Large Indirect Effects of Renewable Portfolio Standards on Carbon Emissions

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Abstract

Renewable Portfolio Standards (RPS) are a popular class of state-level renewable energy policies in the United States. We analyze how existing electricity generation markets adjust to the introduction of RPS policies, and the implications of this adjustment on carbon emissions. We estimate the effect of RPS policies on total carbon emissions from generation, decomposed into: (1) change in demand for electricity, (2) changes in the utilization shares of different fuels in generation, and (3) changes in the carbon intensity of generation by fuel type. We find that, while RPS policies do increase renewable generation, the carbon implications of this are small compared to those of indirect effects of RPS policies. In particular, decreasing quantities demanded (carbon-negative), increasing coal generation relative to natural gas (carbon-positive), and increasing the carbon intensity of fuel generation (carbon-positive). We do not find a statistically significant net effect of RPS policies on carbon emissions.

1 Introduction

In recent years, concerns about carbon emissions and climate change have led many state governments to pass regulations encouraging renewable generation. The most popular of these are Renewable Portfolio Standards (RPS), versions of which are currently in effect in 31 states and Washington, DC.

Renewable portfolio standards are a class of policies that encourage renewable generation by mandating that some proportion α of a state's energy generation[1] come from eligible renewable sources by a target year $\bar{t}$. These eligible sources typically only include wind and solar. We refer to α as the "nominal requirement." RPS policies enforce this mandate by introducing tradable Renewable Energy Credits (RECs). Starting in the target year $\bar{t}$, eligible renewable generators receive RECs for each MWh of energy produced. All generators must then trade RECs until each owns RECs equal to α times the total amount of electricity it generated that year.

[1] Or, occasionally, consumption. See next paragraph.

We analyze how existing electricity generation markets adjust to the introduction of RPS policies, and the implications of this adjustment on carbon emissions. We do this by first using panel data at the state-year level from 1997 to 2013 to estimate the effect of RPS policies on per capita generation and carbon emissions intensity for each of the following energy sources: coal, natural gas (gas), combined wind and solar, and other. Next, we perform a counterfactual exercise in which we compare all treated states in 2013 with an untreated counterfactual. We compare the difference in total emissions between the data and the counterfactual, and decompose this difference into: (1) change in total per capita generation, (2) change in the relative utilization of energy sources in generation, and (3) change in the average carbon intensity of generation by energy source.

We find that the effect on total emissions is statistically insignificant but likely positive. More interestingly, we find that coal generation tended to increase relative to natural gas in response to RPS policies, increasing carbon emissions, and that the carbon emissions intensity of fuel (coal and gas) generation also tended to increase. However, we also find that total generation quantities tended to decrease in response to RPS policies, decreasing carbon emissions. Previous literature suggests that the increase in coal generation relative to natural gas is the result of differential substitutability of these energy sources with the intermittent renewables whose growth RPS policies encourage, and that the increase in carbon intensity is a result of generators adjusting their operation to accommodate these renewables. Previous work has found that RPS policies tend to increase retail electricity prices, likely because adjusting to RPS policies causes generation to reduce in efficiency. This may explain the decrease in quantities.

Our decomposition of these effects as determinants of carbon emissions reveal that while an increased renewable share of generation reduces emissions, this effect is dwarfed by the indirect channels described above: reduction in total generation quantities (carbon-negative), increased coal share relative to natural gas (carbon-positive), and increased carbon intensity of fuel generation (carbon-positive). Overall, however, these channels cancel out somewhat, and we do not find a statistically significant effect on total carbon emissions. However, the errors on our estimate on total carbon emissions is an order of magnitude than the estimated effect, and error thereof, of increased renewable share.

We reiterate that we only estimate the effect of RPS policies on 2013 emissions within the state of the RPS. Thus, we do not take into account effects materializing after 2013, even though all but eight of the policies we study have target years after 2013. High fixed costs of entry might also lead to slow adjustment and the full effect materializing later. Furthermore, we do not consider these policies' role in accelerating innovation in renewable energy, which could catalyze or hasten their adoption. Finally, we do not consider the effect of RPS policies on surrounding states, though these effects are probably important.

Section 2 describes existing research on RPS policies. Section 3 describes our data sources and the construction of the stringency measure. Section 4 discusses emissions and the power mix. In it we present summary statistics on U.S. power mix, explicitly define the decomposition we outline above, and discuss the economics of these channels in relation to RPS policies. Section 5 describes our two-stage empirical approach. Section 6 presents the results of our analysis. Section 7 concludes.

2 Previous Work

2.1 Renewable Portfolio Standards

Theoretical and simulation-based work on RPS policies have the longest history. Palmer and Burtraw (2005) simulate a national RPS and find that it increases renewable capacity and energy prices, decreases demand, and that renewables disproportionately displace gas over coal. Fischer (2010) finds that we might expect RPS policies to lower electricity prices in the short run, but that prices will rise if the policy is sufficiently stringent.

As RPS policies have been legally introduced, research has begun to study their effects ex post. They have to varying degrees encountered certain empirical challenges. First, RPS policies are highly heterogeneous in their implementation. Wiser and Bolinger (2007) describes many dimensions of RPS heterogeneity, which we discuss in section 3.1.

Second, the adoption of an RPS policy is an endogenous event. Lyon and Yin (2010) analyze the factors leading states to adopt an RPS, arguing that they are popular because they are perceived as advancing multiple political goals simultaneously. They also find that the adoption of an RPS is driven by, *inter alia*, the left/right political leaning of the state legislature, low gas generation, and high state solar and wind potential. Thus, the presence of unobserved pro-renewable trends or policies could be correlated with the adoption of an RPS. However, in general our findings have the opposite sign from what one would expect if coincident carbon-targeting regulation in RPS states were driving our findings.

Third, states are heterogeneous in many ways that could affect the impact of an RPS, including in existing renewable capacity, which is taken into account in the analysis of Yin and Powers (2010). States also vary in their solar potential, wind potential, and the size of their mining and manufacturing sectors. These are taken into account in the analysis of Upton and Snyder (2017).

Due in part to these complicating factors, estimates of the effects of a state-level RPS remain broadly dispersed. Early papers, such as Menz and Vachon (2006) and Adelaja et al. (2010) use a cross-sectional approach and a binary variable for the existence of an RPS and find that renewable development is greater in states with an RPS. Shrimali and Kniefel (2011) use a panel data approach and differentiate between RPS policies based on their nominal requirement, finding that RPS policies based on generation do not increase renewable capacity. Tackling the issue of deeper RPS heterogeneity, Yin and Powers (2010) develop a measure of the effective stringency of an RPS. They find that RPS policies do induce an increase in the renewable share of generation capacity, but only as a function of the shortfall between the introduction-year renewable share and the share actually mandated by the model.[2] With a binary RPS variable taking no heterogeneity into account, they find no effect on renewable share. When interacting this binary variable with the nominal requirement of the RPS, the effect has a positive sign. Also approaching the issue of deeper RPS heterogeneity, Carley and Miller (2012) develop a simple, one-dimensional, time-invariant measure of the stringency of an RPS, which we also adopt. Tackling the issue of state heterogeneity, Upton and Snyder (2017) use the method of synthetic controls to generate composite control observations: linear combinations of actual (non-treated) states into control states that most closely resemble treated states. Furthermore, they study the effect of RPS policies on renewable generation and electricity demand and are the first to empirically study the effect of RPS policies on electricity prices. They also study the effect of RPS policies on state-level carbon emissions from fuel generation, but do not decompose this effect.

Greenstone and Nath (2019) study the effect of RPS policies on generation by fuel type and on emissions, as we do, as well as on total generation. Similarly to us, they emphasize that indirect costs of RPS policies–costs of adjustments they necessitate in the ambient electricity market–are the main component of total costs. However, their concern is primarily costs to consumers through higher retail prices for electricity, whereas we are interested in a finer understanding of the effect of RPS policies on carbon emissions. They do examine the effect of RPS policies on generation by energy source and overall emissions intensity. However, they do not use these results to disaggregate the effect of RPS policies on carbon emissions or examine emissions intensity by energy source.

2.2 Heterogeneous Externalities by Fuel

A key driver of our analysis is that some fuels are more carbon intensive than others. However, production of carbon dioxide by combustion is not the only externality associated with using fuel to generate electricity, even with regard to climate change.

Fuel extraction can have complex and extensive environmental costs. Jenner and Lamadrid (2013) perform a study of negative externalities of coal and gas generation, such as nitrogen oxide and sulfur dioxide emissions from coal generation, which contribute to respiratory illnesses and acid rain; leakage of methane, a greenhouse gas thirty times more potent than CO2, from gas extraction; and groundwater contamination from shale gas extraction via hydraulic fracturing ("fracking"). They find that coal has greater negative externalities on public health, worker safety, local environmental protection, and carbon emissions, but that the relative effect of coal and gas on total greenhouse gas emissions depends on the rate of methane leakage in gas extraction. Fuel supply chains are also responsible for carbon emissions through energy consumption, estimated at 10.5% of generation emissions for coal by Wu et al. (2016).

CO2 emissions are the only externality we directly address. However, our results about influences on fuel mix has direct implications whenever externalities differs by fuel type.

[2]For a more detailed discussion of this shortfall measure, see Section 3.1.

3 Data

We perform our primary analysis at the state-year level from 1997 to 2013. We include every continental U.S. state with nonzero gas and coal generation throughout the sample period, leaving 46 states.[3] We use state-year level data from the EIA on total generation and total emissions by energy source. To put variables in per capita form, we use population estimates from the United States Census Bureau.

3.1 Stringency

RPS policies are highly heterogeneous along a number of dimensions. Wiser and Bolinger (2007) document that state RPS policies vary in, among other things, the nominal requirement, the target year, whether it regulates energy production or consumption, whether RECs can be traded across state lines, which renewable technologies are eligible, penalties for non-compliance, and exclusions for generators. This final dimension is a complex one. RPSs often exclude or differentially regulate different classes of generators: investor-owned, consumer-owned, or publicly-owned; urban or rural; or generators whose annual generation exceeds a threshold quantity. Some RPSs also exclude specific generators by name.

In order to account for this heterogeneity, some empirical papers have introduced one-dimensional measures of the stringency of an RPS, where a stringency of zero is equivalent to the absence of an RPS.

We use a measure of RPS stringency introduced by Carley and Miller (2012), who compute this measure from 1997 through 2008. We use the extended set of values computed by Upton and Snyder (2017) through 2013. It is defined as the annualized increase in the mandated proportion of renewable generation in a state s and year t. Equation 1 describes this measure.

$$AS_{st} \equiv \text{annualized stringency} = AS(R_{st}) = \frac{\alpha_{\text{final}}(R_{st}) - \alpha_{\text{starting}}(R_{st})}{\text{year}_{\text{final}}(R_{st}) - \text{year}_{\text{starting}}(R_{st})} \cdot \text{Coverage}(R_{st}) \cdot 100 \tag{1}$$

Here, R_{st} refers to the RPS policy in effect in state s in year t. The variable $\alpha_{\text{initial}}(R_{st})$ refers to the nominal requirement in effect prior to the passage of the current RPS R_{st}. Unless R_{st} replaced a preexisting RPS, this value will be zero. The variable $\alpha_{\text{final}}(R_{st})$ refers to the nominal requirement of R_{st}. The year that R_{st} was passed is $\text{year}_{\text{starting}}(R_{st})$, and the target year of R_{st} is $\text{year}_{\text{final}}(R_{st})$. Finally, $\text{Coverage}(R_{st})$ refers to the proportion of generation covered by R_{st}. Note that all heterogeneity in coverage (due for example to exemptions or differential requirements for different classes of generators) is thus accounted for in $\text{Coverage}(R_{st})$.

This measure can be thought of as a linear interpolation of the RPS mandate between the start and end year of the policy. In their analysis, Upton and Snyder (2017) use as their independent variable the interaction between "annualized stringency" AS_{st} and the number of years that an RPS has been in effect, RPS_{st}. This product variable essentially linearly interpolates the RPS mandate between the start and end year of the policy. That is, at the

[3] Excluded are Alaska, Hawaii, Vermont and Rhode Island.

start year, their regressor is equal to

$$AS_{st} \cdot \mathrm{RPS}_{st} = AS_{st} = 0$$

and at the target year equal to

$$AS_{st} \cdot \mathrm{RPS}_{st} = (\alpha_{\text{final}}(R_{st}) - \alpha_{\text{final}}(R_{st})) \cdot \mathrm{Coverage}(R_{st}) \cdot 100.$$

We do something very similar, except that we account for preexisting RPS policies and revisions to policies, so that our measure S_{st} has the property that at the start year of a policy

$$S_{st} \cdot \mathrm{RPS}_{st} = \alpha_{\text{starting}} \cdot \mathrm{Coverage}(R_{st}^{\text{previous}}) \cdot 100$$

and at the end year of a policy

$$S_{st} \cdot \mathrm{RPS}_{st} = \alpha_{\text{final}} \cdot \mathrm{Coverage}(R_{st}) \cdot 100.$$

When a policy is revised between its start year and end year, the current year's S_{st} is unaffected, but the values of S_{st} between the current year and end year linearly interpolate between the current value and the new value of $\alpha_{\text{final}} \cdot \mathrm{Coverage}(R_{st}) \cdot 100$. To achieve these properties, we define our measure as in Equation 2.

$$S_{st} = (\text{interpolated stringency})_{st} = \sum_{\tau=-\infty}^{t} AS_{s\tau}. \tag{2}$$

Because revisions to RPS policies are rare in our panel, our measure usually matches up with the measure of Upton and Snyder (2017). In the cases where it differs, we believe ours to be a slightly more reasonable measure of a state's total exposure to RPS legislation.

This measure does not take into account existing generation. In particular, if a state already fulfills the requirement when the policy is passed, we would expect it to have no effect. However, this measure would consider the policy equivalent to an identical policy in a state with preexisting renewable capacity. For an alternative measure of RPS stringency which does take into account existing generation, see Yin and Powers (2010).

4 Emissions and Power Mix

Total carbon emissions arise as the dot product of total generation by energy source and average carbon intensity by energy source. Since energy sources vary significantly in their carbon intensity, the power mix–the relative use of different energy sources in generation–is a key determinant of total emissions. In this section, we first describe levels and trends in generation and carbon intensity by energy source. We then describe a decomposition of a change in net emissions into effects of changes in generation and carbon intensity by energy source. Finally, we relate these mechanisms back to RPS policies.

4.1 Power Mix: Summary Statistics

Coal and gas together accounted for approximately two-thirds of total U.S. electricity generation throughout our panel, from 1997 to 2013. Within that two-thirds, gas gradually began to supplant coal, a trend which continues to the present. The majority of the remaining generation is nuclear and hydroelectric, with levels largely stable. Wind and solar have gained a small foothold in recent years, but levels remained negligible until near the end of our panel. Figure 1 shows trends in total generation by fuel source and Figure 2 shows trends in relative utilization. Table 1 reports relative utilization by power source in a few snapshot years.

While our main analysis will show a positive coefficient on coal generation, new coal capacity is actually very rare. Figure 3 shows newly-activated coal capacity in the U.S.–capacity active in a given year but inactive the previous–by year as a proportion of existing capacity. This is divided into reactivated capacity, capacity which has been utilized at some point in the past, and new capacity, which has not. Together, they average just under 0.2% of total coal capacity per year over 14 years. Our main analysis then largely indicates that RPS policies cause states' coal generation to decline more slowly.

Carbon intensities of different fuel types have also been experiencing differing trends. The average carbon intensity of coal used in electricity generation is higher than gas and has been stable in the 1000 kg/MWh range. The average carbon intensity of gas trended downwards from the 620 kg/MWh range to the 470kg/MWh range over the duration of our panel. The carbon intensity of average U.S. electricity generation, slightly higher, trended downward from the 650 kg/MWh range to the 550 kg/MWh range throughout our panel. Annual values are presented graphically in Figure 4.

4.2 Decomposition

Let $\vec{q}$ denote the vector of total electricity generation by energy source (for some region, over some time period), and let $\vec{b}$ denote the vector of average carbon intensities of generation by energy source. Then total carbon emissions are given by

$$\vec{q} \cdot \vec{b} = q_1 b_1 + q_2 b_2 + \cdots + q_n b_n.$$

Now suppose that $\vec{q}^p$ and $\vec{b}^p$ refer to generation and carbon intensity if some policy were to be implemented, and $\vec{q}^u, \vec{b}^u$ to generation and carbon intensity in the absence of such a policy. Then the effect of the policy on total carbon emissions is given by

$$\vec{q}^p \cdot \vec{b}^p - \vec{q}^u \cdot \vec{b}^u.$$

We wish to decompose this effect.

4.2.1 Coarse Decomposition

We begin by decomposing into three broad channels:

1. Total generation quantity. The effect of a change in total electricity generated.
2. Power mix. The effect of changes in the relative utilization of different energy sources for generation.
3. Carbon intensity. The effect of changes in average carbon intensities by fuel type.

Let C_i denote the contribution of Channel i. Channel 1 is given by simply scaling total emissions by the change in total generation.

$$C_1 = \frac{|\vec{q}^p|}{|\vec{q}^u|}\vec{q}^u \cdot \vec{b}^u - \vec{q}^u \cdot \vec{b}^u$$

where $|\cdot|$ denotes the sum.

Channel 2 is given as the effect of the change to the new vector of quantities $\vec{q}^p$ while keeping carbon intensities constant at $\vec{b}^u$, minus the contribution of Channel 1.

$$C_2 = \vec{q}^p \cdot \vec{b}^u - \frac{|\vec{q}^p|}{|\vec{q}^u|}\vec{q}^u \cdot \vec{b}^u$$

Finally, Channel 3 is given by the effect of the change to the new vector of carbon intensities, given the new vector of quantities.

$$C_3 = \vec{q}^p \cdot \vec{b}^p - \vec{q}^p \cdot \vec{b}^u.$$

4.2.2 Fine Decomposition

We can also perform a finer decomposition, where we look at the contribution by each component of $\vec{q}$ and $\vec{b}$. That is, total generation and carbon intensity for each energy source. In our analysis, we divide energy sources into the following four categories: (1) coal, (2) gas, (3) combined wind and solar, and (4) other, so that

$$\begin{aligned} \vec{q} &= [q_c, q_g, q_r, q_o] \\ \text{and} \quad \vec{b} &= [b_c, b_g, b_r, b_o]\,. \end{aligned}$$

Suppose again the treated and untreated states are $(\vec{q}^p, \vec{b}^p)$ and $(\vec{q}^u, \vec{b}^u)$ as before. Channel 1 is still given by

$$C_1 = \frac{|\vec{q}^p|}{|\vec{q}^u|}\vec{q}^u \cdot \vec{b}^u - \vec{q}^u \cdot \vec{b}^u.$$

Channel 2 is further decomposed into three channels, corresponding to the relative change in wind and solar generation, the relative change in other generation, and the change in coal generation relative to gas. These subchannels, denoted by C_{2r}, C_{2o}, and C_{2c}, are given by

$$
\begin{aligned}
C_{2r} &= \frac{q_c^p + q_g^p + q_o^p}{q_c^u + q_g^u + q_o^u}(q_c^u b_c^u + q_g^u b_g^u + q_o^u b_o^u) + q_r^p b_r^u - \frac{|\vec{q}^p|}{|\vec{q}^u|}\vec{q}^u \cdot \vec{b}^u \\
&= \frac{q_c^p + q_g^p + q_o^p}{q_c^u + q_g^u + q_o^u}\vec{q}^u \cdot \vec{b}^u - \frac{|\vec{q}^p|}{|\vec{q}^u|}\vec{q}^u \cdot \vec{b}^u \qquad\qquad (\text{since } b_r^p = b_r^u = 0) \\
C_{2o} &= \frac{q_c^p + q_g^p}{q_c^u + q_g^u}(q_c^u b_c^u + q_g^u b_g^u) + q_o^p b_o^u - \frac{q_c^p + q_g^p + q_o^p}{q_c^u + q_g^u + q_o^u}\vec{q}^u \cdot \vec{b}^u \\
C_{2c} &= q_c^p b_c^u + q_g^p b_g^u - \frac{q_c^p + q_g^p}{q_c^u + q_g^u}(q_c^u b_c^u + q_g^u b_g^u)
\end{aligned}
$$

Intuitively, for each energy source e, its subchannel is computed by comparing total emissions computed using the untreated carbon intensities $\vec{b}^u$ when e is considered separately, and where e is lumped together with other energy sources.

Channel 3 is further decomposed into three channels, corresponding to the change in carbon intensity of generation using coal, gas, and other. These subchannels, respectively denoted by C_{3o}, C_{3g}, and C_{3c}, are given by

$$
\begin{aligned}
C_{3o} &= q_o^p b_o^p - q_o^p b_o^u \\
C_{3g} &= q_g^p b_g^p - q_g^p b_g^u \\
C_{3c} &= q_c^p b_c^p - q_c^p b_c^u.
\end{aligned}
$$

Thus, the entire difference in carbon emissions between the treated and untreated states is given by these channels:

$$
\begin{aligned}
\vec{q}^p \cdot \vec{b}^p - \vec{q}^u \cdot \vec{b}^u &= C_1 + C_2 + C_3 \\
C_2 &= C_{2r} + C_{2o} + C_{2c} \\
C_3 &= C_{3o} + C_{3g} + C_{3c}.
\end{aligned}
$$

4.3 Power Mix and Renewable Portfolio Standards

To understand the net effect of RPS policies on carbon emissions, we must look at all of the channels detailed above. By contrast, previous work has focused on the effect of RPS policies on renewable generation, essentially only considering only Channel C_{2r}. Exceptions to this are Upton and Snyder (2017) who consider the effect of RPS policies on prices and total generation quantities, i.e., Channel C_1, and total emissions; and Greenstone and Nath (2019), who study the effect of RPS policies on emissions, prices and quantities as well as generation by energy source. However, neither quantitatively analyze the impact of these effects on emissions.

By decomposing the effect of RPS policies on carbon emissions into the effects of different types of market adjustments caused by RPS policies, we can gain insight into how markets adapt to RPS policies. In the following, we relate the channels we have defined to the market adjustments that may contribute to them and the economics of how RPS policies might induce these adjustments.

4.3.1 Channel 1: Total generation quantity

When total generation quantity decreases, *ceteris paribus*, emissions also decrease. The most likely explanation for a decrease in total generation quantity is an increase in prices: an inward shift of supply and movement up the demand curve. Indeed, Upton and Snyder (2017) and Greenstone and Nath (2019) find that RPS policies increase retail electricity prices. Economically, prices likely increase because the adjustments made by the generation market to RPS policies decrease their efficiency.

4.3.2 Channel 2: Power Mix

Wind and Solar

Channel C_{2r}, the increase in (the market share of) wind and solar generation, is the channel that has received the most attention in the literature, and whose mechanism is possibly the clearest and most direct. An RPS induces cross-subsidization of wind and solar by other energy sources, decreasing the effective cost of wind and solar generation while increasing the cost of other generation. This induces a move up the supply curve for wind and solar and a move down the supply curve for the rest. This subchannel is the focus of earlier empirical work such as Yin and Powers (2010) and Nicolini and Tavoni (2017).

Coal, Gas, and Other

Because different fuel types have different carbon intensities, a change in the relative shares of coal and gas, for example, affects emissions. Coal, for instance, is approximately twice as carbon-intensive as gas.

At a high level, the question of how an RPS policy affects relative fuel shares is probably a matter of substitutability. Assuming that coal and gas have similar price elasticity of supply, an RPS should affect them similarly. Relative changes in their shares, then, are probably the result of differential substitutability with wind and solar. The RPS increases wind and solar shares, and whichever energy source is more substitutable with them will experience a greater decline.

At a lower level, this differential substitutability is likely due to the different roles different energy sources play in generation. Some–particularly nuclear, hydroelectric, and coal–are relatively costly or wasteful to cycle on and off. These therefore tend to operate continuously as "baseload" capacity. Other energy sources, such as gas, are more flexible, and often operate only when needed, as "load-following" or "peak" capacity. Wind and solar generation, unlike fuel sources of energy, are highly intermittent, their output determined by transient natural conditions. It is generally accepted (Smith (2019), Marrero and Ramos-Real (2010)) that intermittent renewables require more residual (i.e. not wind or solar) capacity to be load-following, to take over when renewables stop producing.

The question of the substitutability of different energy sources with renewables, however, is still open. Some, such as Marrero and Ramos-Real (2010), argue that gas is more substitutable with intermittent renewables than coal is, while others such as Palmer and Burtraw (2005) predict via simulation that gas would be displaced more than coal. While we focus on coal and gas shares in our analysis, lumping together all other sources as "other," these concerns certainly to these "other" sources as well, and a more complete treatment of their response is an avenue for future work.

An important consideration which we do not take into account is that power mix is largely governed by investment dynamics and slow adjustment. Large fixed costs can cause one type of generation to remain economical long past the point when building more of that type is uneconomical. For example, as we describe in Section 4.1, coal generation in the U.S. has been slowly declining for decades, and new coal capacity is rare. However, coal continues to be widely used for generation, accounting for over a quarter of electricity generation in 2018.

4.3.3 Channel 3: Carbon Intensity

When the average carbon intensity of an energy source increases, total emissions increase. This change in the average, however, might be driven by the extensive or the intensive margin. That is, which plants are used for generation and how those plants are used.

At the extensive margin, within a given energy source, an RPS can affect the composition of generating capacity by inducing entry or exit. Less efficient plants are likely to exit first, while plants that enter are likely to use more modern technologies than average. Thus, we might expect both entry and exit to decrease average carbon intensities.

At the intensive margin, an RPS can affect how existing plants operate. Smith (2019) finds a recent trend of coal plants transitioning from baseload to load-following operation. As we have mentioned, intermittent renewable generation necessitates more load-following generation in the ambient market. Smith (2018) finds that baseload plants transitioning to load-following operation operate less efficiently and with higher carbon intensity. Thus, the introduction of intermittent renewables may increase the carbon intensity of existing capacity.

5 Methodology

5.1 First Stage

We use the data described in Section 3 to estimate the following difference-in-differences model.

$$y_{st} = \delta_1 S_{st} + \delta_2 S_{st}^2 + \alpha_s + \alpha_t + \varepsilon_{st} \tag{3}$$

Here, y_{st} is the endogenous variable of interest, α_s and α_t are state and time fixed effects, respectively, ε_{st} is an error term, S_{st} is the interpolated stringency as described in Equation 2 in Section 3.1, reproduced below, and S^2_{st} is the square of S_{st}.

$$S_{st} = (\text{interpolated stringency})_{st} = \sum_{\tau=-\infty}^{t} AS_{s\tau}. \tag{2}$$

We use panel data on 46 states between 1997 and 2013. The model is estimated via weighted least squares (WLS) weighting by total generation in each state-year. Standard errors are computed via bootstrap at the state level. The bootstrap procedure is as follows: we split the panel of 46 states into a set of 46 time series, one per state. We then select from that set of time series 46 times, with replacement. We then reintegrate this sample of 46 states into a panel, and re-run our analysis on this panel, generating a new set of estimates. We repeat this process 2000 times, yielding 2000 estimates for each parameter. For each parameter, we obtain standard errors as the sample standard deviation of our bootstrap estimates, p-values as the proportion of bootstrap estimates with the opposite sign as our main estimate.

The endogenous variables of interest we examine are per capita generation (MWh per capita) and average carbon intensity of generation (kg/kWh) for each of the following: coal, gas, combined wind and solar, and other.

5.2 Second Stage

We use our estimates from the first stage to generate counterfactual data for generation and carbon intensity in 2013. That is, for each state s with an RPS, having obtained estimates in the first stage for the determinants of the endogenous variable,

$$y_{st} = \hat{\delta}_1 S_{st} + \hat{\delta}_2 S^2_{st} + \hat{\alpha}_s + \hat{\alpha}_t + \hat{\varepsilon}_{st},$$

we compute the counterfactual variable as

$$\bar{y}_{st} = \hat{\alpha}_s + \hat{\alpha}_t + \hat{\varepsilon}_{st}.$$

This then gives us counterfactual values for per capita generation and average carbon intensity by energy source. We multiply per capita generation by state population to obtain total generation by energy source, giving us the vectors of total generation and average carbon intensity by energy source for both observed and counterfactual data, $(\vec{q}^p, \vec{b}^p)$ and $(\vec{q}^u, \vec{b}^u)$, as described in Section 4.2.

We then decompose the difference between total counterfactual and observed emissions in 2013, as described in Section 4.2. We first perform a coarse decomposition into the three channels (C_1, C_2, C_3), then further decompose C_2 into subchannels (C_{2r}, C_{2o}, C_{2c}) and C_3 into (C_{3o}, C_{3g}, C_{3c}).

To obtain p-values and bounds on the C_i variables, we generate bootstrap panels exactly as in the first stage. For each bootstrap panel, we re-estimate each C_i variable. 95% confidence intervals are given as the range between the 2.5% and 97.5% quantiles of the bootstrap estimates, and p-values are given as the proportion of bootstrap estimates with the opposite sign as our main estimate.

6 Results

6.1 First Stage

Our results are summarized in Tables 2 and 3. The coefficient on S_{st} can be interpreted as the difference between the observed value of the endogenous variable, and the value that it would have taken if the interpolated stringency S_{st} was 1pp weaker in year t. Similarly, the coefficient S_{st}^2 refers to the effect on same of a 1pp^2 increase in S_{st}^2.

We grant that the construction of S_{st} and the inclusion of the squared term make the interpretation of these coefficients somewhat opaque. To give a sense of the magnitude of these effects therefore, we present in Table 4 our estimates of the combined effect of all pre-2013 RPS policies on total generation and average carbon intensity, by energy source, in 2013 over all 26 treated states. That is, for each aggregate moment, we report its observed value and the counterfactual value computed by setting $S_{st} = 0$ as described in Section 5.2.

The most statistically significant effect is a decrease in gas generation, corresponding to a 29% decrease from the counterfactual in treated states in 2013. The effect on combined wind and solar generation is large but only significant at the $p < .11$ level, corresponding to a 40% increase over the counterfactual in treated states in 2013. When the endogenous variable is carbon intensity, for both coal and gas the signs on S_{st} and S_{st}^2 do not match. However, the positive effect is in each case the larger and more statistically significant one (although significance is still low in either case). Indeed, in each case we predict the RPS to have caused an increase in average carbon intensity in treated states in 2013, of 8% in the case of coal and 36% in the case of gas.

6.2 Second Stage

We decompose the effect of the RPS policy on total emissions in treated states in 2013, as described in Section 4.2. First, we perform a decomposition into three channels: total generation quantity (C_1), power mix (C_2), and carbon intensity (C_3). We report results numerically in Table 5 and graphically in Figure 5. In Table 5, we report the decomposition both in absolute terms, and as a percent of total emissions in treated states in 2013.

We estimate that total generation quantity decreases, but that both power mix and carbon intensity channels increase emissions, although the estimate for the carbon intensity channel C_3 is larger and much more statistically significant. With $p < .11$, we estimate that the net effect of the policies was to increase carbon emissions.

Second, we perform a further decomposition of the power mix channel C_2 into the effects of changes in wind and solar generation (C_{2r}), other generation (C_{2o}), and coal generation relative to gas (C_{2c}). We report results numerically in Table 6 and graphically in Figure 6.

We find that, within the power mix channel (C_2), the channel of increased renewable share (C_{2r}) is dominated by the effect of an increase in coal generation relative to gas (C_{2c}). The estimated carbon-positive effect C_{2c}, is highly significant and an order of magnitude greater than the estimated carbon-negative effect, and error thereof, of a relative increase in wind and solar generation (C_{2r}). Although it is dominated, we do find a statistically significant carbon-negative effect of a relative increase in wind and solar generation.

Finally, we perform a further decomposition of the carbon intensity channel C_3 into the effects of changes in carbon intensity of generation using "other" sources (C_{3o}), gas (C_{3g}), and coal (C_{3c}). We report results numerically in Table 7 and graphically in Figure 7. We find that the estimated effect of an increase in carbon intensity of gas generation (C_{3g}), is large and carbon-positive, with $p < .05$. We also find that the effect of an increase in carbon intensity of coal generation (C_{3c}) is carbon-positive, and about half the magnitude of C_{3g}.

Figure 8 shows the full decomposition into seven channels. The largest components are C_{2c} and C_{3g}, although demand reduction, C_1, reduced relative use of "other" generation, C_{2o}, and increased carbon intensity of coal generation, C_{3c}, could also play a significant role.

7 Conclusion

Broadly speaking we find that, when looking at the carbon abatement effect of RPS policies, the channel of increased renewable generation is almost negligible compared to the effect through other channels, especially decreased total generation, increased coal generation relative to gas, and increased carbon intensity of fuel generation. Although balanced out to some degree by reduced quantity of generation, the overall effect of RPS policies on treated states in 2013 is likely to be carbon-positive.

Our finding that RPS policies likely reduce quantities demanded is in line with recent literature such as Greenstone and Nath (2019) and Upton and Snyder (2017), who find that RPS policies increase electricity prices and decrease quantities. Our finding that the net effect of RPS policies on emissions is of indeterminate sign is also in line with these two papers, who do find a small or statistically insignificant effect on total carbon emissions from generation. However, a decomposition of this finds that an apparently ambiguous net effect contains more clearly signed components.

We find that RPS policies likely increase coal generation relative to natural gas generation. This favors the prediction of Palmer and Burtraw (2005)–that intermittent renewables are more substitutable with gas than they are with coal–over the prediction of Marrero and Ramos-Real (2010) that the opposite is true. If our findings are true, than this carbon-gas power mix channel is much larger than the direct effect of increasing renewable generation, and could make the net effect of RPS policies carbon positive.

We also find that RPS policies may cause the carbon intensity of fuel generation to increase significantly. This is consistent with Smith (2018), who finds that increased renewable shares cause fuel generation to switch from baseload to load-following operation, and that this makes them more carbon-intensive. We discuss next steps necessary to understand this phenomenon further below.

What our results make clear is that, in terms of carbon abatement, the indirect effects of an RPS policy on the ambient electricity market are apparently much larger than the direct effect– that of increasing renewable generation. While a deeper understanding of the substitutability of different sources of energy and the dynamics of investment in generating capacity are beyond the scope of this paper, our results nevertheless suggest that to understand the net effect of RPS policies on carbon emissions, we must widen our view.

Nevertheless, these results are contingent on our empirical design, which has several issues. The stringency measure that we use does not account for renewable capacity that exists when an RPS policy is passed. That is, if identical RPS policies are imposed on states with different preexisting stocks of renewable capacity, our measure assigns them the same stringency. Of course, we would expect the state with more preexisting renewable capacity to be affected less.

As studied in Lyon and Yin (2010), the passage of an RPS policy is a highly endogenous event, depending on state political climate, wind and solar potential, and the relative power of different interest groups. Upton and Snyder (2017), for example, control for political climate, the size of the state's mining and manufacturing sectors, and wind and solar potential. We control for none of these things, putting the magnitudes of our estimates in question. However, if we suspected that RPS policies were being introduced in states that were already trending toward lower emissions, we would expect the opposite sign on the largest channels we estimate, ruling that particular story out as a driving factor.

We study the within-state effects of RPS policies, and in our decomposition attempt to measure these effects as manifested in 2013. However, whereas a theme of this paper is the need to for a broader scope in accounting for an RPS policy's overall effects, our analysis is still in many ways too narrow. For instance, we do not capture cross-state, global, and long-term/future effects of RPS policies.

Electricity markets cross state lines, and RPS policies and increased renewable generation in one state certainly affect states with which it shares a border, and possibly beyond. It is conceivable for instance, that RPS policies induce out-of-state planned renewable projects to simply relocate in-state, having in these cases zero net effect. Similarly, it is also possible that RPS policies also cause in-state fuel generation to relocate out-of-state, although measured increases in retail electricity prices (Upton and Snyder (2017), Greenstone and Nath (2019)) indicate that generation quantities actually do go down.

We also fail to account for global or public-good externalities of renewable investment, such as induced technical change or proof of viability. Increasing demand for renewables incentivizes innovation in renewables. Also, inducing increased renewable generation in markets forces generators to learn how to most efficiently adapt: lessons which could be used to introduce renewables more efficiently in the future. The creation of these public goods may dwarf even the large indirect effects we estimate.

We emphasize also that we can only report on the effects of RPS policies as manifested in

2013, and that our panel usually only includes a few years after an RPS was introduced.[4] It is possible that RPS policies only start to have an effect close to their target years, in which case we would not observe most of them.[5] It is also possible that, in their early years, RPS policies lay the groundwork for deeper long-term structural change which we cannot see. For example, as we argue in Section 4.3.2, the slow decline of coal generation over decades and dearth of new coal capacity suggest that generation continues to operate long past the point when it has been made "obsolete," in the sense that it is no longer economical to build more of it.

Some of our findings intrigue us and seem deserving of deeper analysis. For one, we do not examine the nature of changes in average carbon intensities. Do individual generators increase their carbon intensities (the intensive margin), or is the change driven by entry (exit) of generators who are more (less) carbon intensive than average (the extensive margin)? Answering this question is the next step toward understanding the carbon intensivity channel.

Though our main analysis consists of a decomposition of changes to carbon emissions, this approach could in principle be applied to any externality of generation that varies by energy source. (Examples of such externalities are listed in Section 2.2.) A full accounting of the costs and benefits of RPS policies should consider a larger set of the externalities of generation.

For simplicity, we grouped together all generation apart from wind, solar, coal, and natural gas as "other." Our summary statistics show that this mostly consists of hydroelectric and nuclear. We find that the net effect of RPS policies on "other" generation, and the carbon intensity thereof, is of indeterminate sign. A further disaggregation of this quantity, even just into renewable and non-renewable components, would be informative, as could a treatment of wind and solar generation separately.

Finally, aforementioned factors such as cross-state effects, investment dynamics, and complex patterns of substitutability, not only by fuel type but also geographically, suggest that any reduced-form approach to the question of how RPS policies affect electricity markets and carbon emissions will ultimately be inadequate. In our data, we observe equilibria of the electricity market, but in our analysis we do not model these as arising as equilibria, instead making strong assumptions about the reduced-form effects of these policies. A model built around the understanding of observed data as equilibria is essential to credibly predicting counterfactual effects of RPS policies, or their absence–that is, such a model is essential to predicting what other equilibria could prevail.

While increasing renewable capacity is important, carbon abatement only occurs when traditional fuel generation, or the carbon intensity thereof, decreases. In evaluating RPS policies, therefore, it is insufficient to score them by their effect on renewable generation. Indeed, it is possible for a policy to increase renewable generation, and even to decrease non-renewable generation, while having no significant abating effect on carbon emissions.

[4] The median RPS in our panel is 7.5 years old in 2013.

[5] All but eight of the RPS policies in our panel have target years after 2013.

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Appendix: Figures

Figure 1: Total U.S. Power Generation By Source

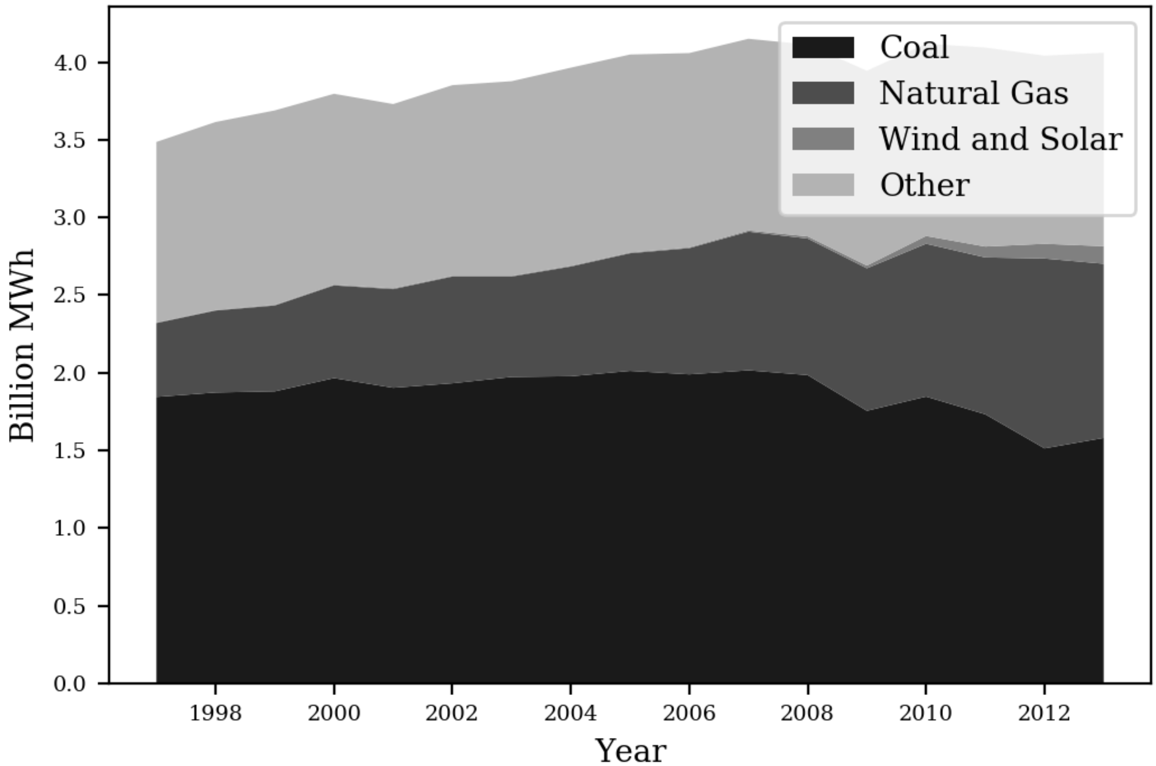

Table 1: Snapshots of U.S. Power Mix

	Share of Total U.S. Generation (%)						
Year	Coal	Gas	Nuclear	Hydroelectric	Wind	Solar	Other
1997	52.8	13.7	18.0	10.2	0.094	0.015	5.14
2003	50.8	16.7	19.7	7.10	0.29	0.014	5.36
2007	48.5	21.6	19.4	5.95	0.83	0.015	3.72
2013	38.9	27.7	19.4	6.61	4.13	0.22	3.31
2018	27.5	35.2	19.4	7.01	6.54	1.53	4.41

Figure 2: Total U.S. Power Generation By Source (% of Total)

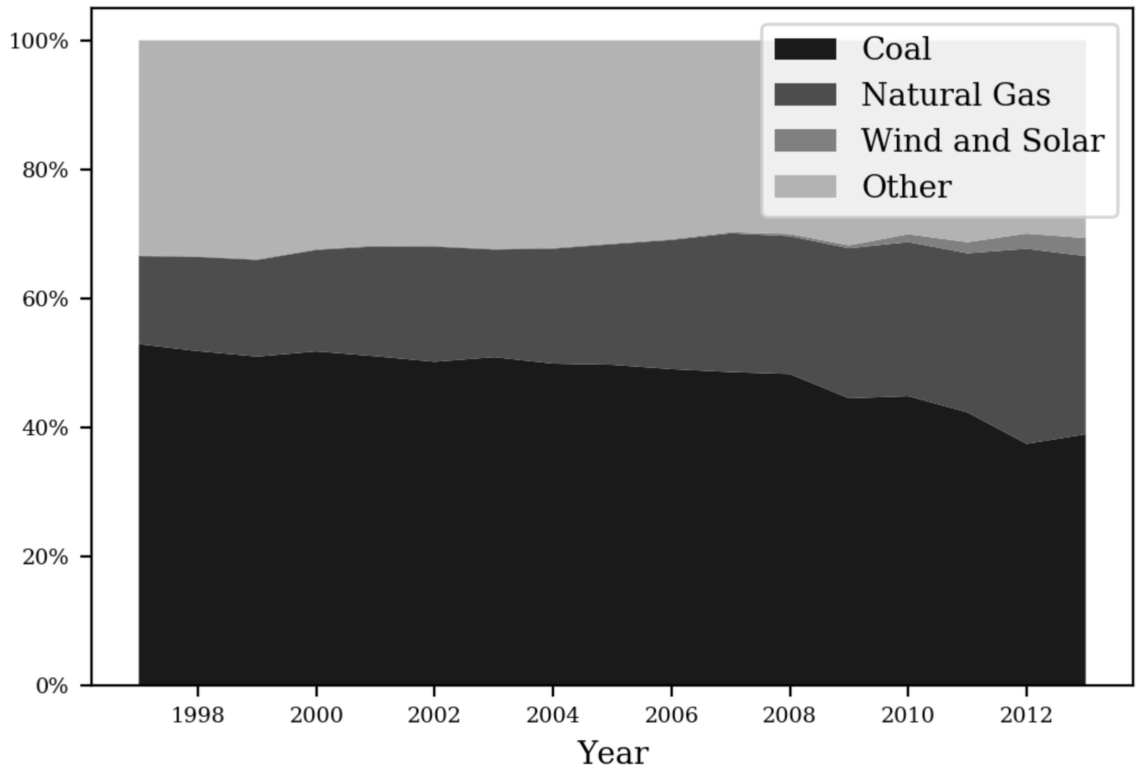

Figure 3: U.S. New and Reactivated Coal Capacity (% of Total Coal Capacity)

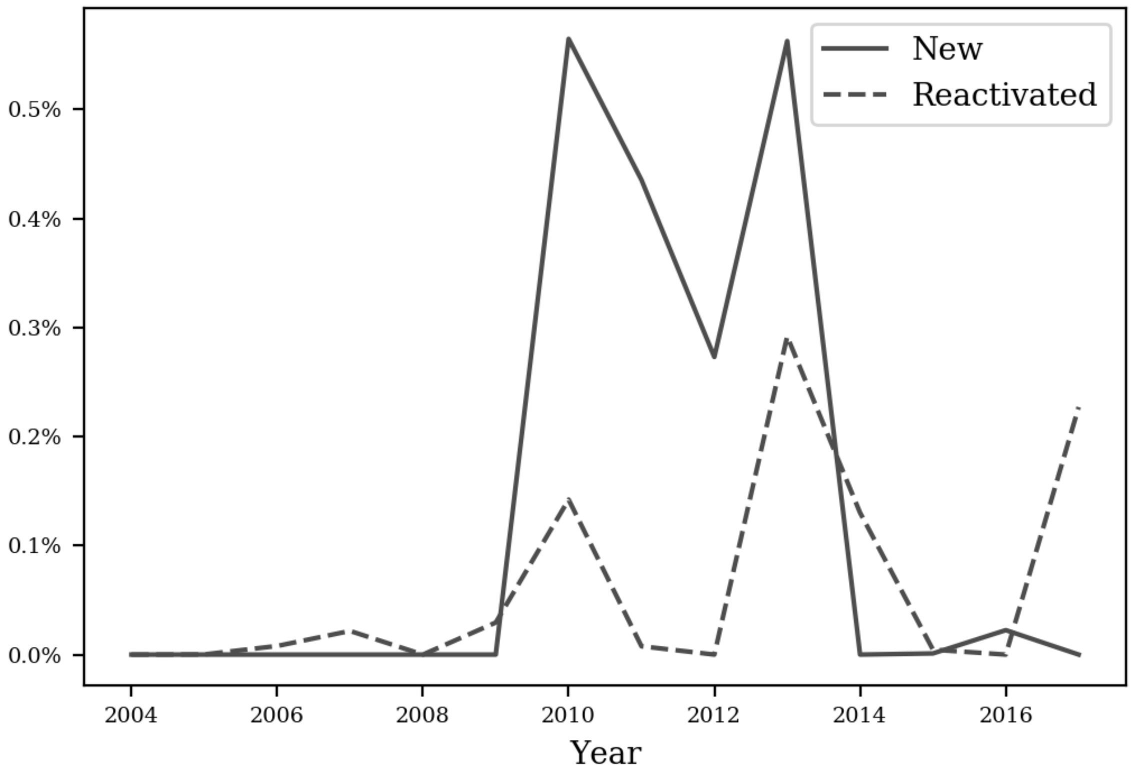

Figure 4: Average Carbon Intensity of U.S. Electricity Generation by Source

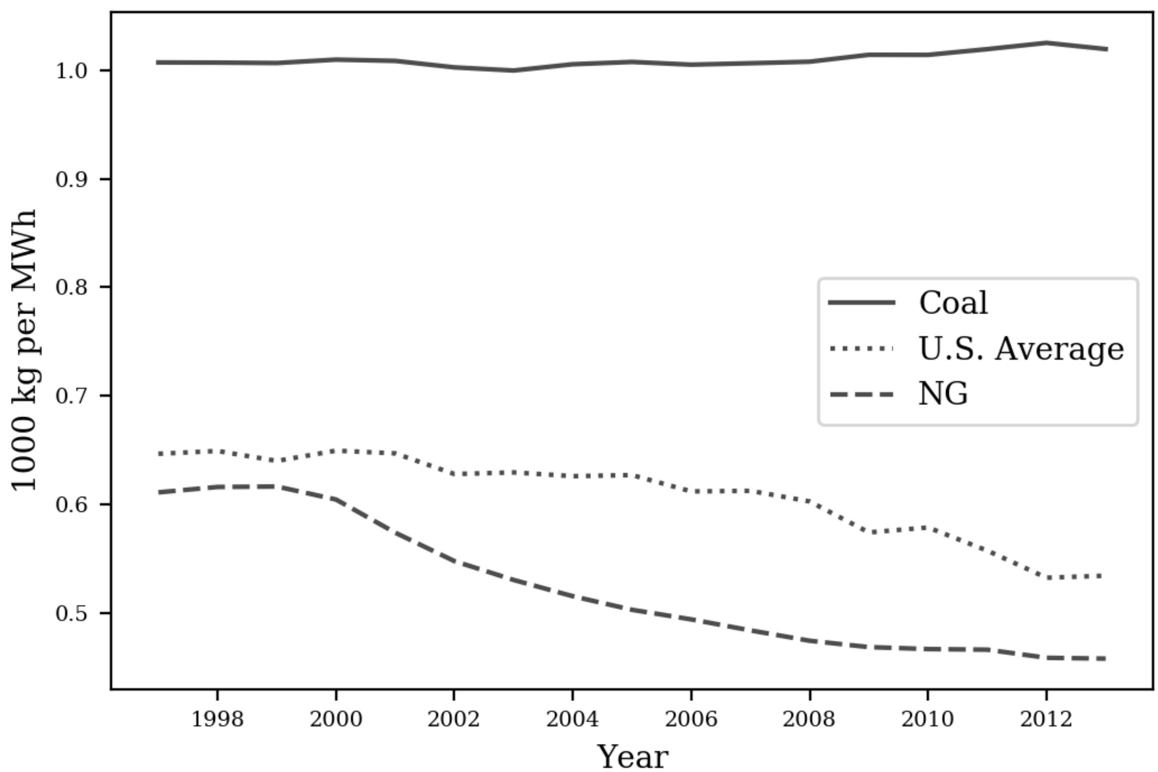

Table 2: Per Capita Generation by Energy Source (MWh per capita)

	Coal	Gas	Wind+Solar	Other
S_{st}	0.935	-3.33^{**}	0.460	0.337
	(1.468)	(1.538)	(0.409)	(1.133)
	p <.27	p <.012	p <.11	p <.31
S_{st}^2	9.38×10^{-4}	1.72×10^{-3}	-2.20×10^{-4}	$-8.57 \times 10^{-4*}$
	(2.05×10^{-3})	(1.80×10^{-3})	(6.96×10^{-4})	(9.03×10^{-4})
	p <.27	p <.15	p <.27	p <.09

Effect of an increase of 1pp in S_{st} (1pp^2 in S_{st}) on per capita generation by energy source. Estimated via WLS weighted by total state generation. Standard errors by bootstrap at the state level. *, **, and *** refer to significance at the 10%, 5%, and 1% levels.

Table 3: Average Carbon Intensity by Energy Source (kg/kWh)

	Coal	Gas	Other
S_{st}	-4.15×10^{-5}	2.20×10^{-4}	7.77×10^{-5}
	(1.65×10^{-4})	(2.12×10^{-4})	(9.87×10^{-5})
	p <.35	p <.17	p <.31
S_{st}^2	2.73×10^{-7}	-5.79×10^{-9}	-9.06×10^{-8}
	(1.82×10^{-7})	(1.82×10^{-7})	(1.03×10^{-7})
	p <.104	p <.53	p <.24

Effect of an increase of 1pp in S_{st} (1pp^2 in S_{st}) on average carbon intensity by energy source. Estimated via WLS weighted by total state generation. Standard errors by bootstrap at the state level. *, **, and *** refer to significance at the 10%, 5%, and 1% levels.

Table 4: Observed Data and Counterfactual in Treated States, 2013

	Total Generation (Million MWh)				Average Carbon Intensity (kg/kWh)		
	Coal	Gas	Wind+Solar	Other	Coal	Gas	Other
Data	899.0	698.0	108.1	798.7	1.146	0.476	0.053
Counterfactual	779.3	985.8	77.4	834.0	1.061	0.350	0.047
Difference	119.7	-287.8	30.67	-35.3	0.085	0.126	0.006

Combined effect of all extant RPS policies on total generation and average carbon intensity, by energy source, across all 26 treated states in 2013. “Data” refers to values observed in the data, “Counterfactual” to values constructed as described in Section 5.

Figure 5: Coarse Decomposition of RPS Effect

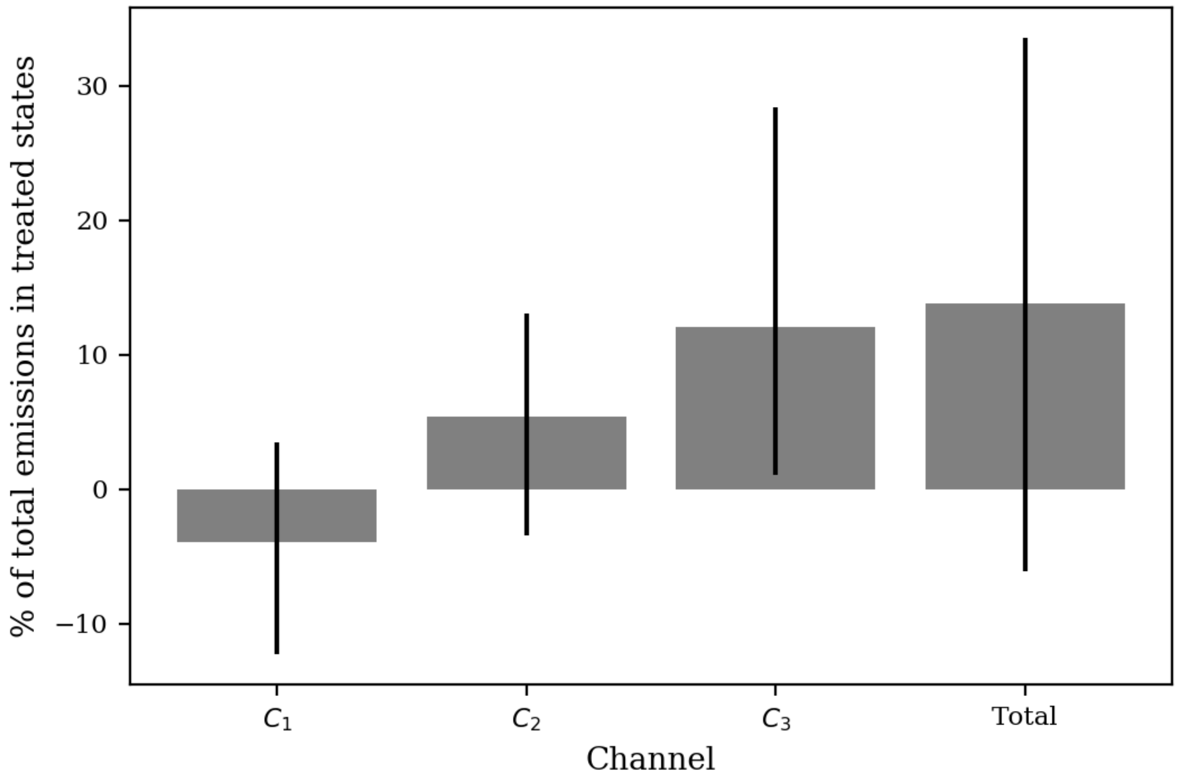

Table 5: Coarse Decomposition

	Absolute Size (Billion Tons)			Share of Total (%)	
	Estimate	95% CI	p value	Estimate	95% CI
C_1 (tot. gen. quantity)	-49.13	[-155.08, 35.59]	.1175	-3.92	[-12.37, 2.84]
C_2 (power mix)	67.18	[-50.02, 160.52]	.1155	5.36	[-3.99, 12.81]
C_3 (carbon intensity)	151.23	[4.61, 373.77]	.0175	12.06	[0.37, 29.82]
Total	173.37	[-77.08, 420.50]	.107	13.83	[-6.15, 33.55]

Decomposition of combined effect of all extant RPS policies on total emissions across all 26 treated states in 2013, as described in Section 4.2. "Absolute Size" refers to the absolute size of the channel. "Share of Total" is the size of the channel divided by total 2013 emissions in the treated states.

Figure 6: Further Decomposition of Channel C_2

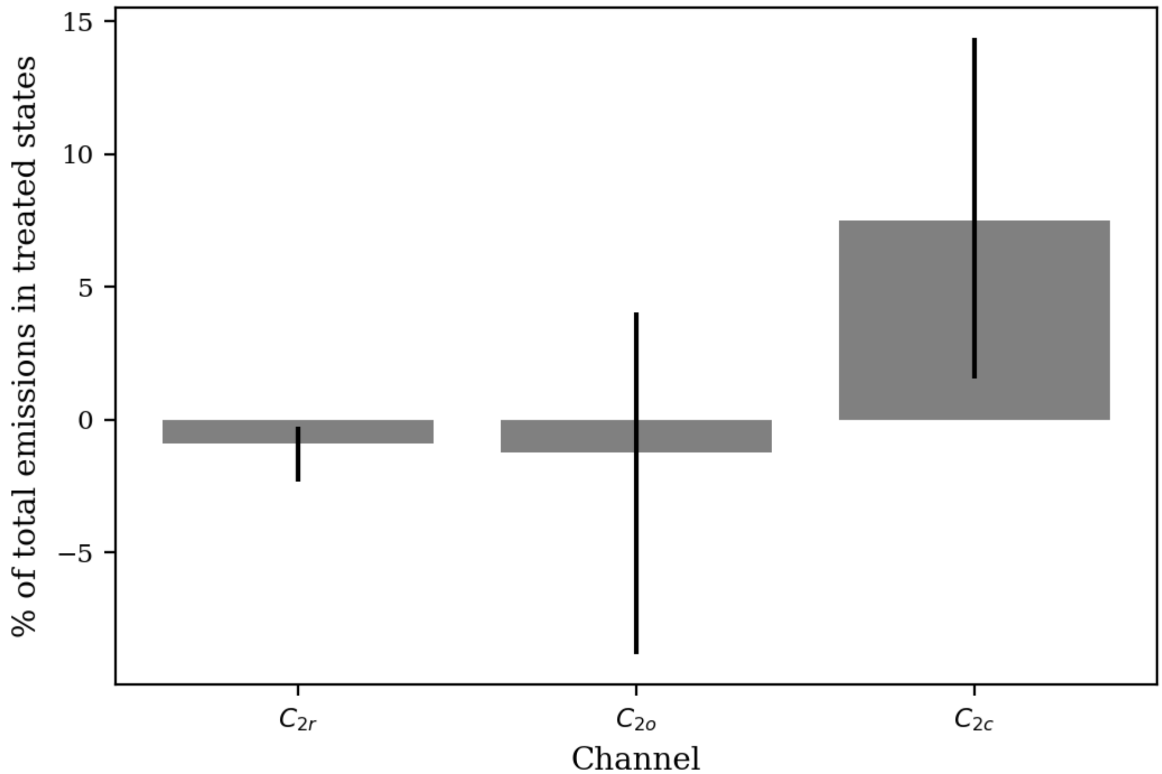

Table 6: Further Decomposition of Power Mix Channel C_2

	Absolute Size (Billion Tons)			Share of Total (%)	
	Estimate	95% CI	p value	Estimate	95% CI
C_{2r} (wind+solar share)	-11.23	[-28.96, -3.63]	.0015	-0.90	[-2.31, -0.29]
C_{2o} (other share)	-15.36	[-113.38, 49.33]	.36	-1.22	[-9.04, 3.94]
C_{2c} (coal vs. gas share)	93.77	[17.78, 173.11]	.0095	7.48	[1.42, 13.81]

Decomposition of C_2 into the effect of changes in generation shares by energy source, as described in Section 4.2. “Absolute Size” refers to the absolute size of the channel. “Share of Total” is the size of the channel divided by total 2013 emissions in the treated states.

Figure 7: Further Decomposition of Channel C_3

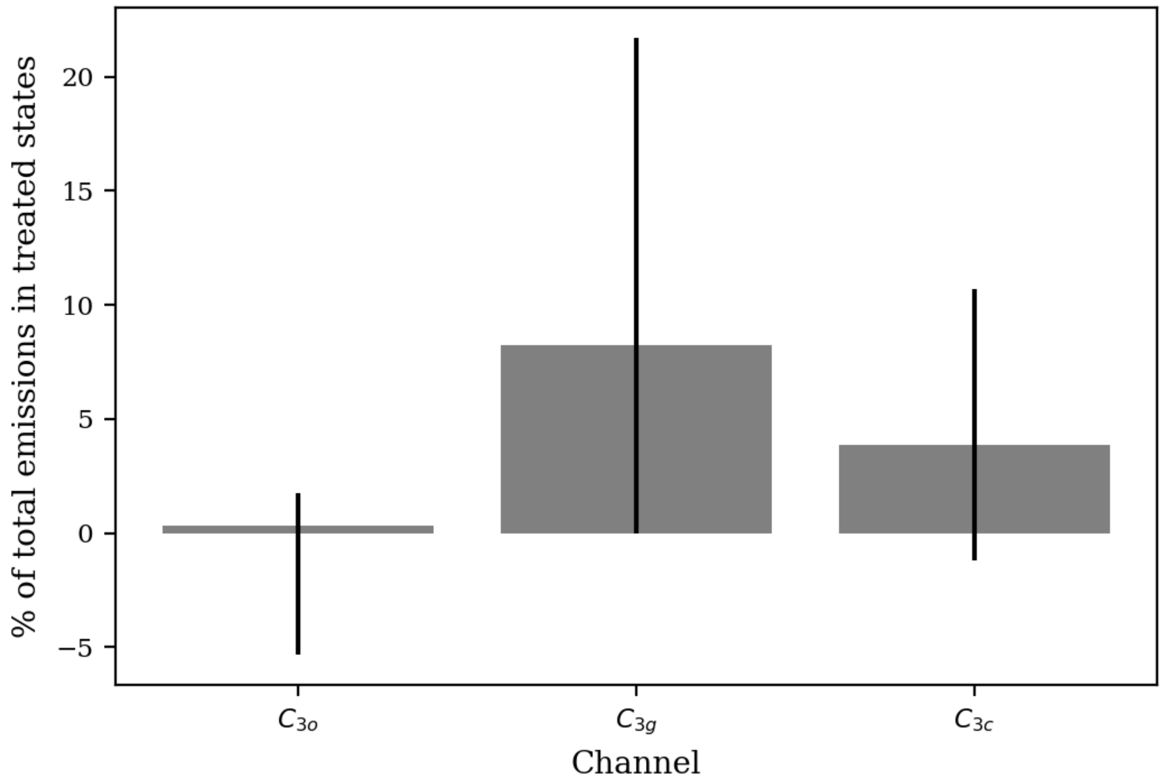

Table 7: Further Decomposition of Carbon Intensity Channel C_3

	Absolute Size (Billion Tons)			Share of Total (%)	
	Estimate	95% CI	p value	Estimate	95% CI
C_{3o} ("other")	4.10	[-64.53, 20.32]	.50	0.33	[-5.15, 1.62]
C_{3g} (gas)	103.04	[-3.80, 294.85]	.034	8.22	[-0.30, 23.52]
C_{3c} (coal)	48.18	[-13.13, 127.82]	.094	3.84	[-1.05, 10.20]

Decomposition of C_3 into the effect of changes in average carbon intensity by energy source, as described in Section 4.2. "Absolute Size" refers to the absolute size of the channel. "Share of Total" is the size of the channel divided by total 2013 emissions in the treated states.

Figure 8: Full Decomposition of RPS Effect