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Emissions reductions or green booms? General equilibrium effects of a renewable portfolio standard[☆]

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ABSTRACT

Renewable portfolio standards (RPS) are commonly promoted as a policy tool to reduce emissions associated with fossil generation, while also stimulating development of local renewable resource endowments. We develop a general equilibrium model of an RPS policy that captures key features such as a fixed factor renewable endowment, substitution across sectors of the economy, and endogenous price responses. We analytically decompose the effects of an RPS into a) a substitution effect, b) an output-tax effect, and c) an output effect. We show that an increase in the RPS can either deliver large resource booms or large emissions savings but not both. Our framework can translate different renewable resource endowments and pre-existing standards across states into economic and environmental impacts to inform current renewable energy and climate policies.

1. Introduction

In the absence of comprehensive federal climate policy in the United States, Renewable Portfolio Standards (RPS) adopted by a majority of states are some of the most important policies related to climate change in the electricity sector.[1] RPS policies require a specific percentage of electricity generation to be met by renewable fuel sources, generally displacing "dirty" fuel

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[1] See http://www.dsireusa.org/ for a comprehensive database of RPS and other renewables fuel policies across the United States.

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sources for electricity such as coal with cleaner fuel sources such as wind and solar.[2] However, as noted by Lyon and Yin (2010), Schmalensee (2012), and Jenner et al. (2012), adoption of RPS policies has also been driven by concerns other than emissions or climate change - for example a desire by states to take advantage of local "endowments" of renewable resource potential.[3] For instance, the governor of Iowa, Terry Branstadt, who signed the first state RPS into law in 1983 noted "…we're in the farm crisis, this was a mechanism to provide some additional income for farmers at a time when they critically needed it."[4] On the other hand, the Ohio House of Representatives noted concerns about economic impacts while voting to repeal the state RPS in March 2017. Recently economists have examined the impacts of non-renewable energy booms Muehlenbachs et al. (2015); Jacobsen and Parker (2016); Allcott and Keniston (2017), but even as 29 states (plus DC and 3 territories) have established mandatory RPSs and at least 13 states are currently debating either strengthening or weakening their RPSs, no research, to the best of our knowledge, evaluates these competing objectives of an RPS. As such, we ask: under what conditions does a RPS provide emissions reductions, green booms, or both?

To answer this question, we develop a simple general equilibrium model with three sectors (clean energy production, fossil energy production, and a composite sector) and three inputs (capital, labor and a renewable fixed factor).[5] While the general class of environmental standards has been addressed extensively in the literature, several features of RPSs render existing models insufficient to answer the question of the trade-off in achieving emissions reductions versus green booms with an RPS.

First, partial equilibrium analysis Helfand (1991); Holland et al. (2009) ignores prospective substitution across multiple sectors as well as price responses. Second, general equilibrium analyses considering the impacts of taxes or standards Harberger (1962); Fullerton and Heutel (2007, 2010) have not considered output-output standards, where the outputs subject to the standard are perfect substitutes from the perspective of household consumption.[6] In effect, renewable-based electricity and fossil-based electricity are imperfect substitutes on the supply side but perfect substitutes on the demand side. Finally, computational models of RPSs that capture the omitted features above are generally intractable analytically, and as such rely on "blackbox" methods that mask the underlying economic forces.

We extend the previous literature on modeling standards in three distinct ways. First, we incorporate a renewable fixed factor that captures region-specific endowments of renewable resource potential and allows us to analytically express the returns accrued to the region-specific fixed factor and hence the local green economic boom.[7] In turn, we can identify the economic conditions under which an RPS generates local green booms. Second, we include a composite sector that allows us to examine not just the movement of inputs within the electricity sector between dirty and clean sources of energy production (as in Fullerton and Heutel (2010) and Holland et al. (2009)), but also movement of inputs away from the electricity sector. Third, we capture the general equilibrium price effects that further reinforce the tradeoff across the electricity and composite sector.

Our innovations allow us to develop an analytically tractable general equilibrium framework for output-output RPS that captures substitution between sectors of the economy, endogenous price responses, gains to fixed factor renewable resource endowments, mobile capital, and multiple renewable technologies. In this paper, we highlight three key results. First, because states can meet an RPS either by increasing renewable energy production or by reducing fossil energy production, an increase in the RPS can generate either large resource booms or large emission savings, but not both. While economists are generally aware that a tradeoff exists between adjusting either the denominator or the numerator of the standard, our approach allows us to decompose the drivers of this trade-off. Whether an increase in RPS delivers emissions reductions or green booms depends critically on the pre-existing standard (high pre-existing standards favor emissions reductions) as well as the supply price elasticity of electricity generated from renewable fuel sources (inelastic supply curve favors emissions reductions). For instance, our simulations indicate that Arizona, with its low pre-existing standard and highly elastic supply curve, will primarily see local green booms from an increased RPS, whereas New York with a high pre-existing standard and relatively inelastic supply curve will experience a smaller green boom but more substantial emissions reductions from an increase in the RPS.

Second, the cross-sector mobility of capital in our model allows for multiple channels through which changes in an RPS can affect the size and composition of the electricity sector. We find three channels of adjustment – the substitution effect (movement of capital from composite and fossil sectors to the renewable sector), output-tax effect (movement of capital out of the electricity sector) and the output effect (trade-off between composite and energy sectors due to changes in relative prices).

Third, capital mobility across regions can generate positive or negative leakage in other regions in terms of both emissions reductions and green booms.[8] Furthermore, RPS policies with designated carve-outs for specific renewable technologies (e.g., NJ has an overall mandate for electricity produced from all renewable resources and a specific mandate for electricity produced

[2] While no RPS exists at the federal level, the federal Renewable Fuel Standard (RFS) has a similar design, and many of the insights below also apply to the RFS.

[3] For example, as Schmalensee (2012) notes, the statute for Michigan's RPS mentions the development of in-state resources, but does not mention climate change.

[4] http://qctimes.com/wind-turbines-dot-iowa-s-landscape-fueling-a-strong-economy/article_6202dbf6-1148-11e1-afda-001cc4c002e0.html.

[5] In an extension, we also consider the case of two regions (own state, neighboring state) with electricity traded across states and two renewable technologies subject to the RPS (e.g. wind, solar).

[6] We use the term "output-output" standard in the sense that the RPS affects both fossil fuel - and renewable-based electricity which are consumed by households. An important contrast with Fullerton and Heutel (2010) is that while in their formulation, pollution is separable in utility, in our model, both goods that the standard applies to (fossil fuel- and renewable-based electricity) are non-separable in utility.

[7] Bento and Jacobsen (2007) incorporate the use of a fixed-factor to examine conditions under which environmental policy can produce a double dividend.

[8] An increase in the standard in a region with a highly elastic supply curve (AZ) will generate positive emissions leakage into other regions but this is accompanied by a local economic boom in the other region (NY).

from solar energy) create large resource booms for the targeted technology, at the expense of a resource bust for non-targeted technologies and lower emission savings relative to a true portfolio standard that treats all technologies equally.

Finally, calibrated numerical simulations for US states with RPS policies reveal several interesting results. First, they show that, because most states currently have small existing standards, an RPS is more likely to generate local resource booms than emission savings. Second, the impact of an RPS on electricity prices is likely to be small; because utilities can meet an RPS by increasing renewable production or decreasing fossil production, an increase in the standard induces a "tug-of-war" between capital entering and exiting between the electricity and composite sector, leading to a small net effect on prices.[9] Third, we show that based on pre-existing standards and a state's renewable potential, an increase in the RPS can either deliver large resource booms or large emissions savings but not both.

We organize the rest of the paper as follows. In section 2, we develop the analytical model. In section 3, we solve the model and present our closed-form solutions. In section 4, we present simulation results and in section 5 we conclude with policy implications.

2. Analytical framework

This section presents a static analytical model to compare the changes in emissions and rents from renewable energy endowments as a result of a renewable portfolio standard.[10] Our base model considers a single region with a single renewable energy technology, a fossil-based energy technology, and a composite good. We further extend this model by introducing multiple regions to demonstrate the pattern of leakage from the change in one region's standard on the others when capital is mobile. We also extend the model to multiple technologies to contrast the effects of two forms of a renewable portfolio standard - a portfolio standard that mandates a minimum ratio of renewable energy to total energy, and a carve-out standard that mandates a minimum ratio of renewable energy from a specific technology (e.g. solar) to total energy. For simplicity, we assume that there are many firms that behave competitively in a situation with no uncertainty.

2.1. Model assumptions

We develop a static model of a single region closed economy in which there are two final goods, electricity (Q) and the composite good (C).[11] Electricity is generated from fossil (X) or renewable resources (Y) using their respective technologies. There are three productive inputs, labor (L), capital (K) and a renewable fixed factor ($\overline{Z}$) that represents the amount of "potential" renewable energy in the region.[12] Labor and capital have a fixed endowment, $\overline{L}$ and $\overline{K}$ respectively and these are mobile across different sectors of the economy. We assume that fossil energy production is constant returns to scale in capital, composite good production is constant returns to scale in capital and labor, and renewable energy production is constant returns to scale in capital and the renewable fixed factor, and therefore decreasing returns in capital.[13] We further stipulate that emissions are generated linearly in the production process of fossil-based electricity.

2.1.1. Composite sector

Given unit price of the composite good P_c and input prices for capital (r) and labor (w), the representative firm in the composite sector chooses capital and labor to maximize profits. First-order conditions satisfy the standard requirement that marginal productivity is equated to input prices.

2.1.2. Electricity sector

The total amount of electricity produced (Q) is assumed to be the sum of the electricity produced from fossil (X) and renewable (Y) sectors which can be thought of as intermediate goods.[14] Specifically,

$$Q = X + Y \tag{1}$$

[9] Our base model does not consider cross-state electricity trading and so our modest price effects are at best exaggerated with true price effects being even smaller.

[10] The static model we present is well-suited for comparing across different equilibria. For consideration of transitions due to imperfect factor mobility, see Goulder and Summers (1989). We leave the important question of dynamic transitions between different RPSs for future work.

[11] While our baseline model considers a single region closed economy, we later develop extensions to the model with multiple jurisdictions and a market for trade in inputs and outputs.

[12] In practical terms, we can think of the fixed factor as the number of sunny days, average wind-speeds etc. These represent immobile characteristics of a given jurisdiction that determine the ease/difficulty of producing renewable energy. Given their fixed nature, there will rents accrued to the owners of the renewable endowment (e.g. landowners who lease their land to wind developers).

[13] Clearly the electricity sector has other inputs such as labor (for fossil and renewables) and fuel (for fossil). However, given that they constitute relatively small shares of these sectors, and the difficulty of deriving and interpreting closed-form solutions, excluding them from the theoretical model is a reasonable trade-off in exchange for being able to derive economically meaningful closed-form solutions below. Nonetheless, we return to these inputs in numerical extensions below. Also, note that we abstract from the distinction between capacity and generation in the electricity sector, and thus capital used in that sector should be interpreted as capacity factor-adjusted capital.

[14] In practice, electricity produced from renewables may not be perfectly substitutable for fossil due to intermittency and dispatch issues Verdolini et al. (2016). We abstract from such considerations here.

Firms are price-takers. Given the price of electricity (P) and input prices for capital (r) and the fixed factor P_Z, the representative firms optimization problem in the presence of a renewable portfolio standard s allocates capital to fossil K_X and renewable K_Y per[15]:

$$\max_{K_X,K_Y} P\left[X(K_X) + Y(K_Y;\overline{Z})\right] - r\left[K_X + K_Y\right] - P_Z\overline{Z}$$
$$s.t.\quad \frac{Y}{X+Y} \geq s. \tag{2}$$

The renewable portfolio standard stipulates a minimum fraction s of total energy production that must come from renewable sources, which in equilibrium is binding. The standard can be met in two ways - directly, by increasing production of electricity from renewable sources, and indirectly, by decreasing the production of energy from fossil sources. As a binding constraint, the RPS distorts the allocation of capital across the two energy intermediate sectors. Specifically, if $X_K(K_X)$ and $Y_K(K_Y;\overline{Z})$ are the marginal products of fossil and renewable energy respectively, and μ is the lagrange multiplier associated with the binding standard, then the resultant first order conditions are,

$$X_K(K_X)\left[P - \mu s\right] = r$$
$$Y_K(K_Y;\overline{Z})\left[P + \mu(1-s)\right] = r. \tag{3}$$

The standard acts as an implicit tax on fossils and an implicit subsidy for renewables, with the magnitude of the implicit tax increasing in s and the magnitude of the implicit subsidy decreasing in s. It is important to note that, with some additional manipulation, the RPS can also be interpreted as a tax on total electricity (denominator in equation (2)) and a subsidy to renewables (numerator in equation (2)), or as a tax on fossil and a subsidy to output (see Appendix C). The former interpretation is emphasized by Lapan and Moschini (2012) in the context of an ethanol mandate. The latter interpretation is taken by Holland (2012) who stresses the importance of the output subsidy as a key driver of the inefficiency of standards. However, given the equivalence of the three interpretations above, our discussion to follow will rely on the characterization of the RPS as an implicit tax on fossil and an implicit subsidy to renewables.[16] Finally, we note that because the production of electricity from fossil sources, X is constant returns to scale in capital, X_K is constant. Substituting for μ, the standard distorts the production of renewables per:

$$Y_K(K_Y;\overline{Z}) = \frac{rsX_K}{PX_K - (1-s)r}. \tag{4}$$

The marginal product of capital in renewables will be lower under the standard, reflecting the fact that the standard pushes renewable production passed the point where the marginal product is equated to the input cost of capital.

2.1.3. Consumer's problem

We consider a representative consumer in each region whose utility depends on consumption of electricity and the composite good, as well as disutility from emissions, which are assumed to be additively separable. This characterization of utility implicitly asserts that the consumer is indifferent to the source of electric power, effectively removing any "green premium" that consumers may place on a renewable generation source Jacobsen et al. (2012). Formally, the consumer's maximization problem is given as:

$$\max_{Q,C} u(Q,C) - \phi(E)$$
$$s.t. PQ + P_C C \leq r\overline{K} + w\overline{L} + P_Z\overline{Z}. \tag{5}$$

To close the model, we consider the consumer as the owner of factors of production and so the expenditure on electricity and composite good must be less than the revenue generated from capital rental and wages earned from labor, as well as rents generated from the fixed factor ($P_Z\overline{Z}$). Changes in the RPS will affect the rents from the fixed factor, which we characterize as local economic booms. Emissions are assumed to emanate from the production of fossil energy. The additive separability of emissions in the utility function allows us to distinguish between the price effects on consumption from preferences on air quality.

[15] We can also think about this problem as two separate firms producing the two forms of energy separately. The standard is then met at a geographic aggregate (normally the state level) with e.g. fossil based electricity generating firms purchasing Renewable Energy Credits (RECs) from producers that generate renewable energy. Or, one could also include local distribution companies that are legally obligated to hold enough RECs to cover the RPS. The mechanics and results of the problem are unchanged.

[16] This is similar to the interpretation in Holland et al. (2009) of the Low Carbon Fuel Standard (LCFS), whereby the LCFS taxes high-carbon fuel and subsidizes low-carbon fuel. In the case of an LCFS, the inefficiency of the standard arises because low-carbon fuels should be taxed instead of subsidized. However, in the case of an RPS, a subsidy for renewables is not necessarily inefficient as there may be other market failures justifying a subsidy to renewables (e.g. learning-by-doing). Thus, the inefficiency of an RPS may be better characterized by noting that an RPS is a single instrument (with the magnitude of the implicit tax and subsidy linked by μs) while efficiency would require multiple instruments to correct multiple market failures.

2.2. Closed form solutions

To avoid making assumptions about the exact functional form of production and utility functions, for the analytical model above we obtain closed-form equilibrium solutions to fractional changes in equilibrium quantities and prices by using the log-differential approach in Harberger (1962).[17] These are discussed in section 3 and the full set of results are in the appendix.

2.2.1. Producer's problem

We begin with the fossil sector and totally differentiate the production function $X(K_X)$ and the profit function (from (2)). Defining $\widehat{X} \equiv dX/X$

$$\widehat{X} = \widehat{K}_X \tag{6}$$

$$\widehat{P} + \widehat{X} = \widehat{K}_X + \widehat{r}. \tag{7}$$

Similarly for the composite good sector, from the production function and the zero-profit condition we obtain,

$$\widehat{C} = \theta_{CK}\widehat{K}_C + \theta_{CL}\widehat{L}_C \tag{8}$$

$$\widehat{P}_C + \widehat{C} = \theta_{CK}\left[\widehat{K}_C + \widehat{r}\right] + \theta_{CL}\left[\widehat{L}_C + \widehat{w}\right], \tag{9}$$

where θ_{CK} and θ_{CL} are the shares of production that belong to owners of capital and labor respectively, such that $\theta_{CK} = rK_C/P_C C$ and $\theta_{CL} = wL_C/P_C C$. Finally, if σ_C is the elasticity of substitution between capital and labor, then,

$$\widehat{K}_C - \widehat{L}_C = \sigma_C\left(\widehat{w} - \widehat{r}\right). \tag{10}$$

For the renewable technology, differentiating the production function $Y(K_Y; \overline{Z})$ yields:

$$\widehat{Y} = \theta_{YK}\nu\widehat{K}_Y. \tag{11}$$

Note that $\theta_{YK} = rK_Y/PY$ is the capital share in the production of renewable generation, while $\theta_{YZ} = 1 - \theta_{YK}$ is the share of the renewable fixed factor in the production of renewables. The term ν is the adjustment factor since the standard distorts the allocation of capital to the renewable sector (per equation (4)), and is given as $\nu = \frac{Ps}{P-r(1-s)}$.

Next, we differentiate the input demand equation, $K_Y(r, P_Z)$, which yields:

$$\widehat{K}_Y = \sigma_Y(\widehat{P}_Z - \widehat{r}), \tag{12}$$

where σ_Y is the elasticity of substitution between capital and the fixed factor in the production of renewable energy. In the presence of decreasing returns, the fixed factor accrues *Ricardian Rents* as in Bento and Jacobsen (2007). The term $\widehat{P}_Z$, captures the change in these rents, which are essentially the profits made by owners of this fixed factor.

2.2.2. Consumer's problem

By totally differentiating the utility function in (5), we obtain

$$\widehat{Q} - \widehat{C} = \sigma_u\left(\widehat{P}_C - \widehat{P}_X\right), \tag{13}$$

where σ_U is the elasticity of substitution between electricity and the composite good.

2.2.3. Closing conditions

To close the model, capital satisfies:

$$\lambda_{KX}\widehat{K}_X + \lambda_{KY}\widehat{K}_Y + \lambda_{KC}\widehat{K}_C = 0, \tag{14}$$

where λ_{Kj} is the share of capital in sector $j \in \{X, Y, C\}$ such that $\lambda_{Kj} = \frac{K_j}{K}$. Labor satisfies:

$$\widehat{L}_C = 0. \tag{15}$$

With the normalization that $\widehat{P}_C = 0$, equations (6)–(15) provide 10 equations for 11 unknowns $(\widehat{X}, \widehat{K}_X, \widehat{Y}, \widehat{K}_Y, \widehat{C}, \widehat{K}_C, \widehat{L}_C, \widehat{r}, \widehat{w}, \widehat{P}, \widehat{P}_Z,)$. The final equation comes from the standard itself. Log-differentiating the standard in (2) gives:

$$\widehat{X} = \widehat{Y} - \widehat{s}\left(\frac{1}{1-s}\right). \tag{16}$$

[17] This technique following Harberger (1962) has since been used in a number of studies Bovenberg et al. (2005); Fullerton and Heutel (2010).

Taken together, the above system of equations yield the unique equilibrium solutions discussed in the following section. These analytical solutions are derived via iterative substitution similar to the method in Appendix B of Fullerton and Heutel (2007).

3. Analytical results

In this section we present and interpret the solutions to the model developed in the previous section (equations (6)–(16)). Due to the large number of endogenous variables and parameters, the full solutions are presented in Appendix B.1. This section begins by decomposing the key channels of adjustment to a change in the RPS. With an understanding of the key effects, we then focus on the magnitudes of these effects in terms of emissions savings versus local resource booms. Finally, we explore the implications for these effects in the presence of multiple regions and technologies.

3.1. Decomposition of effects of a change in the RPS

We begin by decomposing the effects of a change in the RPS. We first consider the changes in the key electricity sector outputs. The effect of an increase in the RPS ($\hat{s} > 0$) on changes in fossil generation $\hat{X}$ and renewable generation $\hat{Y}$, can be decomposed into *substitution, output,* and *output-tax effects* as follows:

$$\hat{X} = [\underbrace{\frac{-\frac{\lambda_{KY}}{\theta_{YK}\nu}\sigma_c}{D}}_{substitution} + \underbrace{\frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D}}_{output-tax} + \underbrace{\frac{-\frac{\theta_{CL}\lambda_{KY}}{\theta_{CK}\theta_{YK}\nu}\sigma_u}{D}}_{output}]\hat{s}[\frac{1}{1-s}] \tag{17}$$

$$\hat{Y} = [\underbrace{\frac{(\lambda_{KX}+\frac{\lambda_{KC}}{\theta_{CK}})\sigma_c}{D}}_{substitution} + \underbrace{\frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D}}_{output-tax} + \underbrace{\frac{\frac{\theta_{CL}\lambda_{KX}}{\theta_{CK}}\sigma_u}{D}}_{output}]\hat{s}[\frac{1}{1-s}] \tag{18}$$

$$\text{where} \quad D = \left(\lambda_{KX} + \frac{\lambda_{KY}}{\theta_{YK}\nu} + \frac{\lambda_{KC}}{\theta_{CK}}\right)\sigma_C + \frac{\theta_{CL}}{\theta_{CK}}\left(\lambda_{KX} + \frac{\lambda_{KY}}{\theta_{YK}\nu}\right)\sigma_u > 0.$$

The first terms in equations (17) and (18) are substitution effects arising from the movement of capital from fossil and composite sectors into the renewable sector in response to the implicit subsidy to the renewable sector in equation (3). To develop intuition, first consider a simple partial equilibrium model where the composite sector is absent. In this simple case, capital must flow out of the fossil sector ($-\frac{\lambda_{KY}}{\theta_{YK}\nu}\sigma_C$ in equation (17)) and into the renewable sector ($\lambda_{KX}\sigma_C$ in equation (18)) in response to the change in the standard. When the composite sector is incorporated, capital can also flow from the composite sector to the renewable sector ($\frac{\lambda_{KC}}{\theta_{CK}}\sigma_C$) to increase $Y$to meet the change in standard.

The second terms are *output-tax effects* arising from the movement of capital out of electricity and into the composite sector ($-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_C$). This effect is associated with the decrease in capital used in electricity generation (the denominator of the standard $X + Y$) as the standard is increased, resulting in decreases in both X and Y. The *output-tax effect*, therefore, reflects the implicit tax on the electricity sector (from equation (3) in the term $(-\mu s)$). Thus, the *substitution* and *output-tax effects* reflect the two direct ways in which the standard can be met - increasing renewable energy production or decreasing fossil energy production, and as such the standard acts as an implicit tax on fossil energy production and as an implicit subsidy to renewable production.

The final terms are the general equilibrium *output effects* arising from changes in prices due to the change in the standard. Specifically, the *output effects* arise from household substitution between the composite sector and the electricity sector in response to relative prices, as governed through equation (13). As an understanding of changes in relative prices is necessary to understand this term fully, we will return to this effect below.

The following equations describe the responses of the remaining endogenous variables:

$$\hat{P} = \frac{\theta_{CL}}{\theta_{CK}}\left[\frac{\frac{\lambda_{KY}}{\theta_{YK}\nu}}{D} + \frac{-s(\lambda_{KX}+\frac{\lambda_{KY}}{\theta_{YK}\nu})}{D}\right]\hat{s}\left[\frac{1}{1-s}\right], \tag{19}$$

$$\hat{P}_Z = \hat{P} + \frac{1}{\theta_{YK}\nu\sigma_Y}\hat{Y}. \tag{20}$$

The effect of an increase in the RPS on electricity prices $\hat{P}$ is positive, with the magnitude of the effect determined by the difference in the marginal cost of renewable and fossil production.[18] Substitution of the relationship between electricity prices

[18] With manipulation, we can show that the numerator in equation (19) can be written as $\frac{\overline{K}}{(X+Y)r}[\frac{rK_Y}{Y\nu\theta_{YK}} - \frac{rK_X}{X}$ which is always positive since the share of capital in fossils is 1, which follows from the single input constant returns to scale production function. The fact that electricity prices increase is consistent with the intuition in Fischer (2010), whereby prices increase when the renewable energy supply curve is more inelastic than the fossil supply curve.

and the composite sector in equation (19) into the household substitution equation (13) yields the following relationship: $\frac{\hat{Q}}{\hat{P}} = -(\sigma_u + \frac{\theta_{CL}}{\theta_{CK}}\sigma_C)$. As expected, prices and quantities move in opposite directions, implying that total electricity production falls as the standard increases.

Returning to the *output effects* in equations (17) and (18) and per the above discussion, electricity prices as well as capital prices $\hat{r}$ increase in response to a change in the standard. As a result, because the fossil sector is more capital-intensive relative to the renewable sector, there is an additional reduction in fossil given by the negative *output effect* $-\frac{\theta_{CL}\lambda_{KY}}{\theta_{CK}\theta_{YK}\nu}\sigma_u$ in equation (17) as well as an additional increase in renewables given by the positive output effect $\frac{\theta_{CL}\lambda_{KX}}{\theta_{CK}}\sigma_u$ in equation (18).[19]

Finally, equation (20) gives the change in $\hat{P}_Z$ due to the standard, or the change in the value of the renewable endowment, which accrues to the owner of the fixed factor. This term is increasing in both changes in renewable production $\hat{Y}$ as well as the price of electricity $\hat{P}$. Intuitively, owners of the fixed factor stand to gain if either the price of electricity increases, or if the amount of renewable production increases. For a given change in renewable production $\hat{Y}$, owners of the fixed factor gain the most when: the share of the fixed factor in the production of renewables is large (θ_{YK} is small) and substitution between capital and the fixed factor (σ_Y) is small.

The above discussion decomposes the effects of a change in the RPS into substitution, output-tax and output effects, reflecting the capital movement both from fossil to renewables, as well as from electricity to the composite sector. This in turn allows us to characterize the effect of an RPS on emissions (via changes in fossil) as well as on rents earned by the fixed factor renewable endowment. Our findings are consistent with and extend prior literature on environmental standards (e.g., Holland et al. (2009), Fullerton and Heutel (2010), Lapan and Moschini (2012), Holland (2012), Bushnell et al. (2017)).

We build on these important papers in three ways. First, we include a fixed factor for renewable production that allows us to characterize the changes in rents accrued to the owners of the fixed factor due to changes in the standard. Second, to integrate the electricity sector in the broader economy, we add a composite sector that enables us to differentiate between movements of capital within the electricity sector and movements of capital out of the electricity sector. Finally, we fully characterize a general equilibrium model that allows us to capture price effects, which accelerate the decline of fossil and reinforce the increase in renewable production.

3.2. What do RPSs deliver? Emission savings or local booms?

The above discussion decomposed the effects of an RPS into *substitution*, *output-tax*, and *output effects*. We now examine the impacts of these effects on emission reductions and local booms. For simplicity, we assume that emissions are a linear function of fossil energy generation and hence emission reductions $\hat{E}$ will simply be reflected through $\hat{X}$ (equation (17)). Local booms are captured by the term $\hat{P}_Z$ (equation (20)), which itself depends on changes in renewable generation $\hat{Y}$ (equation (18)) and electricity prices $\hat{P}$ (equation (19)). While quick inspection of equations (17) and (18) and the discussion above surrounding equation (19) shows that the change in fossil $\hat{X}$ is unambiguously negative and the change in renewables $\hat{Y}$ and electricity prices $\hat{P}$ are unambiguously positive, the discussion below will allow us to tease out the underlying features that influence the *magnitude* of these changes. An understanding of these magnitudes will allow us to examine the key question of the extent to which RPSs provide emissions savings, local booms, or both.

To facilitate the discussion of emissions reductions versus local booms, we focus on varying two key features: the level of the pre-existing standard and the supply elasticity of renewables.[20] To formalize this, we will consider essentially limiting cases where the pre-existing standard is either large ($s > 0$) or small ($s \approx 0$), combined with cases where either renewable generation is relatively inelastic ($\lambda_{KY} > 0$ and $\lambda_{KX} \approx 0$) or elastic ($\lambda_{KX} > 0$ and $\lambda_{KY} \approx 0$).[21] Table 1 provides a summary of the following discussion.

To begin, consider the case of a large pre-existing standard where renewables are relatively inelastic ($s > 0$, $\lambda_{KY} > 0$, $\lambda_{KX} \approx 0$). From equation (17), the reduction in fossil generation and thus emissions will be large, as all three effects (*substitution, output-tax* and *output*) are in play. By contrast, the impact on resource booms per equation (20) is more muted. While electricity prices increase ($\hat{P} > 0$), the magnitude of the change in renewable generation (equation (18)) will tend to be small. The *output effect* and the first term of the *substitution effect* are inactive, while the remaining component of the *substitution effect* is offset by the negative *output-tax effect*. Maintaining our assumption about the elasticities but considering a small pre-existing standard ($s \approx 0$, $\lambda_{KY} > 0$, λ_{KX}), the reduction in fossil generation and emissions will be smaller than above, as the negative

[19] The intuition for this finding comes from the fact that while both forms of electricity generation see an increase in their output price, fossil sees a proportional increase in the cost of its sole input, while renewables see an increase in the cost of only one of its inputs. Note that the greater the elasticity of substitution between electricity and the composite good σ_U, the larger in magnitude this effect will be.

[20] While there are a large number of parameters we could also examine, varying these two features capture key sources of heterogeneity across states. For example, RPSs vary from 2% to over 30%, and fossil and renewable generation mixes vary considerably. A state with poor renewable potential would have an inelastic renewable supply curve, while a state that had substantial renewable generation opportunities would have a relatively more elastic renewable supply curve.

[21] If the renewable supply curve is relatively inelastic, then for any given standard, the amount of capital in the renewable sector will be relative large and $\lambda_{KY} > 0$. By contrast, if the supply curve is relatively elastic, less capital will be needed in the renewable sector for a given standard and $\lambda_{KY} \approx 0$.

Table 1
Summary of effects due to change in RPS.

	Substit. effect	Output-tax effect	Output effect	Net effect
Large standard, inelastic renewables				
Change in fossil $\widehat{X}$	–	–	–	– – –
Change in renewable $\widehat{Y}$	+	–		
Small standard, inelastic renewables				
Change in fossil $\widehat{X}$	–		–	– –
Change in renewable $\widehat{Y}$	+			+
Large standard, elastic renewables				
Change in fossil $\widehat{X}$		–		–
Change in renewable $\widehat{Y}$	+ +	–	+	+ +
Small standard, elastic renewables				
Change in fossil $\widehat{X}$				
Change in renewable $\widehat{Y}$	+ +		+	+ + +

Notes: Positive sign indicates an increase in the change in fossil $\widehat{X}$ or renewable generation $\widehat{Y}$, while a negative sign indicates a decrease in the change in generation. Large changes in fossil imply large emission savings, while large changes in renewables indicate large resource booms.

output-tax effect disappears from equation (17). Nonetheless, the *substitution* and *output effects* will still drive down emissions. On the other hand, the magnitude of the change in renewables (equation (18)) is now larger, as the negative *output-tax effect* is no longer offsetting the *substitution effect*, implying a relatively larger resource boom.

Turning now to the case where the renewable supply curve is relatively elastic and there is a large pre-existing standard, ($s > 0$, $\lambda_{KY} \approx 0$, $\lambda_{KX} > 0$), the only active effect for fossil in equation (17) is the *output-tax effect*, implying relatively modest reductions in emissions. By contrast, all three effects in equation (18) for renewable generation are in play, with the negative *output-tax effect* somewhat offsetting part of the *substitution effect*. The larger *substitution effect* and the presence of the *output effect* would suggest larger resource booms in this case, which are further amplified by increasing electricity prices ($\widehat{P} > 0$). Finally, when renewable supply is relatively elastic and there is a small pre-existing standard, ($s \approx 0$, $\lambda_{KY} \approx 0$, $\lambda_{KX} > 0$), the change in emissions will be extremely small, as none of the effects in equation (17) are active. By contrast, the change in renewables will be the largest of all the cases considered, as the *substitution effect* is large, the *output effect* is active, and the negative *output-tax effect* is inactive. This substantial increase in renewables will in turn generate a substantial resource boom.

We summarize our analytical results in Table 1; an increase in the RPS always increases renewable generation $\widehat{Y}$, decreases fossil generation $\widehat{X}$, and increases the price of electricity $\widehat{P}$. Increasing the relative elasticity of the renewable supply curve tends to favor local booms, while increasing the pre-existing standard tends to favor emission savings. Thus, when renewables are relatively inelastic and the pre-existing standard is large, substantial emission savings are generated, but the local resource boom will be small. Conversely, when renewable supply is relatively elastic and the pre-existing standard is small, substantial resource booms are created, but emissions reductions will be small. As such, it appears that the goals of reducing emissions and exploiting a green boom from renewable endowments are, in some sense, substitutes for one another. The conditions required for large reductions in emissions are precisely the conditions that lead to small changes in renewable returns, while the conditions for a large resource boom lead to small reductions in emissions.

3.3. Multiple region and technology extensions

The above discussion considered the case of a single renewable technology in a closed state economy. However, given the multiple technologies typically covered under existing RPS policies and the patchwork of states who have implemented RPS policies with varying stringencies, one might wonder how the results above may be altered if multiple technologies or regions are considered. Below we briefly discuss the main analytical insights from extensions that add additional renewable technologies and additional regions. In Appendix A we provide a fuller analytical treatment of these extensions, and we return to these extensions in the numerical section to follow.

First, we consider an extension whereby two adjacent regions each have RPSs but different renewable endowments, and capital can freely move between regions and electricity is traded across regions resulting in a single price of electricity. For this two region extension, an increase in the RPS in one region generates positive leakage of emissions in adjoining regions if the *output-tax effect* dominates the *substitution effect*. By contrast, there will be negative leakage of emissions if the *substitution effect* dominates the *output-tax effect*. If the leakage is negative, it is also accompanied by a resource bust in the other region. The intuition as to why negative leakage can occur follows a similar logic to the “abatement resource effect” highlighted in Baylis et al. (2014); here, capital may move out of one region in order to meet the RPS increase in the other, shrinking the electricity sector as a whole and reducing emissions. If the emissions leakage is positive, it is also accompanied by a resource boom in the other region. Thus, while RPS policies may generate emissions leakage to neighboring regions, that leakage is accompanied by a

Table 2
Parameters for numerical analysis.

Parameter	Symbol	Value
Labor share from composite	L_C	0.60
Capital share from composite[a]	K_C	0.36
Capital share from electricity[a]	$K_X + K_Y$	0.04
Capital share from fossil[a]	K_X	0.036
Capital share from renewable[a]	K_Y	0.004
Share of capital in renewable production	θ_{YK}	varies[b]
Pre-existing RPS	s	varies[b]
Elasticity of substitution in composite	σ_c	1.0
Elasticity of substitution in utility	σ_u	0.4
Elasticity of substitution in renewables	σ_y	1.0

Notes:
[a] Initial capital shares based on baseline of $s = 0.10$. Adjusted for $s > 0.10$ as discussed in text.
[b] Calculated for each state based on NREL and DSIRE databases. See Table 3 for specific values by state.

resource boom in that region as well.

Second, we consider an extension where a single region has two renewable technologies with different corresponding endowments (wind and solar for example). We consider two variants of RPSs - an RPS with technology specific carve-outs, and a more general "portfolio" standard where the change in the standard can be flexibly met by either renewable technology. For this two technology extension, an increase in a carve-out RPS leads to a larger increase in deployment of the targeted renewable technology (resource boom), at the expense of reduced deployment of other renewable technologies (resource bust) and lower emission savings relative to the portfolio standard. Because our model is static, it is not well-suited to address the learning-by-doing benefits frequently attributed to carve-out standards; nevertheless, the above finding provides some insight into a potentially non-obvious cost of carve-out standards.

4. Numerical results

In this section, we present calibrated numerical results with two goals: 1) Illustrate the mechanisms and magnitudes of the analytical effects discussed above, and 2) Identify the extent to which we expect emissions savings or resource booms across the 28 US states (including D.C.) with binding, percentage-based RPS policies.[22] Thus, for the plausible parameter estimates discussed below, we illustrate how the magnitudes of effects vary with the pre-existing RPS and renewable endowments, and how these magnitudes compare across the US.

4.1. Calibration

For the calibration, Table 2 summarizes the parameters used in the analysis. We normalize national income to 1, with a labor share of 0.60 Fullerton and Heutel (2010) and capital shares as described below. From the analytical model, two key parameters are the pre-existing RPS s, and the share of capital in the renewable sector λ_{KY}. The pre-existing RPS s for each state in 2016 is taken from the DSIRE database. To determine the share of capital in the renewable sector λ_{KY}, we first determine the parameter θ_{YK}, or the share of renewable production from capital. To determine θ_{YK} for wind- and solar-based energy, we obtain state-level capacity factor estimates Y/K_Y from the National Renewable Energy Lab (NREL). States with higher wind or solar endowments will have correspondingly higher capacity factors, and thus less capital in the renewable sector (λ_{KY}) to meet a given RPS.[23] Because $\theta_{YK} = rK_Y/PY$, the value of r/P is needed to pin down θ_{YK}. Using a common break-even capacity factor of 0.30 (0.13) for wind (solar) and the zero profit condition, we compute the r/p ratio. This ratio is then multiplied by the average capacity factor for wind and solar to obtain θ_{YK} as 0.857 for wind and 0.928 for solar. See Table 3 for 2016 RPS targets and capacity factors by state.[24]

Because we are interested in the magnitude of effects at different pre-existing standards, the share of capital in the renewable, fossil and composite sectors ($\lambda_{KX}, \lambda_{KY}, \lambda_{KC}$) must vary to reflect the different levels of the pre-existing standard as well as different capacity factors across states.[25] For the states with existing RPSs, the average standard in 2012 was approximately 10%,

[22] Note that a number of states have non-binding or voluntary RPSs, while Texas and Iowa have binding capacity-based standards.

[23] Note that we are assuming that wind and solar are the technologies employed to meet the RPS, though of course some states do count geothermal, hydro, and other technologies towards the standard. To the extent some states have the potential to increase e.g. geothermal in response to a change in the standard, this would imply a flatter (more elastic) renewable supply curve, which would favor green booms over emission savings per the discussion in Section 3.2.

[24] Capacity factors for the various states align with the general pattern for renewable endowments across the US. Solar endowment is greatest in the Southwest (AZ, NM, NV), wind endowment is greatest in the Central Plains regions (KS, MN), etc. Generally, the capacity factor for solar is less than that for wind, consistent with the fact that in most areas, solar requires more capital (and thus cost) per unit of generation than wind.

[25] It would be inappropriate to assume that ($\lambda_{KX}, \lambda_{KY}, \lambda_{KC}$) is the same for $s = 0.10$ and $s = 0.30$ given that we know capital will adjust as the RPS is altered.

Table 3
State-level parameters.

State	2016 RPS	Wind CF	Solar CF
Arizona	0.06	0.374	0.19
California	0.25	0.334	0.18
Colorado	0.20	0.354	0.17
Connecticut	0.21	0.380	0.14
Delaware	0.13	0.314	0.15
DC	0.135	0.307	0.15
Hawaii	0.15	0.432	0.17
Illinois	0.10	0.349	0.14
Kansas	0.15	0.437	0.16
Maine	0.39	0.342	0.14
Maryland	0.15	0.329	0.15
Massachusetts	0.173	0.369	0.14
Michigan	0.10	0.327	0.13
Minnesota	0.20	0.392	0.14
Missouri	0.05	0.337	0.15
Montana	0.15	0.390	0.15
Nevada	0.20	0.328	0.19
New Hampshire	0.137	0.359	0.14
New Jersey	0.15	0.323	0.14
New Mexico	0.15	0.381	0.20
New York	0.29	0.331	0.14
North Carolina	0.06	0.339	0.15
Ohio	0.045	0.316	0.13
Oregon	0.15	0.341	0.13
Pennsylvania	0.14	0.334	0.14
Rhode Island	0.115	0.374	0.14
Washington	0.09	0.343	0.12
Wisconsin	0.10	0.330	0.14

Notes: Capacity factor data provided by NREL.

which we take as our initial calibration point (the average standard has increased to approximately 15% as of 2016). We note that the Energy Information Administration (EIA) estimates that approximately 8% of US GDP comes from energy, with roughly half from petroleum and the rest from electricity. Thus, total expenditure in electricity is set to 0.04 for the baseline $s = 0.10$ for a state with an average wind capacity factor of 35.2%.[26] Of this total share, we then allocate shares to renewable and fossil based on the pre-existing RPS, such that initially $K_X = 0.036$ and $K_Y = 0.004$. To account for differences in renewable endowment (reflected in the capacity factor), we adjust the share of capital in the renewable sector proportionately relative to the average capacity factor.[27] To calculate the corresponding shares at standards beyond 10%, we utilize the predicted changes in capital generated by the model $(\widehat{K}_X, \widehat{K}_Y, \widehat{K}_C)$ to update the capital shares.[28] The above procedure determines the share of capital in the renewable, fossil and composite sectors $(\lambda_{KX}, \lambda_{KY}, \lambda_{KC})$ for any state and any RPS.

For the remaining model parameters, the elasticity of substitution in the composite sector σ_C is taken to be 1.0 Fullerton and Heutel (2007). The elasticity of substitution between the composite sector and electricity in the utility function σ_u is set to 0.4 to generate a price elasticity of demand for electricity of -1.[29] Finally, the elasticity of substitution between capital and the renewable endowment σ_y is set to 1.0.[30]

4.2. Magnitudes of effects

For the figures below, we consider a 10% increase in the RPS $(\widehat{s} = 0.1)$ at various pre-existing RPSs. It is important to note that the figures below should be interpreted as *marginal* effects - that is, the vertical axis represents the percentage change in the variable of interest due to a 10% increase in the RPS from the pre-existing standard given on the horizontal axis.

4.2.1. Decomposition of effects

We first illustrate the analytical results above using wind power in a state that has an average wind capacity factor $(\theta_{YK} = 0.857)$. This corresponds to a state like Colorado (capacity factor of 35.4%) which had a 12% RPS in 2012 and is slated to

[26] Given solar plays such a small role in total generation, we initially focus on wind for calibrating renewable shares. We examine the role of solar when we consider multiple technologies in Section 4.2.3.

[27] For example, a state with a 10% RPS and a wind capacity factor would have $K_Y = 0.004 * \frac{CF}{0.352}$.

[28] For example, to determine the share of capital to evaluate an increase in the RPSs starting from a pre-existing standard of 11%, the capital shares for $s = 0.10$ are calculated by generating $\widehat{K}_X, \widehat{K}_Y, \widehat{K}_C$ for a 10% increase in the RPS from the baseline of $s = 0.10$. This procedure is repeated for increasing pre-existing standards, generating an internally consistent capital share for the values of s considered below.

[29] While slightly larger than older estimates, this is roughly consistent with more recent elasticity estimates in Alberini et al. (2011) and Fell et al. (2014).

[30] This is consistent with the fact that the production for wind generation is commonly modeled in a Cobb-Douglas form Kaffine and Worley (2010).

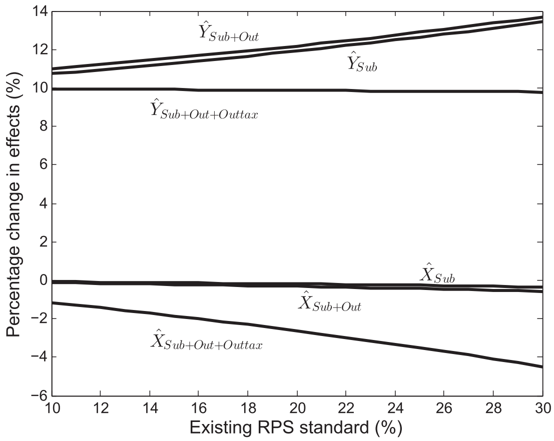

Fig. 1. Decomposition of marginal effects - fossil and renewable electricity.

increase to 30% by 2030. As such the range of pre-existing standards we consider runs from 10% to 30%. In Fig. 1, we plot the effects outlined in Section 3.1, with key results summarized as follows:

Numerical Result 1. *The substitution effect in renewables dominates all other effects, though the output-tax effect grows in importance for both electricity sectors as the pre-existing standard increases. The output effect is modest in magnitude.*

From Fig. 1, we see that the *substitution effect* in the renewable sector ($\widehat{Y}_s$) is the largest single effect and increases with the pre-existing standard, while the *substitution effect* in the fossil sector ($\widehat{X}_s$) is quite small and slightly growing in magnitude. Adding in the *output effect* results in a small increase in magnitude in both the renewable sector ($\widehat{Y}_{s+O}$) and the fossil sector ($\widehat{X}_{s+O}$). By contrast, the (negative) *output-tax effect* in both sectors is much larger than the *output effect*, and grows in magnitude as the existing standard grows, as given by the wedge between $\widehat{Y}_{s+O}$ and $\widehat{Y}_{s+O+OT}$ and between $\widehat{X}_{s+O}$ and $\widehat{X}_{s+O+OT}$. The importance of the general equilibrium framework is clear when we look at the effects of a change in the standard on fossil and thus emissions. The *substitution effect*, reflecting the partial equilibrium impact on emissions from the change in standard, is extremely small relative to the *output-tax effect*, implying that emissions savings would have been underestimated by roughly an order of magnitude in a partial equilibrium framework.[31]

4.2.2. Emissions savings or green booms?

Turning now to the overall effects of an RPS discussed in Section 3.2, Fig. 2 displays the change in the outputs (fossil $\widehat{X}$, renewables $\widehat{Y}$, and total electricity $\widehat{Q}$) and prices (electricity $\widehat{P}$ and renewable rents $\widehat{P}_Z$) of interest. First, we note that *substitution effects* initially dominate the *output-tax effects*. As a result, for a low pre-existing standard we see big increases in renewables and rents to renewables and small decreases in fossil and emissions. However, the change in renewables becomes slightly smaller and the change in fossil becomes substantially larger as the *output-tax effect* increases in magnitude as the pre-existing standard increases. Finally, electricity prices increase in magnitude and total electricity output decreases, though the overall changes are small in magnitude.[32] While the changes in the electricity output and electricity prices are small on net, this is not because general equilibrium effects do not “matter.” Rather, the changes are small in magnitude because of the nature of the RPS - an increase in the standard induces a tug-of-war between capital entering (renewables) and exiting (fossil) the electricity sector, leading to small net effects.

Total effects are also computed and displayed in Fig. 3. The vertical axis measures the cumulative percentage change in output or prices starting from a baseline RPS of 10% and moving to the level indicated by the horizontal axis.[33] Moving from 10% to 30% results in an increase in renewable rents of nearly 200%, renewable generation increases 120%, while fossil generation falls by 25%. Total changes in electricity price and output are on the order of 1.25% increase and decrease respectively, mirroring the relatively small marginal effects in Fig. 2. Note that while the standard increases by 200%, renewable generation increases by substantially less than that. This is due to the fact that the reduction in fossil becomes increasingly important as the standard grows larger, which is reflected in the concave curve for renewables and the convex curve for fossil. Summarizing the above discussion of Figs. 2 and 3:

[31] The larger reductions in emissions are consistent with papers that have shown a substantial effect of RPS policies in terms of reducing fossil generation and emissions using detailed simulation methods (e.g. Palmer and Burtraw (2005)).

[32] The modest increase in electricity prices under from an RPS are consistent with the simulation studies mentioned above. The fact that an RPS will lead to smaller increases in prices relative to a carbon tax has been noted in Goulder et al. (2014).

[33] Note, total effects are not simply computed by setting $\widehat{s} = 2$ (a 200% increase in the standard), but rather by computing the sum of discrete changes in the RPSs from 10% to 30%.

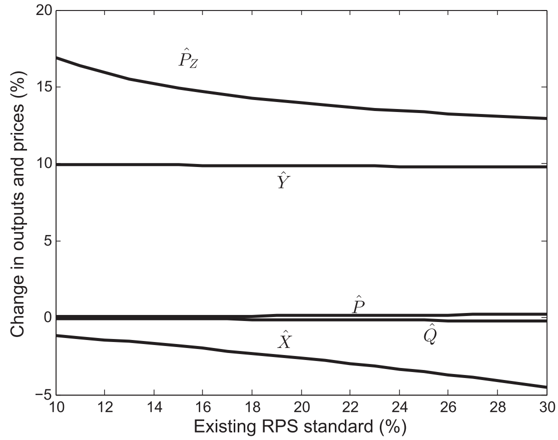

Fig. 2. Marginal effects of a 10% change in RPS on outputs and prices.

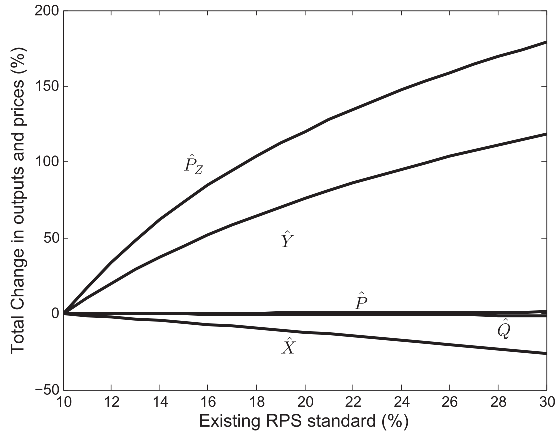

Fig. 3. Cumulative effects of RPS on outputs and prices.

Numerical Result 2. *At current pre-existing RPS levels (10%–30%), increases in the RPS will lead to larger green booms than emission savings. However, emission savings in response to RPS changes grow in magnitude for higher levels of the pre-existing standard.*

4.2.3. Multiple region, multiple technology RPS policies

We now examine the numerical results when we extend the model to include a) multiple regions and b) multiple technologies as discussed in Section 3.3. For the multiple regions extension, we consider Colorado and Kansas to be the two regions on the grounds that they neighbor each other and both have RPSs. Colorado is region A (denoted by superscript), and is the state that increases its RPS while Kansas's RPS (region B) is held constant at 10%. For the multiple technologies, we consider wind and solar in Colorado, with solar requiring more capital in production of renewable output. Wind is technology 1 and solar is technology 2, with the carve-out pertaining to solar.

We first consider the numerical results pertaining to the multiple region model. The effects of an RPS increase in region A on region A itself are similar to the model above (see Appendix Fig. 9). Of greater interest are the leakage effects in region B displayed in Fig. 4:

Numerical Result 3. *An increase in Region A's RPS creates both negative leakage (reduced emissions) and a resource bust (reduced renewable generation and rents) in Region B.*

Here we see that because substitution effects dominate output-tax effects, capital is being pulled from the electricity sector in region B to region A to produce more renewables in Region A. Thus, we see negative leakage in terms of emissions (reduced emissions via $\widehat{X}^B$), but coupled with a decrease in renewable production ($\widehat{Y}^B$) and renewable rents ($\widehat{P}_Z^B$) in region B. Again, the fact that leakage effects are small is not because capital mobility does not matter, but rather because of the tug-of-war on capital induced by the nature of the RPS (capital moves in to build renewables, but moves out as fossil is decreased).

Next, we consider the effect of an RPS in the presence of two renewable technologies: wind (denoted by superscript 1) and solar (denoted by superscript 2). Fig. 5 illustrates the results of an increase in the RPS for a carve-out targeting solar (increase

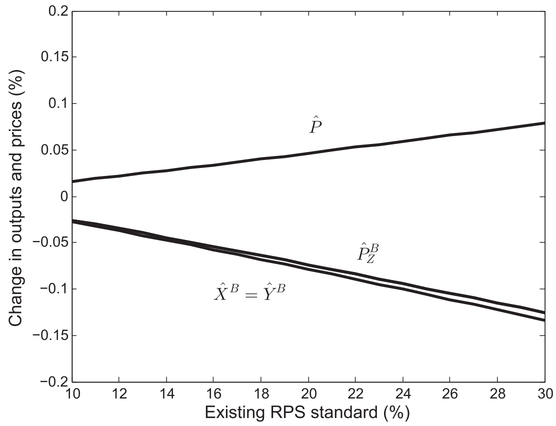

Fig. 4. Marginal effects of a 10% change in RPS on outputs and prices - 2 region, 1 tech.

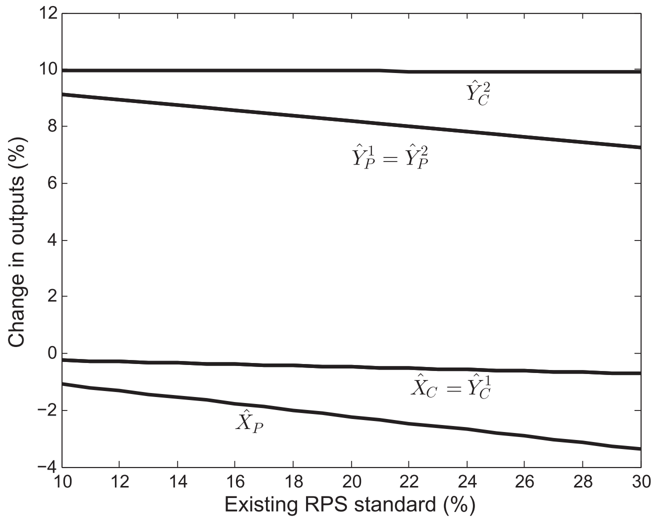

Fig. 5. Marginal effects of a 10% change in RPS on outputs - 1 region, 2 tech.

solar by 10%, denoted by subscript C) and a portfolio standard (increase in total renewables by 10%, denoted by subscript P):

Numerical Result 4. *RPS policies with designated carve-outs for specific renewable technologies create large resource booms for the targeted technology, at the expense of a resource bust for non-targeted technologies and lower emission savings, relative to a portfolio standard.*

In terms of outputs, we see that the carve-out policy increases the output of the targeted technology (solar $\widehat{Y}_C^2$) at the expense of the other renewable technology (wind $\widehat{Y}_P^1$) and small emission savings ($\widehat{X}_C$). By contrast, the portfolio approach yields greater emissions savings (compare $\widehat{X}_P$ with $\widehat{X}_C$) and results in increases in output for both renewable technologies ($\widehat{Y}_P^1$ and $\widehat{Y}_P^2$).[34] While carve-outs for specific technologies are frequently based on “learning-by-doing” arguments Van Benthem et al. (2008), the above results suggest that the modest increase in deployment of the targeted renewable technology would need to be weighed against the reduction in deployment of other renewable technologies, as well as the smaller emissions savings.

Finally, to summarize the above results in terms of our central question of emissions savings or green booms, in Fig. 6 we plot the ratio of the change in renewable rents over the change in emission savings $\frac{\widehat{P}_Z}{\widehat{X}}$. A ratio less than −1 indicates a large resource boom relative to emission savings, a ratio between 0 and −1 indicates large emissions savings relative to a small resource boom, and a ratio greater than 0 indicates a resource bust coupled with emission savings. First, under the basic model (*Base*), even

[34] In terms of rents to the renewable resources, consistent with the impacts on outputs in Fig. 5, Appendix Fig. 10 shows that the carve-out yields a substantial boom for the targeted technology ($\widehat{P}_{ZC}^2$) but a bust for the other renewable technology ($\widehat{P}_{ZC}^1$), while the portfolio policy generates booms for both technologies (($\widehat{P}_{ZP}^1$) and ($\widehat{P}_{ZP}^2$)).

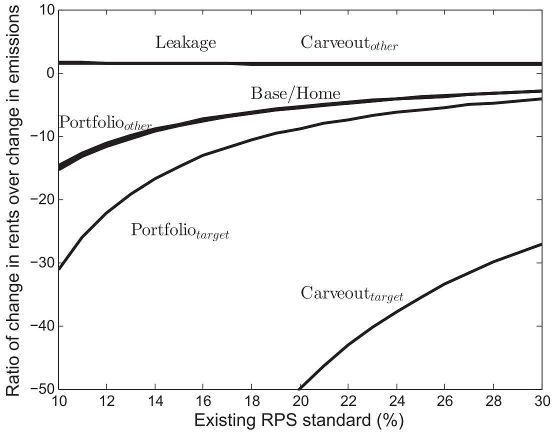

Fig. 6. Ratio of change in renewable rents to change in emission savings due to 10% increase in RPS.

at an existing RPS of 30%, resource booms are larger in magnitude than emission savings. Under the carve-out policy, a very large resource boom is achieved in the targeted technology ($Carveout_{target}$) at the expense of a bust in the other technology ($Carveout_{other}$). By contrast, the portfolio policy looks more or less like the basic model, but the resource boom is "shared" across the two renewable technologies ($Portfolio_{other}$ and $Portfolio_{target}$). Finally, under capital mobility across states, the boom-savings tradeoff is very similar to the base model for the home region that increases its standard (*Home*), but the leakage effects are such that a resource bust occurs in the other region (*Leakage*).

4.3. Emissions savings versus resource booms across US states

While the previous section focused on illustrating the magnitudes of the effects described in the analytical model, we now turn to the 28 states in the US with percentage-based RPSs. To what extent do we expect to see resource booms or emission savings in these states?

Fig. 7 displays a scatter-plot of the 28 RPS states displaying their change in emissions and change in renewable rents. First, consistent with the analytical model, we see either large resource booms or large emission savings, or modest levels of each. However, we never observe both large emission savings and large resource booms (the NE quadrant is empty). Second, if we examine common features of states in the different quadrants, we see that states with low existing standards and good endowments will tend to favor resource booms (down and to the right). On the other hand, states with high existing standards and poor endowments tend to result in larger emission savings (up and to the left). Based on the magnitudes of the axes of the scatter-plot in Fig. 7:

Numerical Result 5. *Across states with existing RPS policies in the US, resource booms are dominating emissions savings as the main outcome of RPS policies.*

In other words, given current RPS levels, states will likely meet their requirements by expanding production from renewables relative to cutting back on fossil generation. Our simulations can inform current legislative debates in 13 different states where bills have been introduced to either strengthen or weaken their existing RPSs.[35]

4.4. Additional numerical extensions and further discussion

Finally, we revisit a number of assumptions we have made in the analysis developed above, in particular a) fixed factors for fuel in fossil, b) labor inputs in the electricity sector, and c) cross-state trade in renewable energy credits.

In our base model, we assumed that fossil generation solely depended on a capital input, implicitly treating fuel as a form of capital input. A natural extension would be to consider fuel as a fixed factor input in fossil generation. For example, states like Wyoming may have large wind resources, but also have substantial fossil endowments as well. While cumbersome to handle analytically, the simulation model can accommodate this extension readily. Specifically, we adjust the equations for the fossil sector in Section 2.2 to include a fixed factor input R with corresponding price P_R, and we add an additional equation to capture the substitution between fuel and capital. This gives rise to two additional parameters to calibrate, θ_{RK}, the share of fuel rents in the production of fossil, and σ_X, the elasticity of substitution between fuel and capital. We follow Bento and Jacobsen (2007)

[35] The following states are debating bills to strengthen their RPS: CA (SB 584), CT (SB 630), KY (HB 338), MD (SB 291), MA (HB 1747; SB 1849, 1876, 1880, 1846), MN (SB 1531/ HB 1772), NV (AB 206), NM (SB 312) and, NY (A 5105). The following states are debating bills to weaken their RPS: NH (HB 225), NC (HB 267) and OH (HB 114). For more details, see: https://insideclimatenews.org/news/24032017/renewable-energy-clean-energy-solar-wind-power-states-climate-change.

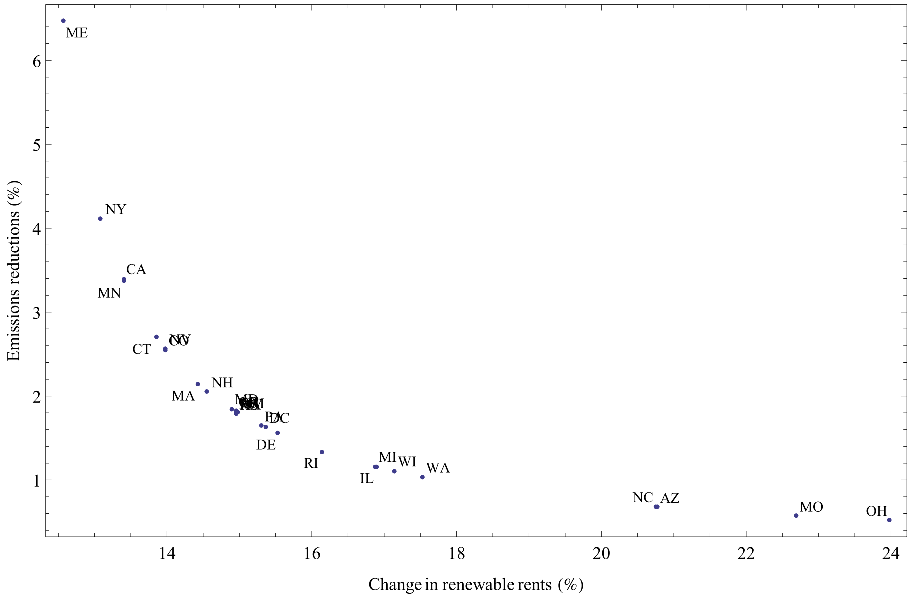

Fig. 7. Change in emission savings and renewable rents by state due to 10% increase in RPS.

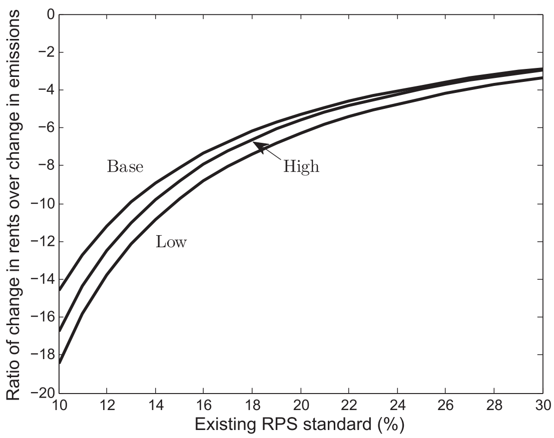

Fig. 8. Ratio of change in renewable rents to change in emission savings due to 10% increase in RPS. "High" corresponds to parameterizations where fossil fuel rents are a large share of fossil expenditures, while "Low" corresponds to parameterizations where fossil fuel rents are a smaller share of fossil expenditures.

in calibrating these parameters - our "High" scenario assumes a substitutability of $\sigma_x = 0.5$ and a relatively high share of rents $\theta_{RK} = 0.125$, while the "Low" scenario assumes a substitutability of $\sigma_x = 2.0$ and a small share of rents $\theta_{RK} = 0.025$.[36]

In Fig. 8 we plot the green boom to emission savings ratio under our base model and the High and Low scenarios described above. The general pattern remains similar when we incorporate this fuel fixed factor, regardless of parameter setting, though the ratio of green boom to emission savings is slightly higher than in the base case. Examining the outputs of the endogenous variables, this reflects the fact that due to the presence of the fixed factor, the reduction in fossil generation $\widehat{X}$ is slightly smaller than in the base model. As expected, there is also a decline in the rents to the fuel fixed factor $\widehat{P}_R$ as the standard increases. In sum, the addition of a fuel fixed factor tilts the inherent RPS tradeoff towards green booms and away from emission savings, but it also leads to a decrease in the rents accruing to the fuel fixed factor - a consequence that policymakers may wish to take account of in considering RPS policies.

Next, recall that labor only enters as an input into the composite sector. As above, including labor as an input into the fossil and renewable sectors yields closed-form solutions that are not interpretable. However, we do include labor in the production of both fossil and renewable electricity in our numerical framework. The key calibration challenge is that while this introduces only

[36] This calibration reflects the bounds considered in Bento and Jacobsen (2007). The "High" scenario assumes that 25% of fossil expenditure is on fuel (based on EIA data), with 50% of that reflecting rent payments, while the "Low" scenario assumes the same fuel expenditure, but a 10% share for rent payments.

two more endogenous variables, the number of exogenous parameters required to characterize the electricity sector increases from 4 to 14.[37]

Under plausible parameters values that are comparable to those in our base model, we find a similar trade-off between green booms and emission savings as in our base model - see Appendix Figs. 11 and 12. As might be expected, increasing the standard increases the amount of labor allocated to renewables and decreases the amount of labor allocated to fossil and the composite sector. However, given the small labor share and expenditure share in the electricity sectors, the resulting pattern that emerges is generally unchanged.

Finally, our specification of the RPS policy implies a production standard, such that the standard must be met by in-state production. However, in some states, compliance can be achieved by the purchase of out-of-state RECs. There are considerable restrictions and idiosyncrasies in REC trading across states Hollingsworth and Rudik (2018). For instance, North Carolina accepts RECs from many states to comply with an RPS whereas Texas accepts RECs only from other producers within Texas. As such, because there is no standard REC system, it is beyond the scope of the paper to model the numerous REC regimes. That said, for states that do not allow out-of-state RECs, our model is clearly appropriate. For states that do allow trade, we speculate that this will lead to both smaller green booms and smaller emission savings, but there are no obvious reasons why it would alter the relative tradeoff between green booms and emission savings.

5. Conclusions

The RPS is an important policy for climate change and the electricity sector, and in this paper we have examined the extent to which RPS policies generate emissions reductions and foster local green booms. In particular, we have extended the prior literature by (1) including a renewable fixed factor that captures region specific endowments of renewable potential, (2) including a composite sector to capture movement of capital in and out of the electricity sector and (3) consequently, capturing general equilibrium price effects. These innovations allow us to generate an analytically tractable general equilibrium framework for understanding the impact of RPSs that captures substitution between sectors, endogenous price responses, and rents accrued to the renewable fixed factor.[38]

This model generates three important results. First, because the RPS can be met by increasing renewable production or decreasing fossil production, RPS policies can generate either large resource booms or large emission savings, but not both. Second, the cross-sector mobility of capital in our model allows for multiple channels through which changes in an RPS can affect the size and composition of the electricity sector through three channels of adjustment - the substitution effect, output-tax effect, and the output effect. When the *substitution effect* dominates, RPS policies create large resource booms, but when the *output-tax effect* dominates, RPS policies create large emissions reductions. Third, capital mobility across regions can generate positive or negative leakage in other regions in terms of both emissions reductions and green booms. Furthermore, RPS policies with designated carve-outs for specific renewable technologies create large resource booms for the targeted technology, at the expense of a resource bust for non-targeted technologies and lower emission savings relative to a true portfolio standard that treats all technologies equally.

These considerations in state-level climate policy are of particular interest in the current legislative environment. For instance, the Ohio house of representative voted in March 2017 to repeal the RPS mandate in Ohio citing it as a "pro-business bill" that "encourages economic growth".[39] Our numerical results suggests that, due to its small RPS, Ohio would primarily experience a large decline in renewable rents coupled with a small increase in emissions if the standard were to be repealed. The differentiated effects across various pre-exiting standards and renewable endowments underscores the importance of our framework in informing future renewable energy policy.

Appendix A. Extensions to multiple regions and technologies

A.1. Model

In this Appendix section we briefly discuss an extension of the model in 2.1 to two renewable energy technologies to consider the within-state equilibrium in states that have multiple renewable technologies at their disposal. This two technology model considers two different kinds of standards that are observed in practice - a carveout standard and a portfolio standard. A portfolio standard, in its basic form, requires that a certain percentage of total electricity generation come from a combination of renewable/renewable portfolio sources. A carve-out standard on the other hand, stipulates that in addition to an overall renew-

[37] We follow Fullerton and Heutel (2010) in deriving input demand equations for the renewable sector, which now depends on three inputs. The additional parameters are: labor shares in fossil and renewables, expenditures share on labor in fossil, expenditure share on labor in renewables, elasticity of substitution between labor and capital in fossil, and then five own-price and cross-price elasticities between capital, labor, and the fixed factor in renewables.

[38] A caveat of this analysis is that it is static and thus cannot address important dynamic issues associated with RPS policies. A richer model that included differences between old capital and new capital and considered investment dynamics could yield important insights into transitory effects due to changes in RPS policies. We view this as an important direction for future research, as transition effects from RPS policies and other related climate policies may become increasingly more salient to the extent these policies become more ambitious in their climate targets.

[39] See: https://solarindustrymag.com/ohio-house-passes-bill-repeal-renewable-energy-mandate.

able portfolio standard, a specific technology is required to constitute a pre-determined percentage of the overall electricity production.

The other extension we consider is a single technology model, but with multiple (two) regions to analyze spillovers across regions. Capital is assumed to be freely mobile within and across regions[40]. While technology is uniform across the two regions, the two regions differ primarily in their endowment of the renewable fixed factor. The composite good is traded in a national market, equalizing its price across the regions.

A.1.1. Portfolio standard

The producer, under a portfolio standard, faces the constraint,

$$\frac{Y_1 + \beta Y_2}{X + Y_1 + Y_2} \geq s \tag{A.21}$$

where β is the rating assigned to a particular technology that in practice can weight the technologies differently in meeting the standard. A portfolio standard, therefore, treats the technologies as linearly additive and perfectly substitutable (1 for 1 in the special case of $\beta = 1$).

A.1.2. Technology carve-outs

As mentioned above, a carve-out standard requires that in addition to an overall renewable portfolio standard, a specific technology is required to form at least a pre-determined percentage of the overall electricity production. Since the carveout is established with the premise that the carveout technology will not meet the designated percentage of production in the market, a carve-out can be thought of as two standards - a technology specific standard and a standard for all other technologies (not including the technology for which a carve-out exists). In the case of two renewable technologies, this can be further simplified to be a standard for each technology.

A.1.3. Multiple regions with capital mobility

Modeling capital mobility is critical to understanding the spillover effects of changes in RPS when one region implements a differentially higher standard. We consider the special case of one uniform renewable technology in two different regions each with its own endowment of labor and renewable fixed factor. The standard faced by the producers in this case is identical to the standard in (2).

A.2. Results

With the basic effects of the single region, single technology model explained in the main text, we now consider the effects of a change in the RPS with multiple technologies or multiple regions. Extending the model to two regions or two renewable technologies, the effect of an increase in the RPS includes an additional *capital mobility effect* and *technology substitution effect*, respectively.

Consider two regions A and B, where region A increases its standard. The *capital mobility effect* on fossil generation occurs as capital leaves fossil generation in region A for fossil OR renewable generation in region B. This term can be also be thought of as an additional *output-tax effect*, as it reflects movement in capital out of fossil generation into region B due to meeting the change in standard by reducing output. The *capital-mobility effect* on renewable generation occurs as capital may leave fossil OR renewable generation in region B to increase renewable generation in region A. This term can be thought of as a *substitution effect* as the change in standard is met by capital moving from fossil to renewables to meet the standard, which is then mitigated by an output-tax effect to the extent that capital exits the electricity sector.

Next, consider two renewable technologies 1 and 2, where a carve-out standard for technology 1 is increased. The *technology substitution effect* reflects the movement of capital away from technology 2 into technology 1. The *technology-substitution effect* can decomposed further, as the increase in the standard for technology 1 pulls capital from renewable technology 2 directly via a *substitution effect*, and also pulls capital from technology 2 indirectly via an *output effect* due to the fact that the standard distorts output and capital prices.

A.2.1. RPS policies and mobile capital

Turning to the case of multiple regions, we now consider the impacts on emissions and resource booms due to a change in the standard for one region. For a two region, single technology RPS, an increase in an RPS in one region generates positive (negative) leakage of emissions in adjoining regions if the *output-tax effect (substitution effect)* dominates the *substitution effect (output-tax effect)*. If the emissions leakage is positive, it is also accompanied by a resource boom in the other region. If the leakage is negative, it is also accompanied by a resource bust in the other region. The *capital mobility effect* in the own region

[40] The assumption of capital being perfectly mobile may be an extreme assumption. To the extent that there are frictions, the magnitude of the net effect will change, but the relative size of the individual components will remain unchanged.

augments emission savings if the pre-existing standard is high, while the *capital mobility effect* will augment resource booms if the pre-existing standard is low.

The leakage effects on fossil and renewable generation in Region B again depend on the tradeoff between the *substitution effect* and the *output-tax effect*. If the *substitution effect* dominates, capital is pulled into the region changing the standard, decreasing both fossil AND renewable generation in the other region. This implies that there is emissions reductions and a resource bust in the other region. Conversely, if the *output-tax effect* dominates, capital flees the region changing the standard, increasing both fossil and renewable generation in the other region. As such, there will be an increase in emissions and a resource boom in the other region.

Within the region actually implementing the increase in the standard, the *capital mobility effect* can increase either emission savings or resource booms, depending on the pre-existing standard. If the pre-existing standard is high, then emission savings is augmented as capital flees fossil for the other region. On the other hand, if the pre-existing standard is low, then resource booms are augmented as capital is drawn to the renewable sector from other regions. Thus, relative to the single region model above, at low levels of the pre-existing standard, it is more likely that resource booms are created with small emission savings, while at high levels of the pre-existing standards, it is more likely that emission savings are large with correspondingly small resource booms or potentially busts.

A.2.2. RPS policies with multiple renewable technologies

We now return to the single region model and add an additional renewable technology. We consider two variants of RPSs - an RPS with technology specific carve-outs (e.g. for technology 1), and a more general "portfolio" standard where the change in the standard can be flexibly met by either renewable technology.

For a single region, two renewable technology RPS, an increase in a carve-out RPS leads to a larger increase in deployment of the targeted renewable technology (resource boom) via the *technology substitution effect*, at the expense of reduced deployment of other renewable technologies (resource bust) and lower emission savings relative to the portfolio standard. Under a carve-out, the presence of a second renewable technology always has a positive effect on the targeted technology as additional capital can now move from technology 2 into technology 1 to meet the increase in the carve-out via the *technology substitution effect*. By the same logic, an increase in the carve-out for one technology always leads to a decrease in the other renewable technology, and that decrease is exactly equal to the change in fossil generation. Intuitively this reflects the fact that, from the perspective of an increase in the carve-out standard, fossil generation and the other renewable technology are equivalent - they are both forms of generation that increase the denominator of the standard and thus should decrease as the carve-out standard for technology 1 is increased. The carve-out also results in smaller reductions in fossil generation, relative to a true portfolio standard.

In terms of emissions reductions, compared to the carve-out, the change in emissions should be larger under a portfolio standard, as it is no longer possible to partially meet the standard by reducing the other renewable technology. As such, under a portfolio standard an increase in the standard no longer sacrifices one renewable sector for the other - both renewable sectors will unambiguously grow under a portfolio standard, though the growth will be smaller than for the technology targeted by the carve-out. Under a carve-out, the resource boom for technology 1 comes at the cost of a likely resource bust for technology 2 (unless *substitution effects* are large enough to generate a sufficient large increase in electricity price to offset the reduction in technology 2). Thus, a carve-out standard creates two potentially unintended consequences: emissions savings may be reduced as the change in standard is partially met by a reduction in the other renewable technology, and any resource boom in the targeted renewable sector comes at the expense of a potential resource bust in the other renewable sector. For the portfolio standard, if a resource boom occurs (when the *substitution effects* dominate the *output-tax effects*, it must occur for both renewable endowments. Thus, we can conclude that while a portfolio standard may generate less growth in the targeted carve-out technology, the portfolio standard is more likely to lead to emissions reductions and resource booms for all renewable endowments.

Appendix B. Full solutions

B.1. Single region, single tech

$$\widehat{X} = [\frac{-\frac{\lambda_{KY}}{\theta_{YK}\nu}\sigma_c}{D} + \frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{-\frac{\theta_{CL}\lambda_{KY}}{\theta_{CK}\theta_{YK}\nu}\sigma_u}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.22}$$

$$\widehat{Y} = [\frac{(\lambda_{KX} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c}{D} + \frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{\frac{\theta_{CL}\lambda_{KX}}{\theta_{CK}}\sigma_u}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.23}$$

$$\widehat{C} = [\frac{s(\lambda_{KX} + \frac{\lambda_{KY}}{\theta_{YK}\nu})\sigma_c}{D} + \frac{-\frac{\lambda_{KY}}{\theta_{YK}\nu}\sigma_c}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.24}$$

$$\widehat{Q} = [\frac{s(\lambda_{KX} + \frac{\lambda_{KY}}{\theta_{YK}\nu})(\sigma_c + \frac{\theta_{CL}}{\theta_{CK}}\sigma_u)}{D} + \frac{-\frac{\lambda_{KY}}{\theta_{YK}\nu}(\sigma_c + \frac{\theta_{CL}}{\theta_{CK}}\sigma_u)}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.25}$$

$$\widehat{P}_z = \widehat{P} + \frac{1}{\theta_{YK}\nu\sigma_Y}\widehat{Y} \tag{B.26}$$

$$\widehat{P} = -\frac{1}{\sigma_c}\frac{\theta_{CL}}{\theta_{CK}}\widehat{C} = \widehat{r} = -\frac{\theta_{CL}}{\theta_{CK}}\widehat{w} \tag{B.27}$$

where

$$D = (\lambda_{KX} + \frac{\lambda_{KY}}{\theta_{YK}\nu} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c + \frac{\theta_{CL}}{\theta_{CK}}(\lambda_{KX} + \frac{\lambda_{KY}}{\theta_{YK}\nu})\sigma_u > 0 \tag{B.28}$$

B.2. Multi region, single tech

$$\widehat{X}^A = [\frac{-\frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A}\sigma_c}{D} + \frac{-s^A\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{-\frac{\theta_{CL}\lambda^A_{KY}}{\theta_{CK}\theta^A_{YK}\nu^A}\sigma^A_u}{D} - s^A(\frac{(\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B})\sigma_c}{D} + \frac{\frac{\theta_{CL}}{\theta_{CK}}(\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B})\sigma^B_u}{D})](\frac{\widehat{s}^A}{1-s^A}]) \tag{B.29}$$

$$\widehat{X}^B = [\frac{s^A(\lambda^A_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A})\sigma_c}{D} + \frac{-\frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A}\sigma_c}{D} + \frac{\frac{\theta_{CL}}{\theta_{CK}}s^A(\lambda^A_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A})\sigma^B_u}{D} + \frac{-\frac{\theta_{CL}}{\theta_{CK}}\frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A}\sigma^B_u}{D}](\frac{\widehat{s}^A}{1-s^A}]) \tag{B.30}$$

$$\begin{aligned}\widehat{Y}^A = [&\frac{(\lambda^A_{KX} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c}{D} + \frac{-s^A\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{\frac{\theta_{CL}\lambda^A_{KX}}{\theta_{CK}}\sigma^A_u}{D} + \frac{(\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B} - s^A(\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B}))\sigma_c}{D}\\ &+ \frac{\frac{\theta_{CL}}{\theta_{CK}}(\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B} - s^A(\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B}))\sigma^B_u}{D}](\frac{\widehat{s}^A}{1-s^A}])\end{aligned} \tag{B.31}$$

$$\widehat{Y}^B = [\frac{s^A(\lambda^A_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A})\sigma_c}{D} + \frac{-\frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A}\sigma_c}{D} + \frac{\frac{\theta_{CL}}{\theta_{CK}}s^A(\lambda^A_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A})\sigma^B_u}{D} + \frac{-\frac{\theta_{CL}}{\theta_{CK}}\frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A}\sigma^B_u}{D}](\frac{\widehat{s}^A}{1-s^A}]) \tag{B.32}$$

$$\widehat{C} = [\frac{s^A(\lambda^A_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A})\sigma_c}{D} + \frac{-\frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A}\sigma_c}{D}](\frac{\widehat{s}^A}{1-s^A}]) \tag{B.33}$$

$$\widehat{P}_z^A = \widehat{P} + \frac{1}{\theta^A_{YK}\nu^A\sigma_Y}\widehat{Y}^A \tag{B.34}$$

$$\widehat{P}_z^B = \widehat{P} + \frac{1}{\theta^B_{YK}\nu^B\sigma_Y}\widehat{Y}^B \tag{B.35}$$

$$\widehat{P} = -\frac{1}{\sigma_c}\frac{\theta_{CL}}{\theta_{CK}}\widehat{C} = \widehat{r} = -\frac{\theta_{CL}}{\theta_{CK}}\widehat{w} \tag{B.36}$$

where

$$D = (\frac{\lambda_{KC}}{\theta_{CK}} + \lambda^A_{KX} + \lambda^B_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B})\sigma_c + \frac{\theta_{CL}}{\theta_{CK}}((\lambda^A_{KX} + \frac{\lambda^A_{KY}}{\theta^A_{YK}\nu^A})\sigma^A_u + (\lambda^B_{KX} + \frac{\lambda^B_{KY}}{\theta^B_{YK}\nu^B})\sigma^B_u) > 0 \tag{B.37}$$

B.3. Single region, multi tech - Carve-outs

$$\widehat{X} = [\frac{-\frac{\lambda_{KY1}}{\theta_{YK1}\nu_1}\sigma_c}{D} + \frac{-s_1\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{-\frac{\theta_{CL}\lambda_{KY1}}{\theta_{CK}\theta_{YK1}}\sigma_u}{D}](\frac{\widehat{s_1}}{1-s_1}]) \tag{B.38}$$

$$\widehat{Y_1} = [\frac{(\lambda_{KX} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c}{D} + \frac{-s_1\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{\frac{\theta_{CL}\lambda_{KX}}{\theta_{CK}}\sigma_u}{D} + \frac{\frac{\lambda_{KY2}}{\theta_{YK2}\nu_2}\sigma_c}{D} + \frac{\frac{\theta_{CL}\lambda_{KY2}}{\theta_{CK}\theta_{YK2}\nu_2}\sigma_u}{D}](\frac{\widehat{s_1}}{1-s_1}]) \tag{B.39}$$

$$\widehat{Y_2} = [\frac{-\frac{\lambda_{KY1}}{\theta_{YK1}\nu_1}\sigma_c}{D} + \frac{-s_1\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{-\frac{\theta_{CL}\lambda_{KY1}}{\theta_{CK}\theta_{YK1}\nu_1}\sigma_u}{D}](\frac{\widehat{s_1}}{1-s_1}]) \tag{B.40}$$

$$\widehat{C} = [\frac{s_1(\lambda_{KX} + \frac{\lambda_{KY1}}{\theta_{YK1}\nu_1})\sigma_c}{D} + \frac{-\frac{\lambda_{KY}}{\theta_{YK}}\sigma_c}{D} + \frac{s_1\frac{\lambda_{KY2}}{\theta_{YK2}\nu_2}\sigma_c}{D}](\frac{\widehat{s_1}}{1-s_1}]) \tag{B.41}$$

$$\widehat{P}_{z1} = \widehat{P} + \frac{1}{\theta_{YK1}\nu_1\sigma_{Y1}}\widehat{Y}_1 \tag{B.42}$$

$$\widehat{P}_{z2} = \widehat{P} + \frac{1}{\theta_{YK2}\nu_2\sigma_{Y2}}\widehat{Y}_2 \tag{B.43}$$

$$\widehat{P} = -\frac{1}{\sigma_c}\frac{\theta_{CL}}{\theta_{CK}}\widehat{C} = \widehat{r} = -\frac{\theta_{CL}}{\theta_{CK}}\widehat{w} \tag{B.44}$$

where

$$D = (\lambda_{KX} + \frac{\lambda_{KY1}}{\theta_{YK1}\nu_1} + \frac{\lambda_{KY2}}{\theta_{YK2}\nu_2} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c + \frac{\theta_{CL}}{\theta_{CK}}(\lambda_{KX} + \frac{\lambda_{KY1}}{\theta_{YK1}\nu_1} + \frac{\lambda_{KY2}}{\theta_{YK2}\nu_2})\sigma_u > 0 \tag{B.45}$$

B.4. Single region, multi tech - portfolio

$$\widehat{X} = [\frac{-\frac{\lambda_{KY1}}{\theta_{YK1}\nu}\sigma_c}{D} + \frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{-\frac{\theta_{CL}\lambda_{KY1}}{\theta_{CK}\theta_{YK1}\nu}\sigma_u}{D} + \frac{-\frac{\lambda_{KY2}}{\theta_{YK2}\nu}\sigma_c}{D} + \frac{-\frac{\theta_{CL}\lambda_{KY2}}{\theta_{CK}\theta_{YK2}\nu}\sigma_u}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.46}$$

$$\widehat{Y}_1 = [\frac{(\lambda_{KX} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c}{D} + \frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{\frac{\theta_{CL}\lambda_{KX}}{\theta_{CK}}\sigma_u}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.47}$$

$$\widehat{Y}_2 = [\frac{(\lambda_{KX} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c}{D} + \frac{-s\frac{\lambda_{KC}}{\theta_{CK}}\sigma_c}{D} + \frac{\frac{\theta_{CL}\lambda_{KX}}{\theta_{CK}}\sigma_u}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.48}$$

$$\widehat{C} = [\frac{s(\lambda_{KX} + \frac{\lambda_{KY1}}{\theta_{YK1}\nu})\sigma_c}{D} + \frac{-\frac{\lambda_{KY1}}{\theta_{YK1}\nu}\sigma_c}{D} + \frac{s\frac{\lambda_{KY2}}{\theta_{YK2}\nu}\sigma_c}{D} + \frac{-\frac{\lambda_{KY2}}{\theta_{YK2}\nu}\sigma_c}{D}]\,\widehat{s}\,[\frac{1}{1-s}] \tag{B.49}$$

$$\widehat{P}_{z1} = \widehat{P} + \frac{1}{\theta_{YK1}\nu\sigma_{Y1}}\widehat{Y}_1 \tag{B.50}$$

$$\widehat{P}_{z2} = \widehat{P} + \frac{1}{\theta_{YK2}\nu\sigma_{Y2}}\widehat{Y}_2 \tag{B.51}$$

$$\widehat{P} = -\frac{1}{\sigma_c}\frac{\theta_{CL}}{\theta_{CK}}\widehat{C} = \widehat{r} = -\frac{\theta_{CL}}{\theta_{CK}}\widehat{w} \tag{B.52}$$

where

$$D = (\lambda_{KX} + \frac{\lambda_{KY1}}{\theta_{YK1}\nu} + \frac{\lambda_{KY2}}{\theta_{YK2}\nu} + \frac{\lambda_{KC}}{\theta_{CK}})\sigma_c + \frac{\theta_{CL}}{\theta_{CK}}(\lambda_{KX} + \frac{\lambda_{KY1}}{\theta_{YK1}\nu} + \frac{\lambda_{KY2}}{\theta_{YK2}\nu})\sigma_u > 0 \tag{B.53}$$

Appendix C. RPS equivalence with taxes and subsidies

Here we prove the claim that for any given RPS s, there exists a set of taxes τ and subsides σ such that: A tax on fossil and a subsidy to renewables, a tax on fossil and subsidy for generation, and a subsidy to renewables and a tax on generation all yield the same allocation as the standard s. Under an RPS,

$$\max_{K_X,K_Y}\pi = p\left(X(K_X) + Y(K_Y)\right) - r(K_X + K_Y)$$

$$s.t.\frac{Y}{X+Y} \geq s$$

$$L = p\left(X(K_X) + Y(K_Y)\right) - r(K_X + K_Y) + \lambda\left(Y(K_Y) - s\left(X(K_X) + Y(K_Y)\right)\right) \tag{C.54}$$

and we have the FOCs

$$\begin{aligned} L_{K_X} &= pX' - r - s\lambda X' = 0 \\ L_{K_Y} &= pY' - r + \lambda Y' - s\lambda Y' = 0 \end{aligned} \tag{C.55}$$

Under a tax on fossil and subsidy to renewables,

$$\max_{K_X,K_Y}\pi = p\left(X(K_X)+Y(K_Y)\right) - r(K_X+K_Y) - \tau X(K_X) + \sigma Y(K_Y) \tag{C.56}$$

and we have the FOCs:

$$\begin{aligned}\pi_{KX} &= pX' - r - \tau X' = 0\\ \pi_{KY} &= pY' - r + \sigma Y' = 0\end{aligned} \tag{C.57}$$

Setting $\tau = s\lambda$ and $\sigma = (1-s)\lambda$ yields the same as the RPS above in (55).

Under a tax on fossil and subsidy for generation,

$$\max_{K_X,K_Y}\pi = p\left(X(K_X)+Y(K_Y)\right) - r(K_X+K_Y) - \tau X(K_X) + \sigma(X(K_X)+Y(K_Y)) \tag{C.58}$$

And we have the FOCs:

$$\begin{aligned}\pi_{KX} &= pX' - r - \tau X' + \sigma X' = 0\\ \pi_{KY} &= pY' - r + \sigma Y' = 0\end{aligned} \tag{C.59}$$

Setting $\tau = \lambda$ and $\sigma = (1-s)\lambda$ yields the same as the RPS above in (55).

Under a tax on generation and subsidy for renewables,

$$\max_{K_X,K_Y}\pi = p\left(X(K_X)+Y(K_Y)\right) - r(K_X+K_Y) - \tau(X(K_X)+Y(K_Y)) + \sigma Y(K_Y) \tag{C.60}$$

And we have the FOCs:

$$\begin{aligned}\pi_{KX} &= pX' - r - \tau X' = 0\\ \pi_{KY} &= pY' - r + -\tau Y + \sigma Y' = 0\end{aligned} \tag{C.61}$$

Setting $\tau = s\lambda$ and $\sigma = \lambda$ yields the same as the RPS above in (55).

Appendix D. Additional figures

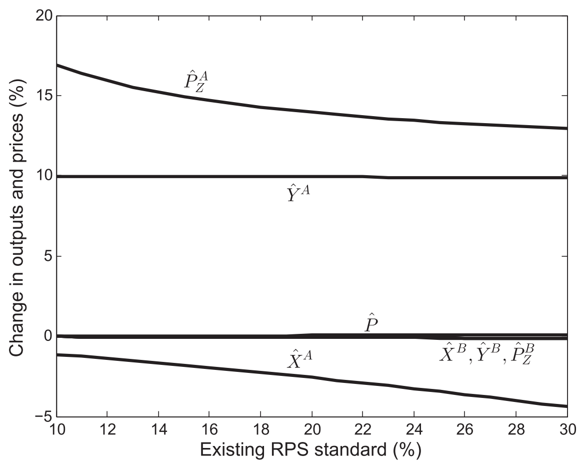

Fig. 9. Effect of change in RPS on outputs and prices - 2 region, 1 tech.

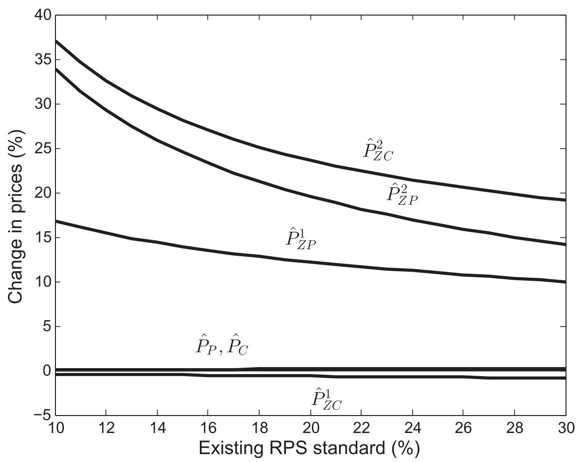

Fig. 10. Effect of change in RPS on prices - 1 region, 2 tech.

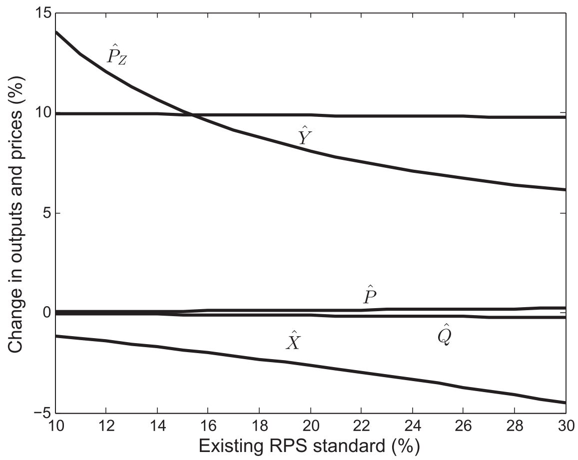

Fig. 11. Effect of change in RPS on outputs and prices - labor included as input into electricity sector.

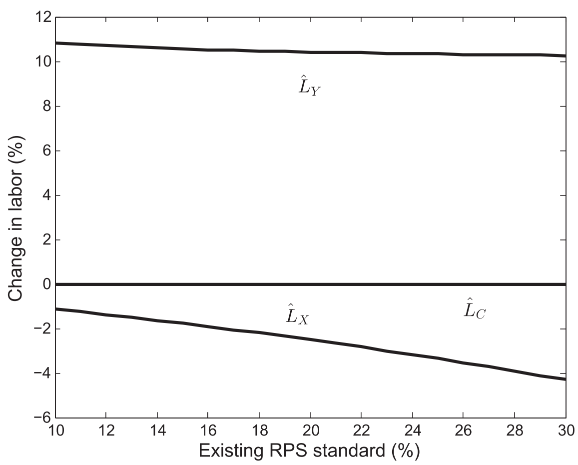

Fig. 12. Effect of change in RPS on labor allocation across sectors.

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