nuclear, or hydro, x is equal to $-As$, the number RECs the producers must purchase for each MWh of electricity generated multiplied by the cost of the RECs. For producers using qualifying renewable resources, x is equal to s, as each MWh of electricity generated by qualifying renewables also generates one REC that is sold to producers using non-qualifying renewable resources at the price s. $c_f(\cdot)$ represents the cost of generating electricity from each fuel, f, and is assumed to be continuous, increasing, and strictly convex. The constraints prevent generation from each fuel from being negative. Nuclear and hydro generation is assumed to have zero marginal cost but to face a capacity constraint such that $q_{nh}^p + q_{nh}^n \leq Q_{nh}$ where Q_{nh} is the total existing capacity of nuclear and hydro generation.

The first order conditions determining the solution to the maximization problem solved by the producers using coal, natural gas, or renewables are:

$$p^p + x = c_f'(q_f^p + q_f^n) - \lambda_f^p \tag{2}$$

$$p^n = c_f'(q_f^p + q_f^n) - \lambda_f^n \tag{3}$$

λ_f^p and λ_f^n are the Lagrange multipliers on the non-negativity constraints above. For producers using nuclear and hydro, the first order conditions are:

$$p^p - As = \psi - \lambda^p_{nh} \tag{4}$$

$$p^n = \psi - \lambda^n_{nh} \tag{5}$$

where ψ is the Lagrange multiplier on the capacity constraint.

Combining equations (1) for each region, (2)-(3) for coal, for natural gas, and for renewables, and (4)-(5) for nuclear and hydro with the non-negativity constraints for generation from each fuel in each region, the capacity constraint for nuclear and hydro generation, and the following market clearing conditions and RPS constraint yields a set of equations that can be solved for the equilibrium quantities and prices in each region.

$$\text{Market Clearing: } q^p = q^p_c + q^p_g + q^p_{nh} + q^p_r \tag{6}$$

$$q^n = q^n_c + q^n_g + q^n_{nh} + q^n_r \tag{7}$$

$$\text{RPS Constraint: } q^p_r \geq A(q^p_c + q^p_g + q^p_{nh}) \tag{8}$$

Each pair of equations, (2) and (3) for coal, for natural gas, and for renewables, and (4) and (5) for nuclear and hydro implies a specific relationship between the prices in the policy and no-policy regions that must be true in any equilibrium. This occurs because each pair contains the same marginal cost (or the same capacity constraint multiplier in the case of nuclear and hydro) in both equations. Thus, each pair of equations can be combined into one equation. By examining the four equations below, the characteristics of the possible equilibria are revealed.

$$\text{Coal: } p^p - As = p^n + \lambda_c^n - \lambda_c^p \tag{9}$$

$$\text{Natural Gas: } p^p - As = p^n + \lambda_g^n - \lambda_g^p \tag{10}$$

$$\text{Nuclear \& Hydro: } p^p - As = p^n + \lambda_{nh}^n - \lambda_{nh}^p \tag{11}$$

$$\text{Renewables: } p^p + s = p^n + \lambda_r^n - \lambda_r^p \tag{12}$$

Proposition 1. *(a) If the electricity produced by either coal, natural gas, nuclear, or hydro (the non-qualifying-renewable fuels) is purchased by consumers in both regions, then the net price received by non-qualifying-renewable fuels in the policy region will be equal to the no-policy region price,* $p^p - As = p^n$. *(b) Conversely, if the net price received in the policy region is greater than the no-policy region price,* $p^p - As > p^n$, *the non-qualifying-renewable fuels will be utilized only in the policy region, and vice versa if* $p^p - As < p^n$.

Proof. Part (a): Without loss of generality, assume the electricity produced by coal is utilized in both regions. This implies $\lambda_c^n = \lambda_c^p = 0$, and by equation (9), $p^p - As = p^n$.
Part (b): By equations, (9)-(11), if $p^p - As > p^n$, then $\lambda_f^n - \lambda_f^p > 0 \, \forall f \in \{c, g, nh\}$. As $\lambda_f^n, \lambda_f^p \geq 0$ by definition, $\lambda_f^n > 0$. As $\lambda_f^n > 0 \, \forall f \in \{c, g, nh\}$, electricity from those fuels is not consumed in the no-policy region but can be consumed in the policy region. □

Corollary 1. *If one non-qualifying-renewable fuel is utilized in both regions, then the other non-qualifying-renewable fuels must either be utilized in both regions or in neither.*

Proof. Without loss of generality, assume coal is utilized in both regions. By Proposition 1, coal receives the same price in each region, $p^p - As = p^n$. From equations (10) and (11), $p^p - As = p^n$ implies that for natural gas and nuclear and hydro, either $\lambda_f^n = \lambda_f^p = 0$ (natural gas and/or nuclear and hydro operate in both regions) or $\lambda_f^n - \lambda_f^p = 0$ (natural gas and/or nuclear and hydro operate in neither region). □

Proposition 2. *If one of the non-qualifying-renewable fuels is utilized in one region, but not the other, then the other non-qualifying-renewable fuels cannot be utilized in the former region either.*

Proof. Without loss of generality, suppose coal is utilized only in the policy region. Then by equation (9), $p^p - As = p^n + \lambda_c^n$, which implies $p^p - As > p^n$. By equations (10) and (11) and the fact that Lagrange multipliers are non-negative, $\lambda_g^n > 0$ and $\lambda_{nh}^n > 0$, which implies that natural gas and nuclear and hydro cannot be utilized in the no-policy region either. □

Proposition 3. *Qualifying renewables will be utilized only in the policy region and at least one of the non-qualifying-renewable fuels will be utilized in the policy region whenever the REC price, s, is positive.*

Proof. Suppose not. If the REC price, s, were greater than zero, and qualifying renewables were consumed in both regions, then by equation (12), $p^p + s = p^n$. Note that qualifying renewables must be consumed in the policy region when an RPS policy is in effect. As A, the required number of RECs coal, natural gas, and nuclear and hydro generators must purchase is greater than zero when an RPS policy has been enacted, the price received by generators using qualifying renewables is greater than the price received by generators using other fuels, $p^p + s > p^p - As$. This implies that $p^n > p^p - As$ and therefore that all non-qualifying-renewable fuels will be utilized only in the no-policy region by Proposition 1 and renewables will be the only fuel utilized in the policy region. However, when the REC price is positive, the RPS constraint, $q_r^p \geq A(q_c^p + q_g^p + q_{nh}^p)$ is binding. When non-qualifying-renewable fuels are not utilized in the policy region, a binding RPS constraint states that $q_r^p = 0$, which is a contradiction. Thus, qualifying renewables can only be utilized in both regions when s is zero, and at least one non-qualifying-renewable fuel must be utilized in the policy region in any feasible equilibrium with s positive. □

In the following propositions, the superscript or subscript 0 indicates the pre-policy generation, consumption, or price.

Proposition 4. *If the required share of renewables in the policy region,* α*, is such that the required generation from qualifying renewables is less than or equal to pre-policy qualifying renewable generation,* $\alpha q_0^p \leq q_r^0$*, then the REC price,* s*, will be zero, and the only change in the equilibrium will be in how the electricity from each fuel is divided across regions.*

Proof. Suppose the equilibrium post-policy is such that $0 < q_r^p < q_r^0$ and $q_r^n = q_r^0 - q_r^p$. If $q_r^p = q_r^0$, $q_r^n = 0$, but the non-negativity constraint is not binding. By equations (2) and (3) for qualifying renewables, $p^p + s = c_r'(q_r^p + q_r^n) = p^n$. With $q_r^n = q_r^0 - q_r^p$, $p^p + s = c_r'(q_r^0) = p^n$. By Proposition 3, s must be zero if qualifying renewables are consumed in both regions. Pre-policy, $c_r'(q_r^0) = p_0$, therefore $p^n = p^p = p_0$ by the strict convexity of $c_r(\cdot)$. As the price in each region is the same as pre-policy, demand in each region, q^p and q^n, will be the same as pre-policy demand by the strict concavity of demand, and production of electricity from each fuel will be the same as pre-policy production by the strict convexity of the cost functions.

For this to be a feasible equilibrium, the RPS constraint must also be satisfied. In its original formulation, the RPS constraint is:

$$\frac{q_r^p}{q_c^p + q_g^p + q_{nh}^p + q_r^p} = \frac{q_r^p}{q^p} \geq \alpha$$

If the policy region consumes the same quantity of electricity pre and post-policy, then $q^p = q_0^p$ and $q_r^p \geq \alpha q_0^p$. Thus, this is a feasible equilibrium when αq_0^p, the minimum required quantity of electricity from qualifying renewables is less than or equal to q_r^0, the pre-policy generation from qualifying renewables. $\square$

In the following proof, we ignore the case in which the RPS policy requires 100 percent qualifying renewables as this policy is unlikely to be enacted.

Proposition 5. *One or more of the non-qualifying-renewable fuels will be utilized in both regions.*

Proof. If $\alpha q_0^p \leq q_r^0$, by Proposition 4, production of electricity from each fuel will be the same as pre-policy production. Assume that prior to the policy, production was split evenly across the two regions according to the size of each region relative to the market and that the policy mandates at least as large a share of qualifying renewables as existed pre-policy. Then post-policy, the quantity of qualifying renewables utilized in the policy region will either be larger than or the same as pre-policy usage and usage of non-qualifying-renewable fuels in the policy region will adjust such that total consumption in the policy region remains the same as pre-policy. Therefore, either the same amount or a larger amount of generation from non-qualifying-renewable fuels will be utilized in the no-policy region when the policy is such that $\alpha q_0^p \leq q_r^0$ and non-qualifying-renewable fuels will be utilized in both regions.

If $\alpha q_0^p > q_r^0$, the REC price, s, must be positive to induce additional generation from qualifying renewable fuels or to decrease consumption in the policy region. If s is positive, Corollary 1 provides 3 possible equilibria: (1) all non-qualifying renewable fuels are utilized in both regions, (2) some non-qualifying renewable fuels are utilized in both regions, and some in neither region, or (3) the non-qualifying renewable fuels are not used. Proposition 2 adds additional equilibria: (4) all non-qualifying renewable fuels are utilized in only the policy region, if at all, or (5) all non-qualifying renewable fuels are utilized in only the no-policy region, if at all. As Proposition 3 shows that when s is positive, qualifying renewables can only be consumed in the policy region, the no-policy region would consume no electricity if (3) or (4) were the case. Therefore cases (3) and (4) are not possible equilibria. Additionally, by Proposition 3, case (5) is not feasible. In the feasible cases, (1) and (2), at least one non-qualifying renewable fuel is utilized in both regions. $\square$

By Propositions 1 and 5, non-qualifying-renewable fuels will always receive the same net price in both regions, $p^n = p^p - As$. As long as the net price received is greater than or equal to the marginal cost at zero generation for a particular fuel, that fuel will continue to be utilized in both regions. If the price received drops below the marginal cost at zero generation for a particular fuel, that fuel will no longer be utilized.

2.2 Clean Energy Standard

In lieu of mandating a specific share of renewables, a clean energy standard (CES) sets a maximum weighted average level of CO_2 emissions, or CO_2 emissions intensity, $\bar{z}$. The CES requirement is represented by:

$$\frac{z_c q_c + z_g q_g}{q_c + q_g + q_{nh} + q_r} \leq \bar{z}$$

z_c represents the emissions of CO_2 per MWh of electricity generated by coal, and z_g represents the emissions of CO_2 per MWh of electricity generated by natural gas. Natural gas emits less CO_2 per MWh of electricity than coal, and therefore, $z_g < z_c$. Renewable, nuclear, and hydro generation emit no CO_2.

The CES requirement can be rearranged such that:

$$Z_c q_c + Z_g q_g \leq q_{nh} + q_r$$

where

$$Z_c = \frac{z_c - \bar{z}}{\bar{z}} \qquad \text{and} \qquad Z_g = \frac{z_g - \bar{z}}{\bar{z}}$$

Similar to an RPS, there would emerge a market for carbon credits under a CES. Under a CES, each MWh of electricity generated by renewables or nuclear and hydro yields 1 carbon credit, which can be sold to an LSE. The LSEs are required to ensure that the weighted average emissions intensity of their retail sales is less than or equal to the requirement, $\bar{z}$. Since coal and natural gas emit different quantities of CO_2 per MWh, LSEs are required to purchase different quantities of carbon credits per MWh of generation from coal versus natural gas. In the above equation, Z_c represents the number of carbon credits that LSEs must purchase for each MWh of coal-generated electricity, and Z_g is the number of carbon credits that LSEs must purchase for each MWh of natural gas-generated electricity where Z_c is greater than Z_g because coal emits more CO_2 per MWh of electricity. The price of a carbon credit is represented by s. Note that Z_g may be negative, indicating producers using natural gas can sell carbon credits, if $\bar{z}$ is greater than the CO_2 emissions/MWh of natural gas-fired generation. Qualifying renewables, nuclear, and hydro receive the price of electricity plus the price of a carbon credit, s, for each MWh of generation because they do not emit CO_2.

Rewriting equations (2)-(5) for a CES and condensing the eight equations for the four fuels to four equations reveals some of the properties of the possible equilibria:

$$\text{Coal: } p^p - Z_c s = p^n + \lambda_c^n - \lambda_c^p \tag{13}$$

$$\text{Natural Gas: } p^p - Z_g s = p^n + \lambda_g^n - \lambda_g^p \tag{14}$$

$$\text{Nuclear \& Hydro: } p^p + s = p^n + \lambda_{nh}^n - \lambda_{nh}^p \tag{15}$$

$$\text{Renewables: } p^p + s = p^n + \lambda_r^n - \lambda_r^p \tag{16}$$

Proposition 6. *If the CES constraint binds, such that the carbon credit price, s, is greater than zero, then no two CO_2-emitting fuels (fossil fuels) with different CO_2 emissions intensities can be utilized in both the policy and no-policy regions.*

Proof. Suppose generation from natural gas and coal (both CO_2-emitting fuels) was sold in both regions. Then $\lambda_c^n = \lambda_c^p = \lambda_g^n = \lambda_g^p = 0$ and equations (13) and (14) would be reduced to $p^p = p^n + Z_c s$ and $p^p = p^n + Z_g s$, respectively. As the CO_2 emissions intensity of coal is strictly greater than the CO_2 emissions intensity of natural gas, Z_c is strictly greater than Z_g. Thus at most one of the aforementioned equations can be true. Either, coal generation can be sold in both regions and natural gas can be sold in only one region, natural gas generation can be sold in both regions and coal can be sold in only one region, or generation from natural gas can be sold in one region, while generation from coal can be sold in the other. $\square$

Proposition 7. *Zero-emissions fuels will be utilized only in the policy region and at least one of the fossil fuels will be utilized in the policy region whenever the carbon credit price, s, is positive.*

Proof. Suppose not. If the carbon credit price, s, were greater than zero, and either or both of the zero-emissions fuels were consumed in both regions, then by equations (15) and (16), $p^p + s = p^n$. As Z_c and Z_g, the required number of RECs producers using coal and natural gas, respectively, must purchase is greater than zero when a CES policy has been enacted and $Z_c > Z_g$, the price received by generators using zero-emissions fuels is greater than the price received by generators using fossil fuels, $p^p + s > p^p - Z_g s > p^p - Z_c s$. This implies that $p^n > p^p - Z_g s > p^p - Z_c s$ and therefore that both fossil fuels will be utilized only in the no-policy region and zero-emissions fuels will be the only fuels utilized in the policy region. However, when the carbon credit price is positive, the CES constraint, $q_r^p + q_{nh}^p \geq Z_c q_c^p + Z_g q_g^p$ is binding. When fossil fuels are not utilized in the policy region, a binding CES constraint states that $q_r^p + q_{nh}^p = 0$, which is a contradiction. Both zero-emissions fuels cannot be utilized in the no-policy region when $s = 0$ for the same reason. Thus, zero-emissions fuels can only be utilized in both regions when s is zero, and at least one fossil fuel must be utilized in the policy region in any feasible equilibrium with s positive. $\square$

If the emissions intensity standard is greater than the emissions intensity of natural gas, $\bar{z} > z_g$ then $Z_g < 0$, and if s is positive, then generators using natural gas can sell carbon credits. By the same logic as Proposition 7, all generation from natural gas will be utilized in the policy region and coal generation must be utilized in both regions.

Proposition 8. *If the emissions intensity limit in the policy region, $\bar{z}$, is less than the emissions intensity of the cleanest fossil fuel (natural gas in our model) and $\bar{z}$ is such that the number of carbon credits that the fossil fuels must purchase is less than or equal to pre-policy zero-emissions generation, $Z_c q_c^p + Z_g q_g^p \leq q_r^0 + q_{nh}^0$, then the carbon credit price, s, will be zero, and the only change in the equilibrium will be in how the electricity from each fuel is divided across regions. If $\bar{z}$ is greater than the emissions intensity of the cleanest fossil fuel, the same conclusions follow providing $Z_c q_c^p \leq q_r^0 + q_{nh}^0 - Z_g q_g^0$.*

Proof. Suppose the equilibrium post-policy is such that $0 < q_r^p < q_r^0$, $q_r^n = q_r^0 - q_r^p$, and $0 < q_{nh}^p < q_{nh}^0$, $q_{nh}^n = q_{nh}^0 - q_{nh}^p$. If $q_r^p = q_r^0$ or $q_{nh}^p = q_{nh}^0$, then $q_r^n = 0$ or $q_{nh}^n = 0$, but the non-negativity constraint will not bind. By CES versions of equations (2) and (3) for qualifying renewables and nuclear and hydro, $p^p + s = c_r'(q_r^p + q_r^n) = p^n$ and $p^p + s = \psi = p^n$. With $q_r^n = q_r^0 - q_r^p$, $p^p + s = c_r'(q_r^0) = p^n$. By Proposition 7, s must be zero if zero-emissions fuels are consumed in both regions. Pre-policy, $c_r'(q_r^0) = p_0$, therefore $p^n = p^p = p_0$ by the strict convexity of $c_r(\cdot)$. As the price in each region is the same as pre-policy, demand in each region, q^p and q^n, will be the same as pre-policy demand by the strict concavity of demand, and production of electricity from each fuel will be the same as pre-policy production by the strict convexity of the cost functions.

To be a feasible equilibrium, the CES constraint, $Z_c q_c^p + Z_g q_g^p \leq q_{nh}^p + q_r^p$, must also be satisfied. To satisfy the constraint with the same pre-policy generation, $Z_c q_c^p + Z_g q_g^p$, the minimum quantity of electricity that must be generated by zero-emissions fuels to generate sufficient carbon credits must be less than or equal to $q_r^0 + q_{nh}^0$, the pre-policy generation from zero-emissions fuels. If Z_g is negative, then natural gas generates $-Z_g$ carbon credits for each MWh of electricity. In this case, the same conclusions will follow providing $Z_c q_c^p$ is less than or equal to $q_r^0 + q_{nh}^0 - Z_g q_g^0$. $\square$

2.3 Carbon Dioxide Tax

With a carbon dioxide tax (CO_2 tax), the regulator selects a tax of \$$T$/Ton of CO_2 emissions to achieve a given emissions reduction. The tax is not necessarily the marginal social cost of CO_2 emissions, but may simply be the shadow price of an exogenous constraint on emissions. Producers using coal to generate electricity, which emits z_c tons of CO_2 per MWh, pay $z_c T$ \$/MWh of generation, and producers using natural gas pay $z_g T$ \$/MWh. As nuclear, hydro, and renewable generation emit no CO_2, they pay no tax.

A CO_2 tax and a CES produce a very similar set of equations to define an equilibrium. The only differences are that nuclear, hydro, and renewable generation receive no subsidy and there is no policy constraint. Producers using coal and natural gas face the same equations as with a CES though they pay the tax T rather than the carbon credit price s for each ton of CO_2 emitted. Therefore, Proposition 6 is identical under a CO_2 tax. Under a CO_2 tax, the objective of the agents is to minimize the tax paid. Therefore, when a CO_2 tax is collected, all available zero-emissions fuels will be utilized in the policy region unless the policy region demand pre-policy is less than the existing electricity generation from zero-emissions fuels.

Proposition 9. *For any tax, T, greater than zero, if pre-policy demand for electricity in the policy region is less than or equal to pre-policy zero-emissions generation, $q_0^p \leq q_r^0 + q_{nh}^0$, then zero-emissions fuels will provide all electricity in the policy region, any pre-policy zero-emissions generation not utilized in the policy region will be utilized in the no-policy region, the tax revenue will be zero, and the only change in the equilibrium will be in how the electricity from each fuel is divided across regions.*

Proof. Suppose the equilibrium post-policy is such that $0 < q_r^p \leq q_r^0$, $q_r^n = q_r^0 - q_r^p$, and $0 < q_{nh}^p \leq q_{nh}^0$, $q_{nh}^n = q_{nh}^0 - q_{nh}^p$. If $q_r^p = q_r^0$ or $q_{nh}^p = q_{nh}^0$, $q_r^n = 0$ or $q_{nh}^n = 0$, but the non-negativity constraint is not binding. By CO_2 tax versions of equations (2) and (3) for qualifying renewables and nuclear and hydro, $p^p = c_r'(q_r^p + q_r^n) = p^n$ and $p^p = \psi = p^n$. With $q_r^n = q_r^0 - q_r^p$, $p^p = c_r'(q_r^0) = p^n$. Pre-policy, $c_r'(q_r^0) = p_0$, therefore $p^n = p^p = p_0$ by the strict convexity of $c_r(\cdot)$. As the price in each region is the same as pre-policy, demand in each region, q^p and q^n, will be the same as pre-policy demand by the strict concavity of demand. To generate the same total quantity of electricity, $q_0^p + q_0^n$, production in the market must be the same as pre-policy production. To induce producers to generate the pre-policy quantity of electricity, the price received by producers in each region must be the same as the pre-policy price by the strict convexity of the cost functions, and therefore the producers must pay no tax T. This will occur only if all demand in the policy region is served by zero-emissions fuels. Thus, to be a feasible equilibrium, the quantity of electricity demanded in the policy region, q_0^p must be less than or equal to $q_r^0 + q_{nh}^0$, the pre-policy generation from zero-emissions fuels. $\square$

2.4 Effect of the Relative Size of the Policy Region

Proposition 10. *For any pre-policy generation portfolio that is comprised of both fossil fuels and very low-carbon fuels, some of which qualify as renewables under an RPS and some that do not, there exists a relative policy region size* $\rho \in (\underline{R}, \bar{R}]$ *such that a sufficiently stringent RPS policy can reduce CO*$_2$ *emissions, but a CES or CO*$_2$ *tax cannot.* $\rho \in [0, 1]$ *indicates the size of the policy region relative to the market.* $\underline{R}$ *is such that* $\underline{R}q_0 = q_0^p = q_r^0$*, where the* 0 *superscript or subscript indicates pre-policy.* $\bar{R}$ *is such that* $\bar{R}q_0 = q_0^p = q_r^0 + q_{nh}^0$*. For policy regions of relative size* $\rho \leq \underline{R}$*, none of the three policies can induce a change in CO*$_2$ *emissions.*

The full proof of the proposition is presented in Appendix C. The intuition behind the proof is as follows. First, for $\rho \leq \underline{\text{R}}$, an RPS cannot reduce CO$_2$ emissions because when $\rho \leq \underline{\text{R}}$, the required generation to serve pre-policy demand is less than the existing supply of generation from qualifying renewables, $q_0^p = \rho q_0 \leq q_r^0$. Therefore, even if the RPS policy requires 100 percent qualifying renewables in the policy region, the total quantity of electricity generated will not change by Proposition 4, and therefore, CO$_2$ emissions will not change. Second, when $\rho \leq \bar{R}$, a CES or CO$_2$ tax cannot reduce emissions because when $\rho \leq \bar{R}$, the required generation to serve pre-policy demand is less than the existing supply of generation from zero-emissions fuels, $q_0^p = \rho q_0 \leq q_r^0 + q_{nh}^0$. Therefore, for any CES emissions intensity standard, $\bar{z}$, or any CO$_2$ tax, the total quantity of electricity generated will not change by Propositions 8 and 9 and therefore CO$_2$ emissions will not change. Third, as long as there is generation from a zero-emissions fuel that does not qualify as a renewable under an RPS, $q_{nh}^0 > 0$, $\underline{\text{R}} < \bar{R}$.

Fourth, whenever $\rho > \underline{\text{R}}$, an RPS can reduce CO$_2$ emissions. To show this, we first demonstrate that there exists an α such that the required generation from qualifying renewables given pre-policy demand is greater than existing renewables, $\alpha \rho q_0 > q_r^0$ when $\rho > \underline{\text{R}}$. Next, this implies that the REC price, s, is greater than zero because otherwise there is no incentive to increase production of electricity from qualifying renewables or decrease demand in the policy region to meet the RPS mandate. With s greater than zero, the price received by qualifying renewables increases, and the price received by other fuels decreases in equilibrium. Therefore, given strictly convex marginal cost curves, the production of electricity from fossil fuels declines, reducing CO_2 emissions.

Proposition 11. *The maximum reduction in CO_2 emissions that can be achieved by an RPS will exceed the maximum reduction in CO_2 emissions that can be achieved by a CES or CO_2 tax when the policy region does not cover the full market.*

Proof. If an RPS were to demand 100 percent renewables in the policy region, coal, natural gas, and nuclear and hydro would be utilized only in the no-policy region and therefore the following equations would determine their output:

$$u^{n\prime}(q_c^n + q_g^n + q_{nh}) = c_c^{\prime}(q_c) \tag{17}$$

$$u^{n\prime}(q_c^n + q_g^n + q_{nh}) = c_g^{\prime}(q_g) \tag{18}$$

$$u^{n\prime}(q_c^n + q_g^n + q_{nh}) = \psi \tag{19}$$

If the marginal utility of consumption at the equilibrium quantities in the no-policy region, is greater than 0, the marginal cost of nuclear and hydro, the price in the no-policy region will be positive, ψ will be positive and $q_{nh} = Q_{nh}$, the full capacity of nuclear and hydro will be utilized. If the marginal utility of consumption in the no-policy region is 0, then the price is 0, and only part of the nuclear and hydro capacity will be utilized. Assuming the marginal cost of generation from coal and natural gas at zero production is positive, coal and natural gas generators will not be utilized.

For a CES or CO_2 tax, if the CES were to demand zero emissions or the CO_2 tax were sufficiently high, generation from coal and natural gas would only be used in the no-policy region. The equations determining the production of electricity from coal and natural gas would be:

$$u^{n\prime}(q_c^n + q_g^n) = c_c^{\prime}(q_c) \tag{20}$$

$$u^{n\prime}(q_c^n + q_g^n) = c_g^{\prime}(q_g) \tag{21}$$

Assuming that the marginal cost at zero generation for coal and/or natural gas is positive but less than the marginal benefit of zero electricity consumption in the no-policy region, the price in the no-policy region will be positive.

If no generation from coal or natural gas is utilized under the most stringent RPS, CO_2 emissions will certainly be less under the most stringent RPS than under the most stringent CES or CO_2 tax because generation from coal and/or natural gas will always be utilized in the no-policy region under a CES or CO_2 tax by the above.

If generation from coal and natural gas is utilized under the most stringent version of an RPS, then q_{nh} is a positive constant. If q_c and q_g solve equations (17) and (18) then $c_c'(q_c) > u^{n\prime}(q_c^n + q_g^n)$ and $c_g'(q_g) > u^{n\prime}(q_c^n + q_g^n)$ by the strict concavity of demand. Note that the right side of each of these equations now matches the left side of equations (20) and (21). By continuity of the demand and cost functions, the strict concavity of demand, and the strict convexity of costs, increasing q_c to $\hat{q}_c$ and q_g to $\hat{q}_g$ will yield $u^{n\prime}(\hat{q}_c^n + \hat{q}_g^n) = c_c'(\hat{q}_c)$ and $u^{n\prime}(\hat{q}_c^n + \hat{q}_g^n) = c_g'(\hat{q}_g)$. Thus, the quantities of generation from coal and natural gas that would be provided under the most stringent RPS are less than the quantities of generation from coal and natural gas that would be provided under the most stringent CES or CO_2 tax and therefore the maximum reduction in emissions is larger under an RPS when the policy region does not cover the full market. $\square$

3 Numerical Simulation

To illustrate the order of magnitude of difference between the different policies with respect to multiple criteria such as emissions and economic surplus, we perform numerical simulations. We simulate the three policies, namely, RPS, CES and CO_2 tax, for four different scenarios concerning the share of the policy region's electricity consumption relative to the electricity market, namely, 1/4, 1/2, 3/4 and the full market. As the model assumes perfect competition, a marginal cost curve is synonymous with a supply function, and a marginal utility curve is synonymous with a demand function. For illustration, we assume these are linear functions. We calculate the surplus accruing to the consumers in each region and the surplus accruing to the different types of of producers. The sum of the consumer surplus, producer surplus and tax revenue yields the market surplus under each scenario. Details of the calculations can be found in Appendices A and B.

3.1 Data and calibration

To choose the correct data with which to calculate the parameters of the model it is important to consider the economic meaning behind the supply and demand curves utilized here. The curves represent not a response to short term fluctuations in the price of electricity, but a longer term response to long-term price trends in the market. Thus, the demand curve represents the average consumer response to price changes over the long term, and the supply curve is modeled as a long-term adjustment by producers taking into account the cost of new generation capacity.

To ensure our demand and supply functions have the required interpretation, we utilize data from the Annual Energy Outlook 2011 (AEO2011) published by the U.S. Energy Information Administration (EIA) . This report focuses on the factors that shape the U.S. energy system over the long term and contains estimates of prices, demand, and supply for electricity and other energy sources for the U.S. for the next 30 years.

Although the data pertain to the entire U.S., a market should be interpreted as an integrated market in which electricity can flow freely between locations and in which a centralized body clears wholesale transactions and manages power flows. Examples of this type of market are Independent System Operator New England (ISO-NE), the Pennsylvania Jersey Maryland (PJM) Interconnection, covering much of the Mid-Atlantic and Midwest, Electric Reliability Council of Texas (ERCOT), and the California ISO. A region is to be interpreted as an individual state within a market. For instance, Virginia represents approximately 1/4 of the PJM market, Massachusetts represents approximately 1/2 of the ISO-NE market, [4] California represents approximately 3/4 of

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[4] These figures are based upon annual sales from EIA Table 10: Class of ownership, number of consumers, sales,

the California ISO market,[5] and Texas comprises the entire ERCOT market.

For our numerical simulation, we selected data from the AEO2011 reference case on the average U.S. retail electricity price, the total net electricity generation from all sources, and the net generation from coal, natural gas, and renewables (excluding hydro) for 2008-2035. Nuclear and hydro generation is computed as the difference between total net electricity generation and the generation from coal, natural gas, and renewables as the majority of the residual generation consists of nuclear and large hydro. The data for 2008 and 2009 are actual data, while data for later years are the EIA's predictions. For our baseline pre-policy scenario, we utilized the 2009 data.

To compute the elasticity of the supply curves, we compared the reference case in AEO2011 with two side cases: a high demand growth case and a low demand growth case. For each side case, year, and fuel, we computed the elasticity of supply implied by the difference between the reference case and the side case. As we are interested in the long-term elasticity of supply, we utilized the average of the elasticity observations from 2020 to 2035 from the high demand case and from 2022 to 2035 from the low demand case for each fuel. The years were selected based upon when the estimated elasticities began to converge to a long-term average. Our calculations rest upon the assumption that the high demand and low demand cases create shocks to the aggregate demand for electricity, moving the demand curve, while the supply curves remain unaffected on average. Thus, the new equilibrium is just a move up or down the original supply curves.

On the demand side, we performed a similar analysis comparing the reference case with a side case developed to examine the effect of a clean energy standard for Senator Jeff Bingaman. Here we assume that the clean energy standard would shift the supply curve but would not affect the demand curve, yielding a new equilibrium that is simply a move up or down the original demand curve. Using this data, we estimated that the elasticity of demand is approximately -0.20, which

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revenue, and average retail price by State and utility: all sectors, 2011

[5] While the California ISO market technically covers only investor-owned utilities located in California, the Federal Energy Regulatory Commission reports that approximately 25 percent of the energy consumed in the market is imported from neighboring states.
http://www.ferc.gov/market-oversight/mkt-electric/california.asp#gen.

is the same elasticity found in much of the literature (Bernstein and Griffin, 2005; Fischer, 2010, e.g.).

Parameter	**Interpretation**	**Value**
p_0	Pre-Policy Price ($/KWh)	0.098
q_0	Pre-Policy Total Generation (KWh)	3.98E+12
q_{b0}	Pre-Policy Nuclear & Hydro Generation (KWh)	1.13E+12
q_{s0}	Pre-Policy Renewable Generation (KWh)	1.45E+11
q_{g0}	Pre-Policy Natural Gas Generation (KWh)	9.31E+11
q_{c0}	Pre-Policy Coal Generation (KWh)	1.77E+12
ε	Demand Elasticity	-0.2
ε_r	Renewables Elasticity	1.49
ε_g	Natural Gas Elasticity	2.57
ε_c	Coal Elasticity	1.10

Table 1. Parameters of the Model

The baseline price, quantities, and elasticities used to calculate the parameters of the supply and demand curves are shown in Table 1. As our model contains two regions, it is necessary to compute two demand curves, one for each region. As mentioned earlier, we consider four possible sizes of the policy region relative to the market, 1/4 of the market, 1/2 of the market, 3/4 of the market, and all of the market. If the policy region is 1/4 of the full market, then 1/4 of the pre-policy generation is consumed in the policy region, etc. The price and elasticity of demand are assumed to be the same in each market in the base case. Therefore, as the pre-policy quantity enters into the calculation of the slope of the demand curve inversely, the slope of the demand curve increases by four if the policy region is 1/4 of the market relative to the slope of the demand curve for the full market. The pre-policy quantity does not enter into the computation of the intercept of the demand curve, and thus it remains the same for both regions.

Information on the CO_2 emissions intensity of each fuel comes from the EPA's website, which indicates that CO_2 emissions from coal generation are approximately 1.125 Tons/MWh on average. CO_2 emissions from natural gas generation are approximately 0.5625 Tons/MWh.[6] Thus, the CO_2 emissions per MWh of coal generation are roughly double the CO_2 emissions per MWh of natural gas generation.

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[6] http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html

4 Results

We discuss the results with respect to emissions, distributional effects and finally cost-effectiveness.

4.1 Emissions

Figures 1 - 3 show the reduction in CO_2 emissions as the stringency of an RPS, a CES, or a CO_2 tax policy increases. PR stands for policy region and the arrow denotes reduction. The heavy lines, labeled PR=1/4 of market, e.g., denote the actual reduction in CO_2 for each policy region size. The thin lines represent 1/4, 1/2, and 3/4 of the emissions reduction achieved in the full market. If there was a linear relationship between the size of the region and the reduction in emissions for a given policy requirement, the thin lines and the heavy lines would coincide. When the heavy lines, denoting the actual change in emissions due to a policy, fall to the left of the thin lines, denoting the change in emissions that would occur if emissions were reduced in proportion to the size of the policy region, this implies that the actual decrease in emissions is less than proportional to the size of the region. An example of this is shown in Figure 1. Note that for a CES (Figure 2) and a CO_2 tax (Figure 3) in a policy region 1/4 the size of the full market, no emissions reduction is possible because nuclear, hydro, and renewables, which emit no CO_2 in producing electricity, are sufficient to meet pre-policy demand in the policy region.

As Figures 1 - 3 show, the net emission reduction achieved by a policy depends on the size of the policy region relative to the full region. As a result, setting an RPS target of 20 percent renewables by 2020, for instance, would yield a 1.7 percent reduction in CO_2 emissions for a policy region 1/4 the size of the market, a 9.1 percent reduction for a policy region that is 1/2 the market, an 18.2 percent reduction for a policy region that is 3/4 of the market, and a 28.9 percent reduction if the policy region were the full market. The emissions reduction achieved in these figures is also highly dependent on the pre-policy distribution of resources. A higher initial share of coal would result in a larger reduction in emissions for a given policy level relative to a smaller

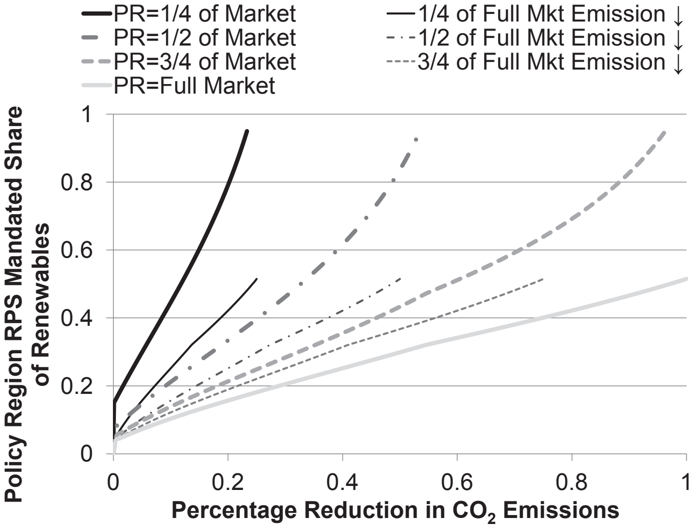

Figure 1. Reduction in CO_2 Emissions by RPS Required Share of Renewables and Policy Region Size

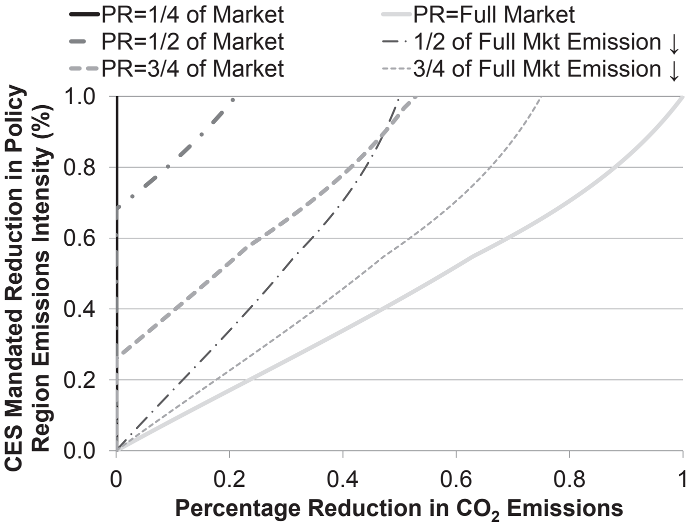

Figure 2. Reduction in CO_2 Emissions by CES Required Reduction in Emissions Intensity and Policy Region Size

initial share of coal since coal is the most CO_2 intensive resource.

As can be seen in the position of the thin lines relative to the heavy lines in Figures 1-3, the relationship between the reduction in CO_2 emissions and the size of the policy region relative to the market is non-linear. Figures 1 and 2 show that under an RPS or CES, the emissions reduction for a given policy region size is always less than proportional to the size of the policy region. Using the example above, emissions in a 1/4 size policy region under an RPS requiring a 20 percent

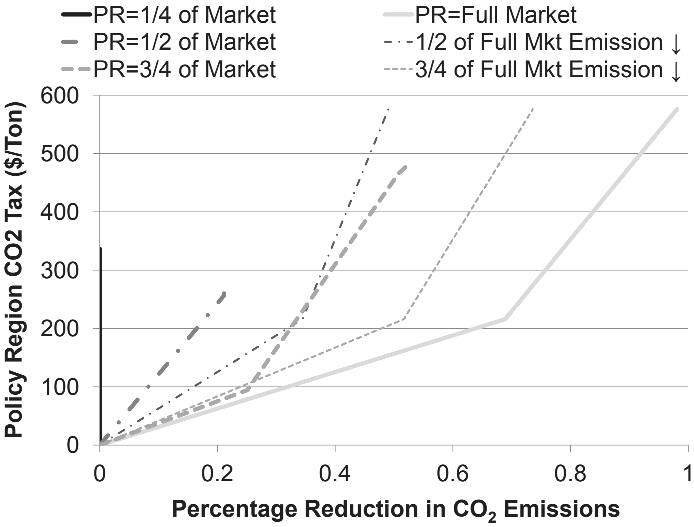

Figure 3. Reduction in CO_2 Emissions by CO_2 Tax Level and Policy Region Size

share of renewables would decrease by 1.7 percent whereas emissions in the full market under the same policy would decrease by 28.9 percent. Were the reduction in emissions in the 1/4 size policy region proportional to its size, the reduction would be 28.9*1/4 or 7.3 percent. As the policy region grows larger, the difference shrinks between the feasible reduction in emissions and the reduction in emissions that would occur if the reduction was proportional to region size. With a CO_2 tax, this same pattern holds for mid-size and small policy regions and for very large policy regions, see for instance the relationship between the heavy, PR=1/2 of Full Market, line and the thin, 1/2 of Full Market Emission Reduction, line. For regions in between, e.g. policy regions 3/4 the size of the market, a low CO_2 tax will generate a decrease in emissions that is greater than 3/4 of the reduction in CO_2 emissions that would occur in the full market under the same tax. This seems to be due to the difference in behavior under a tax, in which agents try to minimize the tax burden, versus behavior under an RPS or CES, in which agents must meet a quota.

The reduction in emissions is generally less than proportional to the size of the policy region because resources can be shuffled between the regions to meet a given policy requirement or minimize a tax burden. If the policy region is the full market, any RPS policy that mandates a share of renewables greater than the pre-policy share will induce an increase in renewable resources, while in a policy region that is less than the full market, consumers can simply switch from purchasing electricity from existing coal, natural gas, nuclear, or hydro, to purchasing electricity from existing renewables. This rationale explains the result for a CES as well. With a CO_2 tax, there is no requirement for a certain share of renewables or certain emissions intensity; however, consumers will adjust their purchases to minimize the tax burden, often, though not always, resulting in the same effect.

Size of Policy Region	**RPS - Share of Renewables**	**CES - Reduction in Emissions Intensity (%)**	**CO_2 Tax**
1/4 of Market	14.6%	–	–
1/2 of Market	7.3%	68.2%	\$0.00
3/4 of Market	4.9%	26.0%	\$0.00
Full Market	3.6%	0.0%	\$0.00

Note: The Pre-Policy Share of Renewables in the Full Market is 3.6%.

Table 2. Minimum level of stringency of a policy required to induce a reduction in total CO_2 emissions

Table 2 shows the minimum policy requirement that is necessary to induce a change in CO_2 emissions for each of the three policies. As pre-policy demand in a policy region 1/4 the size of the market is less than the amount of existing generation from zero-emissions fuels, a CES or CO_2 tax in a 1/4 size policy region can achieve no reduction in CO_2 emissions, by Proposition 10. For an RPS, the minimum policy level required to induce a change in CO_2 emissions is equal to the share of pre-policy demand in the policy region that can be fulfilled using generation from pre-existing renewables. In the full market, the pre-policy the share of renewables is 3.6 percent, implying a mandate of at least 3.6 percent renewables is required to induce change in the full market. For a policy region 1/2 the size of the market, all renewables can be shifted at no cost to the policy region which yields a share of renewables in the policy region equal to 7.3 percent. An RPS policy requiring greater than 7.3 percent renewables would therefore be required to provoke a change in emissions.

For a CES, the minimum policy level is set by the emissions intensity when all nuclear, hydro, and renewables are moved into the policy region, and the remaining pre-policy demand is filled first by existing natural gas generation then by existing coal generation, if necessary. In view of the fact that nuclear and hydro generate 28.5 percent of electricity pre-policy and renewables generate 3.6 percent, a very large reduction in CO_2 emissions intensity is required in the policy region to stimulate a change in total market emissions. For either a CO_2 tax or CES, if the policy region is less than 32.1 percent of the market (the pre-policy share of nuclear, hydro, and renewables), any policy level will simply cause consumers in the policy region to utilize only nuclear, hydro, and renewables, resulting in no change in market emissions, by Proposition 10. For a larger region, any CO_2 tax above zero will generate a reduction in emissions as agents seek to minimize the tax paid.

	RPS		**CES/CO_2 Tax**	
Size of Policy Region	**Max Emissions Reduction (Mil. Tons of of CO_2)**	**Max Emissions Reduction as a Share of Total Emissions**	**Max Emissions Reduction (Mil. Tons of of CO_2)**	**Max Emissions Reduction as a Share of Total Emissions**
1/4 of Market	609.1	24.2%	0.0	0.0%
1/2 of Market	1,378.0	54.7%	531.7	21.1%
3/4 of Market	2,473.2	98.3%	1,330.7	52.9%
Full Market	2,517.2	100.0%	2,517.2	100.0%

Table 3. Maximum Possible Emissions Reduction by Policy and Policy Region Size

Table 3 shows the maximum possible CO_2 emissions reduction for each policy and policy region size. As predicted by Proposition 11, an RPS can achieve a larger reduction in emissions than a CES or CO_2 tax is able to achieve when the policy does not apply to the full market. For a CES or CO_2 tax and a policy region that is smaller than the full market, the maximum reduction in CO_2 emissions relative to pre-policy emissions is less than the size of the policy region relative to the market. This occurs because the best the policies can do is eliminate the consumption of coal and natural gas within the policy region. For an RPS, electricity from nuclear and hydro is shifted to the no-policy region along with electricity from coal and natural gas. At very high required shares of renewables, the quantity of nuclear and hydro generation that is shifted to the no-policy region overwhelms the market demand and drives price toward zero, the marginal cost of nuclear and hydro generation. The low price causes less electricity from coal and natural gas to be produced in both regions, which reduces emissions in the no-policy region as well as the policy region. If the no-policy region is large relative to the policy region, the influx of nuclear and hydro generation will not drive price sufficiently low in the no-policy region to reduce the emissions from coal and natural gas production below the pre-policy level, explaining the result for the 1/4 size policy region.

These results show the importance of considering the size of the policy region relative to the market and the type of behavior the policy will induce when setting the policy requirement. Setting a goal of 20 percent renewables in the policy region, for instance, will have a smaller effect on emissions in a relatively small policy region than in a relatively large region. Additionally, for a policy region small relative to the market as a whole, only an RPS can induce a change in emissions. The other policies simply cause consumers in the policy region to shift to consuming only nuclear, hydro, and renewables. Were an RPS policy to treat nuclear and hydro as a renewable resource, which is not unreasonable based upon their lack of CO_2 emissions, the RPS, like a CES or CO_2 tax, would be incapable of inducing a change in emissions for small policy regions. This provides a significant justification for the current policy landscape, in which RPS policies have been implemented in the majority of U.S states and several territories, that is not intuitively obvious.[7] However, not all of the states with an RPS are small relative to the market in which they participate. Texas, for instance, constitutes its own market, while California makes up about 75 percent of its market. As will be discussed in Section 4.3, for these states, a CES or CO_2 tax yield a smaller decrease in market surplus for a given reduction in emissions.

4.2 Distributional effects

Table 4 shows how surplus varies for each sector as the size of the policy region, the type of policy and the emissions reduction target varies. To provide a point of comparison for the percentage changes shown in the Table 4, Table 5 shows the initial surplus of each group represented in the data. Initial CO_2 emissions are 2,517 million tons.

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[7] Database of State Incentives for Renewables & Efficiency, http://www.dsireusa.org.

		Policy Region Size									
	Emissions	1/4	1/2			3/4			Full		
Sector	**Reduction**	**RPS**	**RPS**	**CES**	**Tax**	**RPS**	**CES**	**Tax**	**RPS**	**CES**	**Tax**
Consumers in the Policy Region	10%	-18.6	-7.8	-19.0	-20.8	-4.2	-6.2	-9.4	-2.4	-2.9	-7.4
	20%	-50.5	-22.2	-39.0	-39.3	-12.9	-13.8	-18.4	-8.2	-7.0	-14.5
	40%	–	-58.1	–	–	-35.6	-45.5	-49.2	-24.0	-17.7	-27.9
	80%	–	–	–	–	-76.5	–	–	-53.2	-54.7	-59.2
Coal generators	10%	-15.1	-15.1	-15.1	-15.1	-15.1	-32.8	-29.4	-15.1	-32.9	-27.1
	20%	-29.0	-29.0	-29.0	-29.0	-29.0	-57.7	-53.6	-29.0	-58.1	-49.9
	40%	–	-53.0	–	–	-53.0	-63.7	-63.7	-53.0	-89.3	-82.7
	80%	–	–	–	–	-93.9	–	–	-93.9	-100.0	-100.0
Natural Gas generators	10%	-33.4	-33.4	-33.4	-33.4	-33.4	44.7	26.3	-33.4	45.4	15.0
	20%	-60.0	-60.0	-60.0	-60.0	-60.0	85.8	55.6	-60.0	89.4	31.0
	40%	–	-93.0	–	–	-93.0	-66.3	-66.3	-93.0	164.5	66.2
	80%	–	–	–	–	-100.0	–	–	-100.0	-11.7	-11.7
Qualifying Renewable producers	10%	662.9	678.5	286.8	232.0	683.2	118.9	84.8	685.5	120.3	64.2
	20%	1,369	1,540	613.2	599.0	1,584	258.8	195.4	1,604	266.3	144.3
	40%	–	2,925	–	–	3,366	1,239	884.4	3,547	595.5	352.0
	80%	–	–	–	–	4,728	–	–	6,208	2,044	1,261
Nuclear & Hydro generators	10%	-7.2	-7.2	64.9	55.2	-7.2	32.2	24.1	-7.2	32.5	18.9
	20%	-14.3	-14.3	112.1	110.3	-14.3	60.0	48.2	-14.3	61.3	37.8
	40%	–	-28.6	–	–	-28.6	178.5	143.5	-28.6	109.9	75.6
	80%	–	–	–	–	-68.5	–	–	-68.5	243.6	180.5

Table 4. Percentage Change in Surplus by Sector, Policy Region Size, and Emissions Reduction Target

As Table 4 indicates, the size of the policy region increases, consumers in the policy region experience a smaller drop in surplus for a given emissions reduction target regardless of the policy. When the policy region is the full market, a CO_2 tax unambiguously costs consumers in the policy region more than a CES or an RPS for any level of emission reduction. Depending on the level of emission reduction to be achieved, the consumer surplus may be higher or lower under a CES relative to an RPS. Consequently, if a policy-maker is considering whether to implement a CES or CO_2 tax and consumer welfare in the policy region is his or her priority, implementing a CES would be preferable to implementing a CO_2 tax.

Table 4 shows that, as the policy region grows, producers using coal experience a steeper drop in surplus under a CO_2 tax than under an RPS, and an even steeper drop under a CES. Producers using natural gas, however, experience a gain for some emissions reductions targets under a CES

Group	**Initial Surplus (Bil. $)**
Market	1,188.0
Total Consumer	975.5
Coal	78.9
Natural Gas	17.8
Renewable	4.8
Nuclear & Hydro	111.1

Table 5. Initial Surplus Received by Consumers and Producers

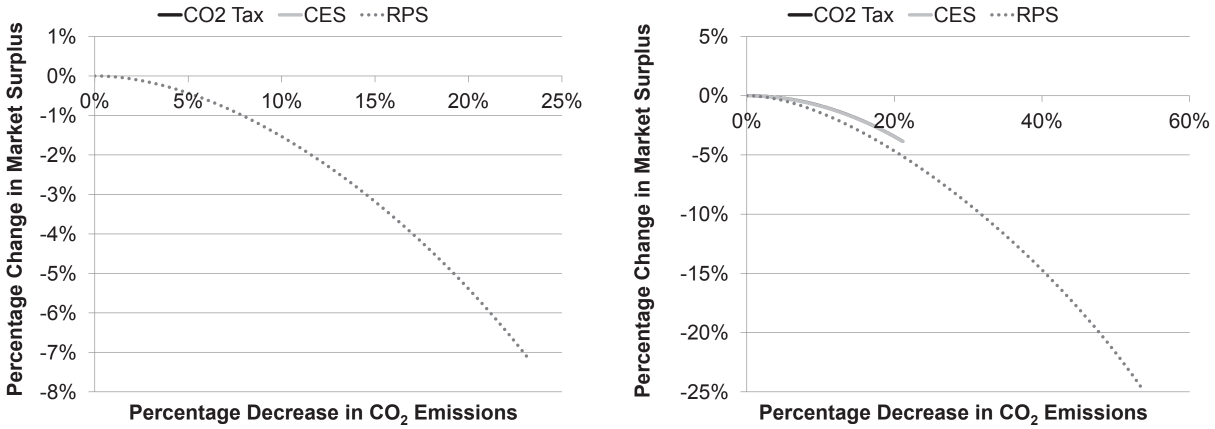
or CO_2 tax. This occurs because natural gas has a lower emissions intensity than coal causing production to shift to natural gas from coal. For high emissions reduction targets or very high CO_2 taxes, producers using natural gas experience a loss because the policy requirement or tax also squeezes out natural gas production. In this situation, the decline in surplus is smaller under a CES or CO_2 tax than under an RPS.

As can be seen in Table 4, an RPS provides the greatest benefit to producers using qualifying renewable resources as it subsidizes only these producers while taxing all others. A CES provides a somewhat larger benefit to producers using renewables than a CO_2 tax does, as it provides a subsidy to them. However, the benefit is much smaller than that experienced under an RPS.

The final rows of Table 4 demonstrate that the impact on producers of nuclear and hydro power varies across policies. Nuclear and hydro producer surplus is reduced under an RPS as they are not considered to be qualifying renewable resources, but is increased by a CES or CO_2 tax due to the resources' low or zero carbon intensity. As the CES provides a subsidy to zero-emissions generation, nuclear and hydro benefit the most from a CES policy.

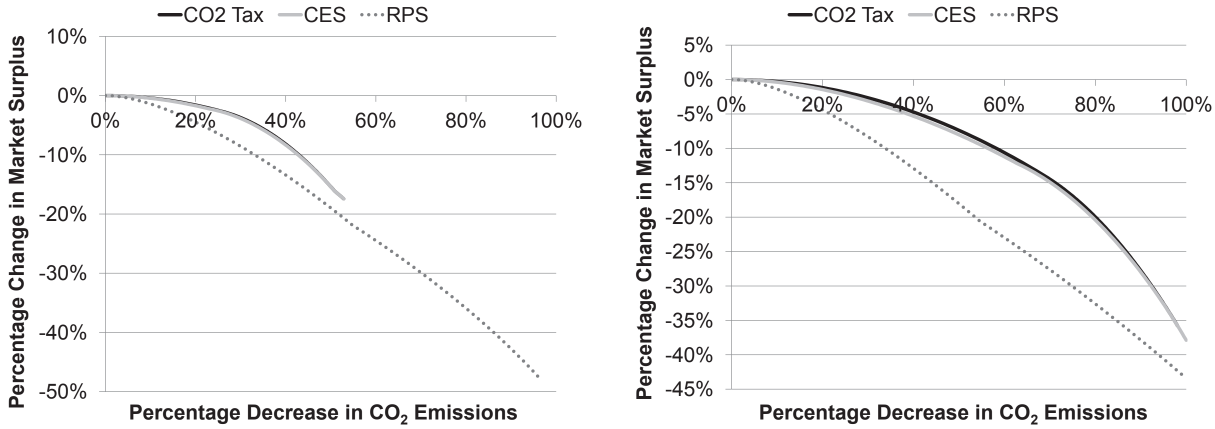
4.3 Cost-effectiveness

Interpreting the reduction in market surplus as the cost of a policy, where market surplus refers to the sum of consumer surplus and producer surplus in both regions, and government tax revenue for the case involving a tax, we calculate the cost-effectiveness of a policy as the percent change in market surplus at each potential CO_2 emissions reduction target.



(a) Policy Region=1/4 of Market
(e.g. Virginia in the PJM Market)

(b) Policy Region=1/2 of Market
(e.g. Massachusetts in the ISO-NE Market)



(c) Policy Region=3/4 of Market
(e.g. California in the CA ISO Market)

(d) Policy Region=Full Market
(e.g. Texas in the ERCOT Market)

Figure 4. Change in Market Surplus vs. Reduction in CO_2 Emissions

As can be seen in Figure 4, the larger the decrease in CO_2 emissions, the larger the reduction in market surplus. Regardless of the relative size of the policy region, a CO_2 tax and a CES yield very similar reductions in total market surplus per unit of emissions eliminated, although the reduction is somewhat smaller for a CO_2 tax. This suggests that a CES can achieve an outcome similar to a CO_2 tax. Note, however, that if a large reduction in emissions is sought, an RPS may be the only policy that can achieve the target when the policy region does not cover the full market, as shown in Proposition 11. This occurs because a CES or CO_2 tax is only able to shift consumption of electricity from coal and natural gas from the policy region to other areas, while an RPS will also force nuclear and hydro out of the policy region. The influx of nuclear and hydro generation into the rest of the market reduces demand for coal and natural gas generation in the rest of the market, thereby reducing CO_2 emissions in both regions. For a small emissions reduction target, the three policies achieve similar overall results, and the smaller the policy region relative to the market, the smaller the difference between the outcomes of the three policies.

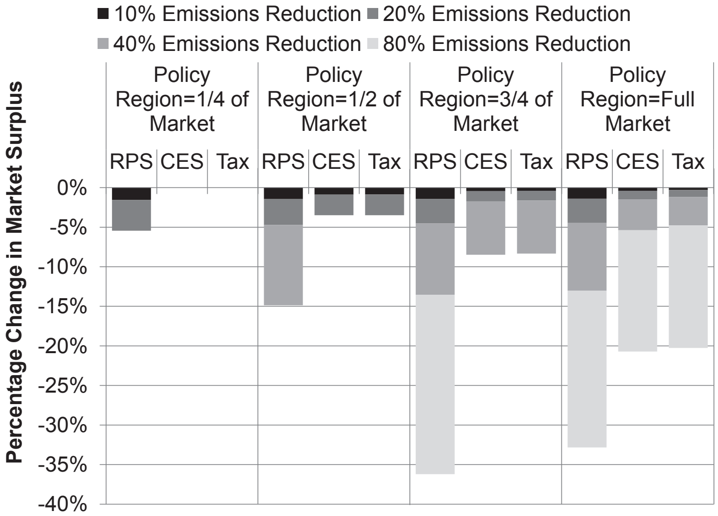


Figure 5. Change in Market Surplus for Various CO_2 Emissions Reduction Targets

Figure 5 shows the same data as Figure 4, but allows us to directly compare the effect of a given reduction in emissions as the size of the policy region relative to the market varies. We see that the change in market surplus for an RPS policy that achieves a 10 or 20 percent emission reduction varies little with the size of the policy region. For larger emissions reduction targets, the larger the policy region relative to the market, the smaller the reduction in market surplus for a given emissions reduction target under an RPS. For a CES or CO_2 tax policy, the policies cannot achieve the targets for the 1/4 size policy region, which explains the missing bars. For the 1/2 size or larger policy regions however, a CES or CO_2 tax can achieve the same emissions reduction with a smaller reduction in market surplus than occurs under an RPS. Further, as the policy region size grows relative to the market, the difference between market surplus reduction under a CES or a CO_2 tax grows relative to that of an RPS.

5 Conclusion

When the policy region covers the full market, a CO_2 tax is the most cost-effective policy while an RPS is the least cost-effective policy for a given reduction in CO_2 emissions, as measured by the reduction in market surplus caused by the policy. A CES is nearly as cost-effective as a CO_2 tax but the distribution of gains and losses across consumers and producers differs from that produced by a CO_2 tax. As the size of the policy region relative to the market shrinks, the ordering of the policies does not change, but the difference between the outcomes of each policy decreases. Additionally, smaller policy regions will require more stringent policies to achieve the same reduction in CO_2 emissions.

When the policy region does not cover the entire market, however, an RPS can achieve larger reductions in CO_2 emissions than can a CES or CO_2 tax (see Proposition 11). The numerical results show that the smaller the policy region, the larger the difference between the maximum emissions reduction achievable by an RPS and that achievable by a CES or CO_2 tax. For a sufficiently small policy region, an RPS is the only policy of the three considered here that can induce a reduction in CO_2 emissions (see Proposition 10). The cutoff policy region size, below which a CO_2 tax or CES cannot achieve a reduction in emissions, is determined by the share of zero-emissions resources in the market, e.g. renewable resources and nuclear power. If the policy region's relative size, e.g. 1/4 of the market, is less than the share of generation from renewables and nuclear power, a CO_2 tax or CES will be unable to induce a change in CO_2 emissions.

Consequently, for a policy region that is small relative to the market, an RPS is the only policy among the three policies considered that appears effective in reducing emissions. This provides one justification for the RPS policies currently in place in many states. Even for a larger policy region, if the CO_2 emissions reduction target is sufficiently large, only an RPS will be able to achieve the target. Conversely, a small CO_2 emissions reduction target causes a CO_2 tax or a CES to be marginally more cost-effective. If the policy region covers a large majority or all of the market, a CO_2 tax or CES would be significantly more cost-effective than an RPS. Further, the similarity of the reduction in market surplus between a CES or CO_2 tax and the lower cost to consumers from a CES relative to a CO_2 tax suggest that a CES may be the best alternative when the policy region is sufficiently large to permit a CES to be effective.

An RPS is one among several policies to promote renewables. Other examples include feed-in tariffs, which are common in several countries in the European Union and renewable energy subsidies. Often more than one policy is pursued. We therefore do not imply that the RPS is the only mechanism by which a small region could impact global emissions. Instead we aim to convey that given that policies to address global pollution impose a cost on the policy region, there exists a rationale for small regions to prefer a renewable energy-based policy, such as an RPS, over pollution-based policies such as emission standards or pollution pricing. For this reason, the size of the policy region relative to the market may be a critical consideration in policy selection.

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Appendices

A Parametrization of the Supply and Demand Curves

To parametrize the supply and demand functions, we assume for simplicity that the functions are linear. A linear supply or demand curve is represented by the equation $P = a+bQ$. To compute the parameters a and b, we begin with an estimated elasticity of demand or supply and a pre-policy price and quantity demanded or supplied. The definition of the elasticity of supply or demand is: the percent change in quantity over the percent change in price or:

$$\varepsilon = \frac{\frac{dQ}{Q_0}}{\frac{dP}{P_0}}$$

Where dP and dQ represent change in price and quantity from the pre-policy prices and quantities, P_0 and Q_0. This can be rearranged such that:

$$\varepsilon = \frac{dQ}{dP}\frac{P_0}{Q_0}$$

As $\frac{dQ}{dP}$ is also known as the derivative of quantity with respect to price, rearranging $P = a + bQ$ taking the derivative with respect of Q with respect to P yields, $\frac{dQ}{dP} = \frac{1}{b}$. Plugging this fact into the above equation and solving for b gives the slope of the curve in terms of the estimated elasticity and pre-policy prices and quantities:

$$b = \frac{P_0}{\varepsilon Q_0} \tag{22}$$

As the pre-policy prices and quantities are on the supply or demand curve, plugging P_0, Q_0 and the formula for b into $P = a + bQ$ and solving for a yields the intercept of the curve:

$$a = P_0 - bQ_0 = P_0 - \frac{P_0}{\varepsilon} \tag{23}$$

The supply and demand curves are plotted in Figure 6 along with the pre-policy equilibrium quantities demanded and supplied by each fuel represented by diamonds in the figure. The abbreviation PR stands for policy region. Coal currently supplies the majority of U.S. electric power, followed by nuclear and hydro, natural gas, and renewables. Notice that for a given quantity, the cost of electricity from natural gas is greater than the cost of electricity from coal. Electricity from renewable energy is always more expensive than electricity from coal or natural gas, except at very low quantities.[8]

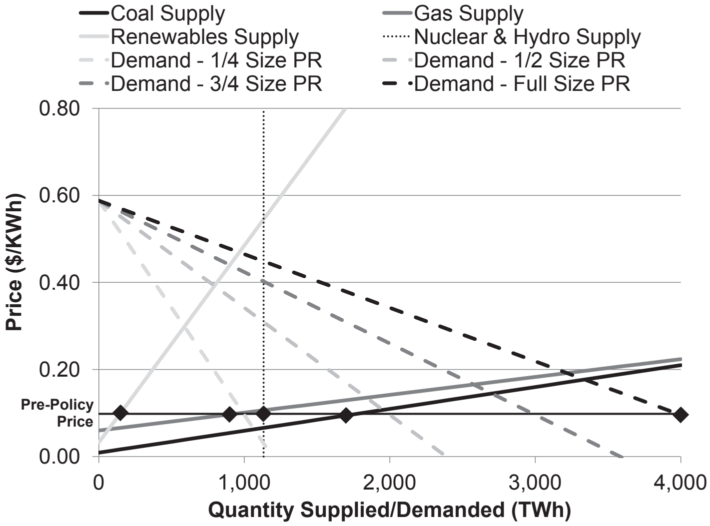

Figure 6. Supply and Demand Curves

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[8] This may be due to subsidies already in place that are not accounted for in our calculations which enable renewables to operate despite high costs.

B Surplus Calculations

Consumer surplus is equal to the utility the consumer derives from the electricity consumed less the cost of the electricity or the area under the demand curve (marginal utility curve) from zero to the total quantity of electricity demanded in region r (q^r) minus price times quantity demanded in region r:

$$CS^r = \int_0^{q^r} u^{r\prime}(q)\mathrm{d}q - p^r q^r$$

For coal, natural gas, nuclear, hydro, and qualifying renewables the producer surplus is equal to producer's profit: price times quantity of electricity supplied by that fuel minus the cost of supplying the electricity (the area under the marginal cost (or supply) curve from zero to the quantity supplied). For nuclear and hydro, the marginal cost of supplying electricity is zero, therefore the nuclear and hydro producer surplus, PS^{nh} is simply price times quantity. In calculating the surplus, one must be careful to use the correct price and adjust for taxes and subsidies, denoted here by x. If nuclear and hydro are only supplied in the policy region, the policy region price should be used and the tax or subsidy received must be included, yielding $PS^{nh} = (p^p + x)q_{nh}$. Conversely, if nuclear and hydro are only supplied in the no-policy region, the no-policy region price should be used, yielding $PS^{nh} = p^n q_{nh}$ since there are no taxes or subsidies there. If nuclear and hydro are used in both regions, the price they receive is the same in each region.

For the other fuels, an upward sloping supply curve is assumed. Again, one must be careful to use the correct price and adjust for the subsidy received or tax paid by the producer in the policy region. The general formula for the producer surplus of coal, natural gas and qualifying renewables is:

$$PS^f = pq_f - \int_0^{q_f} c_f'(q)\mathrm{d}q$$

p represents the relevant price received by each fuel, f. If a fuel is consumed only in the policy region, the relevant price is the policy region price plus the implicit subsidy or less the tax, depending on the fuel and policy. If the fuel is consumed only in the no-policy region or consumed in both regions, the relevant price is the no-policy region price, in the latter case the price received by the fuel in both regions would be the same.

Under a CES or an RPS, the tax revenue from the producers using coal and natural gas (and nuclear and hydro for an RPS) is paid directly to the producers using qualifying renewables (and nuclear and hydro under a CES). Thus, the above calculations take into account the tax revenue implicitly. Under a CO_2 tax, however, the tax revenue simply goes to the general treasury and is assumed to be redistributed to the population. The above calculations do not account for this, so the tax revenue must be calculated separately and added to the market surplus:

$$TR = T(z_c q_c + z_g q_g)$$

C Proof of Proposition 10

Part (1): For $\rho \leq \underline{\mathrm{R}}$, an RPS cannot reduce CO_2 emissions.

By Proposition 4, if the required share of renewables in the policy region, α, is such that the required generation from qualifying renewables is less than or equal to pre-policy qualifying renewable generation, $\alpha q_0^p \leq q_r^0$, there will be no change in total electricity production in the market and therefore no change in CO_2 emissions. Setting α to one, the most stringent RPS policy, if $q_0^p \leq q_r^0$ there will be no reduction in CO_2 emissions. As a policy region that consists of $\rho \in (0, 1)$ of the market consumes ρ of the electricity pre-policy, $q_0^p = \rho q_0$. Therefore if $\rho q_0 \leq q_r^0$, no RPS policy can cause a reduction in CO_2 emissions, and $\underline{\mathrm{R}}$, where $\underline{\mathrm{R}} q_0 = q_r^0$, will be the largest relative policy region size in which an RPS policy will be ineffective.

Part (2): For $\rho \leq \bar{R}$, a CES or CO_2 tax cannot reduce CO_2 emissions.

Suppose that the emissions intensity requirement of the CES policy, $\bar{z}$, is set to zero. Then only qualifying renewables, nuclear, and hydro would be permitted to sell electricity to the policy region. In this case, if pre-policy demand was less than or equal to pre-policy qualifying renewable, nuclear, and hydro generation, $q_0^p \leq q_r^0 + q_{nh}^0$, there would be no change in the pre-policy generation from each fuel or in CO$_2$ emissions by the same logic as the proof for Proposition 8. Also by Proposition 8, if $\bar{z}$, is less than the emissions intensity of natural gas, z_g, such that $Z_g > 0$ and $\bar{z}$ is such that $Z_c q_c^p + Z_g q_g^p \leq q_r^0 + q_{nh}^0$, then there will be no change in total electricity production in the market and therefore no change in CO$_2$ emissions. For $\bar{z}$ greater than z_g, causing $Z_g < 0$, and $Z_c q_c^p \leq q_r^0 + q_{nh}^0 - Z_g q_g^0$, the same conclusions follow.

By Proposition 9, for any tax, T, greater than zero, if pre-policy demand for electricity in the policy region is less than or equal to pre-policy zero-emissions generation, $q_0^p \leq q_r^0 + q_{nh}^0$, then zero-emissions fuels will provide all electricity in the policy region and there will be no change in total electricity production in the market and therefore no change in CO$_2$ emissions.

Therefore if $q_0^p = \rho q_0 \leq q_r^0 + q_{nh}^0$, no CES or CO$_2$ tax policy can cause a reduction in CO$_2$ emissions, and the largest relative policy region size ρ in which a CES or CO$_2$ tax policy will be ineffective will be $\bar{R}$ where $\bar{R} q_0 = q_r^0 + q_{nh}^0$.

Part (3): As long as $q_{nh}^0 > 0$, $\underline{\mathrm{R}} < \bar{R}$.

Part (4): For $\rho > \underline{\mathrm{R}}$, a sufficiently stringent RPS policy can reduce CO$_2$ emissions.

Part (4a): There exists an α such that $\alpha \rho q_0 > q_r^0$, $\rho > \underline{\mathrm{R}}$ and $\alpha \in (0, 1)$.

At $\rho = \underline{\mathrm{R}}$, $\underline{\mathrm{R}} q_0 = q_r^0$. For $\rho > \underline{\mathrm{R}}$, $\rho q_0 > q_r^0$. For α sufficiently close to one, $\alpha \rho q_0 > q_r^0$.

Part (4b): If α is such that $\alpha \rho q_0 > q_r^0$, then $s > 0$ if $\alpha < 1$.

Suppose not. Then $s = 0$ and $p^p = p^n = p$ by Propositions 1 and 5. If the price is the same in both regions, then the system of equations determining the equilibrium is reduced to the pre-policy set of equations, with the addition of the RPS constraint. Given the pre-policy set of equations, the production from each fuel must be the pre-policy production by the strict convexity of the cost functions and the consumption of electricity must be the same as pre-policy consumption by strict concavity of demand. Thus, $q_r = q_r^0$. But to satisfy the RPS constraint, $\alpha q_r^p = q_r$. With pre-policy

policy region consumption equal to ρq_0, this implies $\alpha \rho q_0 = q_r^0$, which is a contradiction to the initial assumption that $\alpha \rho q_0 > q_r^0$. Thus $s > 0$.

Part (4c): $p^n < p_0$

With $\alpha \rho q_0 > q_r^0$, to meet the RPS constraint either $q^p < \rho q_0$ or $q_r > q_r^0$ or both. Suppose that $q^p \geq \rho q_0$ but $q_r > q_r^0$. This implies that $p^p + s > p_0$, by strict convexity of the qualifying renewables cost function, equation (2), and Proposition 3, and $p^p \leq p_0$ by strict concavity of demand and equation (1). As $p^p \leq p_0$, $p^p - As < p_0$ and by Propositions 1 and 5, $p^n < p_0$ as required.

Suppose instead that $q^p < \rho q_0$. This implies $p^p > p_0$ by strict concavity of demand. With $s > 0$, $p^p + s > p_0$ and $q_r > q_r^0$. At the $\hat{\alpha}$ such that $\hat{\alpha} \rho q_0 = q_r^0$, $\rho q_0 - q_r^0 = \hat{q}^p - q_r^0 = \hat{q}_c^p + \hat{q}_g^p + \hat{q}_{nh}^p$, $\hat{q}_c^n + \hat{q}_g^n + \hat{q}_{nh}^n = q_0^n$, and $\hat{q}_c^p + \hat{q}_g^p + \hat{q}_{nh}^p + \hat{q}_c^n + \hat{q}_g^n + \hat{q}_{nh}^n = q_c^0 + q_g^0 + q_{nh}^0$ by Proposition 4. $\hat{q}$ indicates the equilibrium quantity when $\alpha = \hat{\alpha}$. We have assumed, $q^p < \rho q_0$ and $q_r > q_r^0$ which implies $q^p - q_r < \rho q_0 - q_r^0$ and therefore $q^p - q_r = q_c^p + q_g^p + q_{nh}^p < \hat{q}_c^p + \hat{q}_g^p + \hat{q}_{nh}^p$. Suppose $q^n = q_c^n + q_g^n + q_{nh}^n \leq \hat{q}_c^n + \hat{q}_g^n + \hat{q}_{nh}^n = q_0^n$. Then $p^n \geq p_0$ by strict concavity of demand. But $q_c^n + q_g^n + q_{nh}^n + q_c^p + q_g^p + q_{nh}^p < q_c^0 + q_g^0 + q_{nh}^0$, which implies $p^n < p_0$ by strict convexity of costs. Therefore, $q^n = q_c^n + q_g^n + q_{nh}^n > \hat{q}_c^n + \hat{q}_g^n + \hat{q}_{nh}^n = q_0^n$, in which case as long as $q_c^n + q_g^n + q_{nh}^n + q_c^p + q_g^p + q_{nh}^p < q_c^0 + q_g^0 + q_{nh}^0$, $p^n < p_0$ will be implied by strict concavity of demand and strict convexity of costs.

Since non-qualifying renewable producers receive p^n by Propositions 1 and 5 and $p^n < p_0$, $q_c < q_c^0$ and $q_g < q_g^0$ by strict convexity of costs. Therefore CO_2 emissions will decline: $z_c q_c + z_g q_g < z_c q_c^0 + z_g q_g^0$.

Thus, for $\rho \in (\underline{R}, \bar{R}]$, a sufficiently stringent RPS policy will reduce CO_2 emissions, while a CES or CO_2 tax cannot.