Comparing renewable portfolio standards, emission intensity standards and pollution taxes in the electricity sector

Megan H. Accordino* and Deepak Rajagopal†

September 7, 2012

1 Introduction

In 2010, electric power generation was the single largest source of carbon dioxide (CO$_2$) emissions in the U.S. accounting for 40 percent of CO$_2$ emissions (EPA, 2012, Table 2-1). Furthermore, several studies show that it is cost-effective to first target CO$_2$ emission reduction in electricity sector (EPA, 2008; EIA, 2009). As a result, this sector has become 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

---

*Department of Economics, University of California, Los Angeles, maccordino@ucla.edu. Acknowledgement: Megan H. Accordino was supported by The National Science Foundation Integrative Graduate Education Research Traineeship on Clean Energy for Green Industry at UCLA.

†Assistant Professor, Institute of the Environment and Sustainability, University of California, Los Angeles, La Kretz Hall, Suite 300, Los Angeles, CA 90095-1567, (310) 794-4903, rdeepak@ioes.ucla.edu

$^1$This policy targets CO$_2$ emissions from 11 industrial sectors including power generation, http://ec.europa.eu/clima/policies/ets/index_en.htm
additional eight states and two territories have voluntary RPS goals.\textsuperscript{2} Globally, RPS policies have been adopted in eleven countries and by several state or provincial governments.\textsuperscript{3} A limitation of an RPS is that constraining pollution reduction strategies to increasing the share of renewable energy excludes options such as fuel-switching between fossil fuels of varying CO\textsubscript{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 to an RPS or CO\textsubscript{2} tax 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\textsubscript{2} emissions per MWh of electricity produced. Similar to the RPS and CO\textsubscript{2} tax, a CES can permit trading of credits, which would be linked to the emissions intensity of each fuel. Different from an RPS, such a regulation allows for fuel switching from coal to natural gas.

Several studies have explored how various CO\textsubscript{2} emissions reduction policies perform. Fischer and Newell (2008) found that a CO\textsubscript{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. Their paper also highlights the difference in distributional outcomes between the policies. Fischer (2010) analyzes the impact on electricity prices from implementing an RPS. Varying the required share of electricity from renewable resources under the RPS policy, she 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. Thus, consumers may experience an increase in surplus under an RPS. 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.

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. The report focuses on the commonalities between the results and the policy design features that improve the performance of the policies. 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\textsubscript{2} emissions increases the cost of the policy to consumers for a given reduction in CO\textsubscript{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\textsubscript{2} eliminated.

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

\textsuperscript{2}Database of State Incentives for Renewables & Efficiency, http://www.dsireusa.org/documents/summarymaps/RPS_map.pdf

resources between in-state and rest of the market, without affecting total emissions or even increase total emissions. Leakage especially undermines greenhouse gas (GHG) policies, for they are global pollutants.

The contribution of this paper is to analyze the implications of the size of the policy jurisdiction on policy choice. We compare three policies, namely, an RPS, a CES and a CO\textsubscript{2} tax as the size of the policy region varies from a fraction of the electricity market to the entire market in terms of relative impact on emissions and the distribution of economic impacts. We analyze these policies in a static, partial-equilibrium context assuming perfect competition.

We find that when the policy region is the full market, for a given reduction in CO\textsubscript{2} emissions, the CO\textsubscript{2} tax is the most cost-effective policy while an RPS is the least cost-effective policy, as measured by the reduction in market surplus caused by the policy, a conclusion similar to that of Fischer and Newell (2008). The CES produces a reduction in market surplus that is similar to the CO\textsubscript{2} tax, but the distribution of gains and losses across consumers and producers differs from that produced by the CO\textsubscript{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\textsubscript{2} emissions than can a CES or CO\textsubscript{2} tax. The 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\textsubscript{2} tax. For a sufficiently small policy region, only an RPS can induce a reduction in CO\textsubscript{2} emissions. The cutoff policy region size, below which a CO\textsubscript{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\textsubscript{2} tax or CES will be unable to induce a change in CO\textsubscript{2} emissions.

We conclude that for a policy region that is small relative to the market, an RPS is the only policy that will be effective in reducing emissions. This is a significant justification for the RPS policies currently in place in many states. Even for a larger policy region, if the CO\textsubscript{2} emissions reduction target is sufficiently large, only an RPS will be able to achieve the target. Conversely, a small CO\textsubscript{2} emissions reduction target causes a CO\textsubscript{2} tax or a CES to be marginally more cost-effective. However, if the policy region covers a large majority or all of the market, a CO\textsubscript{2} tax or CES would be significantly more cost-effective than an RPS. Thus, the size of the policy region relative to the market is a critical consideration in designing an effective policy.

The rest of the paper is as follows. Section 2 describes the formulation of the model. Section 3 explores some analytical results that are not determined by function form assumptions. Section 4 explains the numerical simulation exercise and data used therein. Section 5 details the results of the numerical simulations and Section 6 investigates the sensitivity of our results to our parametrization. Section 7 concludes.
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, namely, a home region, which is the policy region and a rest-of-the-market region. We model electricity supply from four sources: coal, natural gas, renewable resources, and a fourth category, nuclear and hydroelectric power. Nuclear and large hydro generation are not treated as renewables in most states under the RPS policies. As a consequence of the significant environmental and regulatory hurdles to building new nuclear or hydro generation capacity in addition to their high capital cost, it is unlikely additional nuclear or large hydroelectric facilities will be built in the future (CBO, 2011). We therefore assume that nuclear and hydro generation supply is fixed, but allow the producers to maximize profit by choosing whether to sell the nuclear and hydro generation to the policy or non-policy regions (or both). As the marginal cost of nuclear and hydro power is near zero, the marginal cost of nuclear and hydro generation is assumed to be zero.

When the policy applies to the full market, in which case there effectively is but a single region, a representative consumer chooses electricity consumption given a utility function and price, and a representative producer for each technology chooses output given a cost function and price. In the one-region model, all nuclear and hydro capacity is utilized when the price of electricity is non-negative. The market clearing condition ensures that the quantity supplied equals the quantity demanded and, consequently, determines the price. In the two-region model, a representative consumer for each region chooses electricity consumption. It is assumed that consumers in both regions have the same preferences, that consumers can purchase electricity from any producer in the market regardless of the consumer’s region, and that there are no transmission constraints. Producers of electricity from coal, natural gas, and renewable resources choose how to allocate production between the regions as well as the total amount of electricity to produce. Producers of electricity from nuclear and hydro choose how to allocate the fixed supply of nuclear and hydro between regions. If the price received when nuclear and hydro operates at full capacity would be less than zero, the nuclear and hydro operators can choose to reduce output. The marginal cost curves are assumed to be upward sloping and the marginal utility curves are assumed to be downward sloping.

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, 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, $\alpha$. 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 $\alpha$ 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 $As$. As a result, under an RPS, owners of conventional generation capacity pay an implicit tax to owners of qualifying renewable generation capacity.

The consumers in each region solve the following problem:

$$\max_q u(q^r)$$

s.t. $p^r q^r = B$

Here $u(\cdot)$ is the consumer’s utility function for electricity consumption, $p^r$ is the price of electricity in the consumer’s region, $q^r$ is the quantity of electricity consumed, and $B$ is the consumer’s budget. This yields the following first order conditions for the consumers in each region where the superscript $p$ indicates the policy region, and the superscript $n$ indicates the region with no policy:

$$u'(q^p) = p^p \quad (1)$$

$$u'(q^n) = p^n \quad (2)$$

Producers generating electricity from coal seek to maximize profit by solving:

$$\max_{q^p_c, q^n_c} p^p q^p_c + p^n q^n_c - c_c(q^p_c + q^n_c) - Asq^p_c$$

s.t. $q^p_c \geq 0, q^n_c \geq 0$

$p^p$ is the price in the policy region, $p^n$ is the price in the region with no policy, $q^p_c$ and $q^n_c$ are the quantities of electricity produced from coal in the policy and no-policy regions. $c_c(\cdot)$ is the cost function for electricity produced from coal and $As$ is the REC price multiplied by the number of RECs a coal producer must purchase to satisfy the RPS requirement in the policy region. The two constraints prevent the producer from choosing to produce negative quantities.

The solution to this problem is found by taking the first order conditions:

$$p^p = c'_c(q^p_c + q^n_c) + As - \lambda^p_c \quad (3)$$

$$p^n = c'_c(q^p_c + q^n_c) - \lambda^n_c \quad (4)$$

$\lambda^p_c$ and $\lambda^n_c$ are the Lagrange multipliers on the non-negativity constraints above.

The problem for producers using natural gas is identical to the problem for producers using coal except that the cost function is $c_g(\cdot)$. Thus, the first order conditions for the natural gas producers
are:

\begin{align*}
p^p &= c_g'(q_p^p + q_g^n) + As - \lambda_g^p \\
p^n &= c_g'(q_p^p + q_g^n) - \lambda_g^n
\end{align*}

The producers of electricity from qualifying renewable resources receive a subsidy \( s \) for each MWh of electricity. The cost function for producers using renewables is \( c_r(\cdot) \). Therefore, the first order conditions determining the production of electricity from renewable resources are:

\begin{align*}
p^p &= c_r'(q_{p}^p + q_{n}^g) - s - \lambda_{p}^r \\
p^n &= c_r'(q_{p}^r + q_{n}^g) - \lambda_{n}^r
\end{align*}

For nuclear and hydro, the marginal cost of generation is zero. As a result, the problem solved by the producers using nuclear and hydro are:

\[
\max_{q_{p}^n, q_{n}^n} p^p_{q_{p}^n} + p^n_{q_{n}^n} - Asq_{p}^n \\
\text{s.t. } q_{p}^n + q_{n}^n \leq Q_{nh} \\
q_{p}^n \geq 0, q_{n}^n \geq 0
\]

As nuclear and hydro generation is treated no differently than coal or gas generation under an RPS, nuclear and hydro generators receive \( p^p - As \) per MWh of electricity in the policy region. The first constraint for the nuclear and hydro generators is the capacity constraint where the available capacity of nuclear and hydro generation is indicated by \( Q_{nh} \). In the first order conditions it will have the Lagrange multiplier, \( \psi \). The second and third constraints prevent negative nuclear and hydro generation.

This problem yields the first order conditions:

\begin{align*}
p^p &= \psi + As - \lambda_{p}^{nh} \\
p^n &= \psi - \lambda_{n}^{nh}
\end{align*}

Combining equations (1)-(10), 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.

\begin{align*}
\text{Market Clearing: } q^p &= q_{c}^p + q_{g}^p + q_{p}^{n} + q_{r}^p \\
q^n &= q_{c}^{n} + q_{g}^{n} + q_{p}^{n} + q_{r}^{n} \\
\text{RPS Constraint: } q_{p}^{r} \geq A(q_{c}^{p} + q_{g}^{p} + q_{p}^{n})
\end{align*}

Each pair of equations (2) and (3) through (9) and (10) 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.

\[
\begin{align*}
\text{Coal: } p^p &= p^n + As + \lambda^n_c - \lambda^p_c \\
\text{Natural Gas: } p^p &= p^n + As + \lambda^n_g - \lambda^p_g \\
\text{Nuclear & Hydro: } p^p &= p^n + As + \lambda^n_{nh} - \lambda^p_{nh} \\
\text{Renewables: } p^p &= p^n - s + \lambda^n_r - \lambda^p_r
\end{align*}
\] (14) (15) (16) (17)

Note that for coal, natural gas, and nuclear and hydro, the first three terms in each equation are identical and the only difference between the equations are the Lagrange multipliers on the non-negativity constraints, which are always non-negative. As three of the four terms in each equation are identical, if either of the Lagrange multipliers are positive for one fuel, the sum of the Lagrange multipliers in each of the three equations must have the same value. As a result, the three equations (14)-(16) form only one unique equation and all non-renewable fuels must either (1) produce electricity for both regions, (2) produce electricity for only one region, or (3) no produce electricity at all.

When the required share of renewables in the policy region is less than the existing quantity of renewables divided by the pre-policy demand in the policy region, the RPS will not bind as existing renewables can be shifted to the policy region at no cost and the price of a REC, \( s \), will be zero. With the REC price equal to zero, all fuels receive the same price and prices in both regions must be the same, otherwise all generation will be consumed in the region with the higher price. Further, if the REC price is zero, the electricity price will not change from the pre-policy price.

As the stringency of the policy is tightened, the RPS constraint will bind, which will raise the price of a REC above zero. With a positive REC price, renewable generation will increase in the policy region and non-renewable generation will be shifted out of the policy region to the rest of the market. Because coal and natural gas generation is costly, while nuclear and hydro have zero marginal cost, coal and natural gas generation will diminish before nuclear and hydro generation diminishes. The market-wide quantity of nuclear and hydro will only diminish if the price in the no-policy region goes to zero.

Additionally, as the stringency of the RPS policy increases, the price in the policy region will increase (as more expensive resources must be utilized) while the price in the no-policy region decreases (as less expensive resources are shifted to this region). The price change causes demand to rise in the no-policy region and demand to fall in the policy region. This same pattern of results will occur if the policy region is equal to the full market. However, the quantity of nuclear and hydro in the market will begin to diminish once coal and natural gas generation is eliminated as this is the only method of fulfilling a very stringent RPS requirement. No further emissions reductions can occur after coal and gas generation withdraw, as nuclear and hydro emit zero \( \text{CO}_2 \).
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 CO₂ emissions, or CO₂ 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 CO₂ per MWh of electricity generated by coal, which, according to the EPA, is approximately 1.125 Tons/MWh.⁴ $z_g$ represents the emissions of CO₂ per MWh of electricity generated by natural gas, which is approximately .5625 Tons/MWh. Thus, CO₂ emissions per MWh from coal generation are twice the level of emissions per MWh from natural gas generation. Renewable, nuclear, and hydro generation emit no CO₂.

The CES requirement can be rearranged such that:

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

where

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

Similar to an RPS, there would be 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 must show 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 CO₂ per MWh, LSEs are required to purchase different quantities of carbon credits per MWh of generation from coal versus natural gas. As can be seen in the above equation, LSEs must purchase $Z_c$ carbon credits for each MWh of coal-generated electricity and $Z_g$ carbon credits for each MWh of natural gas-generated electricity where $Z_c$ is greater than $Z_g$ because coal emits more CO₂ per MWh of electricity. The price of a carbon credit is represented by $s$. Note that $Z_g$ may be negative if $\bar{z}$ is greater than .563 Tons/MWh, the CO₂ emissions/MWh of natural gas-fired generation.

The system of equations that defines an equilibrium under a CES is derived in the same manner as was used for an RPS, with two minor differences. First, in the policy region, coal and natural gas now receive the policy region price less the implicit tax on coal, $p^p - Z_c s$ and policy region price less the implicit tax on natural gas, $p^p - Z_g s$, respectively. Second, nuclear and hydro are now treated the same as renewable resources and receives the policy region price plus a subsidy, $p^p + s$, because it emits no CO₂. The market clearing conditions and the equations determining optimal consumption, however, are the same under a CES as under an RPS. Again the eight equations for the four fuels can be condensed to four equations to understand what types of equilibria can be

⁴http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html
expected in the numerical simulations:

\[
\text{Coal: } p^p = p^n + Z_c s + \lambda^c_n - \lambda^p_c \quad (18)
\]
\[
\text{Natural Gas: } p^p = p^n + Z_g s + \lambda^n_g - \lambda^p_g \quad (19)
\]
\[
\text{Nuclear & Hydro: } p^p = p^n - s + \lambda^c_{nh} - \lambda^p_{nh} \quad (20)
\]
\[
\text{Renewables: } p^p = p^n - s + \lambda^n_r - \lambda^p_r \quad (21)
\]

Unlike under an RPS, coal and natural gas do not receive the same price in the policy region under a CES. Therefore, if the CES constraint binds, such that the carbon credit price, \( s \), is greater than zero, coal and natural gas cannot both be utilized in both regions. If generation from both fuels were to sold in both regions, all of the Lagrange multipliers in equations (18) and (19) would be zero and the equations would be reduced to \( p^p = p^n + Z_c s \) and \( p^p = p^n + Z_g s \). 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 only 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.

Equations (20) and (21) demonstrate that because nuclear, hydro, and renewables receive the same price, the producers’ maximization problems generate the same conditions for the relationship between the policy and no-policy regions’ prices. Either nuclear, hydro, and renewables must all be utilized in both regions, they must be utilized in only one region, or none can operate in either region. As it is least expensive to meet a CES requirement by utilizing existing nuclear, hydro, and renewables in the policy region, nuclear, hydro, and renewables will only be used in the policy region for any CES requirement that binds.

If the policy region is small enough that existing nuclear, hydro, and renewables are sufficient to meet the entire pre-policy demand of the policy region, no price changes will occur, the carbon credit price will be zero, and most importantly, it is impossible to achieve a reduction in emissions. For a mid size region, reshuffling of resources will occur for low stringencies, followed by consumption of only gas, nuclear, hydro, and renewables in the policy region for average stringencies. For highly stringent policies, only nuclear, hydro, and renewables will be consumed at home. As the policy increases in stringency, the price in the policy region increases, decreasing demand, and the price in the no-policy region decreases, increasing demand. The larger the no-policy region, the greater the increase in emissions in the no-policy region due to the increase in demand. A large region will follow a similar path as a mid-size region but reshuffling will be sufficient only for very low stringencies and coal consumption will continue even after the policy binds, though it will decline as the policy becomes more stringent. If the policy region is the full market, no reshuffling can occur and therefore any policy that requires a decrease in CO\(_2\) emissions intensity will bind.

### 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. Producers using coal to generate electricity, which emits
tons of CO\textsubscript{2} per MWh, pay $z_c T$/MWh of generation. For natural gas generation, which emits $z_g$ tons of CO\textsubscript{2} per MWh, the tax is $z_g T$/MWh. Since nuclear, hydro, and renewable generation emit no CO\textsubscript{2}, they pay no tax.

A CO\textsubscript{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 the symbol $s$ for carbon credit price in the CES equations is replaced by a $T$ for tax in the equations for a CO\textsubscript{2} tax. Therefore, the analysis of possible equilibria for a CO\textsubscript{2} tax is virtually identical to the analysis done for a CES and is not repeated here. A CO\textsubscript{2} tax and a CES also produce the same general pattern of prices and quantities as the policies become more stringent and the region gets larger.

3 Some analytical insights

Overall, a CES policy is more cost-effective than an RPS as it allows for more flexibility in reaching the policy target. Specifically, a CES recognizes that natural gas emits less CO\textsubscript{2} than coal and allows for an increase in production using natural gas to reduce the overall emissions intensity. As increasing production using natural gas is more cost-effective than increasing production from renewable resources, the cost of reducing CO\textsubscript{2} emissions is lower under a CES than under an RPS. Crediting nuclear and hydro for their zero emissions under a CES does not reduce the cost of the policy in our model as nuclear and hydro are always fully utilized and cannot increase production.

A CO\textsubscript{2} tax is more cost-effective than a CES because it refrains from subsidizing zero-emission technologies, thereby raising the policy region price and reducing consumption relative to a CES. Therefore consumers in the policy region are more negatively affected by a CO\textsubscript{2} tax than by a CES or RPS. As renewable producers receive no subsidy, renewable producers do not benefit as much from a CO\textsubscript{2} tax as they do from a CES or RPS. For a given decrease in emissions, the tax on fossil-fuel producers will be lower under a CO\textsubscript{2} tax than under a CES because consumers decrease consumption more under the CO\textsubscript{2} tax. Thus, a CO\textsubscript{2} tax is better than a CES for generators that use coal and natural gas.

Both a CES and a CO\textsubscript{2} tax benefit natural gas generators and harm coal generators for small emissions reduction targets in large policy regions that require both coal and natural gas to meet pre-policy demand. This occurs because the CO\textsubscript{2} emissions intensity of natural gas is lower than coal, causing coal to be replaced with natural gas in the policy region. In other situations, producers using both coal and natural gas are harmed as the output of both must be reduced in the policy region. Under an RPS, coal and natural gas pay an equal tax and are both harmed by any RPS policy that binds.

When the policy region is medium-sized, such that all three policies are able to reduce emissions, the three policies will have identical effects on coal and natural gas generators and on the price and quantity of electricity in the no-policy region for a given emissions reduction target. This is due specifically to the region size. As a medium-size region, for most emission reduction targets, the equilibrium under a CES and CO\textsubscript{2} tax will require that natural gas, nuclear, hydro, and
renewables be used in the policy region, which will allow natural gas and coal to be used in the no-policy region. For a larger region, this will not be true under a CES or CO$_2$ tax for most emissions reduction targets. Conversely, for any policy region size and any RPS policy, natural gas and coal will be used in the no-policy region.

To achieve a targeted decrease in emissions, total coal and natural gas production must decline. If both fuels operate in the no-policy region, both receive the same price in the no-policy region and will set marginal cost equal to price to determine output. Setting the marginal cost curves equal to each other, yields generation using coal in terms of generation using natural gas. Setting the change in emissions from the pre-policy level equal to the target yields a second equation with generation using coal in terms of generation using natural gas, which can be solved for generation from each fuel. Consequently, if both coal and natural gas are operating in the no-policy region, the total output of coal and natural gas are completely determined by the emissions reduction target. Additionally, because under an RPS, coal and natural gas generate in the no-policy region regardless of the policy region size, the price in the no-policy region and the total output of coal and natural gas for a given emissions reduction target are the same for any policy region size.

4 Numerical Simulation

To illustrate the order of magnitude of the difference between the different policies with respect to multiple criteria such as emissions and economic surplus, we perform numerical simulations. We simulate policies for four different scenarios concerning the share of the policy region’s electricity consumption relative to the electricity market, namely, a 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 curve, and a marginal utility curve is synonymous with a demand curve. To parametrize the supply and demand functions, we assume for simplicity that the functions are linear. As an estimate of the effects of a policy on consumers and producers of electricity, we calculate the surplus to the consumers in each region (the utility received from electricity consumption less the cost of the electricity), the profit (or surplus) of each producer, and any tax revenue yielded by the policy. The sum of the consumer surplus, producer surplus and tax revenue yields the market surplus under each scenario. These metrics summarize the effect of the changes in prices and quantities on the market participants. Details of the calculations can be found in Appendices A and B.

4.1 Data

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 where increases in the quantity of electricity supplied imply that new generation has been installed to increase 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 a centralized body clears wholesale transactions and manages power flows. Examples of this type of market are Independent System Operator (ISO) New England, 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 ERCOT or the California ISO, a single state composes the majority of the market, whereas in ISO-New England or the PJM Interconnection a single state is only a small part of the 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 is the same elasticity found in much of the literature (Bernstein and Griffin, 2005; Fischer, 2010, e.g.).

The baseline prices, 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. For the purposes of this analysis, 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. 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.

## 5 Results

To enable an easy comparison between the policies, we consider the effect of each policy as a function of the reduction in CO$_2$ emissions. The emissions reductions calculated here represent the total change in CO$_2$ emissions across the full market, not the change in emissions within the policy region. Due to the shuffling of resources between regions when a policy is enacted in only a part of a market, calculating the change in emissions in the policy region and ignoring the change in the no-policy region would overstate the effect of the policy.

### 5.1 Effect of policy choice on 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 and a CO$_2$
tax 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.

**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

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 initial share of coal since coal is the most CO$_2$ intensive resource.

![Figure 3. Reduction in CO$_2$ Emissions by CO$_2$ Tax Level and Policy Region Size](image)

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 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. 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.

<table>
<thead>
<tr>
<th>Size of Policy Region</th>
<th>RPS - Share of Renewables</th>
<th>CES - Reduction in Emissions Intensity (%)</th>
<th>CO₂ Tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 of Market</td>
<td>14.6%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1/2 of Market</td>
<td>7.3%</td>
<td>68.2%</td>
<td>$0.00</td>
</tr>
<tr>
<td>3/4 of Market</td>
<td>4.9%</td>
<td>26.0%</td>
<td>$0.00</td>
</tr>
<tr>
<td>Full Market</td>
<td>3.6%</td>
<td>0.0%</td>
<td>$0.00</td>
</tr>
</tbody>
</table>

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 CO₂ emissions

Table 2 shows the minimum policy requirement that is necessary to induce a change in CO₂ emissions for each of the three policies. As previously discussed, a CES or CO₂ tax in a policy region 1/4 the size of the market will achieve no reduction in CO₂ emissions. For an RPS, the minimum policy level required to induce a change in CO₂ 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 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 CO₂ emissions intensity is required in the policy region to stimulate a change in total market emissions. For either a CO₂ 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 will simply cause consumers in the policy region to utilize only nuclear, hydro, and renewables, resulting in no change in market emissions. For a larger region, any CO₂ tax above zero will generate a reduction in emissions as agents seek to minimize the tax paid.

Table 3 shows the maximum possible CO₂ emissions reduction for each policy and policy region size. For a CES or CO₂ tax and a policy region that is smaller than the full market, the maximum reduction in CO₂ 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.

Shifting only electricity from coal and natural gas to the no-policy region, as in a CES or CO\textsubscript{2} tax policy, does not reduce price as significantly since the quantity shifted is smaller. As a result, emissions in the no-policy region are always higher than they were pre-policy (the pre-policy level is determined by multiplying pre-policy market CO\textsubscript{2} emissions by the size of the no-policy region relative to the market). Thus, although all emissions are eliminated in the policy region for sufficiently high CO\textsubscript{2} taxes or a zero emissions intensity CES requirement, emissions in the no-policy region would be higher than they were pre-policy. This leads the maximum possible emissions reduction to be less than the relative size of the 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. 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\textsubscript{2} emissions, the RPS, like a CES or CO\textsubscript{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 29 states plus the District of Columbia and 2 U.S. territories, that is not intuitively obvious.\footnote{Database of State Incentives for Renewables & Efficiency, http://www.dsireusa.org/documents/summarymaps/RPS\_map.pdf.} However, not all of the states with an RPS are small relative to the market in which they participate. Texas, for instance, makes up its entire market, while California makes up about 75 percent of its market.\footnote{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.} As will be discussed in Section 5.3, for these states, a CES or CO\textsubscript{2} tax yield a smaller decrease in market surplus for a given reduction in emissions.

<table>
<thead>
<tr>
<th>Size of Policy Region</th>
<th>RPS</th>
<th>CES/CO\textsubscript{2} Tax</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Emissions Reduction (Mil. Tons of CO\textsubscript{2})</td>
<td>Max Emissions Reduction as a Share of Total Emissions</td>
</tr>
<tr>
<td>1/4 of Market</td>
<td>609.1</td>
<td>24.2%</td>
</tr>
<tr>
<td>1/2 of Market</td>
<td>1,378.0</td>
<td>54.7%</td>
</tr>
<tr>
<td>3/4 of Market</td>
<td>2,473.2</td>
<td>98.3%</td>
</tr>
<tr>
<td>Full Market</td>
<td>2,517.2</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 3. Maximum Possible Emissions Reduction by Policy and Policy Region Size
5.2 Effect of policy choice on distribution of surplus

When determining whether to implement a particular policy and how stringent to set the policy, legislators often emphasize the welfare of the consumers in their region over other interests. Accordingly, Figure 4 shows how policy region consumer surplus varies with the size of the policy region, the type of policy, and the emissions reduction target. The colored sections of each bar represent the incremental change in surplus due to 4 increasing emissions reduction targets. The black sections indicate the change in surplus due to a 10 percent emissions reduction target. The sum of the darkest grey and black sections indicates the change in surplus due to a 20 percent emissions reduction target and so on. To provide a point of comparison for the percentage changes shown in the figures, Table 4 shows the initial surplus of each group represented in the data. Initial CO\textsubscript{2} emissions are 2,517 million tons.

Figure 4. Change in Policy Region Consumer Surplus for Various CO\textsubscript{2} Emissions Reduction Targets

<table>
<thead>
<tr>
<th>Group</th>
<th>Initial Surplus (Bil. $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market</td>
<td>1,188.0</td>
</tr>
<tr>
<td>Total Consumer</td>
<td>975.5</td>
</tr>
<tr>
<td>Coal</td>
<td>78.9</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>17.8</td>
</tr>
<tr>
<td>Renewable</td>
<td>4.8</td>
</tr>
<tr>
<td>Nuclear &amp; Hydro</td>
<td>111.1</td>
</tr>
</tbody>
</table>

Table 4. Initial Surplus Received by Consumers and Producers

As 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 CES costs consumers less than an RPS for a 20 or 40 percent reduction in CO\textsubscript{2} emissions, while an RPS costs consumers less for a 10 or 80 percent reduction in CO\textsubscript{2} emissions. A CO\textsubscript{2} tax unambiguously costs consumers in the policy region more than a CES or
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.

**Figure 5.** Change in Coal Producer Surplus for Various CO$_2$ Emissions Reduction Targets

Legislators may also be concerned with how the gains and losses from the policy are distributed among the producers. Figure 5 illustrates the effect of each policy on producers using coal. As was found in Section 3, the size of the policy region will not affect the reduction in surplus from an RPS for a given emissions reduction target. For a mid-size policy region, in which coal and natural gas are consumed in the no-policy region, the effect of a CES or a CO$_2$ tax on producers using coal and natural gas will be identical to the effect of an RPS on these producers. As the policy region grows however, Figure 5 shows that 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.

**Figure 6.** Change in Natural Gas Producer Surplus for Various CO$_2$ Emissions Reduction Targets
As can be seen in Figure 6, unlike producers using coal, producers using natural gas experience a gain for some emissions reductions targets under a CES or CO₂ tax. This occurs because natural gas has a lower emissions intensity than coal and for low emissions reduction targets, production will shift to natural gas from coal. For high emissions reduction targets or very high CO₂ taxes, producers using natural gas experience a loss because the policy requirement or tax also squeezes out natural gas production. When the CES or CO₂ tax does cause a fall in natural gas producer surplus, the fall is smaller than the fall under an RPS. When a CO₂ tax results in a different allocation of surplus to producers using natural gas than a CES policy, the CO₂ tax gives a smaller windfall to producers using natural gas than does a CES.

![Figure 7. Change in Renewable Producer Surplus for Various CO₂ Emissions Reduction Targets](image)

As Figure 7 illustrates, 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 CO₂ tax does, as it provides a subsidy to them. However, the benefit is much smaller than that experienced under an RPS.

Nuclear and hydro producers receive the most inconsistent treatment between the policies, as can be seen in Figure 8. Under an RPS, nuclear and hydro producer profit is unambiguously lowered as they are not considered qualifying renewable resources. Under a CES or CO₂ tax, nuclear and hydro producer profit increases as the zero emissions from nuclear and hydro generation is acknowledged. As the CES provides a subsidy to zero-emissions generation, nuclear and hydro benefit the most from a CES policy.

### 5.3 Trade-off between emissions and market surplus

To derive the implicit cost of emission reduction, we compare the change in market surplus relative to the change in total CO₂ emissions. 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 interpret the reduction in market surplus as the cost of a policy. For reference, the market surplus
and CO₂ emissions in the baseline, i.e., no policy scenario, are $1,188 billion and 2,517 million tons respectively.

As can be seen in Figure 9, the larger the decrease in CO₂ emissions, the larger the reduction in market surplus. Regardless of the relative size of the policy region, a CO₂ 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 CO₂ tax. This suggests that a CES can achieve an outcome similar to a CO₂ tax. Note, however, that if a large reduction in emissions is sought, an RPS is the only policy that can achieve the target when the policy region does not cover the full market. This occurs because a CES or CO₂ 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 CO₂ 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 10 shows the same data as 9, 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. From the figure, 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 CO₂ 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 CO₂ tax can achieve the same emissions reduction with a smaller reduction in market surplus than occurs under an RPS. Further, as the region size grows relative to the market, the market surplus reduction is smaller for a CES or a CO₂ tax than for an RPS.
Interpreting the fall in market surplus as the cost of the policy, this implies that the cost-effectiveness of a CES or CO$_2$ improves at a faster rate under a CES or CO$_2$ tax than under an RPS. For a CES policy that yields a 20 percent reduction in CO$_2$ emissions, the market surplus reduction, or cost, is .25 percent ($3 billion) less if the policy region is the full market than in a 3/4 size policy region. For a CES policy that yields a 40 percent reduction in CO$_2$ emissions, the cost of the policy is 3.1 percent ($37 billion) less if the policy region is the full market than it would be in a 3/4 size policy region. The comparable differences for an RPS are .09 percent ($1 billion) and .51 percent ($6 billion). Thus, the cost-effectiveness of a CES or CO$_2$ tax policy is heavily influenced by the size of the policy region relative to the market, while the cost-effectiveness of an RPS is affected much less by the relative size of the policy region.

Figure 9. Change in Market Surplus vs. Reduction in CO$_2$ Emissions
6 Sensitivity Analysis

Several of our results depend only upon the quantity of electricity from each fuel available in the pre-policy period. For instance, the finding that no emissions reduction can occur for small regions under a CES or CO₂ tax is a result of the large quantity of nuclear, hydro, and renewable generation relative to the amount of demand in the policy region pre-policy. Additionally, the large amount of nuclear and hydro pre-policy causes the maximum possible emissions reduction from an RPS to exceed that from a CES or CO₂ tax for policy regions smaller than the full market. Smaller amounts of nuclear and hydro pre-policy would reduce this effect. In a market with little coal use, the three policies are more likely to induce the same surplus for producers using coal and natural gas at a given reduction in CO₂ emissions as there will be many policy levels at which a CES or CO₂ tax would lead to production using coal and natural gas in the no-policy region. If there were no coal in the market, surplus for producers using natural gas would always be the same across policies for a given reduction in CO₂ emissions. This does not imply, however, that total market surplus would be the same under all three policies.

The distribution of benefits and costs from the different policies across consumers and producers is determined by the characteristics of the policy, the emissions intensity of the fuels, and the parameters of supply curves. For instance, the higher emissions intensity of coal relative to gas ensures that producers using coal lose more than producers using natural gas under a CES or CO₂ tax policy. However, an RPS policy treats all fossil fuels equal, and so increasing the stringency of the policy decreases the electricity output from coal and natural gas according to the supply function and initial quantities. Under the current parameters, the supply function for electricity from natural gas lies above the supply function for electricity from coal for all relevant quantities, yielding a smaller quantity of electricity from natural gas than from coal at each price, and therefore a smaller share of surplus for natural gas than for coal. Different elasticities, causing the supply functions to cross or reversing their order, would change this result. Producers of renewable energy gain more under an RPS while nuclear and hydro gain more CES or CO₂ tax. Consumers in the policy region
incur the largest loss under a CO₂ tax since unlike with RPS or CES there is no implicit subsidy that increases supply of non-carbon energy while reducing supply of carbon-based energy.

Figure 11 shows the percentage change in market surplus for a 20 percent emissions reduction target in a policy region that is 1/2 of the market and in a policy region that is the full market for each policy as the elasticities of supply and demand vary. The baseline scenario in the center of each chart utilizes the original elasticities. 1/2x indicates the elasticity was reduced by a factor of 1/2, and the 2x indicates the elasticity was increased by a factor of 2. The data for a policy region that consists of 3/4 of the market demonstrates the same characteristics as the data for a policy region that is the full the market.

Changing the elasticities does not change the ordering of the policies as can been seen from the markers representing the three policies, which have the same ordering in all cases. An increase in the elasticity of supply of coal or renewables decreases the percentage change in price necessary to achieve a given CO₂ reduction and therefore lowers the required REC price, carbon credit price or CO₂ tax. This causes the required stringency of the policy to fall and market surplus to increase relative to that achieved at the original elasticity. Thus, a more elastic supply curve reduces the percentage decline in market surplus due to a given reduction in CO₂ emissions. While an increase in the elasticity of demand has the same absolute effect as an increase in the elasticity of supply, pre-policy consumer surplus is lower due to the more elastic demand. As the absolute decline in consumer surplus post-policy is more than proportional to the decline in pre-policy consumer surplus, the percentage change in consumer surplus and therefore market surplus increases due to the more elastic demand curve.  

An RPS in a policy region of any size, or a CES or CO₂ tax in a small policy region, generates a larger percentage decline in the surplus of producers using natural gas when the supply from natural

\footnote{The absolute decline in surplus is more than proportional due to the elasticity of the supply curves. A more elastic supply from renewables would yield the smaller percentage change in consumer surplus due to the elasticity of demand under an RPS, while a more elastic supply from renewables or natural gas would do the same under a CES or CO₂ tax.}
gas becomes more elastic. The direction of the change is the same under these circumstances because coal and natural gas both operate in the no-policy region which causes the equilibrium to require the same production of natural gas and coal as explained in Section 3. Therefore, if the supply of electricity from natural gas becomes more elastic, the slope of the supply curve for natural gas flattens. As coal-fired generation and natural gas-fired generation earn the same price, the share of generation from coal increases relative to the share under the original elasticity. However, because coal emits more CO$_2$ than natural gas, the total quantity of electricity from these two sources must go down to achieve the same emissions reduction. Thus, the percentage decline in surplus increases under the above conditions when the elasticity of natural gas goes up. In larger policy regions subject to a CES or CO$_2$ tax, the effect on market surplus of increasing the elasticity of natural gas is very small and can result in a larger or smaller percentage change in surplus.

7 Conclusion

In conclusion, a CES or CO$_2$ tax reduces market surplus less, and therefore costs less, than an RPS for an achievable CO$_2$ emissions reduction target. The similarity between a CES or CO$_2$ tax in terms of the reduction in market surplus and the lower cost to consumers from a CES relative to a CO$_2$ tax suggest that a CES may be preferable to a CO$_2$ tax or RPS when the policy region is sufficiently large to permit a CES to be effective. Further, as suggested by the work of Mignone et al. (2012), reducing the subsidy paid to nuclear and hydro producers under a CES would reduce the cost of policy to consumers for a given reduction in CO$_2$ emissions. However, the difference between the three policies, as currently modeled, is small when the policy region is small relative to the market, but not so small as to render a CES or CO$_2$ tax inoperative. For a sufficiently small policy region or a very large CO$_2$ emissions reduction target in a policy region that does not cover the full market, an RPS is the ideal policy of the three, as it is the only one that would induce the required reduction in CO$_2$ emissions.
References


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:

\[
b = \frac{P_0}{\varepsilon Q_0}
\]

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:

\[
a = P_0 - bQ_0 = P_0 - \frac{P_0}{\varepsilon}
\]

The supply and demand curves are plotted in Figure 12 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.\(^8\)

\(^8\)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 that period \(Q_t\) minus price times quantity demanded:

\[
CS^r = \int_0^{q^r} u'(q) dq - p^r q^r = \int_0^{q^r} (a^D - b^D q) dq - p^r q^r = \frac{1}{2} (a^D - p^r) q^r
\]

The superscript \(r\) indicates the region, either the policy or no-policy region, and the superscript \(D\) indicates that \(a^D\) and \(b^D\) are the parameters of the demand curve. The first equality follows by definition of the demand curve, the second from integrating and using the relationship \(p^r = a + bq^r\).

For coal, natural gas, nuclear, hydro, and 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 \(PS^{nh} = (p^r + x)q_{nh}\). 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 must be the same in each region. As the price received in the no-policy region is always simply \(p^n\) for all fuels, it is simplest to use the formula \(PS^{nh} = p^n q_{nh}\).

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.
region. The general formula for the producer surplus of coal, natural gas and renewables is:

\[ PS^f = pq_f - \int_0^{q_f} c'_f(q) dq = pq_f - \int_0^{q_f} (a^f - b^f q) dq = \frac{1}{2}(p - a^f)q_f \]

\( p \) 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 under a CES) is paid directly to the producers using 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:

\[ TR = T(z_c q_c + z_g q_g) \]