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Tradable Credit Markets for Intensity Standards

Ivan Rudik
Iowa State University, irudik@iastate.edu

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Many environmental standards are expressed in terms of intensity rather than absolute levels. In some cases, intensity standards are associated with tradable credit markets to mitigate the firms' compliance costs. I develop a jurisdictional model of credit trading under an intensity standard, framed in terms of a Renewable Portfolio Standard for electric utilities. I find that jurisdictions of firms with high costs of compliance may actually be better off by not allowing inter-jurisdictional credit trading. Counterintuitively, increasing the stringency of the intensity standard under credit trading can have the opposite of the intended effect and decrease renewable electricity generation.

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Agricultural and Resource Economics | Natural Resource Economics | Oil, Gas, and Energy | Public Economics

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Ivan Rudik*

Department of Economics, Iowa State University
479 Heady Hall, Iowa State University, Ames, IA, 50011-1070, USA
irudik@iastate.edu

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Many environmental standards are expressed in terms of intensity rather than absolute levels. In some cases, intensity standards are associated with tradable credit markets to mitigate the firms' compliance costs. I develop a jurisdictional model of credit trading under an intensity standard, framed in terms of a Renewable Portfolio Standard for electric utilities. I find that jurisdictions of firms with high costs of compliance may actually be better off by not allowing inter-jurisdictional credit trading. Counterintuitively, increasing the stringency of the intensity standard under credit trading can have the opposite of the intended effect and decrease renewable electricity generation.

JEL: H70, Q40, Q48

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Despite growing concerns about pollution and climate change, first-best environmental policies for mitigating pollution are uncommon. The first-best policies that have had political success are typically cap-and-trade systems, or are limited both spatially and in terms of stringency.[1] Second-best policies, such as intensity standards, have gained more traction despite their shortcomings in achieving efficient outcomes. In particular, a majority of states in the US have passed a Renewable Portfolio Standard (RPS), which mandates that a minimum percentage of an electricity provider's retail sales come from renewable sources. Complying with intensity standards like an RPS can be burdensome for firms with high costs of clean production. In particular, electricity providers facing an RPS cannot simply reduce non-renewable electricity because they are required to satisfy highly inelastic retail demand. Moreover, increasing the percentage of renewables, such as wind or solar, in the generation mix raises concerns about intermittent generation. Indeed, an RPS policy may be a prohibitively expensive policy tool for achieving a given level of emissions reductions (Fischer and Newell, 2008).

To help reduce compliance costs, policymakers can couple intensity standards with tradable credit systems, similarly to how policymakers have developed tradable permit markets for for cap-and-trade regulation. Tradable credits allow for renewable production to be reallocated towards lower cost firms and actually achieves the cost-efficient outcome under intensity targets, equating marginal costs across firms.[2] Indeed, a majority of RPS states allow for inter-state Renewable Energy Credit (REC) trading. Under REC trade, utilities are awarded one REC for each megawatt-hour of renewable sales, and RECs can potentially be unbundled from the energy itself. REC markets are highly active with inter-state trading

[1]For example, carbon taxes in the United States are only at the city or county level. A clear exception to this is EU-ETS.

[2]There may be caveats in terms of what units the credits are in, see McKitrick (2001) and Holland et al. (2009) for further details.

volume reaching tens of millions of megawatt-hours annually. Despite the apparent benefits of REC trade in terms of reducing compliance costs, there is significant heterogeneity across states in the degree of restrictions on inter-state REC trade. Some states have taken a lassez-faire approach to trade and place no restrictions on where a REC was generated, while others have completely banned out-of-state RECs.[3]

The heterogeneity in REC trade restrictions across states is a peculiar outcome given the economic evidence on gains from trade. Despite this tension between economic intuition and reality, credit trading under intensity standards has yet to be the primary focus of study.[4] I develop an analytical model of a jurisdictional regulator and a representative electricity firm. The regulator sets an RPS that the firm must meet. In the model, the regulator selects her policy instrument to address two objectives: to reduce pollution externalities from non-renewable electricity generation, and to spur additional in-state energy from clean and renewable sources.[5] In addition to the RPS, the regulator also chooses whether or not to allow the firm to engage in inter-jurisdictional REC trading. Using the model, I characterize the incentives firms and regulators face under REC trade, and analyze what drives jurisdictions to restrict firms from trading RECs.

This paper adds to a rich literature initiated by Helfand (1991) whose analysis of intensity standards demonstrated regulating multiple polluting outputs using an intensity standard can actually lead to increases in emissions.[6] Holland et al. (2009) come to the same conclusion

[3]Several of the trade-eligible states, such as Delaware, are heavily reliant on out-of-state RECs, obtaining up to 94% of the amount necessary to meet the RPS via inter-state trade in 2012. Yet other states, like Iowa or New Mexico, restrict their utilities to obtain RECs solely from in-state generation.

[4]Decisions to engage in trade form a close parallel to the International Environmental Agreement literature which analyzes incentives for countries to form coalitions for emissions reductions. See Barrett (1994) and Karp and Simon (2013) for details on early and more recent work.

[5]It has been noted that the stated reasons for RPSs include development of the in-state renewable industry. See Hollingsworth and Rudik (2015) for details.

[6]McKitrick (2001) analyzes an intensity standard and find that intensity standards should be heterogeneous across firms and stringency should be a function of firm size to achieve efficient outcomes.

in their study of California's low carbon fuel standard; amongst the existing literature, their model is most similar to the one developed in this paper.[7] Parallel to these results, I find a new perverse outcome where increasing the stringency of an intensity standard can actually reduce renewable energy generation when REC trade is allowed because of how the possibility of REC trade alters the relationship between an RPS and its implicit renewable subsidy. This is the first in depth analysis of trade under intensity standards that also closely matches the characteristics of real world REC markets. Trade under intensity standards is briefly analyzed by Holland et al. (2009), who demonstrate that trading effectively minimizes costs subject to the market low carbon fuel standard. Similarly, McKitrick (2005) finds permit trading under intensity standards can be efficient, as long as a permit is a unit of pollution *intensity* with a specific exchange rate between firms.

Extending the existing literature, I allow for a regulator to choose both the stringency of the intensity standard and also whether or not firms in her jurisdiction can trade credits with extra-jurisdictional firms. Using this framework I demonstrate how credit trading changes the regulator's policy instrument by pinning the firm's shadow cost to the credit price instead of it being a function of the regulator's RPS stringency. This alteration of the shadow cost changes the electricity bundles that the regulator can achieve through an RPS and actually changes the sign of the effect of RPS on renewable generation from positive to negative. In addition, I show that whether a utility is a credit seller or credit buyer simply depends on the size of the utility's shadow cost compared to the credit price. Building off of this insight, the primary result of interest is that regulators of firms that would be REC buyers if trade was allowed (due to high relative costs of renewables or a very stringent RPS) may prefer to not engage in credit trading as it can potentially worsen local pollution externalities beyond firm cost

[7] Lemoine (2013) also analyzes California's LCFS but allows the regulator to also control the emissions ratings for fuels in order to achieve greater welfare levels.

reductions through trade. I also demonstrate that symmetric jurisdictions are better off by strictly not allowing for REC trade. Standard economic intuition suggests that the regulators of each jurisdiction should be indifferent between allowing for trade or not. However, allowing trade *does* change outcomes for symmetric firms under intensity standards: in response to opening up trade, regulators adjust their jurisdictional RPS policy to capture rents in the REC market, shifting away from the no-trade optimal levels and reducing welfare. This highlights how strategic responses by regulators can actually deteriorate and even completely offset any benefits of allowing REC trade.

The paper is organized as follows. I begin by describing the firm's problem. I then characterize the determinants of REC buying and selling firms. Finally, I describe the regulators problem and the conditions under which a jurisdiction will engage in inter-jurisdictional REC trade.

1 A model of a firm in a competitive REC market

Suppose there is one representative price-taking firm in a jurisdiction that supplies electricity to a representative consumer within that jurisdiction. The firm generates two types of energy: renewable energy, q_r, and non-renewable energy, q_n.[8] The firm sells its total electricity generation, $q_r + q_n$, to the representative consumer at the retail market price P.[9] The consumer has a continuous, twice-differentiable, strictly increasing, and strictly concave utility function $u(q_r + q_n)$ where $u(0) = 0$ and $\lim_{q_r+q_n \downarrow 0} u'(q_r + q_n) = \infty$. The cost functions for each source of electricity, $C_r(q_r)$ and $C_n(q_n)$, are continuous, twice-differentiable, strictly

[8] I abstract away from intermittency. REC trade could be beneficial in smoothing out uncertain generation from renewable plants and is a line of research left for future work.

[9] In a given year, retail electricity demand may be close to perfectly inelastic and the retail market price would be effectively fixed. This does not change the results.

increasing, and strictly convex.[10]

The market is regulated by a social planner who selects the level of an RPS, α, such that $\alpha \in [0,1]$. The RPS mandates the minimum percentage of renewable energy in the firm's electricity portfolio. Without the ability to trade RECs, this constrains the firm's electricity generation to satisfy $\frac{q_r}{q_r+q_n} \geq \alpha$.[11] From herein assume that the RPS is always binding and the regulator's preferences (defined later) are such that the optimal α is strictly greater than 0. The firm complies with the RPS by retiring renewable energy credits (RECs). For each unit of renewable energy generation, the firm is awarded one REC. Given total output q_r+q_n, the RPS requires the firm to retire $\alpha(q_r+q_n)$ RECs. RECs are distinct commodities from the physical renewable energy and may be bought and sold separately. If the representative firm is able to trade RECs with other firms in a REC market, its constraint must be altered for any trade that occurs. Let x denote the net amount of RECs a firm has sold on the REC market. When trade is possible, the firm's RPS constraint is now $q_r - x \geq \alpha(q_r+q_n)$. If the firm is a net REC seller ($x > 0$), its remaining quantity of RECs, $q_r - x$, must be weakly larger than the amount it's required to retire to maintain compliance: $\alpha(q_r+q_n)$. If the firm is a net buyer of RECs ($x < 0$), the amount of RECs the firm earned from its renewable energy generation, q_r, may be lower than the quantity of RECs it must retire, $\alpha(q_r+q_n)$, due to the additional RECs the firm purchased, $-x$.

In reality, many states impose inter-state trading restrictions on electric utilties. To mathematically capture the regulator's choice to engage in credit trade, I introduce *trading ratios*. If the firm is a seller in a REC market, its trading ratio, $\beta_s \in [0,1]$ requires the firm

[10] The majority of the renewable power sold by utilities is bought from independent power producers (Fremeth and Shaver, 2014). In this static setting we can think of the firm as a utility who contracts with the cheapest independent producers first in order to meet renewable energy needs.

[11] Technically RPS regulate a utility's electricity *sales*, but in this stylized model we use them interchangeably.

to sell $\frac{1}{\beta_s}$ RECs to obtain REC revenues of ξ. This implies that the effective REC price the REC selling firm faces is $\beta_s \xi \leq \xi$. For a firm potentially buying RECs, the trading ratio $\beta_b \in [0, 1]$ determines what fraction of a REC purchased at price ξ can be used towards the RPS. For a buyer, the effective price for one REC is $\frac{\xi}{\beta_b} \geq \xi$. Both trading ratios are parameters that I will use to perform comparative statics and welfare analysis for REC trade. If a firm's trading ratio is zero, it is not in a REC market: a sold REC obtains a price of 0 when $\beta_s = 0$, and a purchased REC will not count towards the RPS if $\beta_b = 0$. If the trading ratios are equal to unity, then a REC sold returns the full market price ξ and the full amount of a purchased REC may be used toward the RPS.

Assuming the firm is a price taker in both the electricity and REC markets, the firm solves one of the following problems:

$$\max_{q_r, q_n, x} \; P\left[q_r + q_n\right] - C_r(q_r) - C_n(q_n) + \beta_s \xi x \tag{1}$$
$$\text{subject to:} \quad \frac{q_r - x}{q_r + q_n} \geq \alpha$$
$$\max_{q_r, q_n, x} \; P\left[q_r + q_n\right] - C_r(q_r) - C_n(q_n) + \xi x \tag{2}$$
$$\text{subject to:} \quad \frac{q_r - \beta_b x}{q_r + q_n} \geq \alpha$$

Where equation (1) is the REC selling firm's problem and equation (2) is the REC buying firm's problem. Given an interior solution, the optimal quantities for each type of energy, and RECs sold, are governed by the first-order conditions for electricity generation, and a buyer or seller specific first order condition for REC trade,

$$P - C_r'(q_r^*) + \lambda^*(1-\alpha) = 0 \tag{3}$$

$$P - C_n'(q_n^*) - \lambda^*\alpha = 0 \tag{4}$$

$$\text{Seller: } \beta_s\xi - \lambda^* = 0, \qquad \text{Buyer: } \xi - \lambda^*\beta_b = 0. \tag{5}$$

Primes indicate derivatives and λ^* is the non-negative equilibrium shadow cost of the constraint. The retail electricity market clears with $P = u'(q_r^* + q_n^*)$, assuming that the two types of generation are perfect substitutes under the representative consumer's preferences.[12]

The outcome of using an RPS policy is the simultaneous subsidization of renewables by $\lambda^*(1-\alpha)$ and taxation of non-renewables by $\lambda^*\alpha$. Increased RPS stringency has two effects on the implicit renewable subsidy. The *direct effect* $(1-\alpha)$ tends to reduce the subsidy due to a higher RPS discouraging overall generation. Each additional unit of renewable generation affords the firm the ability to generate an additional $\frac{1-\alpha}{\alpha}\,q_r$ units of non-renewable generation while maintaining compliance with the RPS. As the RPS becomes more stringent, a unit of renewable generation allows fewer units of non-renewables to be generated while still satisfying the constraint, reducing the marginal benefit of renewables. The *shadow effect* of the policy, λ^*, increases the subsidy and stems from a higher RPS requiring the firm have a larger proportion of renewables in the electricity mix, increasing the marginal benefit of renewables. For more stringent RPS policies, the implicit non-renewable tax increases as both effects tend to make non-renewables more costly.

The third first-order condition captures the marginal cost and benefit of REC sales or purchases. A REC selling firm obtains marginal revenues of $\beta_s\xi$, however selling one more

[12] In reality this may not be true. For example, consumers can contract to specifically purchase renewable energy under a mandatory green power option.

unit carries a cost λ^* due to the firm having to either increase renewables, decrease non-renewables, or some combination of both, to continue meeting the constraint. If $\beta_s = 0$, the marginal cost of selling RECs, λ^*, is always greater than the marginal revenue, $\beta_s\xi = 0$, inducing a corner solution where $x^* = 0$ since x^* must be weakly positive for a REC seller. This effectively reduces the problem to a firm that is not allow to trade RECs. As β_s increases, the firm obtains a greater price for each REC sold until $\beta_s = 1$ where the firm receives ξ for one REC. For a buyer, the marginal cost of buying a REC is ξ and the marginal benefit is $\lambda^*\beta_b$. When $\beta_b = 0$ any REC purchased does not count towards the RPS so the marginal benefit of buying a REC is zero, again inducing a corner solution of $x^* = 0$ and mapping into a scenario with no REC trade allowed. Higher β_b increases the proportion of a purchased REC that counts towards meeting the RPS, increasing the marginal benefit of buying a REC until $\beta_b = 1$ where each REC purchased counts fully towards RPS compliance. Performing comparative statics with the two trading ratios will allow us to determine the effects of allowing credit trade on firm decisions and welfare. If the comparative statics are strictly positive or negative we have a sufficient condition for how REC trade affects outcomes.

1.1 The changing effect of RPSs under trade

The shadow cost captures the firm's benefit of marginally weakening the RPS constraint, or equivalently, it is the value of receiving an additional REC. When fully joining a REC market, i.e. $\beta_b = \beta_s = 1$, the shadow and direct effects of the RPS still remain, but the value of a REC towards the firm, the shadow cost λ, is pinned to the market price as shown in equation (5). This introduces a third effect of the RPS policy, called the REC effect. The appendix shows this precisely offsets the shadow effect, changing how the RPS affects the

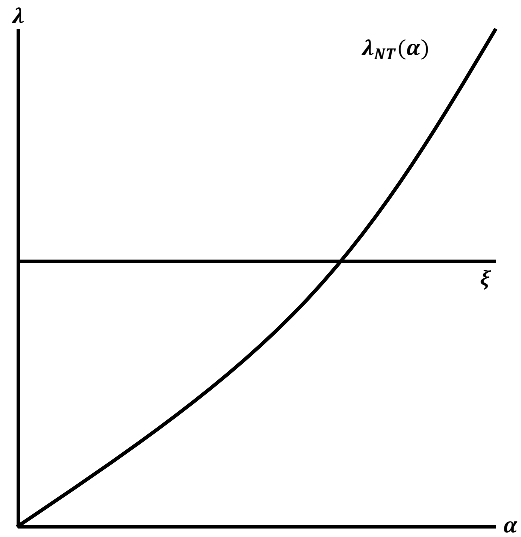

Figure 1: Relationship between RPS level and shadow cost

firm's optimal generation levels. This change is illustrated in Figure 1. Prior to joining the REC market, the regulator simultaneously selected the RPS level α and the shadow cost of the constraint $\lambda_{NT}(\alpha)$, resulting in an upward sloping curve of possible $(\alpha, \lambda_{NT}(\alpha))$ selections, where subscript NT indicates no trade. When a REC market is joined, the shadow effect vanishes due to the offsetting REC effect, therefore the regulator can no longer influence the shadow cost and can now only select α while λ is pinned to ξ.

Pinning the shadow cost changes the regulator's feasible $(\alpha, \lambda(\alpha))$ choice set and therefore changes the tax-subsidy combinations possible with RPS instrument. As we move to the northwest, the renewable subsidy unambiguously increases since the shadow effect grows and the direct effect declines. Moving to the northeast unambiguously increases the non-renewable tax by amplifying both the shadow and direct effects. Moving to the northeast or southwest on the graph pushes the shadow and direct effect in opposite directs so the net effect on the implicit renewable subsidy is ambiguous. Since $\lambda(\alpha)$ has positive slope, increasing the RPS moves us along the northeast-southwest dimension. So a change in the RPS without REC trade will lead to an ambiguous effect on renewable generation. However, when λ is pinned at ξ by the REC market, the regulator can only move left or right on the graph. In this case, increasing the RPS unambiguously reduces the subsidy and decreases renewable output.

So far we have assumed the REC price is fixed for tractability, but in reality the REC price is endogenous. The appendix shows that, under quadratic utility and quadratic costs, the REC price is just a weighted average of the shadow costs of each firm's RPS constraint when it is not allowed to trade RECs.[13] Effectively, the REC market introduces a *global* intensity standard over the entire market.[14] With this intuition, the representative firm of a jurisdiction can potentially represent multiple firms within that jurisdiction, with the possibility of intra-jurisdictional REC trade. When $\beta_b = \beta_s = 0$, the shadow cost of the representative firm of the jurisdiction is just the price that clears the REC market within the jurisdiction. Since all firms face the same RPS, and the representative firm's output is just the aggregate of the represented firms.

1.2 Determinants of buyers and sellers

The difference between the shadow cost of a firm's RPS constraint without trade, λ_{NT}, and the REC price, ξ, will be the determining factor in whether a firm buys or sells RECs. Suppose that a jurisdiction joins a REC market, the jurisdiction's RPS is held constant, and

[13] The weights are given by the ratio of the determinant of the Hessian to the firm's maximization problem when unconstrained by an RPS, to the determinant of the Hessian to the firm's maximization problem when facing an RPS.

[14] This is different from the market LCFS in Holland et al. (2009) where each firm faces the same explicit LCFS. Here, each firm can be facing a different RPS but the REC price gives us the shadow cost of the weighted average of all RPS.

$\xi > \lambda_{NT}$ so that the REC price is larger than the firm's no-trade shadow cost. The last condition implies the implied global RPS policy of the REC market is more stringent, i.e. has a larger shadow cost, than the RPS policy of the joining jurisdiction. When making generation decisions, firms act as if they are facing the implicit global RPS, since the third first-order condition pins the shadow cost to the REC price. Since the implicit global RPS is more stringent, this shifts the firm's generation mix to be more renewable dominant than if it were facing the weaker jurisdictional RPS. Yet, the firm does not need to retire RECs to meet the implied global policy, but only needs to retire enough RECs to satisfy the jurisdictional RPS. In this case the firm has excess RECs and sells them on the REC market. If $\xi < \lambda_{NT}$, the global RPS policy is less stringent than the jurisdictional policy, pinning the shadow cost at a lower value than without REC trade. The firm responds to this change by reducing renewables and increasing non-renewables. But, the firm's generation portfolio no longer has a large enough proportion of renewables to satisfy the regulator's RPS. To maintain compliance, the firm must purchase RECs.

Figures 2 and 3 give graphical intuition for the distinction between REC buying and REC selling firms, and how optimal REC trade links back into firm profits. Figure 2 shows the firm's iso-profit curves for electricity sales, graphed as ovals. The iso-profit curves do not include REC revenues or costs, and profit is increasing as the generation bundles move inward towards the center point of the iso-profit curves. The RPS is an upward sloping line that passes through the origin in the case with no REC trade, and it restricts the firms output choice set to be up and to the left of the line. The regulator sets an RPS to shift the firm's generation bundle closer to the social optimum, which under the assumption of a binding constraint, falls somewhere above or to the left of the of the firm's profit maximizing bundle.

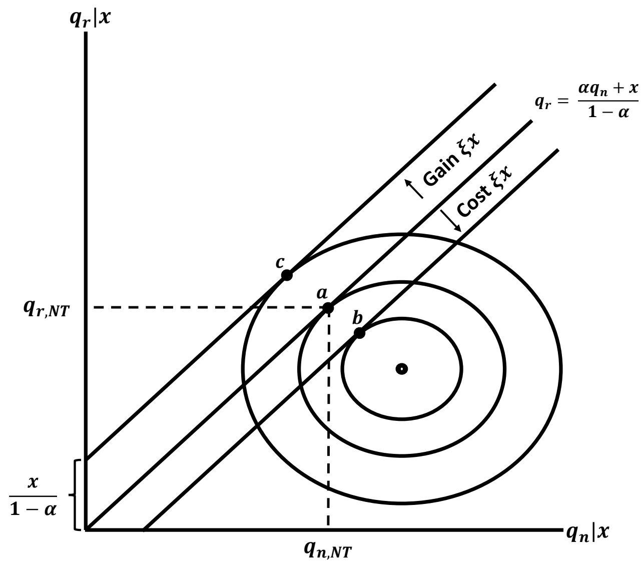

Figure 2: Firm iso-profit curves, net of REC revenues/costs

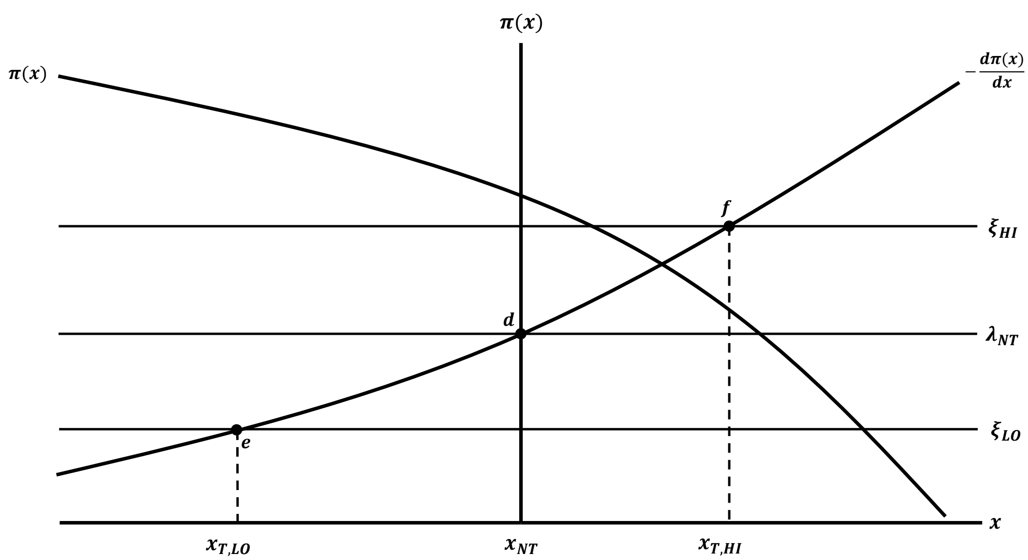

Figure 3: Profit net of REC revenues/costs as a function of RECs sold

Let the middle RPS line be some arbitrary RPS with no REC trade. Then point a is the firms optimal bundle when it is not able to trade RECs ($x = 0$) since it achieves the highest iso-profit curve amongst the generation bundles in the firm's choice set. Suppose the regulator allows the firm to trade RECs at a trading ratio of 1, and for simplicity, maintains the same RPS. Notice that a binding RPS constraint can be rewritten as $q_r = \frac{\alpha q_n + x}{1-\alpha}$. REC purchases or sales vertically shift the RPS constraint. If the firm is a buyer in the REC market, it incurs a cost ξx. REC purchases ($-x$) shift the RPS constraint downward by $\frac{x}{1-\alpha}$, allowing the firm to move up its iso-profit curves to point b. Recall that REC costs are not included in the curves so the iso-profit curves do not move or change shape. Conversely, when a firm sells RECs, it gains REC revenues ξx but its choice set becomes more restricted since the RPS shifts upward by $\frac{x}{1-\alpha}$. The firm moves down its iso-profit curves to point c.

How the firm selects its optimal REC trading quantity is determined by a simple relation of the marginal benefits and marginal costs of REC trade. Figure 3 graphs $\pi(x)$, the firm's equilibrium profit, excluding REC revenues and costs, as a function of x. $\pi(x)$ is the curve that would trace out points a, b and c in Figure 2 as the firm changes its quantity of RECs traded. $-\frac{d\pi(x)}{dx}$ is also graphed and is an increasing function of x since another unit of REC sales requires the firm to shift its generation mix to be more renewable dominant, increasing generation costs and reducing profits. Finally, the firm's shadow cost without trade, λ_{NT} is graphed as a horizontal line along with two potential REC prices: $\xi_{HI} > \lambda_{NT}$ and $\xi_{LO} < \lambda_{NT}$. The firm's optimal level of REC trade equates the marginal costs and benefits of buying or selling RECs. If the firm is selling RECs, it gets marginal revenues equal to ξ and incurs marginal costs equal to $\frac{d\pi}{dx}$ from having to re-optimize electricity generation to be more renewable dominant in order to maintain compliance with the RPS. This is the profit loss from shifting up the RPS as in Figure 2. If the firm is buying RECs, the source of marginal costs and benefits reverse. The firm pays ξ per unit of RECs to shift the RPS down in order to allow a generation bundle closer to the unconstrained optimum so that it receives a marginal profit gain of $\frac{d\pi}{dx}$.

The optimal level of REC trade is where $-\frac{d\pi(x)}{dx}$ equals the REC price for both buyers and sellers. If the REC price and $\frac{d\pi}{dx}$ curves intersect to the right of $x_{NT} = 0$, the firm is a REC seller. If the curves intersect to the left of x_{NT}, the firm is a REC buyer. Recall that the shadow cost of the RPS constraint is the marginal benefit to the firm of marginally weakening the RPS, so without REC trade we have: $-\frac{d\pi(x)}{dx} = \lambda_{NT}$. When the RPS is binding, λ_{NT} must be the value which forces x to zero. If the REC price is different from λ_{NT}, the intersection of $-\frac{d\pi(x)}{dx}$ and the REC price will be at some non-zero level of REC trade. The quadrant where the negative marginal profit curve intersects the REC price is completely determined by the relative magnitudes of the REC price and λ_{NT}. If $\xi > \lambda_{NT}$ such as ξ_{HI}, then the intersection of the marginal curves is always to the right of x_{NT} and the firm sells RECs, following the intuition outlined above. If $\xi < \lambda_{NOREC}$ like ξ_{LO}, the intersection is to the left of x_{NT} and the firm buys RECs.

2 The regulator's problem: RPS and REC trading decisions

For clarity, consider the regulator's problem in terms of setting an RPS conditional on a given trading ratio, or selecting the trading ratio conditional on a pre-determined RPS, but not both simultaneously. I consider both possible ways to order decisionmaking and show that there is a non-trivial difference in outcomes, suggesting that the timing regulators' decisions on REC trade restrictions is critical for firm behavior and welfare outcomes. The regulator's objective is to maximize the social welfare of its jurisdiction. Social welfare is the sum of consumption utility minus the cost of purchasing electricity from the firm, firm profits, and two externalities from electricity generation. The first externality is pollution damages from non-renewable generation. The marginal damage from one unit of non-renewable generation is determined by the damage factor τ. I assume the REC market is sufficiently large so that aggregate output of other firms in the REC market does not change in response to the modeled jurisdiction joining the market so damages of outside, unmodeled firms do not enter the regulator's welfare problem. Alternatively, the regulator takes the REC price as given or may only be concerned with local emissions. The second externality is "green welfare," a benefit from renewable generation above and beyond offsetting dirty non-renewable electricity. An additional unit of renewable generation provides social welfare g. The positive renewable externality may be driven by green preferences of constituents, or a desire to promote "green jobs." It does not necessarily have to provide real welfare in terms of dollars, but captures non-monetary reasons why a jurisdiction may wish to pass an RPS. First, I analyze regulator policy behavior conditional on being in a REC market. The regulator's problem is,

$$\max_{\alpha} u(q_r + q_n) - C_r(q_r) - C_n(q_n) + g\, q_r - \tau q_n + \beta_s \xi x, \tag{6}$$

where β_s is omitted if the representative firm is a potential REC buyer, and β_b does not explicitly enter the regulator's objective.[15] The welfare-maximizing RPS solves the regulators

[15] Recall β_b is inside of the firm's RPS constraint, so q_r and q_n are both functions of β_b.

first-order condition:

$$u'\left(q_n(\alpha^*)+q_r(\alpha^*)\right)\left[\frac{\partial q_n(\alpha^*)}{\partial \alpha}+\frac{\partial q_r(\alpha^*)}{\partial \alpha}\right]-C_r'(q_r(\alpha^*))\frac{\partial q_r(\alpha^*)}{\partial \alpha}-C_n'(q_n(\alpha^*))\frac{\partial q_n(\alpha^*)}{\partial \alpha}$$
$$+g\,\frac{\partial q_r(\alpha^*)}{\partial \alpha}-\tau\frac{\partial q_n(\alpha^*)}{\partial \alpha}+\beta_s\xi\frac{\partial x(\alpha^*)}{\partial \alpha}=0 \qquad (7)$$

After substituting in the firms first-order conditions which determine optimal responses to policy, we have that in equilibrium,

$$g\,\frac{\partial q_r(\alpha^*)}{\partial \alpha}-\tau\frac{\partial q_n(\alpha^*)}{\partial \alpha}=\lambda(\alpha^*)(1-\alpha^*)\frac{\partial q_r(\alpha^*)}{\partial \alpha}-\lambda(\alpha^*)\alpha^*\frac{\partial q_n(\alpha^*)}{\partial \alpha}-\beta_s\xi\frac{\partial x(\alpha^*)}{\partial \alpha} \qquad (8)$$

The left hand side is the net marginal externality benefits of a more stringent RPS and the right hand side is the net marginal costs to the firm. Using this equilibrium condition, we can obtain several key results regarding the regulator's RPS level.

Proposition 1.

1. *α is increasing in τ.*

2. *Suppose $\beta_s = \beta_b = 0$. If the shadow effect (direct effect) dominates, α increases (decreases) in g.*

3. *If $\beta_s = \beta_b = 1$, then q_r always decreases in α.*

Proof. See appendix. □

The appendix shows that non-renewable output is always declining in RPS stringency because a higher RPS increases the implicit tax on non-renewables. Since greater τ leads to lower welfare, the regulator will increase RPS stringency to reduce damages.

If $\beta_s = \beta_b = 0$, the firm is not able to trade RECs. Recall that an RPS has two effects on generation decisions: the shadow effect which increases the difficulty of meeting the RPS constraint, and the direct effect which reduces how many units of non-renewables that are offset by a unit of renewables.[16] If the shadow effect dominates the direct effect, higher RPS lead to more renewable generation. However it is possible that a higher RPS may lead to *less* renewable generation. Therefore, if the marginal social benefit of renewables is sufficiently high, the regulator may actually be better off setting a lower RPS or no RPS at all.

Counter-intuitively, if $\beta_s = \beta_b = 1$, firms decrease renewable generation in response to a more stringent RPS. Recall that under trade there is a third effect, the REC effect, which precisely offsets the shadow effect. This captures the shadow cost being pinned down by the exogenous REC price, resulting in strictly lower renewable subsidies under higher RPS, and therefore lower renewable generation. Indeed, a lower RPS increases the marginal benefit of renewables by allowing the firm to reap higher REC-related profits for any given level of non-renewable generation.

Corollary 2.

If $\beta_s = \beta_b = 1$, then α always decreases in g.

Proof. See appendix. □

As a result of this counter-intuitive response to policy, regulators actually set *weaker* RPSs under REC trade when their jurisdiction has stronger green preferences.

[16] Or alternatively, the direct effect increases the opportunity cost of non-renewables by requiring more renewables to be generated for each unit to meet the RPS.

2.1 Joining decision with a fixed RPS

Thus far I have outlined firm behavior and the regulator's RPS adjustments in response to joining a REC market. Now I investigate under what conditions a regulator will decide to engage in REC trade conditional on their RPS. First I analyze a setting where a regulator has previously set an RPS and is deciding on engaging in REC trade and a special case of a second setting where the regulator decides on engaging in trade and then sets the RPS level conditional on her REC trade decision.

A regulator joins a REC market if and only if social welfare will increase in its jurisdiction. Let ΔW be the change in welfare from joining a REC market conditional on having previously set some RPS α. ΔW can be decomposed into four parts: [1] the change in welfare from externalities, [2] the change in consumer welfare, [3] the change in firm profits net of REC revenue, [4] and the change in REC revenues:

$$\Delta W = \left[g\ \left(q_r^J - q_r^D\right) - \tau\ \left(q_n^J - q_n^D\right)\right] + \left[\left(u\left(q_r^J + q_n^J\right) - P\left(q_r^J + q_n^J\right)\right) - \left(u\left(q_r^D + q_n^D\right) - P\left(q_r^D + q_n^D\right)\right)\right] \\ + \left(\pi^J - \pi^D\right) + \xi\left[\left(1-\alpha\right)q_r^J - \alpha q_n^J\right] \tag{9}$$

where J indicates optimal quantities conditional on the regulator joining a REC market, D indicates optimal quantities conditional on the regulator not joining a REC market, and π is equilibrium firm profit net of REC revenues: $P(q_r + q_n) - C_r(q_r) - C_n(q_n)$. All quantities are at their equilibrium levels but stars are omitted for notational clarity. The first bracketed term is the change in externality welfare, the second is the change in consumer welfare, the third is the change in firm profits and the last term is REC revenues or costs. We can sign ΔW by analyzing the regulator's first-order condition for the trading ratio. If the first-order condition is always positive regardless of the value of the trading ratio, we have a corner solution and the trading ratio is set to 1. However if the first-order condition is always negative then the trading ratio will be set to 0 at the other possible corner solution.

Proposition 3. *If the REC price, ξ, is larger than the shadow cost the firm faces without trade, λ_{NT}, then the regulator will set $\beta_s = 1$ (i.e. join a REC market).*

Proof. See appendix. □

$\xi > \lambda_{NT}$ implies the firm is a REC seller if trade is allowed. Consider the regulator's joining decision assuming she will not be able to change the RPS after she makes her joining decision. The appendix shows that since the firm is a REC seller, the firm's renewable generation increases and non-renewable generation decreases upon allowing REC trade, improving both externalities. Since the RPS is fixed and the firm is free to reoptimize across electricity types, the firm can weakly reduce costs and is weakly better off compared to not trading, and this gain dominates any potential utility loss to consumers. Therefore, welfare strictly increases when the RPS is fixed so welfare will also improve even when the RPS restriction is relaxed. The regulator will only adjust the RPS to improve welfare further, so the regulator always joins a REC market if the firm will be a REC seller.

Corollary 4. *If the REC price, ξ, is smaller than the shadow cost the firm faces without trade, λ_{NT}, then the regulator selects an interior trading ratio.*

Proof. See appendix. □

For the regulator of a REC buying firm, there no corner solution where selecting $\beta_b^* = 1$ or $\beta_b^=0$. Since interior trading ratios are an artifact of the model, it's unclear whether $\beta_b = 1$ or $\beta_b = 0$ achieves greater welfare. I next show a special case where there may actually be no trade.

2.1.1 Special case: Symmetric jurisdictions

Consider a special case where all jurisdictions are symmetric and regulators simultaneous choose the RPS and their trading ratio. Under a conventional cap and trade policy, the decision to allow firms to engage in trade has no influence on jurisdictional or global welfare. However, with credit trading under intensity standards this will not be true.

Proposition 5. *Suppose the REC price is exogenous. A REC market of an arbitrary number of identical jurisdictions makes all jurisdictions strictly worse off if* $\frac{\partial x_i}{\partial \alpha_i} \neq 0$ *for all jurisdictions* i *in the REC market.*

Proof. See appendix. □

A common necessary condition for trade is heterogeneity in production costs or preferences. Otherwise, no trade occurs, the outcome is identical to when trade was forbidden, and the REC price will be equivalent to the symmetric shadow cost of each jurisdiction's RPS constraint. However, when regulation is localized, regulators have an incentive to capture REC rents by lowering their RPS after opening up REC trade. For example, if a regulator weakens its RPS, its representative firm will increase renewables as shown in the appendix. This increases green welfare within the jurisdiction, and increases firm profits by weakening the RPS constraint and allowing the firm to sell its excess RECs (or purchase fewer RECs) on the market. Pollution also unambiguously increases as the implicit non-renewable tax decreases. Yet, all firms are symmetric, so even though regulators have adjusted their RPS to capture rents, they obtain none of them since there cannot possibly be trade. This leaves the regulators' RPSs strictly different from the optimal level given no REC trade, incentivizing generation levels that strictly different from the no-trade socially optimal levels.

3 Discussion

Within several years RPS will be in full force in a majority of states in the US. Although there's a vast literature on trading schemes under a conventional quantity standard, existing research on trading under intensity standards, and inter-jurisdictional trade is sparse. I find that whether a firm buys or sells RECs in a REC market is driven by the relationship of its shadow cost to the market shadow cost, the REC price. Moreover, joining a REC market changes the set of social outcomes achievable by the regulator due to the REC market pinning down the shadow cost. A more stringent internal shadow cost leads firms to be REC buyers while a more lenient shadow cost induces REC selling. I find that REC selling jurisdictions will always improve by engaging in trade, however, REC buyers face worsening externalities from trade and the welfare implications of trade are ambiguous. These results suggest that decisions by state regulators to restrict inter-state REC trade may in fact be locally optimal.

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A Lemmas for the main results

There are several lemmas required before proving the propositions.

Lemma 6. *There exists a unique maximum.*

Proof. Form the bordered Hessian for a REC seller:

$$H_{firm} = \begin{bmatrix} 0 & -(1-\alpha) & \alpha & 1 \\ -(1-\alpha) & u'' - C_r'' & u'' & 0 \\ \alpha & u'' & u'' - C_n'' & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \tag{10}$$

We must show the upper-left justified 3x3 matrix has a positive determinant and that the determinant of the entire Hessian is negative for the Hessian to be negative-definite and existence of a unique maximum. The 3x3 matrix's determinant is:

$$(1-\alpha)\left[-(1-\alpha)(u''-C_n'') - u''\alpha\right] + \alpha\left[-(1-\alpha)u'' - \alpha(u''-C_r'')\right] > 0 \tag{11}$$

The determinant of the Hessian is:

$$u''^2 - (u''-C_r'')(u''-C_n'') < 0 \tag{12}$$

For a buyer, replace elements (4,1) and (1,4) in the matrix with β_b. The determinant of the upper left justified 3x3 matrix is the same. The determinant of the entire Hessian is the seller's determinant multiplied by β_b^2 which is still weakly positive. In the case where β_b equals zero precisely, we construct the 3x3 Hessian where trade is strictly not allow and obtain conditions for a unique maximum.

□

Lemma 7. *q_n is decreasing in α. If the trading ratios are 1, q_r is decreasing in α. If the trading ratios are zero for the seller, or less than 1 for the buyer, q_r is decreasing in α if the shadow effect dominates the direct effect. The quantity of RECs sold may be increasing or decreasing in α.*

For a seller the comparative statics for each output are proportional to the Hessian where the column mapping to that output is replaced by a vector of derivatives of the first-order conditions and constraint with respect to the parameter being varied.

If the trading ratio is zero, the selling firm's problem reduces to attempting to satisfy the RPS without trade. The Hessian for the no-trade case is:

$$H_{notrade} = \begin{bmatrix} 0 & (1-\alpha) & -\alpha \\ (1-\alpha) & u'' - C_r'' & u'' \\ -\alpha & u'' & u'' - C_n'' \end{bmatrix}, \tag{13}$$

which is positive following lemma 6. The upper left justified 2x2 matrix is clearly negative so by the second derivative condition there exists a unique maximum. Next I derive the comparative statics for the firm without trade beginning with renewables,

$$\begin{aligned} \frac{\partial q^r}{\partial \alpha} &\propto - \begin{vmatrix} 0 & -(q_r+q_n) & -\alpha \\ (1-\alpha) & \frac{\partial \lambda}{\partial \alpha}(1-\alpha) - \lambda & u'' \\ -\alpha & -\frac{\partial \lambda}{\partial \alpha}\alpha - \lambda & u'' - C_n'' \end{vmatrix} \\ &= \underbrace{(q_r+q_n)\left[(1-\alpha)C_n'' - u''\right]}_{\text{Shadow effect}} + \underbrace{-\alpha\lambda}_{\text{Direct effect}} \end{aligned} \tag{14}$$

where the shadow effect is positive and the direct effect is negative so the net effect is ambiguous. The non-renewable response is proportional to:

$$\frac{\partial q^n}{\partial \alpha} \propto - \begin{vmatrix} 0 & (1-\alpha) & -(q_r+q_n) \\ (1-\alpha) & u''-C_r'' & \frac{\partial\lambda}{\partial\alpha}(1-\alpha)-\lambda \\ -\alpha & u'' & -\frac{\partial\lambda}{\partial\alpha}\alpha-\lambda \end{vmatrix}$$
$$= -\left[\lambda\left(1-\alpha\right)+\left(q_r+q_n\right)\left[\alpha C_r''-u''\right]\right] \leq 0 \tag{15}$$

Suppose the trading ratio β_s is non-zero. The non-renewable response to a marginal change in the RPS for a REC seller is,

$$\frac{\partial q_r}{\partial \alpha} \propto \begin{vmatrix} 0 & q_r+q_n & \alpha & 1 \\ -(1-\alpha) & \frac{\partial\lambda}{\partial\alpha}(1-\alpha)-\lambda & u'' & 0 \\ \alpha & \frac{\partial\lambda}{\partial\alpha}(-\alpha)-\lambda & u''-C_n'' & 0 \\ 1 & -\frac{\partial\lambda}{\partial\alpha} & 0 & 0 \end{vmatrix}$$
$$= \underbrace{-\lambda C_n''}_{\text{Direct effect}} \underbrace{-\frac{\partial\lambda}{\partial\alpha}\left[u''-(1-\alpha)C_n''\right]}_{\text{Shadow effect}} + \underbrace{\frac{\partial\lambda}{\partial\alpha}\left[u''-(1-\alpha)C_n''\right]}_{\text{REC effect}}$$
$$= -\lambda C_n'' < 0 \tag{16}$$

Similarly for non-renewables,

$$
\begin{aligned}
\frac{\partial q_n}{\partial \alpha} &\propto \begin{vmatrix} 0 & -(1-\alpha) & q_r + q_n & 1 \\ -(1-\alpha) & u'' - C_r'' & \frac{\partial \lambda}{\partial \alpha}(1-\alpha) - \lambda & 0 \\ \alpha & u'' & \frac{\partial \lambda}{\partial \alpha}(-\alpha) - \lambda & 0 \\ 1 & 0 & -\frac{\partial \lambda}{\partial \alpha} & 0 \end{vmatrix} \\
&= -\left[\lambda C_r'' - \frac{\partial \lambda}{\partial \alpha}\left(u'' - (1-\alpha)C_r''\right)\right] - \frac{\partial \lambda}{\partial \alpha}\left[u'' - (1-\alpha)C_n''\right] \\
&= -\lambda C_r'' < 0 \qquad (17)
\end{aligned}
$$

Suppose β_b is non-zero. The comparative statics for a REC buyer are,

$$
\begin{aligned}
\frac{\partial q_r}{\partial \alpha} &\propto \begin{vmatrix} 0 & q_r + q_n & \alpha & \beta_b \\ -(1-\alpha) & \frac{\partial \lambda}{\partial \alpha}(1-\alpha) - \lambda & u'' & 0 \\ \alpha & \frac{\partial \lambda}{\partial \alpha}(-\alpha) - \lambda & u'' - C_n'' & 0 \\ \beta_b & -\beta_b \frac{\partial \lambda}{\partial \alpha} & 0 & 0 \end{vmatrix} \\
&\propto \underbrace{-\lambda C_n''}_{\text{Direct effect}} \underbrace{- \frac{\partial \lambda}{\partial \alpha}\left[u'' - (1-\alpha)C_n''\right]}_{\text{Shadow effect}} + \underbrace{\frac{\partial \lambda}{\partial \alpha}\left[u'' - (1-\alpha)C_n''\right]}_{\text{REC effect}} \\
&= -\lambda C_n'' < 0 \qquad (18)
\end{aligned}
$$

and,

$$\frac{\partial q_n}{\partial \alpha} \propto \begin{vmatrix} 0 & -(1-\alpha) & q_r + q_n & \beta_b \\ -(1-\alpha) & u'' - C_r'' & \frac{\partial \lambda}{\partial \alpha}(1-\alpha) - \lambda & 0 \\ \alpha & u'' & \frac{\partial \lambda}{\partial \alpha}(-\alpha) - \lambda & 0 \\ \beta_b & 0 & -\beta_b \frac{\partial \lambda}{\partial \alpha} & 0 \end{vmatrix}$$

$$= -\lambda C_r'' < 0 \tag{19}$$

Lemma 8. *For a seller, q_r is increasing in β_s and q_n is decreasing in β_s. For a buyer, q_r decreases and q_n increases in β_b*

$$\frac{\partial q_r}{\partial \beta_s} \propto \begin{vmatrix} 0 & 0 & \alpha & 1 \\ -(1-\alpha) & (1-\alpha)\frac{\partial \lambda}{\partial \beta_s} & u'' & 0 \\ \alpha & -\alpha \frac{\partial \lambda}{\partial \beta_s} & u'' - C_n'' & 0 \\ 1 & \xi - \frac{\partial \lambda}{\partial \beta_s} & 0 & 0 \end{vmatrix}$$

$$= -\xi[u'' - (1-\alpha)C_n''] > 0 \tag{20}$$

$$\frac{\partial q_n}{\partial \beta_s} \propto \begin{vmatrix} 0 & -(1-\alpha) & 0 & 1 \\ -(1-\alpha) & u'' - C_r'' & (1-\alpha)\frac{\partial \lambda}{\partial \beta_s} & 0 \\ \alpha & u'' & -\alpha \frac{\partial \lambda}{\partial \beta_s} & 0 \\ 1 & 0 & \xi - \frac{\partial \lambda}{\partial \beta_s} & 0 \end{vmatrix}$$

$$= \xi(u'' - \alpha C_r'') < 0 \tag{21}$$

$$\frac{\partial q_r}{\partial \beta_b} \propto \begin{vmatrix} 0 & 0 & \alpha & 1 \\ -(1-\alpha) & (1-\alpha)\frac{\partial \lambda}{\partial \beta_b} & u'' & 0 \\ \alpha & -\alpha\frac{\partial \lambda}{\partial \beta_b} & u'' - C_n'' & 0 \\ 1 & -\lambda - \beta_b\frac{\partial \lambda}{\partial \beta_b} & 0 & 0 \end{vmatrix}$$

$$= [\lambda + (\beta_b - 1)\frac{\partial \lambda}{\partial \beta_b}][u'' - (1-\alpha)C_n''] < 0 \tag{22}$$

$$\frac{\partial q_n}{\partial \beta_b} \propto \begin{vmatrix} 0 & -(1-\alpha) & 0 & 1 \\ -(1-\alpha) & u'' - C_r'' & (1-\alpha)\frac{\partial \lambda}{\partial \beta_b} & 0 \\ \alpha & u'' & -\alpha\frac{\partial \lambda}{\partial \beta_b} & 0 \\ 1 & 0 & -\lambda - \beta_b\frac{\partial \lambda}{\partial \beta_b} & 0 \end{vmatrix}$$

$$= -[\lambda + (\beta_b - 1)\frac{\partial \lambda}{\partial \beta_b}](u'' - \alpha C_r'') > 0 \tag{23}$$

A.1 Proof of Proposition 1

Assume the regulator's problem is strictly concave in α. By the implicit function theorem we have that $\frac{\partial \alpha}{\partial \tau} \propto -\frac{\partial q_n}{\partial \alpha} > 0$ and $\frac{\partial \alpha}{\partial g} \propto \frac{\partial q_r}{\partial \alpha}$. If $\beta_s = 0$ for a REC seller and $\beta_b = 0$ for a REC buyer, the renewable comparative static is positive (negative) if the shadow effect (direct effect) dominates. If β_s and β_b are 1, the renewable comparative static is negative. This is shown in Lemma 7.

A.2 Proof of Proposition 3 and Corollary 4

Note that $x = (1-\alpha)q_r - \alpha q_n$ when the RPS binds. I drop the arguments for the functions and the equlibrium selections of q_r and q_n. First, hold the RPS fixed at some level α^f. Then the FOC that governs the regulator's joining decision when the RPS is held constant is,

$$\frac{\partial W^*}{\partial \beta_s^*} = (u' - C_r' + \beta_s^* \xi(1-\alpha^f))\frac{\partial q_r^*}{\partial \beta_s^*} + (u' - C_n' - \beta_s^* \xi \alpha^f)\frac{\partial q_n^*}{\partial \beta_s^*} + g\frac{\partial q_r^*}{\partial \beta_s^*} - \tau\frac{\partial q_n^*}{\partial \beta_s^*}. \qquad (24)$$

The first two terms in parentheses are the firm's first-order conditions for generation after substituting in for λ^* using the first-order condition for REC trade. These are zero in equilibrium. The last two externality terms are always positive as shown in Lemma 8, therefore the regulator's first order condition is strictly greater than zero. This results in a corner solution of $\beta_s = 1$. If the regulator always sets $\beta_s^* = 1$ for any given α^f, then the regulator will join if able to select α herself.

The first order condition for the regulator after substituting in the REC buying firm's first order conditions is,

$$\frac{\partial W^*}{\partial \beta_b} = g\frac{\partial q_r}{\partial \beta_b^*} - \tau\frac{\partial q_n}{\partial \beta_b^*} + \xi(1-\alpha)\left[1 - \frac{1}{\beta_b}\right]\frac{\partial q_r}{\partial \beta_b} - \xi\alpha\left[1 - \frac{1}{\beta_b}\right]\frac{\partial q_n}{\partial \beta_b} \qquad (25)$$

The first two terms are negative and the last two terms are positive. If $\beta_b = 1$ then the first-order condition is negative, which, in a complementarity problem, implies that $\beta_b = 0$: a contradiction. However if $\beta_b \to 0$ then the first order condition goes to infinity, and due to the nature of a complementarity problem, implies that $\beta_b = 1$: another contradiction. Therefore the regulator of a REC buying firm selects an interior trading ratio.

A.3 Proof of Proposition 5

Suppose all jurisdictions are symmetric. The optimality condition for an arbitrary regulator governing a firm that cannot trade is,

$$\frac{\partial W}{\partial \alpha^*} = (u' - C_r' + g)\frac{\partial q_r}{\partial \alpha^*} + (u' - C_n' - \tau)\frac{\partial q_n}{\partial \alpha^*} = 0 \tag{26}$$

When trade is allowed, the condition changes to:

$$\frac{\partial W}{\partial \alpha^+} = (u' - C_r' + g)\frac{\partial q_{ri}}{\partial \alpha_i^+} + (u' - C_n' - \tau)\frac{\partial q_{ni}}{\partial \alpha_i^+} - \sum_{j \neq i} \tau \frac{\partial q_{nj}}{\partial \xi}\frac{\partial \xi}{\partial \alpha_i^+} + \frac{\partial x_i}{\partial \alpha_i^+}\xi + x_i \frac{\partial \xi}{\partial \alpha_i^+} = 0 \tag{27}$$

Where j indicates all other firms. Since all jurisdictions are symmetric and regulators act simultaneously, their actions will also be symmetric. Therefore, in equilibrium, there will be no trade. However, α^* is the unique no-trade optimal RPS. Therefore if

$$-\sum_{j \neq i} \tau \frac{\partial q_{nj}}{\partial \xi}\frac{\partial \xi}{\partial \alpha_i^+} + \frac{\partial x_i}{\partial \alpha_i^+}\xi + x_i \frac{\partial \xi}{\partial \alpha_i^+} \neq 0, \tag{28}$$

then $\alpha^+ \neq \alpha^*$. If the REC price is exogenous, i.e. fixed, the first and third terms in equation (28) are zero. Applying the derivative, the second term is zero only when $(1 - \alpha)\frac{\partial q_r}{\partial \alpha_i^+} - \alpha \frac{\partial q_n}{\partial \alpha_i^+} = q_r + q_n$. If this is non-zero, then $\alpha^+ \neq \alpha^*$ and welfare is strictly lower with trade with an exogenous REC price.

A.4 Derivation of a Global RPS Under Quadratic Utility and Costs

A.4.1 The Firm's Problem Without REC Trade

To maintain clarity in this section I move the subscripts that indicate electricity type to be superscripts and change notation to explicitly show the partial derivatives. Consider utility i's profit-maximization problem when trade is not allowed,

$$\max_{q_i^r, q_i^n} \; P_i \cdot (q_i^r + q_i^n) - C_i^r(q_i^r) - C_i^n(q_i^n) \tag{29}$$

$$\text{subject to:} \quad \frac{q_i^r}{q_i^r + q_i^n} \geq \alpha_i \tag{30}$$

The first order conditions that govern the optimal quantities of each type of electricity are,

$$\frac{\partial u_i(q_i^r + q_i^n)}{\partial q_i^r} - \frac{\partial C_i^r(q_i^r)}{\partial q_i^r} + \lambda_i(1 - \alpha_i) = 0 \tag{31}$$

$$\frac{\partial u_i(q_i^r + q_i^n)}{\partial q_i^n} - \frac{\partial C_i^n(q_i^n)}{\partial q_i^n} - \lambda_i \, \alpha_i = 0, \tag{32}$$

where λ_i is the positive shadow cost of the constraint. Form the bordered Hessian for utility i,

$$H_i = \begin{bmatrix} \frac{\partial^2 u_i(q_i^r + q_i^n)}{(\partial q_i^r)^2} - \frac{\partial^2 C_i^r(q_i^r)}{(\partial q_i^r)^2} & \frac{\partial^2 u_i(q_i^r + q_i^n)}{\partial q_i^n \partial q_i^r} & 1 - \alpha_i \\ \frac{\partial^2 u_i(q_i^r + q_i^n)}{\partial q_i^r \partial q_i^n} & \frac{\partial^2 u_i(q_i^r + q_i^n)}{(\partial q_i^n)^2} - \frac{\partial^2 C_i^n(q_i^n)}{(\partial q_i^n)^2} & -\alpha_i \\ 1 - \alpha_i & -\alpha_i & 0 \end{bmatrix} \tag{33}$$

Using Schwarz' theorem, the determinant of the bordered Hessian is,

$$-\left[(1-\alpha_i)\left(\frac{\partial^2 u_i(q_i^r+q_i^n)}{\partial q_i^n \partial q_i^r} - (1-\alpha_i)\frac{\partial^2 C_i^n(q_i^n)}{(\partial q_i^n)^2}\right) + \alpha_i\left(\frac{\partial^2 u_i(q_i^r+q_i^n)}{\partial q_i^n \partial q_i^r} - \alpha_i \frac{\partial^2 C_i^r(q_i^r)}{(\partial q_i^r)^2}\right)\right] > 0 \tag{34}$$

At a global maximum, $|H_i|$ must have the same sign as $(-1)^N$ where N is the number of first order conditions. This system satisfies this condition with $N = 2$.

A.5 Derivation of REC price under quadratic utility and costs

In equilibrium, the first order conditions are satisfied for each firm i, along with the market clearing condition. The Jacobian of this system of 2N+1 equations forms the bordered Hessian for the system of firm profit maximization problems. Re-write the utility and cost functions using the assumption that all firms' utility functions and cost functions are quadratic:

$$\frac{\partial u_i(q_i^r+q_i^n)}{\partial q_i^r} = \frac{\partial u_i(q_i^r+q_i^n)}{\partial q_i^n} = u_i^1+u_i^2(q_i^r+q_i^n) \qquad \frac{\partial C_i^r(q_i^r)}{\partial q_i^r} = r_i^1+r_i^2 q_i^r \qquad \frac{\partial C_i^n(q_i^n)}{\partial q_i^n} = n^1+n^2 q_i^n,$$

where $u_i^1, u_i^2, r_i^1, r_i^2, n_i^1, n_i^2 \in \mathbb{R}$ for all firms i. The system of $2N+1$ first order conditions that govern the N state equilibrium can be written as:

$$\begin{bmatrix} u_1^2 - r_1^2 & u_1^2 & 0 & 0 & ... & 0 & 0 & 1-\alpha_1 \\ u_1^2 & u_1^2 - n_1^2 & 0 & 0 & ... & 0 & 0 & -\alpha_1 \\ 0 & 0 & u_1^2 - r_2^2 & u_2^2 & ... & 0 & 0 & 1-\alpha_2 \\ 0 & 0 & u_1^2 & u_2^2 - n_2^2 & ... & 0 & 0 & -\alpha_2 \\ ... & ... & ... & ... & ... & ... & ... & ... \\ 0 & 0 & 0 & 0 & ... & u_N^2 - r_N^2 & u_N^2 & 1-\alpha_N \\ 0 & 0 & 0 & 0 & ... & u_N^2 & u_N^2 - n_N^2 & -\alpha_N \\ 1-\alpha_1 & -\alpha_1 & 1-\alpha_2 & -\alpha_2 & ... & 1-\alpha_N & -\alpha_N & 0 \end{bmatrix} \begin{bmatrix} q_1^r \\ q_1^n \\ q_2^r \\ q_2^n \\ ... \\ q_N^r \\ q_N^n \\ \xi \end{bmatrix} = \begin{bmatrix} r_1^1 - u_1^1 \\ n_1^1 - u_1^1 \\ r_2^1 - u_2^1 \\ n_2^1 - u_2^1 \\ ... \\ r_N^1 - u_N^1 \\ n_N^1 - u_N^1 \\ 0 \end{bmatrix} \tag{35}$$

The bordered Hessian of the system of firm profit maximization problems is a (2N+1)x(2N+1) matrix in a bordered block diagonal form. Simplfying it into block matrix form:

$$H_{sys} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{36}$$

Where A is the upper left justified 2Nx2N matrix, B is the 2Nx1 matrix in the last column, C is the 1x2N matrix in the last row, and D is the bottom right most 1x1 matrix which is equal to zero. The inverse of H_{sys} is given by:

$$H_{sys}^{-1} = \begin{bmatrix} A^{-1} + A^{-1}B(D - CA^{-1}B)^{-1}CA^{-1} & -A^{1}B(D - CA^{-1}B)^{-1}CA^{-1} \\ -(D - CA^{-1}B)^{-1}CA^{-1} & (D - CA^{-1}B)^{-1} \end{bmatrix} \tag{37}$$

Notice that A is block diagonal so A^{-1} is a block diagonal matrix where the subblocks are the inverse of the 2x2 subblocks of A. Also note that D is zero. This implies that the bottom left block of A^{-1} is $-(CA^{-1}B)^{-1}CA^{-1}$ and the bottom right block is $(-CA^{-1}B)^{-1}$. To obtain ξ, only the last row of the inverse must be calculated. Next we derive the terms that compose the inverse Hessian. Using the no REC trade Hessian from Section A.4.1, we can show that,

$$\underbrace{(-CA^{-1}B)^{-1}}_{1x1} = \frac{-1}{\sum_{i=1}^{N} \frac{1-\alpha_i}{|U_i|}\left((1-\alpha_i)(u_i^2 - n_i^2) + \alpha_i u_i^2\right) + \frac{\alpha_i}{|U_i|}\left((1-\alpha_i)u_i^2 + \alpha_i(u_i^2 - r_i^2)\right)}. \tag{38}$$

CA^{-1} is a matrix of dimension 2Nx1 where the 2x1 submatrix at elements (2k-1, 2k) is given by,

$$\left[\left(\frac{1-\alpha_k}{|U_k|}(u_k^2 - n_k^2) + \frac{\alpha_k}{|U_k|}u_k^2\right) \quad \left(-\frac{1-\alpha_k}{|U_k|}u_k^2 - \frac{\alpha_k}{|U_k|}(u_k^2 - r_k^2)\right)\right] \tag{39}$$

where $|U_k| = (u_k^2 - r_k^2)(u_k^2 - n_k^2) - (u_k^2)^2$ is the firm's Hessian when not constrained by an RPS policy. Let the 2N+1 system of equations be denoted by $H_{sys}\,x = b$. Inverting H_{sys}, ξ is given by the following matrix product, noting that the last element of b is zero:

$$\xi = [-(D - CA^{-1}B)^{-1}CA^{-1} \quad (D - CA^{-1}B)^{-1}]b$$

. Performing the matrix operations yields:

$$\xi(\alpha_1, ..., \alpha_N) = \frac{\sum_{k=1}^{N} \frac{1}{|U_k|} \left\{ (r_k^1 - u_k^1) \left[(1-\alpha_k)(u_k^2 - n_k^2) + \alpha_k u_k^2 \right] - (n_k^1 - u_k^1) \left[(1-\alpha_k) u_k^2 + \alpha_k (u_k^2 - r_k^2) \right] \right\}}{\sum_{i=1}^{N} \frac{1}{|U_i|} \left\{ (1-\alpha_i) \left((1-\alpha_i)(u_i^2 - n_i^2) + \alpha_i u_i^2 \right) + \alpha_i \left((1-\alpha_i) u_i^2 + \alpha_i (u_i^2 - r_i^2) \right) \right\}} \tag{40}$$

Before continuing, we bring up two important points. First, recognize that the denominator of equation (40) can be re-written as $\sum_{k=1}^{N}(CA^{-1}B)_k$ where $(CA^{-1}B)_k$ is the vector $CA^{-1}B$ where all elements $i \neq k$ are zero. Second, consider the 1 firm system of equilibrium conditions when REC trade is not allowed,

$$\begin{bmatrix} u_1^2 - r_1^2 & u_1^2 & 1-\alpha_1 \\ u_1^2 & u_1^2 - n_1^2 & -\alpha_1 \\ 1-\alpha_1 & -\alpha_1 & 0 \end{bmatrix} \begin{bmatrix} q_1^r \\ q_1^n \\ \lambda_1 \end{bmatrix} = \begin{bmatrix} r_1^1 - u_1^1 \\ n_1^1 - u_1^1 \\ 0 \end{bmatrix} \tag{41}$$

Using Cramer's rule, we can demonstrate that,

$$\lambda_1 = \frac{1}{|H_1|} \left\{ (r_1^1 - u_1^1) \left[(1-\alpha_1)(u_1^2 - n_1^2) + \alpha_1 u_1^2 \right] - (n_1^1 - u_1^1) \left[(1-\alpha_1) u_1^2 + \alpha_1 (u_1^2 - r_1^2) \right] \right\} \tag{42}$$

where $|H_1|$ is the bordered Hessian for the utility's profit maximization problem when constrained by an RPS. Notice that the shadow cost of the firm with no REC trade is equivalent to the expression inside the sum of the numerator in equation (40), but with $|U_k|$ replaced by $|H_k|$. We multiply each term k inside the sum of the numerator in equation (40) by $\frac{|H_k|}{|H_k|}$ so that we can form a new term in the sum: $\frac{|H_k|}{|U_k|}\lambda_k$. Last, recognize that $\frac{|H_k|}{|U_k|} = (CA^{-1}B)_k$.

Therefore using these two points we can determine that,

$$\xi(\alpha_1, ..., \alpha_N) = \frac{\sum_{k=1}^{N} (CA^{-1}B)_k \, \lambda_k}{\sum_{k=1}^{N} (CA^{-1}B)_k}, \tag{43}$$

which is a weighted average of the shadow cost of each utility when there is no REC trade.