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# Imperfect Competition in Electricity Markets with Renewable Generation: The Role of Renewable Compensation Policies

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# Imperfect Competition in Electricity Markets with Renewable Generation: The Role of Renewable Compensation Policies

by

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**Abstract**

We analyze the effects of commonly employed renewable compensation policies on firm behavior in an imperfectly competitive market. We consider a model where firms compete for renewable capacity in a procurement auction prior to choosing their forward contract positions and competing in wholesale electricity markets. We focus on fixed and premium-priced feed-in tariff (FIT) compensation policies. We demonstrate that the renewable compensation policy impacts both the types of resources that win the renewable auction and subsequent market competition. While firms have stronger incentives to exercise market power in wholesale markets under a premium-priced FIT, they also have increased incentives to sign pro-competitive forward contracts. Despite these countervailing incentives, in net firms have stronger incentives to exercise market power under the premium-priced policy. We find conditions under which renewable resources that are more correlated with market demand are procured under a premium-priced design, while the opposite occurs under a fixed-priced policy. If the cost efficiencies associated with the "more valuable" renewable resources are sufficiently large, then welfare is larger under the premium-priced policy despite the stronger market power incentives in the wholesale market. Finally, we consider incumbent behavior in the renewable auction when competing against entrants with more valuable resources.

**Keywords**: Electricity, Renewables, Market Power, Regulation, Procurement
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# 1 Introduction

Reducing greenhouse gas emissions has become an increasingly important economic issue worldwide. Governments often employ policies to motivate the deployment of renewable generation to reduce the reliance on fossil fuels in electricity markets. There has been an increased use of competitive auctions for contracts to deploy renewable resources. As of July 2017, forty-eight countries have adopted renewable auctions to subsidize renewable energy (Attia et al., 2017).[1] There is substantial heterogeneity in the details of these procurement auctions. One important detail is the form of compensation that firms receive when they win a contract to build renewable capacity.

In this paper, we analyze the impacts of different compensation policies in renewable procurement auctions in an oligopolistic setting where firms have market power and can invest in potentially heterogeneous renewable resources. We focus on the two most widely used compensation policies: a fixed-priced and premium-priced Feed-in Tariff (FIT).[2] Under a fixed-priced FIT, firms that win a contract receive a fixed-price per unit of output that is independent of the wholesale market price. Alternatively, under a premium-priced FIT firms receive the wholesale price plus a fixed mark-up (premium) per unit of output.[3] We demonstrate that the renewable compensation policy has important effects on both the nature of competition in wholesale markets and the characteristics of the renewable resources that win the renewable procurement auction.

We employ a model where the regulator specifies a fixed quantity of renewable capacity that it aims to procure. Then, firms compete in a renewable procurement auction to deploy renewable capacity before competing via Cournot competition in a wholesale spot market. An important additional feature that needs to be considered when modeling firm behavior in electricity markets is the presence of forward markets in which firms trade in advance of the wholesale market to supply output at fixed prices. Forward contracts have been found to reduce market power incentives in the wholesale spot market (Wolak, 2000; 2007). Consequently, after the renewable auction, we allow firms to choose forward contracts before competing in wholesale spot markets.

We find that firms have a stronger incentive to exercise market power in the wholesale spot market when their renewable generation is compensated under a premium-priced compared to a fixed-priced FIT. This arises because renewable output is compensated at the prevailing spot price. As renewable output expands, firms have a stronger incentive to withhold production from conventional generation in order to mitigate the reduction in spot market prices that is paid both to their conventional and renewable generation output.

In addition, we find that increases in renewable output have an ambiguous impact on firms' incentives to sign forward contracts. Firms expand their forward output as renewable output

[1] For example, renewable procurement auctions were implemented in 2017 in numerous countries including Argentina, Canada, Chile, France, Germany, Japan, Mexico, Turkey, and United Kingdom (REN21, 2018).

[2] See Couture and Gagnon (2010) and CEER (2017) for an overview of different compensation approaches.

[3] Jurisdictions such as Alberta Canada and the United Kingdom implemented policies that include a fixed-priced per unit of output (AESO, 2016; REN21, 2018). Alternatively, countries such as China, France, Germany, and Spain implemented policies that included elements of premium-priced FITs (CEER, 2017; REN21, 2018).

expands under a premium-priced FIT, while they reduce their forward quantities when a sufficiently large proportion of their renewable output is compensated at a fixed-priced FIT. This arises because of the larger strategic incentive to forward contact in the premium-priced setting. This result is in contrast to the previous literature which has found that forward contracting unambiguously declines as renewable output expands (Ritz, 2016; Acemoglu et al., 2017). The increased incentive to forward contract under the premium-priced FIT mitigates some of the elevated incentives to exercise market power in the spot market, but prices remain unambiguously higher under the premium-priced setting for a fixed quantity of renewable capacity.

In our model, firms compete in a renewable auction where the identity of the winner of the auction impacts firms' subsequent wholesale profits. Consequently, firms internalize the impact that the allocation of renewable capacity has on their subsequent profits when making their bidding decisions. In this setting, we demonstrate that the renewable compensation policy affects the types of resources that win the renewable auction. Under a premium-priced FIT, we identify conditions under which the "more valuable" renewable resource wins the procurement auction.[4] The opposite result arises under the fixed-priced FIT. If the cost-reductions from the more efficient renewable resource is sufficiently large, then the efficiency gains of the more valuable renewable resource being adopted under the premium-priced FIT dominates the elevated market power observed in the spot market. This results in an overall increase in welfare under the premium-priced FIT. These findings emphasize the various trade-offs under the premium-priced and fixed-priced FIT environments, and stress the importance of accounting for both the endogenous adoption of heterogeneous renewable resources and the nature of market competition.

We extend the baseline model to allow a potential entrant to compete for the renewable capacity. Under a fixed-priced FIT, the least valuable renewable resource continues to win the auction regardless of ownership. However, under the premium-priced FIT, an incumbent wins the auction if the cost of production from conventional resources are sufficiently large or the entrant's potential renewable resource is not substantially more productive in high demand hours than the incumbents' potential renewable investment. Importantly, we identify conditions under which an incumbent with a less valuable renewable resource wins the auction to prevent entry.

Section 2 discusses our contribution to the literature. The model is detailed in Section 3. Section 4 presents the equilibrium results for the forward and wholesale (spot) markets. We detail the solution to the renewable auction in Section 5. Section 6 introduces a competitive fringe into our model. Section 7 concludes. The proofs of all formal results are presented in the Appendix.[5]

[4] In our model, we define more valuable resources as renewable resources whose output is more correlated with market demand (and market prices), and assume that the renewable resources generate the same output in aggregate across all time periods. This abstracts from the setting where there is a renewable resource that is less correlated with demand, but generates more in aggregate across all time periods. Brown and Eckert (2018) demonstrate that the renewable resource whose less correlated with market demand may win the renewable auction if its aggregate market output is sufficiently larger than the resource whose output is more correlated with demand.

[5] Brown and Eckert (2018) present a Technical Appendix with additional findings and robustness checks.

## 2 Related Literature

There exists a large literature that investigates the trade-offs associated with different renewable compensation policies. These studies often assume markets are perfectly competitive or that output decisions are made by a central planner or system operator, focusing on the incentives for renewable investment created by different compensation mechanisms (e.g., Lesser and Su (2008), Garcia et al. (2012), Ambec and Crampes (2017), Antweiler (2017), and Schneider and Roozbehani (2017)).

Several recent articles consider the implications of wholesale market power on the effectiveness of different forms of renewable compensation. In a closely related study, Oliveira (2015) considers a two-stage model in which firms with exogenous conventional generation capacity first choose investments in renewable capacity, and then act as Cournot competitors in the spot market. The author compares outcomes when renewable generation is compensated by a fixed-priced versus a premium-priced FIT. The author highlights results that also emerge in our analysis; while premium-priced FITs can result in greater exercise of market power, premiums also provide a stronger incentive to invest in renewable capacity with production more highly correlated with demand.

Our paper differs from Oliveira's (2015) analysis in several ways. We introduce forward markets, which play an important role on firm behavior. Our model allows firms to own a combination of fixed-priced and premium-priced FIT renewable contracts. We model renewable procurement auctions that are increasingly employed in practice. This form of procurement has important impacts on strategic behavior as firms consider the impact of their rivals' winning the auction on their subsequent wholesale profits when making their bidding decisions. In addition, we consider the relative incentives of incumbents and new entrants to invest in renewable generation under different compensation policies.[6]

Our study is also related to a recent literature that considers the interaction of increased penetration of renewables with forward markets. It has been established in prior studies that firms' incentives to exercise market power depend critically on the quantities committed to through forward contracts signed in advance at fixed prices (e.g., Allaz and Vila, 1993; Wolak, 2000, 2007; Bushnell et al., 2008). Ritz (2016) extends the strategic forward-contracting model of Allaz and Vila (1993) to consider the effect of intermittent renewables production owned solely by a competitive fringe, and finds that renewable output reduces firms' forward quantities.[7]

In contrast, Acemoglu et al. (2017) examine the effect of shifting ownership of renewable capacity from non-strategic third parties to oligopolists who also operate conventional generation in a Cournot setting with forward markets.[8] The authors demonstrate that the "merit order" effect

[6]Regarding strategic behaviour, our paper is related to von der Fehr and Ropenus (2017), who consider the potential for foreclosure by a dominant firm through its behaviour in a market for tradeable green certificates.

[7]Similarly, Twomey and Neuhoff (2010) use monopoly and Cournot duopoly models with forward contracting and wind generation owned by a competitive fringe. The authors find in their setting that permitting market power may disadvantage intermittent renewable generation and reduce the incentives for investment.

[8]See also Genc and Reynolds (2017) for an analysis of the effects of renewable generation ownership in the setting of a dominant firm with a competitive fringe.

through which increased renewable generation reduces market prices is weakened as the proportion of renewable capacity owned by the Cournot producers increases.[9] Conventional generators who also own renewable capacity have an incentive to withhold conventional generation. While instructive, certain assumptions limit the generality of their results. In particular, the authors assume that conventional generators hold an equal amount of renewable capacity. We demonstrate that this assumption proves to be an important driver of their result that renewable output unambiguously lowers forward contracting incentives.

Notably, Ritz (2016) and Acemoglu et al. (2017) take the ownership of renewable capacity as exogenous. To the best of our knowledge, limited attention has been paid to the design of competitive process to procure renewable capacity, and how behaviour in these competitive mechanisms is related to the form of compensation policy.[10] In a recent contribution, Voss and Madlener (2017) model auction mechanisms for renewable capacity in the context of Germany. However, their focus is on the design of the auction as opposed to the form of the compensation mechanism.[11]

Lastly, our approach is related to two strands of literature where firms undertake investments or purchase products in auctions anticipating how the outcome of these transactions impact subsequent payoffs in future interactions. The innovation literature considers the incentives for firms with market power and facing potential entry to invest in cost-reducing technologies (see Gilbert and Newbery (1984) for a seminal contribution to this literature). As well, there is a growing literature on auctions with allocation externalities, in which the sale of product(s) in an auction affect subsequent payoffs. As a result, firms consider the identity of the winning bidder(s) when they make their bidding decision(s) (e.g., see Jehiel et al. (1996) and Aseff and Chade (2008)).

# 3 Model

In our baseline model, two firms compete to supply a homogeneous product (electricity) in $t = 1, 2, ..., T$ periods. We consider a multi-stage game. In the first-stage, the regulator organizes a renewable auction to procure a specified amount of renewable capacity $R > 0$. Both firms have existing conventional (non-renewable) generation capacity. In the second stage, firms simultaneously choose quantities $q_{it}^f$ to sell in the forward market at a price $P_{it}^f$ for each future period $t = 1, 2, ..., T$. In the third stage, taking forward contracted quantities as given, the firms compete in a (wholesale) spot market by simultaneously choosing quantities $q_{it}$ for each period $t = 1, 2, ..., T$.

Market demand in the spot electricity market is given by $P_t(Q_t) = \alpha_t - \beta_t Q_t$, where $\alpha_t > 0$, $\beta_t > 0$, and $Q_t = q_{1t} + q_{2t}$ reflects total output from both conventional generation and renewable output. Define $R_i \geq 0$ to be firm $i$'s renewable capacity in the spot market with capacity utilization

[9] Empirical estimates of the merit order effect can be found for example in Ciarreta et al. (2017) for Spain, Lunackova et al. (2017) for the Czech Republic, Woo et al. (2016) for California, and Cludius et al. (2014) and Wurzburg et al. (2013) for Germany and Austria.

[10] There is a small related literature on the interaction between forward markets and the incentives for capacity investment; see for example Murphy and Smeers (2010) and Ferreira (2014).

[11] See also Butler and Neuhoff (2008), Becker and Fischer (2013), and Shrimali et al. (2016) for discussions of auctions for renewable capacity in different jurisdictions, and comparisons to other procurement mechanisms.

$\theta_{it} \in [0,1]$ resulting in renewable energy output $\theta_{it}R_i \geq 0$ for each $i = 1,2$ and $t = 1,2,...,T$. For expositional purposes, we assume the realization of $\theta_{it}$ is deterministic and common knowledge among all players in each stage; Brown and Eckert (2018) demonstrate that our findings extend to the setting with stochastic renewable output. Define $q_{it} - \theta_{it}R_i$ to be firm $i$'s output from conventional (non-renewable) generation. Firm $i$'s cost function for conventional generation is given by $C_{it}(q_{it}, \theta_{it}R_i) = \frac{c_{it}}{2}(q_{it} - \theta_{it}R_i)^2$, where $c_{it}$ is a positive constant.

Renewable output is compensated either by a fixed-price FIT $\overline{P}_i$ per-unit or by a premium-priced FIT which compensates renewable supply at the spot market price plus a mark-up (premium) $m_i$. Consequently, the premium-priced FIT results in per-unit compensation $P_t(Q_t) + m_i$. Define $\delta_i \in [0,1]$ and $1 - \delta_i \in [0,1]$ to be the fraction of firm $i$'s renewable output that is compensated at a fixed-priced FIT and a premium-priced FIT, respectively.

At the renewable procurement auction phase, the regulator specifies a fixed amount of renewable capacity $R > 0$ that it aims to procure. We consider a winner-take-all auction where firms compete to win the rights to a contract to construct the $R$ units of renewable capacity.[12] Define $F_i > 0$ to be firm $i$'s fixed cost of building the new renewable facility. The fixed cost of investment is common knowledge to all firms. The firms simultaneously and independently submit bids in the procurement auction. In the fixed-priced FIT setting, a firm's bid reflects the fixed-priced contract it is willing to accept in order to build the renewable facility. In the premium-priced FIT setting, the bid reflects the premium above the spot market price the firm has to be paid in order to build and operate the facility. For either renewable compensation policy, the contract is awarded to the firm with the lowest bid, who is compensated according to its bid.[13]

Similar to Allaz and Vila (1993) and Bushnell (2007), we assume that firms' forward positions are public knowledge, firms are risk-neutral, and forward and spot market prices are efficiently arbitraged resulting in forward market prices equaling expected spot market prices. We solve for the Subgame Perfect Nash Equilibrium (SPNE) using backward induction.

# 4 Forward and Spot Market Equilibrium

We first solve for the equilibrium outcomes in the forward and spot market periods for a given amount of renewable generation capacity $R_i \geq 0$ owned by each firm. This allows us to demonstrate how the presence of renewable generation capacity impacts the nature of competition, and how these effects vary with the prevailing renewable compensation policy.

## 4.1 Spot Market Equilibrium

Consider the third stage spot market where for each firm $i = 1,2$, renewable capacity $R_i$ is fixed, and forward market quantities $q_{it}^f$ have been chosen and committed at price $P_{it}^f$ for each

[12] In practice, firms exploit economies of scale and undertake lumpy renewable capacity investments. We focus on a setting where a single firm bids to supply the fixed quantity of renewable capacity. Section 7 emphasizes the importance of future research that allows for multiple potential winners.

[13] We abstract from information asymmetries in firms' fixed and variable cost functions. Incorporating information asymmetries into the current model is a subject for future research.

$t = 1, 2, ..., T$. For illustrative purposes, throughout the analysis we assume that $q_{it} - \theta_{it} R_i > 0$ in equilibrium, so that each firm $i$ produces a positive amount of conventional generation in each period $t$.[14] Firm $i$'s spot market profit in period $t$ equals:

$$\pi_{it}(\cdot) = P_t(Q_t)[q_{it} - \theta_{it} R_i - q_{it}^f] - C_{it}(q_{it}, \theta_{it} R_i) + \overline{P}_i\, \delta_i\, \theta_{it}\, R_i + [P_t(Q_t) + m_i]\,(1 - \delta_i)\, \theta_{it}\, R_i + P_{it}^f\, q_{it}^f. \quad (1)$$

Firm $i$ sells $q_{it} - \theta_{it} R_i - q_{it}^f$ units of conventional output that is compensated at the spot price. If this term is positive (negative), then the firm is a net seller (buyer) in the spot market. For the forward contracted output $q_{it}^f$, firm $i$ receives a fixed-price $P_{it}^f$ which is taken as given in the spot market. Similarly, a fraction $\delta_i \in [0, 1]$ of renewable output $\theta_{it} R_i$ is compensated at the fixed-price FIT ($\overline{P}_i$), while a portion $1 - \delta_i$ is compensated at the spot price plus a premium ($P_t(Q_t) + m_i$).

Firm $i$'s payoff maximizing total output for a given level of forward contracting is defined by:

$$\frac{\partial \pi_{it}(q_{1t}, q_{2t})}{\partial q_{it}} \;=\; P_t'(Q_t)[q_{it} - \delta_i\, \theta_{it} R_i - q_{it}^f] + P_t(Q_t) - C_{it}'(q_{it}) \;=\; 0. \quad (2)$$

Condition (2) demonstrates that firm $i$'s marginal revenue converges to the spot price $P_t(Q_t)$ as the amount of forward contracted output ($q_{it}^f$) and renewable output that is compensated at the fixed-price FIT ($\delta_i \theta_{it} R_i$) converges to its total spot market output ($q_{it}$). This induces firm $i$ to behave more like a perfectly competitive firm. This captures the well-established pro-competitive impacts of forward contracting (e.g., Allaz and Vila (1993)). As the amount of renewable output that is exposed to market prices increases (e.g., $\delta_i$ decreases), firm $i$'s has a stronger incentive to withhold output to elevate market prices because the higher price is passed onto its renewable output that is compensated at the prevailing spot price.

Lemma 1 summarizes how changes in critical variables impact the firms' spot-market output decisions, holding all else constant.[15]

**Lemma 1.** For each period $t = 1, 2, ..., T$ and firms $i, j = 1, 2$ with $i \neq j$, and for a given level of forward quantities, the equilibrium output in the spot electricity market changes as follows:

$$(i).\ \frac{\partial q_{it}^*}{\partial \theta_{it} R_i} \in (0, 1); \quad (ii).\ \frac{\partial q_{it}^{*\,2}}{\partial \theta_{it} R_i\, \partial \delta_i} > 0; \quad (iii).\ \frac{\partial q_{it}^*}{\partial \theta_{jt} R_j} \in (-1, 0); \quad (iv).\ \frac{\partial q_{it}^*}{\partial q_{it}^f} \in (0, 1);$$

$$(v).\ \frac{\partial q_{it}^*}{\partial q_{jt}^f} \in (-1, 0); \ (vi).\ \frac{\partial q_{it}^*}{\partial \delta_i} > 0\,; \ \text{ and } \ (vii).\ \frac{\partial q_{it}^*}{\partial \delta_j} < 0.$$

Lemma 1 provides several findings. From *(i)*, an increase in firm $i$'s renewable output increases its total output, but at a rate less than 1. This captures the "merit order" effect where oligopolistic

[14]This requires that renewable generation is not sufficiently large such that conventional generation is reduced to zero. In the Conclusion, we emphasize the importance of future research that considers renewable curtailment.

[15]We provide a detailed summary of the equilibrium spot market price, aggregate output, and each firm's optimal total quantity for a given level of forward quantities and renewable capacity in the Proof of Lemma 1.

competitors reduce output from conventional generation as renewable output expands to mitigate the price-reducing impact of renewable output expansion.[16] From *(ii)*, the magnitude of this "merit order" effect varies positively with $\delta_i$. Intuitively, as $\delta_i$ falls, so that more of the firm's renewable output is compensated by a premium-priced FIT, the firm has a greater incentive to withhold conventional generation. Result *(iii)* follows from the fact that increasing firm $j$'s renewable output increases its total output, and the outputs of the two firms are strategic substitutes.

Conditions *(iv)* and *(v)* demonstrate the strategic commitment of forward contract expansion.[17] An increase in firm $i$'s forward quantity commits firm $i$ to increase its spot market quantity, so that it induces its rivals to reduce their output. Similarly, as firm $i$'s rival increases its forward quantity, firm $i$ reduces its output because its rival is now committed to higher spot market quantities. From *(vi)*, an increase in the amount of renewable output that is compensated at the fixed-priced FIT ($\delta_i$) induces firm $i$ to increases its total output because less of firm $i$'s output is exposed to the reduction in the spot market price as its output expands. Condition *(vii)* demonstrates that an increase in firm $i$'s rival's renewable output that is compensated at a fixed-priced FIT ($\delta_j$) decreases firm $i$'s spot market output because its rival will expand its output (as shown in *(vi)*).

**Lemma 2.** In the spot market equilibrium, for a given level of forward contracted quantities, for each period $t = 1, 2, ..., T$ and $i, j = 1, 2$ with $i \neq j$:

(i) If $\delta_1 = \delta_2 = 1$, then $\frac{\partial q^*_{it} - \theta_{it} R_i}{\partial \theta_{it} R_i} = \frac{\partial q^*_{it} - \theta_{it} R_i}{\partial \theta_{jt} R_j} < 0$; and

(ii) If $\delta_1 < 1$ or $\delta_2 < 1$, then $\frac{\partial q^*_{it} - \theta_{it} R_i}{\partial \theta_{it} R_i} < \frac{\partial q^*_{it} - \theta_{it} R_i}{\partial \theta_{jt} R_j} < 0$.

Lemma 2 details how a firm's output from conventional generation ($q^*_{it} - \theta_{it} R_i$) changes as renewable output increases. Condition (i) demonstrates that the change in conventional generation is independent of who owns the renewable output when firms' renewable output is fully compensated at a fixed-priced FIT ($\delta_1 = \delta_2 = 1$). Consequently, increased renewable output has no strategic implications for the firm who acquires it. The only effect of a marginal increase in renewable output is through its impact on reducing residual demand to be served by conventional generation which is the same regardless of who owns the increased renewable output.

From condition (ii), when a portion of renewable output is compensated at the spot market price (i.e., $\delta_i < 1$), firm $i$ reduces its conventional generation by more in response to an increase in its own renewable output. This arises because as renewable output expands, it reduces the spot market price paid to conventional generation and a portion (or all) of firm $i$'s renewable output. Consequently, firm $i$ has a stronger incentive to reduce its flexible conventional generation to mitigate the reduction in the spot market price.

A cursory examination of equation (2) suggests that renewable capacity and quantities committed under forward contracts may play similar strategic roles, as they both reduce the amount

[16] This effect has been highlighted in other studies (e.g., Ben-Moshe and Rubin, 2015; Acemoglu et al., 2017).

[17] For additional details, see Allaz and Vila (1993), Wolak (2000, 2007), Bushnell (2007), and Bushnell et al. (2008).

of total output subject to the spot price, and potentially reduce the incentive for market power. The different strategic implications of changes in forward contracting and renewable output on equilibrium spot market quantities is investigated in Proposition 1.

**Proposition 1.** In the spot market equilibrium, for each $i = 1, 2$ and period $t = 1, 2, ..., T$:

$$\frac{\partial q_{it}^*}{\partial \theta_{it} R_i} \gtreqless \frac{\partial q_{it}^*}{\partial q_{it}^f} \quad \text{as} \quad c_{it} \gtreqless (1 - \delta_i)\beta_t.$$

Suppose $\delta_i = 1$ such that firm $i$'s renewable output is compensated at a fixed-price FIT. From Proposition 1, $\frac{\partial q_{it}^*}{\partial \theta_{it} R_i} > \frac{\partial q_{it}^*}{\partial q_{it}^f}$ such that the increase in firm $i$'s output is larger when renewable output expands (holding forward contracting constant) compared to an increase in forward contracting. When $\delta_i = 1$, increases in renewable output and forward contracting both increase the quantity of output that is compensated at an exogenous price. Hence, renewable output has a similar strategic commitment effect as forward contracting in the spot market. However, expanding zero-marginal cost renewable output also reduces firm $i$'s production cost for any level of total output $q_{it}^*$ (Recall $C_{it}(\cdot) = \frac{c_{it}}{2}(q_{it}^* - \theta_{it} R_i)^2$). This additional cost-reducing effect motivates firm $i$ to increase its total equilibrium output by more in response to an increase in renewable output.

As $\delta_i \to 0$, $\frac{\partial q_{it}^*}{\partial \theta_{it} R_i} < \frac{\partial q_{it}^*}{\partial q_{it}^f}$ if $c_{it}$ is sufficiently small. While expanding renewable output reduces cost and increases output committed at a fixed price (if $\delta_i > 0$), this also lowers the spot market price that is paid to conventional generation and a portion (or all) of renewable output. This latter effect can dampen firm $i$'s incentive to increase its spot market quantity in response to increased renewable output by a sufficiently high amount that firm $i$ increases its spot market output by more in response to an increase in its forward committed quantity.

### 4.2 Forward Market Equilibrium

Following Allaz and Vila (1993) and Bushnell (2007), we assume that forward markets are sufficiently liquid that there are no arbitrage opportunities, so that forward market prices equal expected spot market prices. Consequently, using (1), firm $i$'s profit function evaluated at the spot market quantities can be rewritten as:

$$\begin{aligned} \pi_{it}(q_{1t}^*(q_{1t}^f, q_{2t}^f), q_{2t}^*(q_{1t}^f, q_{2t}^f)) \;&=\; P_t(Q_t^*(q_{1t}^f, q_{2t}^f))[q_{it}^*(q_{1t}^f, q_{2t}^f) - \theta_{it} R_i] - C_{it}(q_{it}^*(q_{1t}^f, q_{2t}^f) \\ &\quad + \overline{P}_i \, \delta_i \, \theta_{it} \, R_i + [P_t(Q_t^*(q_{1t}^f, q_{2t}^f)) + m_i] \, (1 - \delta_i) \, \theta_{it} \, R_i, \end{aligned} \tag{3}$$

where $q_{1t}^*(q_{1t}^f, q_{2t}^f)$ and $q_{2t}^*(q_{1t}^f, q_{2t}^f)$ are the equilibrium third stage spot quantities of each firm.

Lemma 3 characterizes the equilibrium forward quantity decision for each firm $i = 1, 2$.

**Lemma 3.** For each period $t$, in equilibrium firm $i$'s forward quantity decision is determined by:

$$P_t'(Q_t^*) \, q_{it}^f \frac{\partial q_{it}^*}{\partial q_{it}^f} + P_t'(Q_t^*)[q_{it}^* - \delta_i \, \theta_{it} \, R_i] \frac{\partial q_{jt}^*}{\partial q_{it}^f} \;=\; 0. \tag{4}$$

The first term in (4) is negative and reflects the *direct effect* of forward contracting. Holding rival firm $j$'s spot market quantity constant, an increase in $q_{it}^f$ increases firm $i$'s spot quantity (Recall Lemma 1). This lowers the spot price and revenues earned on the $q_{it}^f$ forward units, reducing firm $i$'s incentive to expand its forward quantity. The second term in (4) is positive and reflects the *strategic effect* of forward contracting. Holding firm $i$'s spot market quantity constant, a unilateral increase in $q_{it}^f$ reduces firm $i$'s rival's spot market quantity $q_{jt}^*$ putting upward pressure on the spot market price that is paid to $q_{it}^* - \delta_i \theta_{it} R_i$ units of output.[18]

**Proposition 2.** Define $S_{it} \equiv P_t'(Q_t^*)[q_{it}^* - \delta_i\, \theta_{it}\, R_i] \frac{\partial q_{jt}^*}{\partial q_{it}^f}$ to be the strategic effect of forward contracting. Then:

$$\frac{\partial S_{it}}{\partial \theta_{it} R_i} \gtreqless 0 \quad \text{as} \quad \delta_i \lesseqgtr \widetilde{\delta}_{it}$$

where $\widetilde{\delta}_{it} \equiv \frac{c_{it}(2\beta_t + c_{jt})}{\beta_t(\beta_t + c_{jt}) + c_{it}(2\beta_t + c_{jt})} \in (0,1)$ for $i, j = 1, 2$ with $i \neq j$.

Proposition 2 demonstrates that the impact of renewable output on firm $i$'s strategic incentive to forward contract depends critically on the renewable compensation policy. Because the strategic benefit of forward contracting is to reduce firm $i$'s rival's spot market quantity, putting upward pressure on the spot market price, this benefits firm $i$ to the extent that its output is sold at the spot market price. When $\delta_i = 1$, increasing $\theta_{it} R_i$ decreases the quantity sold at the spot price resulting in a weaker strategic effect. Alternatively, when $\delta_i = 0$, increasing $\theta_{it} R_i$ increases firm $i$'s quantity sold at the spot market price resulting in a stronger strategic effect. For intermediate values of $\delta_i$ the relative magnitude of these two countervailing forces determine the sign of $\frac{\partial S_{it}}{\partial \theta_{it} R_i}$.

**Proposition 3.** For each period $t$, in equilibrium the proportion of firm $i$'s total electricity output that is covered by forward contracted output $(\frac{q_{it}^{f\,*}}{q_{it}^*})$ is strictly decreasing in $\delta_i\, \theta_{it} R_i$.

Proposition 3 demonstrates that firm $i$'s percentage of total spot output covered by forward contracts decreases as either more renewable output is compensated at a fixed-priced FIT ($\delta_i$ increases) and/or as renewable output increases for any given level of $\delta_i > 0$ causing the amount of output that is compensated at a fixed-priced FIT to increase. This result reflects the findings in Proposition 2 that a firm's strategic incentive to forward contract is decreasing in renewable output when a sufficiently large amount of the output is compensated at a fixed-priced FIT. Note as well that under our assumptions of linear demand and marginal cost curves, when $\delta_i = 0$, $\frac{q_{it}^{f\,*}}{q_{it}^*}$ becomes independent of $\theta_{it} R_i$ (see the proof of Proposition 3 for details).

Proposition 4 demonstrates that the impact of renewable output on equilibrium forward contracts depends critically on the renewable compensation policy.[19]

[18] Further discussion of the direct and strategic effects of forward contracting can be found for example in Brown and Eckert (2017).

[19] Equilibrium forward market quantities and a formal definition of $\widehat{\delta}_{it}$ is presented in the Proof of Proposition 4.

**Proposition 4.** In equilibrium, for each period $t = 1, 2, ..., T$ and $i, j = 1, 2$ with $i \neq j$:

$$\frac{\partial q_{it}^{f*}}{\partial \theta_{it} R_i} \lesseqqgtr 0 \quad \text{as} \quad \delta_i \gtreqqless \widehat{\delta}_{it} \in (0,1) \quad \text{and} \quad \frac{\partial q_{it}^{f*}}{\partial \theta_{jt} R_j} < 0. \tag{5}$$

Proposition 4 finds that firm $i$'s forward contracted quantity $q_{it}^{f*}$ increases (decreases) as its renewable output expands when $\delta_i$ is sufficiently small (large). This follows directly from Proposition 2 which demonstrates that the strategic incentive to forward contract is increasing (decreasing) in its own renewable output when a sufficiently large portion of renewable output is compensated under a premium-priced (fixed-priced) FIT. As a result, forward contracted quantities are higher when both firms are subject to a premium-priced policy compared to a fixed-priced FIT.[20]

Proposition 4 also illustrates that firm $i$'s equilibrium forward contracted quantity is strictly decreasing in its rival's renewable output. From Lemma 1, increasing firm $i$'s rival's renewable output reduces $i$'s spot market quantity. As noted in the discussion of Proposition 2 above, a reduction in firm $i$'s spot market quantity reduces its strategic incentive of forward contracting.

Proposition 4 demonstrates that an increase in a firm's own renewable output has an ambiguous impact on its forward contracting incentives. This finding is in contrast with Acemoglu et al.'s (2017) result that forward contracts are strictly decreasing in renewable output in a setting where $\delta_i = 0$ for all $i = 1, 2$. This result holds in a special case of our model where firms are symmetric and both firms' renewable output increases in equal proportion (as in Acemoglu et al.'s (2017) analysis) for any value on $\delta_i \in [0, 1]$.[21] The reasoning for this result is as follows. Proposition 4 finds that $\frac{\partial q_{it}^{f*}}{\partial \theta_{it} R_i} > 0$ when $\delta_i$ is sufficiently small and $\frac{\partial q_{it}^{f*}}{\partial \theta_{jt} R_j} < 0$ for any $\delta_i \in [0, 1]$ with $i, j = 1, 2$ and $i \neq j$. If both firms are symmetric and we increase renewable output from both firms in equal proportion, then the net effect of the increased renewable output is to decrease firm $i$'s forward quantity in equilibrium for any $\delta_i \in [0, 1]$, generalizing the result in Acemoglu et al.'s (2017) analysis. However, when firms are not symmetric and the renewable output of one firm increases unilaterally, Proposition 4 illustrates that the change in forward contracted quantities is ambiguous and its sign depends on the prevailing renewable compensation policy.

Proposition 5 compares equilibrium market outcomes when all renewable output is compensated via a fixed-priced or premium-priced FIT.

**Proposition 5.** Define $Q_{t,\overline{P}}{}^*$ and $Q_{t,m}{}^*$ to be the equilibrium spot market quantity in period $t$ when $\delta_1 = \delta_2 = 1$ and $\delta_1 = \delta_2 = 0$, respectively. Then, in equilibrium: $Q_{t,\overline{P}}{}^* > Q_{t,m}{}^*$ and $P_t(Q_{t,\overline{P}}{}^*) < P_t(Q_{t,m}{}^*)$ for all $t = 1, 2, ..., T$.

Proposition 5 demonstrates that the equilibrium market-level spot quantity is higher and prices

[20] We also find that a firm $i$ strictly lowers its forward contracted quantity when renewable output expands, and this effect is identical regardless of who owns the increased renewable capacity when $\delta_1 = \delta_2 = 1$ (i.e., $\frac{\partial q_{it}^{f*}}{\partial \theta_{it} R_i} = \frac{\partial q_{it}^{f*}}{\partial \theta_{jt} R_j} < 0$ when $\delta_1 = \delta_2 = 1$). See Corollaries B1 and B2 in Brown and Eckert (2018) for additional details.

[21] See Proposition B1 in Brown and Eckert (2018) for a formal demonstration of this result.

are lower when both firms' renewable output is compensated at a fixed-priced FIT compared to a premium-priced FIT. While forward contracting incentives are stronger under the premium-priced FIT in the presence of positive renewable output (recall Propositon 4), firms have an incentive to withhold more spot market output under the premium-priced setting because the higher spot market price is paid to both its output from conventional and renewable generation resources (recall Lemma 1). Proposition 5 demonstrates that the latter effect dominates the former resulting in a lower market-level output under a premium-priced FIT. As a result, spot market prices are higher under the premium-priced setting for any given exogenous level of renewable capacity.

# 5 Renewable Procurement Auction

In this section, we investigate the first stage of the game where the regulator aims to procure a specified level of renewable generation capacity in a winner-take-all auction. This allows us to investigate the impact of renewable compensation policies on who wins the renewable procurement auction, and on the nature of subsequent forward and spot market competition.

For analytical tractability, we assume that there is no existing renewable capacity and the regulator aims to auction off a specified amount of renewable generation capacity $R > 0$. We restrict attention to the case of symmetric conventional cost functions ($c_1 = c_2 = c$). Further, we assume that there are two periods: Low ($t = L$) and High ($t = H$). Market demand curves in periods $L$ and $H$ differ by intercept ($\alpha_H > \alpha_L$), but have the same slope parameters ($\beta_L = \beta_H = \beta$).[22] Finally, we suppose that market demand to be served by conventional generation at a given price is larger in the $t = H$ period regardless of whose renewable technology is employed in each period (i.e., $\alpha_H - \beta\theta_{iH}R > \alpha_L - \beta\theta_{jL}R$ for any $i, j = 1, 2$).

We consider two settings based on how the renewable resource will be compensated: (i) fixed-priced FIT ($\delta_1 = \delta_2 = 1$) or (ii) premium-priced FIT ($\delta_1 = \delta_2 = 0$). The firms simultaneously and independently submit bids for the renewable resource. Under a fixed-priced FIT, a firm $i$ bids the fixed-price $\overline{P}_i$ it is willing to accept to build the renewable facility. Under a premium-priced FIT, a firm $i$ bids the premium $m_i$ it is willing to accept to build the renewable facility. The firm that submits the lowest bid must pay a fixed cost $F > 0$ and build the renewable facility. In the case of ties, randomized rationing is assumed. The winning firm's renewable compensation in the subsequent spot market equals the bid that it submits in the renewable procurement auction.

We characterize the equilibrium outcome, taking into account subsequent behavior in the forward and spot markets. Define $(Q^*_{t,Rj}, q^*_{1,t,Rj}, q^*_{2,t,Rj}, q^{f*}_{1,t,Rj}, q^{f*}_{2,t,Rj})$ to be the equilibrium market-level output, firm-level outputs, and firm-level forward contracted quantities in period $t$ when firm $j$ wins the renewable capacity in the auction (which is represented by the subscript notation $Rj$).

Before proceeding to analyzing the renewable auction stage, we acknowledge a technical consideration. Our renewable auction is modeled as a first price sealed-bid auction with complete information. These assumptions have implications for Nash equilibria in the auction stage. The

[22] Brown and Eckert (2018) investigate the robustness of our results to these symmetry assumptions.

complete information assumption implies that a best response to a rival's bid may not be unique. In particular, a firm's best response to its rival's bid may be to undercut their bid by some arbitrarily small amount $\epsilon > 0$. This could be resolved by assuming that firms bid on a discrete grid (e.g., bids must be to the nearest cent). Further, the design of our auction means that there can be multiple Nash equilibria. However, it is the case that in this setting, the Nash equilibria involve the same renewable technology winning the auction. In what follows, we sidestep these issues by focusing not on precise value of the winning bid, but on which renewable technology wins the auction.

### 5.1 Fixed-Priced Feed-in Tariff

Suppose the regulator announces that the winning renewable resource will be compensated via a fixed-priced FIT. Further, suppose initially that the firms compete in the renewable procurement auction for a homogeneous renewable resource with the same capacity utilization profile in each period: $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. Lemma 4 characterizes properties of the subsequent spot and forward market equilibrium outcomes.

**Lemma 4.** Suppose $\delta_1 = \delta_2 = 1$, $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. In equilibrium, for each period $t$ and $i, j = 1, 2$ with $i \neq j$, $Q^*_{t,R1} = Q^*_{t,R2}$, $q^{f*}_{t,i,Ri} = q^{f*}_{t,i,Rj}$, and $q^*_{t,i,Ri} = q^*_{t,i,Rj} + \theta_t R$.

Lemma 4 illustrates that under the fixed-priced FIT, the equilibrium aggregate spot market output and firm-level forward contracting is unaffected by the allocation of renewable capacity. Further, when firm $i$ wins the renewable procurement auction, its spot market output increases by the level of renewable output of its new renewable resource. This reflects the limited strategic implications of renewable capacity in the setting with a fixed-priced FIT (Recall Lemma 2).

Define $\overline{P}_i^{min}$ to be the fixed-priced FIT that makes firm $i$ indifferent between receiving the renewable capacity and its rival receiving the renewable capacity. This reflects the minimum amount that firm $i$ is willing to bid into the renewable procurement auction when $\delta_1 = \delta_2 = 1$.

**Lemma 5.** Under the fixed-priced FIT:

$$\overline{P}_i^{min} \;=\; \frac{F}{\sum\limits_{t=L,H} \theta_{it} R} - \left( \frac{1}{\sum\limits_{t=L,H} \theta_{it} R} \right) \sum_{t=L,H} \Delta\Pi^{Conv}_{i,t} \quad \text{for each} \quad i, j = 1, 2 \quad \text{with} \quad i \neq j \qquad (6)$$

where $\Delta\Pi^{Conv}_{i,t} = \Pi^{Conv}_{i,t,Ri} - \Pi^{Conv}_{i,t,Rj} = P_t(Q^*_{t,Ri})\,[q^*_{i,t,Ri} - \theta_{it} R] - C_{it}(q^*_{i,t,Ri}) - [P_t(Q^*_{t,Rj})\,q^*_{i,t,Rj} - C_{it}(q^*_{i,t,Rj})]$.

Lemma 5 characterizes each firm's minimum fixed-priced bid. The first term in (6) reflects average fixed cost. The second term includes $\Delta\Pi^{Conv}_{i,t} = \Pi^{Conv}_{i,t,Ri} - \Pi^{Conv}_{i,t,Rj}$ which reflects the change in firm $i$'s spot market profits earned by its conventional generation in period $t$ when it wins the renewable resource compared to when its rival $j$ wins the renewable capacity.

Proposition 6 ranks the firms' minimum bids in the homogeneous renewable resource case.

**Proposition 6.** Suppose $\delta_1 = \delta_2 = 1$, $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. Then, $\overline{P}_1^{min} = \overline{P}_2^{min} = \frac{F}{\sum\limits_{t=L,H} \theta_t R}$.

Proposition 6 finds that both firms are willing to bid as low as the average fixed cost of the renewable resource. In the symmetric renewable resource setting, renewable capacity has the same effect on a firms' conventional generation spot market profits regardless of who owns the resource (i.e., the second term in (6) equals zero). This arises because there is no strategic benefit of owning the renewable capacity in a setting with a fixed-priced FIT. From Lemmas 2 and 4, an increase in renewable output that is compensated at an exogenous price simply reduces the residual demand to be served by the strategic firms' conventional generation. This results in intense price competition in the procurement auction where the unique equilibrium entails both firms bidding at average fixed cost and winning with probability $\frac{1}{2}$ under randomized rationing.

Now we consider a setting where the firms have heterogeneous potential renewable capacity investments. Assumption 1 considers a setting where firm 1 has a less valuable potential renewable resource that generates more output in the lower demand period ($t = L$) and firm 2 has a more valuable renewable resource that generates more in the high demand period ($t = H$). However, both renewable investments generate the same aggregate amount of electricity, but the production is distributed differently across the two periods.

**Assumption 1.** Suppose that $\theta_{1L} > \theta_{2L}$, $\theta_{1H} < \theta_{2H}$, and $\theta_{1L} + \theta_{1H} = \theta_{2L} + \theta_{2H}$ .

Proposition 7 ranks the firm's minimum bids in the heterogeneous renewable resource setting.[23]

**Proposition 7.** Suppose $\delta_1 = \delta_2 = 1$ and Assumption 1 holds. Then, $\overline{P}_1^{min} < \overline{P}_2^{min}$.

Proposition 7 demonstrates that the firm with the less valuable resource (firm 1) is willing to accept a lower price in the renewable auction (i.e., $\overline{P}_1^{min} < \overline{P}_2^{min}$). The intuition behind this result is the following. Under the specified conditions, using (6), $\overline{P}_1^{min} < \overline{P}_2^{min}$ holds when:

$$\underbrace{\left(\Pi^{Conv}_{1,H,R1} - \Pi^{Conv}_{1,H,R2}\right)}_{\Delta\Pi^{Conv}_{1,H}} + \underbrace{\left(\Pi^{Conv}_{1,L,R1} - \Pi^{Conv}_{1,L,R2}\right)}_{\Delta\Pi^{Conv}_{1,L}} > \underbrace{\left(\Pi^{Conv}_{2,H,R2} - \Pi^{Conv}_{2,H,R1}\right)}_{\Delta\Pi^{Conv}_{2,H}} + \underbrace{\left(\Pi^{Conv}_{2,L,R2} - \Pi^{Conv}_{2,L,R1}\right)}_{\Delta\Pi^{Conv}_{2,L}}. \quad (7)$$

From Assumption 1, firm 1 (firm 2) has the less (more) valuable renewable resource which generates more output in the low demand (high demand) hour. Regardless of who wins the renewable auction, spot market profits from conventional generation decreases in the presence of renewable output because the spot price decreases. This price reduction is larger in the high (low) demand hour when firm 2 (firm 1) wins the renewable procurement auction under Assumption 1. Consequently, if firm 1 wins the renewable auction its conventional generation spot market profit is higher (lower) in the high demand (low demand) hour compared to the case where firm 2 wins

[23]Using numerical simulations, Brown and Eckert (2018) relax the symmetric cost and demand slope assumptions in order to illustrate that the conclusions in Proposition 7 holds more generally.

the renewable auction (i.e., $\Delta\Pi^{Conv}_{1,H} > 0$ and $\Delta\Pi^{Conv}_{1,L} < 0$). Similarly, if firm 2 wins the renewable auction its conventional spot market profit is higher (lower) in the low demand (high demand) hour compared to the case where firm 1 wins the renewable auction (i.e., $\Delta\Pi^{Conv}_{2,H} < 0$ and $\Delta\Pi^{Conv}_{2,L} > 0$).

The increase in firm 1's conventional spot profit during the high demand hour by winning the procurement auction exceeds the increase in firm 2's conventional spot profit during the low demand hour when it wins the renewable auction ($\Delta\Pi^{Conv}_{1,H} > \Delta\Pi^{Conv}_{2,L}$). Further, the reduction in firm 1's conventional spot profit during the low demand hour by winning the procurement auction is less than the reduction in firm 2's spot market profit during the high demand hour when it wins the renewable auction ($|\Delta\Pi^{Conv}_{1,L}| < |\Delta\Pi^{Conv}_{2,H}|$). Hence, inequality (7) holds.

To summarize, the firm with the less valuable resource has an incentive to win the renewable auction in order to prevent its rival with the more valuable renewable resource from winning the auction and suppressing both firms' subsequent conventional generation spot profits. As a result, firm 1 wins the renewable procurement auction by undercutting its rival's minimum bid $\overline{P}^{min}_2$ by some small amount $\epsilon > 0$.[24]

### 5.2 Premium-Priced Feed-in Tariff

Suppose the regulator announces that the winning renewable resource will be compensated via a premium-priced FIT. Further, suppose initially that the firms compete in the renewable procurement auction for a homogeneous renewable resource with the same capacity utilization profile in each period: $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. Lemma 6 characterizes properties of the subsequent spot and forward market equilibrium outcomes.

**Lemma 6.** Suppose $\delta_1 = \delta_2 = 0$, $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. In equilibrium, for each firm $i, j = 1, 2$ with $i \neq j$, the following inequalities hold in each period $t$: (i) $q^{f*}_{i,t,Ri} - q^{f*}_{i,t,Rj} > 0$; (ii) $q^*_{i,t,Ri} - q^*_{i,t,Rj} > 0$; and (iii) $q^*_{i,t,Ri} - \theta_t R < q^*_{i,t,Rj}$.

Lemma 6 demonstrates several useful findings. Inequality (i) demonstrates that a firm's forward contracted quantities are higher when it is allocated the renewable capacity (recall Proposition 4). Inequality (ii) demonstrates that a firm's total spot market quantity is higher when it receives the renewable capacity. Inequality (iii) demonstrates that firm $i$'s conventional generation is higher when its rival receives the renewable capacity. This arises because firm $i$ withholds conventional generation when it is able to produce a positive amount of zero marginal cost renewable output.

Define $m^{min}_i$ to be the premium above the spot price that makes firm $i$ indifferent between it and its rival receiving the renewable capacity. This reflects the minimum amount that firm $i$ is willing to bid into the renewable procurement auction.

**Lemma 7.** Under the premium-priced FIT:

[24]Formally, this represents an epsilon-Nash Equilibrium in the renewable auction. However, a standard Nash Equilibrium arises if we focus on a setting where the firms submit bids on a grid (e.g., in cents) and firm 1 slightly undercuts its rival's minimum bid on the grid of possible offers. A similar result follows when $\delta_1 = \delta_2 = 0$ below.

$$m_i^{min} = \frac{F}{\sum\limits_{t=L,H} \theta_t R} - \left( \frac{1}{\sum\limits_{t=L,H} \theta_t R} \right) \sum_{t=L,H} \Delta\Pi_{i,t}^{Spot} \text{ for each } \quad i,j = 1,2 \quad \text{with } i \neq j \qquad (8)$$

where $\Delta\Pi_{i,t}^{Spot} \equiv \Pi_{i,t,Ri}^{Spot} - \Pi_{i,t,Rj}^{Spot} = P_t(Q_{t,Ri}^*)q_{i,t,Ri}^* - C_{it}(q_{i,t,Ri}^*) - [P_t(Q_{t,Rj}^*)q_{i,t,Rj}^* - C_{it}(q_{i,t,Rj}^*)]$.

Lemma 7 characterizes each firm's minimum premium-priced bid. The first term in (8) reflects the average fixed cost. The second term includes $\Delta\Pi_{i,t}^{Spot} = \Pi_{i,t,Ri}^{Spot} - \Pi_{i,t,Rj}^{Spot}$ which reflects the change in firm $i$'s total spot market profits in period $t$ earned by both its conventional and renewable generation when it wins the renewable resource compared to its rival $j$ wins the renewable capacity. Unlike the minimum bids in the fixed-priced setting illustrated in (6), firms consider the impact of owning the renewable capacity on their total spot market profits because renewable output is exposed to spot market prices. This has important implications on bidding incentives.

Proposition 8 ranks the firms' minimum premium-priced bids in the homogeneous renewable resource case.

**Proposition 8.** Suppose $\delta_1 = \delta_2 = 0$, $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. Then, $m_1^{min} = m_2^{min} < \frac{F}{\sum\limits_{t=L,H} \theta_{it} R}$.

Proposition 8 demonstrates that a firm is willing to bid for the renewable capacity below its average fixed cost because a firm's total spot market profits are higher when it owns the renewable resource compared to the rival owning the resource (i.e., the second term in (8) is positive). If both firms have symmetric marginal cost, both firms' incentives to deter their rival from owning and operating the renewable resource are symmetric such that $m_1^{min} = m_2^{min}$. This results in intense competition in the procurement auction where the unique equilibrium entails each firm $i$ bidding at $m_i^{min}$ and winning the procurement auction with probability $\frac{1}{2}$ under randomized rationing.

Now we consider the setting with heterogeneous potential renewable capacity investments. Suppose Assumption 1 holds such that firm 1 has the "less valuable" resource that generates more output in the low demand period ($t = L$) and firm 2's potential resource generates more in the high demand period ($t = H$). Proposition 9 ranks the minimum bids in the premium-priced FIT setting. To identify the key forces, we focus on the case with symmetric cost functions and assume the slope of the demand curves are symmetric across periods.[25]

**Proposition 9.** Suppose $\delta_1 = \delta_2 = 0$, Assumption 1 holds, and $\frac{\theta_{2H}}{\theta_{1H}} \geq \frac{\theta_{1L}}{\theta_{2L}}$ or $\alpha_H$ is sufficiently large. Then, $m_2^{min} < m_1^{min}$.

Proposition 9 characterizes conditions under which the firm with the more valuable resource is willing to offer a lower price in the procurement auction (i.e., $m_2^{min} < m_1^{min}$). The intuition behind

[25]Brown and Eckert (2018) utilize numerical simulations to demonstrate that this result holds more generally.

this result is the following. Under the specified conditions, using (8), $m_2^{min} < m_1^{min}$ holds when:

$$\underbrace{\left(\Pi^{Spot}_{2,H,R2} - \Pi^{Spot}_{2,H,R1}\right)}_{\Delta\Pi^{Spot}_{2,H}} + \underbrace{\left(\Pi^{Spot}_{2,L,R2} - \Pi^{Spot}_{2,L,R1}\right)}_{\Delta\Pi^{Spot}_{2,L}} > \underbrace{\left(\Pi^{Spot}_{1,H,R1} - \Pi^{Spot}_{1,H,R2}\right)}_{\Delta\Pi^{Spot}_{1,H}} + \underbrace{\left(\Pi^{Spot}_{1,L,R1} - \Pi^{Spot}_{1,L,R2}\right)}_{\Delta\Pi^{Spot}_{1,L}}. \quad (9)$$

Under a premium-priced FIT, firms' renewable output is compensated at the spot market price. Further, while renewable output reduces the spot market price and spot profit earned by conventional generation, total spot market profit increases when a firm wins the renewable auction compared to its rival receiving the capacity. Consequently, each of the terms in (9) are positive.

Proposition 9 demonstrates that if the capacity utilization of firm 2's resource ($\theta_{2H}$) or market demand ($\alpha_H$) in the high demand hour are sufficiently large, then the change in firm 2's total spot profits from acquiring the renewable resource is larger than the change in firm 1's total spot profits (i.e., inequality (9) holds). This is driven by two factors. First, acquiring a renewable resource results in a downward shift in a firm's spot market marginal cost curve. In the high demand hour firms are producing more conventional output (i.e., we are "higher up" on the marginal cost curve). As a result, for any level of renewable output, the cost reductions associated acquiring the renewable resource is larger in the high demand hour. These cost efficiencies are magnified for firm 2 because its potential renewable investment generates more during the high demand hour under Assumption 1. Second, the firms are exercising more market power and earning higher spot profits in the high demand hour. This elevates firm 2's strategic benefit for acquiring the renewable resource that is more productive in period $t = H$.

To summarize, under plausible conditions, the firm with the more valuable resource has stronger incentives to win the renewable procurement auction due to the larger cost efficiencies and strategic benefit in the subsequent spot markets. As a result, firm 2 wins the renewable procurement auction by undercutting its rival's minimum bid $m_1^{min}$ by some small amount $\epsilon > 0$.

### 5.3 Comparing Across Procurement Policies

We have characterized the equilibrium renewable investments and subsequent forward and spot market competition in a setting with commonly implemented renewable compensation policies. In this section, we compare the level of welfare under the fixed-priced and premium priced FITs. We maintain from the previous section the assumptions that $\beta_L = \beta_H = \beta$, $c_1 = c_2 = c$, and $R_1 = R_2 = R$. Again, robustness of our results to asymmetry across firms or periods is considered in Brown and Eckert (2018).

From Proposition 5, aggregate quantities are lower and spot market prices are higher when renewable output is compensated at a premium-priced FIT because firms have a stronger incentive to withhold output to elevate prices. However, in the setting with heterogeneous renewable resources, Propositions 7 and 9 provide conditions under which the less valuable resource wins under the fixed-priced FIT and the more valuable resource wins the procurement auction under the premium-priced FIT. Consequently, the welfare ranking of these two compensation policies is ambiguous due to the trade-offs of elevates market power execution in the spot market under a premium, and the incentives to invest in renewable resources that are more highly correlated with market demand in the renewable procurement auction.

Proposition 10 provides sufficient conditions under which welfare is strictly higher under the premium-priced FIT compared to the fixed-priced FIT.[26]

**Proposition 10.** Suppose that Assumption 1 holds. Then, in equilibrium, welfare is higher under the premium-priced than the fixed-priced FIT compensation policy if $\alpha_H$, $c$, and $\theta_{2H} - \theta_{1H}$ are sufficiently large and positive.

Proposition 10 demonstrates that if demand in the high demand period ($t = H$), the difference between capacity utilization of firm 2's and firm 1's renewable resources during the high demand period ($\theta_{2H} - \theta_{1H}$), and cost of production from conventional generation ($c$) are sufficiently large, then the production efficiencies of increased renewable output dominate the increased incentives for market power execution under the premium-priced FIT. The larger production efficiencies arise because firm 2 owns the renewable resource that produces more during peak demand periods when we are operating at a higher point on the increasing marginal cost function.

### 5.4 Numerical example

The following numerical example illustrates our main results. Let $\alpha_L = 700$, $\alpha_H = 1000$, and $\beta_L = \beta_H = 5$, so that the market demand is $P_L(Q_L) = 700 - 5Q_L$ in the low demand period and $P_H(Q_H) = 1000 - 5Q_H$ in the high demand period. We assume that $c_1 = c_2 = 1$. These parameters were chosen to yield an elasticity of demand at the perfectly competitive outcome equal to 0.1, broadly consistent with the literature (Faruqui and Sergici, 2010), and a marginal cost for marginal generation in equilibrium of approximately \$70, consistent with a "peaker" natural gas plant (CEC, 2016). Finally, we let $R = 60$, and suppose that firm 2 has the more valuable renewable resource: $\theta_{1L} = \theta_{2H} = 0.75$ and $\theta_{1H} = \theta_{2L} = 0.25$. These numbers were chosen so that when firm 2 wins the auction, renewable production in the high demand period accounts for approximately 30% of conventional generation in the baseline no renewables scenario. Note that these parameter values satisfy our Assumption 1 and the conditions in Proposition 9 because $\frac{\theta_{2H}}{\theta_{1H}} = \frac{\theta_{1L}}{\theta_{2L}} = \frac{0.75}{0.25}$.[27]

Table 1 presents equilibrium outcomes of the forward and spot markets, for both the fixed and premium-priced FITs, assuming first that the renewable capacity is awarded to firm 1, and then to firm 2. For comparison, Table 1 also reports the baseline outcome with no renewable generation. Reported quantities reflect total output (including renewable generation). Revenues earned through a fixed-priced FIT ($\overline{P}_i$) or premium-priced FIT ($m_i$) for renewable output are excluded. However, in the case of a premium compensation mechanism, profits include revenues

[26] We employ numerical simulations in the Appendix to demonstrate that this result holds more generally.

[27] We present additional numerical results in Brown and Eckert (2018) to demonstrate that our key qualitative conclusions hold under general conditions.

earned by renewable generation at the spot price. Profits, production costs, and total surplus (welfare) does not include the costs of renewable capacity. Renewable capacity costs do not affect total surplus comparisons since they are incurred in all four scenarios; however, for this reason one cannot compare the total surplus without renewable generation to the scenarios with renewables.[28]

Table 1: Results from Numerical Example by Compensation Policy

| Variable | No Renewables | Fixed-Priced | | Premium-Priced | |
|---|---|---|---|---|---|
| | | $R$ Awarded to: | | $R$ Awarded to: | |
| | | Firm 1 | Firm 2 | Firm 1 | Firm 2 |
| $P_L$ | 190.07 | 128.97 | 169.70 | 173.68 | 184.60 |
| $P_H$ | 271.52 | 251.16 | 210.43 | 266.06 | 255.13 |
| $q^f_{1L}$ | 23.18 | 15.73 | 20.70 | 26.67 | 22.51 |
| $q^f_{2L}$ | 23.18 | 15.73 | 20.70 | 21.18 | 24.34 |
| $q^f_{1H}$ | 33.11 | 30.63 | 25.66 | 34.28 | 31.11 |
| $q^f_{2H}$ | 33.11 | 30.63 | 25.66 | 32.45 | 36.60 |
| $q_{1L}$ | 50.99 | 79.60 | 45.53 | 58.67 | 49.53 |
| $q_{2L}$ | 50.99 | 34.60 | 60.53 | 46.60 | 53.55 |
| $q_{1H}$ | 72.85 | 82.38 | 56.46 | 75.41 | 68.45 |
| $q_{2H}$ | 72.85 | 67.38 | 101.46 | 71.38 | 80.52 |
| $\Pi_{1L}$ | 8,391.96 | 3,864.15 | 6,690.02 | 10,096.00 | 7,916.43 |
| $\Pi_{2L}$ | 8,391.96 | 3,864.15 | 6,690.02 | 7,006.97 | 9,142.70 |
| $\Pi_{1H}$ | 17,126.4 | 14,653.80 | 10,286.60 | 18,238.10 | 15,121.10 |
| $\Pi_{2H}$ | 17,126.4 | 14,653.80 | 10,286.60 | 16,444.10 | 19,913.20 |
| $\Pi_1$ | 25,518.36 | 18,517.95 | 16,976.60 | 28,334.0 | 23,037.60 |
| $\Pi_2$ | 25,518.36 | 18,517.95 | 16,976.60 | 23,451.10 | 29,055.90 |
| $CS_L$ | 26,003.20 | 32,607.10 | 28,121.60 | 27,701.70 | 26,563.40 |
| $CS_H$ | 53,067.80 | 56,076.30 | 62,342.00 | 53,866.90 | 55,482.80 |
| Total $CS$ | 79,071.00 | 88,683.40 | 90,463.60 | 81,568.60 | 82,046.20 |
| Prod. $\text{Costs}_L$ | 2,600.32 | 1,197.34 | 2,072.96 | 1,179.01 | 1,969.62 |
| Prod. $\text{Costs}_H$ | 5,306.78 | 4,540.62 | 3,187.38 | 4,372.14 | 2,973.60 |
| Total Prod. Costs | 7,907.10 | 5,737.96 | 5,260.34 | 5,551.15 | 4,943.28 |
| $TS_L$ | 42,786.22 | 46,138.13 | 44,047.02 | 44,805.98 | 43,622.35 |
| $TS_H$ | 84,721.16 | 89,149.40 | 92,385.73 | 88,549.71 | 90,515.86 |
| Total $TS$ | 127,507.33 | 135,287.54 | 136,432.75 | 133,355.69 | 134,138.21 |

Notes. $CS$ and $TS$ denotes consumer and total surplus, respectively.

Our example first illustrates findings from Section 5. The ratio of forward quantities to spot market output ($q^{f*}_{it}/q^*_{it}$) are approximately 0.45 in all cases for both firms, with the exception of when the firm is awarded renewable capacity under a fixed-priced FIT. When the renewable capacity is awarded to firm 1 its forward contracting ratio falls to 0.20 in low demand and 0.37 in high demand; likewise, being awarded renewable capacity under a fixed-priced FIT reduces firm 2's forward contracting ratio to 0.34 in low demand and 0.25 in high demand. These results are

[28]Note also that in the case of the fixed-priced FIT, total surplus exceeds the sum of consumer surplus and profit because it includes revenues to renewable generation, but excludes the fixed cost of capital investment.

consistent with that of Proposition 3.

Consistent with Proposition 4, awarding renewable capacity to a firm's rival causes the firm to reduce its forward quantity; being awarded the renewable capacity causes a firm to decrease forward quantity under a fixed-priced FIT, but to increase it under a premium. Finally, as noted in Proposition 5, holding constant the firm with renewable capacity, in both high and low demand periods spot price is higher under the premium-priced policy than if renewable capacity is compensated through a fixed-priced FIT.

To illustrate results from Section 5, first suppose that renewable capacity will be compensated through a fixed-priced FIT, and that both firms face a fixed cost of renewable capacity equal to F. If firm 1 wins the renewable auction, its profits are $18517.95 - F + 60\,\overline{P}_1$, where $\overline{P}_1$ is the fixed price for renewable output. If instead firm 2 wins, firm 1's profits are equal to 16976.60. Therefore, given that the capacity will be awarded to one of the two firms, the minimum $\overline{P}_1$ firm 1 is willing to accept to develop the renewable capacity satisfies $18517.95 - F + 60\overline{P}_1^{min} = 16976.60$, or $\overline{P}_1^{min} = \frac{F-1541.35}{60}$. In contrast, firm 2's profit if it wins the auction is $16976.62 - F + 60\,\overline{P}_2$, versus 18517.95 if firm 1 wins. Therefore, the minimum $\overline{P}_2$ firm 2 would accept to develop the renewable resource, assuming that otherwise firm 1 will develop it, is $\overline{P}_2^{min} = \frac{F+1541.35}{60}$. Because firm 1 is willing to accept a lower premium to develop the renewable resource ($\overline{P}_1^{min} < \overline{P}_2^{min}$), it would be awarded to firm 1, meaning that the least valuable renewable resource is developed.

Next, suppose that the winner of the renewable auction is compensated using a premium-priced FIT; renewable generation is paid the spot price plus a mark up. If firm 1 wins the auction, it earns profit of $28334.00 - F + 60\,m_1$, where $m_1$ is the markup. In contrast, if firm 2 wins the auction 1's payoff is 23037.60. Therefore, the lowest $m_1$ firm 1 would accept to develop the renewable capacity satisfies $28334 - F + 60m_1^{min} = 23037.6$, or $m_1^{min} = \frac{F-5296.4}{60}$. The lowest premium firm 2 is willing to accept to develop the renewable capacity, if the alternative is for the renewable capacity to be developed by firm 1, satisfies $29055.9 - F + 60m_2^{min} = 23451.1$, or $m_2^{min} = \frac{F-5604.8}{60}$. Since firm 2 is willing to accept a lower premium ($m_2^{min} < m_1^{min}$), firm 2 wins the renewable auction.

These results highlight our findings in Section 5.3. In this example, the least valuable resource wins under the fixed-priced FIT, but the most valuable resource wins under the premium. Compensation via a premium, with firm 2 winning the auction, results in higher prices in both demand periods than does the fixed-priced FIT with firm 1 as the winner. As a result, consumer surplus is lower than under a fixed-priced FIT with firm 1 winning the auction. While production costs are lower under the premium when firm 2 wins, this effect is dominated by the reduction in consumer surplus, so that the fixed-priced FIT with firm 1 winning maximizes total surplus.

In our example, the finding that total surplus is greater when firm 1 gets the renewable capacity under a fixed-priced FIT than when firm 2 gets the renewable capacity under a premium is a function of our parameter assumptions. To illustrate, Figure 1 plots combinations of $\alpha_H \in [1000, 1400]$ and $c \in [1, 3]$ for which total surplus is higher under the premium, holding all other parameters constant. As Figure 1 illustrates, and as predicted by Proposition 10, total surplus under the premium exceeds total surplus under the fixed-priced FIT when $\alpha_H$ and $c$ are sufficiently large.

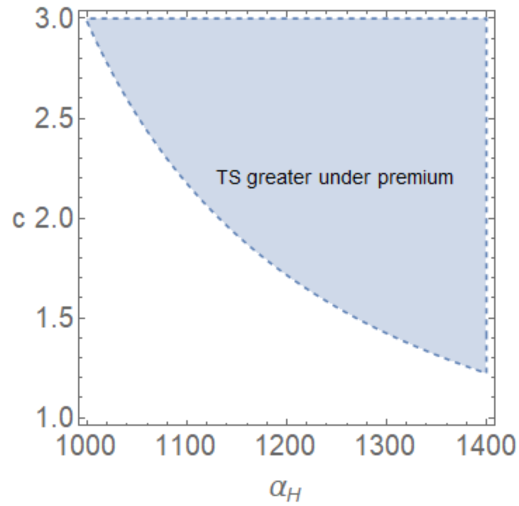


Figure 1: Numeric Example. Set of $\alpha_H$ and $c$ for which Total Surplus is higher under Premium

## 6 Competitive Fringe Entry

Finally, we consider the possibility that the contract for renewable capacity may be won not by an incumbent oligopolist, but by a new entrant with no conventional generation. Here, our focus is on whether new entry will be prevented by the incumbent firms, and whether this incentive can result in entry being prevented even when it possesses the more valuable renewable technology.

We continue to assume that there are two incumbent firms 1 and 2, with conventional generation technology described by $c_1 = c_2 = c$. Now, suppose that in addition to incumbent firms 1 and 2, there is a potential entrant, firm 3. Firm 3 possesses no conventional generation, but has the potential to develop renewable generation capacity $R$. We continue to suppose that there are two periods, with $\alpha_L < \alpha_H$, $\beta_L = \beta_H = \beta$, and such that market demand to be served by conventional generation at a given price is larger in the $t = H$ period (i.e., $\alpha_H - \beta\,\theta_{iH}R > \alpha_L - \beta\,\theta_{jL}R$ for $i, j = 1, 2, 3$). Denote firm 3's renewable capacity utilization by $\theta_{3t}$ for $t = L, H$.

We initially suppose that the renewable technologies of all three firms are homogeneous, with the same fixed costs and profile of capacity utilization over periods. Define $\overline{P}_i^{minRj}$ ($\overline{P}_3^{min}$) to be the fixed-price FIT that makes firm $i = 1, 2$ (firm 3) indifferent between receiving the renewable capacity and its rival $j = 1, 2, 3$ winning the auction with $i \neq j$.

**Proposition 11.** Suppose $\delta_1 = \delta_2 = \delta_3 = 1$ and firms have a homogeneous potential renewable resource with capacity $R$ and capacity utilization $\theta_t \in [0, 1]$ for both $t = L, H$. $\overline{P}_1^{minR2} = \overline{P}_1^{minR3} = \overline{P}_2^{minR1} = \overline{P}_2^{minR3} = \overline{P}_3^{minR1} = \overline{P}_3^{minR2} = \frac{F}{\sum_{t=L,H}\theta_t R}$.

The intuition for Proposition 11 is the same as for Proposition 6. The minimum fixed-price FIT is the one that exactly covers the fixed costs because there is no strategic benefit from owning renewable capacity in this setting. As a result, with a homogeneous renewable technology, our model makes no prediction regarding which firm will win the competitive process.

A different result emerges if renewable generation is compensated through a premium-price in the homogeneous setting. Define $m_i^{minRj}$ ($m_3^{min}$) to be the premium-price FIT that makes firm $i = 1, 2$ (firm 3) indifferent between receiving the renewable capacity and its rival $j$ winning the auction. Proposition 12 illustrates that if all three firms have homogeneous renewable technologies, whether the incumbent firms are willing to provide the renewable capacity for a lower premium than the potential entrant depends critically on the marginal cost for conventional generation.[29]

**Proposition 12.** Suppose $\delta_1 = \delta_2 = \delta_3 = 0$, the firms have homogeneous renewable technologies with capacity $R$ and capacity utilization $\theta_t \in [0, 1]$, and $\alpha_t - 3\beta\theta_t R > 0$ for $t = L, H$. Then, for $i = 1, 2$, $m_3^{min} < m_i^{minR3}$ if $c$ is sufficiently small.

This result resembles the classic horizontal "Merger Paradox" result in a Cournot model.[30] Suppose initially that $c = 0$, so the incumbents have zero marginal costs of conventional generation. For an incumbent firm, the choice of whether to win the auction or to allow firm 3 to enter is analogous to the choice of whether to merge with firm 3, who has the same renewable technology. Following the "Merger Paradox", in the absence of any cost efficiency gain, it is not profitable for two firms to merge, unless they form a near-monopoly in the market. However, as $c$ increases, the additional cost-reducing benefits for the incumbent ultimately make it profitable to acquire the renewable generation.[31] Proposition 12 demonstrates that if $c$ is sufficiently large, an incumbent firm has an incentive to acquire the renewable resource, preventing entry of the potential entrant. The condition that $\alpha_t - 3\beta\theta_t R > 0$ for $t = L, H$ is a sufficient condition to ensure that we are at an interior solution where the incumbents produce a positive amount of conventional generation.

The remainder of this section considers asymmetric renewable resources. To highlight competition between the incumbents and the new entrant, we suppose that the incumbents continue to have symmetric resources; however, the entrant's renewable resource may be either more or less valuable than those of the incumbents. These two cases are captured in the following assumptions:

**Assumption 2 (More Valuable Entrant).** Suppose that $\theta_{1L} = \theta_{2L} = \theta_L$, $\theta_{1H} = \theta_{2H} = \theta_H$, $\theta_{3L} < \theta_L$, $\theta_{3H} > \theta_H$, and $[\theta_{1L} + \theta_{1H}] = [\theta_{2L} + \theta_{2H}] = [\theta_{3L} + \theta_{3H}]$.

**Assumption 3 (Less Valuable Entrant).** Suppose that $\theta_{1L} = \theta_{2L} = \theta_L$, $\theta_{1H} = \theta_{2H} = \theta_H$, $\theta_{3L} > \theta_L$, $\theta_{3H} < \theta_H$, and $[\theta_{1L} + \theta_{1H}] = [\theta_{2L} + \theta_{2H}] = [\theta_{3L} + \theta_{3H}]$.

Assumption 2 considers the case in which the entrant has the more valuable resource, while Assumption 3 describes a setting in which the incumbents have superior renewable resources.

In the context of a fixed-priced FIT, results with a potential entrant parallel the findings presented in Section 5.1. Propositions 13 and 14 demonstrate that: (i) the entrant wins the

[29] We focus on a setting where the incumbent firms have symmetric marginal cost and demand has the same slope across periods. However, using numerical simulations we demonstrate that Proposition 12 holds more generally.
[30] For a detailed treatment of the "Merger Paradox", see Salant et al. (1983).
[31] This finding parallels the results of Perry and Porter (1985) which demonstrate that horizontal mergers can be profitable when the merging firms acquire capital assets that reduce costs.

auction when the incumbents have the more valuable resource and (ii) the auction is won by an incumbent when the entrant's resource is more valuable.[32] This latter result arises because of the incumbents' strong incentive to win the renewable auction to prevent the more valuable resource from winning and suppressing subsequent conventional generation spot profits.

**Proposition 13.** Suppose $\delta_1 = \delta_2 = \delta_3 = 1$ and Assumption 2 holds. Then, for $i = 1, 2$, $\overline{P}_i^{minR3} < \overline{P}_3^{min}$.

**Proposition 14.** Suppose $\delta_1 = \delta_2 = \delta_3 = 1$ and Assumption 3 holds. Then, for $i = 1, 2$, $\overline{P}_3^{min} < \overline{P}_i^{minR3}$.

More interesting is the case of asymmetric resources and entry when renewable generation is compensated via a premium-priced FIT. Assumption 4 presents a setting where the potential entrant has a more valuable renewable resource that is parameterized by the parameter $\eta > 0$, while the incumbents have homogeneous potential investments.

**Assumption 4 (More Valuable Entrant - $\eta$).** Suppose $\theta_{1L} = \theta_{2L} = \theta_L$ and $\theta_{1H} = \theta_{2H} = \theta_H$. Suppose the entrant has a superior technology with $\theta_{3L} = \theta_L - \eta$ and $\theta_{3H} = \theta_H + \eta$, for some $\eta > 0$.

Proposition 15 provides conditions under which the potential entrant is willing to accept a lower premium in the renewable auction than the incumbents.

**Proposition 15.** Suppose $\delta_1 = \delta_2 = \delta_3 = 0$ and Assumption 4 holds. Then, for $i = 1, 2$ the difference $m_i^{minR3} - m_3^{min}$ is increasing in $\alpha_H$, and is increasing in $\eta$ provided $\alpha_H$ is sufficiently large.

Proposition 15 demonstrates that the incumbents are less likely to prevent entry of the potential entrant (i.e., $m_i^{minR3} - m_3^{min} > 0$) if demand is sufficiently large and the entrant's resource is sufficiently more productive in the high demand hour. More specifically, an incumbent $i$ has an incentive to submit a lower premium-priced bid than the entrant when its spot market profits when it wins the renewable auction exceed the summation of its spot profits and the entrant's spot profits when the entrant wins the renewable auction (i.e., $\Pi_{i,Ri}^{Spot} > \Pi_{i,R3}^{Spot} + \Pi_{3,R3}^{Spot}$).[33] However, when the potential entrant's renewable resource is sufficiently productive in the high demand hour (compared to the incumbents) and demand is sufficiently large in the high demand hour, it is too costly for the incumbent to prevent entry in the renewable procurement auction (i.e., $\Pi_{3,R3}^{Spot}$ is too large). Consequently, the potential entrant with a more valuable resource wins in this setting.

To illustrate Proposition 15 , consider the following variation on our example from the previous section. As before we suppose there are two incumbent firms (firms 1 and 2) with conventional generation capacity. Again let $\alpha_L = 700$, $\alpha_H = 1000$, and $\beta_L = \beta_H = 5$, and suppose that $c_1 =$

[32] The Proofs of Propositions 13 and 14 present the detailed expressions on the minimum fixed-priced offers.
[33] This parallels the findings in the preemptive patenting literature (e.g., see Gilbert and Newbery (1982)).

$c_2 = 1$. In contrast to our previous example, suppose that the two incumbent firms have identical potential renewable resources, with $R_1 = R_2 = 60$, $\theta_{1H} = \theta_{2H} = 0.25$ and $\theta_{1L} = \theta_{2L} = 0.75$. However, suppose as well that there is a potential entrant (firm 3), with more valuable renewable technology described by $R_3 = 60$, $\theta_{3H} = 0.25 + \eta$ and $\theta_{3L} = 0.75 - \eta$. Note that as $\eta$ increases from 0 to 0.5 we move from firm 3 having the same technology as the incumbents to the case where the entrant's technology produces 45 units of renewable generation in the high demand period, and 15 in the low demand (i.e., the reverse of the incumbent technology).

To consider the values of $\eta$ for which firm 3 wins the procurement auction, Figure 2 illustrates the difference between the combined spot profits of firms 1 and 3 when firm 3 wins and enters, and firm 1's spot market profit if it wins and firm 3 does not enter; that is, $\Delta\Pi_{R1,R3} = \Pi^{Spot}_{1,R3} + \Pi^{Spot}_{3,R3} - \Pi^{Spot}_{1,R1}$. As explained above, when this difference is positive, firm 3 wins the procurement auction, while an incumbent wins when this difference is negative. Figure 2 demonstrates that for small values of $\eta$ (less than approximately 0.05), the incumbent wins the renewable procurement auction despite having the less valuable resource. However, this reverses for higher values of $\eta$, with firm 3 winning the auction.

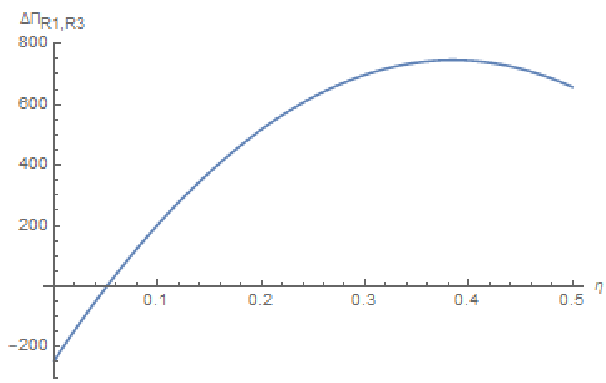


Figure 2: Numeric Example. Firms 1 and 3's Profits with Entry – Firm 1's Profit Without Entry

To summarize, under a fixed-priced FIT with a homogeneous renewable resource, the incumbents and potential entrant have symmetric investment incentives, so that the model makes no prediction regarding which firm wins the auction. However, with heterogeneous renewable resources, the firm with the least valuable renewable resource wins paralleling the findings in Section 5.1. Under the premium-priced FIT, more interesting incentives arise. When the firms have homogeneous renewable technologies, the entrant fails to win the renewable auction if the cost of production from conventional technologies is sufficiently large. Alternatively, the entrant wins the renewable auction when its resource is sufficiently more productive and demand is sufficiently large in the high demand hour.

# 7 Conclusion

We develop a model of electricity market competition where firms compete over renewable capacity in a procurement auction prior to choosing forward and wholesale market quantities. We consider two forms of renewable compensation: a fixed-priced and premium-priced FIT. We demonstrate that the renewable compensation policy has important impacts on the renewable resources that win the auction, firms' forward contracting incentives, and wholesale market competition.

Under a premium-priced FIT, firms have increased incentives to exercise market power in the spot market as renewable output is exposed to spot prices. However, firms also have increased incentives to sign forward contracts. This latter effect mitigates some, but not all of the increased market power incentives. Wholesale prices are higher under a premium-priced FIT for a given level and configuration of renewable capacity.

We find that the renewable compensation policy impacts the types of resources that win the auction. Under a fixed-priced policy, renewable resources whose output is *less* correlated with market demand and prices win the auction. However, we identify conditions that result in the more valuable resource winning the auction under the premium-priced policy. While firms have stronger incentives to exercise market power under a premium policy, welfare can be higher when a premium-priced FIT is employed if the cost-reduction from adopting the "more valuable" renewable resource is sufficiently large. Lastly, we demonstrate that incumbent firms have incentives to prevent entry of a new competitor under a premium-priced policy. As a result, the incumbents can potentially prevent entry of an entrant with a more valuable renewable resource. Alternatively, under a fixed-priced policy, the least valuable renewable resource continues to win the auction.

These findings identify the numerous trade-offs under the premium-priced and fixed-priced compensation policies. Our model highlights the importance of considering the impacts of compensation policies on investment incentives in potentially heterogeneous renewable resources and on the nature of wholesale market competition in imperfectly competitive electricity markets. This has important policy implications as jurisdictions continue to move towards deploying renewable capacity via procurement auctions, and as regulators debate the appropriate compensation policy to employ in these auction mechanisms (Attia et al., 2017; CEER, 2017).[34]

We analyzed a stylized model in order to most clearly illustrate the impacts of renewable compensation policies on investment incentives and forward and spot market quantity decisions. The basic forces persist more generally. For instance, they persist when renewable output is stochastic prior to firms forward contracting and renewable investment decisions.[35] Under a premium-priced policy, firms continue to have increased incentives to sign forward contracts and exercise market power in the wholesale market. Further, under a premium-priced (fixed-priced) policy, the renewable resource that is more (less) correlated with market demand continues to win the renewable procurement auction. In addition, we focused on a setting with two strategic incumbents for analytical tractability. We anticipate that the strategic considerations will persist in the setting with $N \geq 2$ competitors. The critical feature of our analysis is that renewable output is exposed to

[34]In the European Union, premium-priced FITs are becoming increasingly mandatory for utility-scale renewable procurements (CEER, 2017).

[35]Brown and Eckert (2018) present a detailed extension of our model in the presence of stochastic renewable output.

spot market prices under a premium-priced policy. We have outlined how this important factor impacts forward contracting decisions, spot quantity choices, and strategic investment incentives. Alternatively, under a fixed-priced policy, renewable output simply shifts residual demand to be served by the firms' conventional generation inward regardless of who owns the resource.

In concluding, we discuss several extensions that merit further consideration. First, we have abstracted from risk aversion in both firms' forward contracting and renewable investment incentives. A formal analysis that considers risk aversion in renewable investment and risk-hedging incentives when firms sign forward contracts warrants formal investigation.[36] Second, future research should consider additional modeling complexities including non-convexities in conventional generators' cost functions (e.g., minimum stable generation and start up costs), corner solutions in conventional generation production decisions, and the potential for renewable curtailment.

Third, in the renewable procurement auction we assumed that there was no existing renewable generation capacity. While our forward and spot market equilibrium account for this by considering a generic distribution of renewable capacity across the incumbents, existing renewable capacity was not formally considered in the renewable auction. We anticipate that under the premium-priced FIT, the correlation with both market demand and existing renewable generation will determine the relative value of the various renewable resources, and who wins the renewable auction. However, the details of the analysis remain to be determined.

Fourth, we focused on two commonly employed renewable compensation policies. Additional compensation policies exist or have been proposed. One key design parameter in the premium-priced FIT is the design of the premium.[37] For example, regulators can impose caps and floors on renewable payments in a premium policy to mitigate risks of payments being too low or high. We anticipate that the key incentives identified in our analysis will persist. A formal analysis that considers alternative compensation policies is the subject of future research. Fifth, we assume that costs are certain and common knowledge among all firms. A formal consideration of cost uncertainty and information asymmetry in the renewable auction, and subsequent strategic behavior in the forward and spot market is the subject of future research.[38] Finally, we focused on a setting with a winner-take-all renewable auction. A model that considers multiple potential winners warrants investigation. While the precise features of the renewable auction equilibrium will change, we anticipate the key incentives we have identified will persist.

[36]Couture et al. (2010) and Shrimali et al. (2016) emphasize the increased risk of investing in renewable capacity under a premium-priced FIT. The consideration of risk aversion will likely introduce a higher risk-premium in a premium policy. However, we anticipate that the additional strategic forces identified in the model will persist.

[37]See CEER (2017) pages 74 -76 for a detailed treatment of premium-priced policy designs.

[38]Voss and Madlener (2017) model cost uncertainty and information asymmetry in renewable procurement auctions. However, the authors focus on the design of the auction and abstract from subsequent market competition.

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## Appendix

**Proof of Lemma 1**. Using (1) and assuming an interior solution:

$$\frac{\partial \pi_{it}(\cdot)}{\partial q_{it}} = P_t'(Q_t)[q_{it} - \theta_{it}R_i - q_{it}^f] + P_t(Q_t) - C_{it}'(q_{it}) + P_t'(Q_t)(1-\delta_i)\theta_{it}R_i = 0$$

$$\Leftrightarrow \; q_{it} = \frac{\alpha_t + \theta_{it}R_i(\beta_t\,\delta_i + c_{it}) + \beta_t\, q_{it}^f - \beta_t q_{jt}}{2\,\beta_t + c_{it}}. \quad (10)$$

Define:

$$k_{1t} \equiv \theta_{1t}R_1(\beta_t\delta_1 + c_{1t}) + \beta_t q_{1t}^f \geq 0; \quad (11)$$

$$k_{2t} \equiv \theta_{2t}R_2(\beta_t\delta_2 + c_{2t}) + \beta_t q_{2t}^f \geq 0; \text{ and} \quad (12)$$

$$A_t \equiv (2\beta_t + c_{1t})(2\beta_t + c_{2t}) - \beta_t^2 > 0. \quad (13)$$

Using (10) - (13):

$$q_{1t}^* = \frac{\alpha_t\,(\beta_t + c_{2t}) + k_{1t}\,(2\beta_t + c_{2t}) - \beta_t\,k_{2t}}{A_t}; \quad (14)$$

$$q_{2t}^* = \frac{\alpha_t\,(\beta_t + c_{1t}) + k_{2t}\,(2\beta_t + c_{1t}) - \beta_t\,k_{1t}}{A_t}. \quad (15)$$

Using (14) and (15):

$$Q_t^* = \frac{1}{A_t}\big\{\alpha_t(2\beta_t + c_{1t} + c_{2t}) + (\beta_t + c_{2t})k_{1t} + (\beta_t + c_{1t})k_{2t}\big\}$$

$$P_t(Q_t^*) = \frac{1}{A_t}\big\{\alpha_t(\beta_t + c_{1t})(\beta_t + c_{2t}) - \beta_t(\beta_t + c_{2t})k_{1t} - \beta_t(\beta_t + c_{2t})k_{2t}\big\}$$

Using (11) - (13), it is straightforward to show that $k_{1t}$ and $k_{2t}$ are non-negative and $A_t$ is positive because $\beta_t > 0$, $c_{it} > 0$, $\delta_i \in [0,1]$, $\theta_{it}R_i \geq 0$, $q_{it}^f \geq 0$ for both $i = 1, 2$.

Using (11) – (15) and that $\beta_t > 0$, $c_{jt} > 0$, $\delta_i \in [0,1]$, and $A_t > 0$ from (13):

$$\frac{\partial q_{it}^*}{\partial \theta_{it}R_i} = \frac{(2\beta_t + c_{jt})(\beta_t\delta_i + c_{it})}{A_t} > 0; \quad \frac{\partial q_{it}^{*\,2}}{\partial \theta_{it}R_i\;\partial\delta_i} = \frac{(2\beta_t + c_{jt})\beta_t}{A_t} > 0;$$

$$\frac{\partial q_{it}^*}{\partial \theta_{jt}R_j} = -\frac{\beta_t\,(\beta_t\delta_j + c_{jt})}{A_t} < 0; \quad \frac{\partial q_{it}^*}{\partial q_{it}^f} = \frac{\beta_t\,(2\,\beta_t + c_{jt})}{A_t} > 0; \quad \frac{\partial q_{it}^*}{\partial \delta_j} = -\frac{\theta_{jt}\,R_j\,\beta_t^2}{A_t} < 0;$$

$$\frac{\partial q_{it}^*}{\partial q_{jt}^f} = -\frac{\beta_t^2}{A_t} < 0; \quad \frac{\partial q_{it}^*}{\partial \delta_i} = \frac{\theta_{it}\,R_i\,\beta_t(2\beta_t + c_{jt})}{A_t} > 0; \quad \frac{\partial q_{it}^*}{\partial \delta_i} = \frac{\theta_{it}\,R_i\,\beta_t(2\beta_t + c_{jt})}{A_t} > 0. \quad (16)$$

It is without loss of generality to define $i = 1$ and $j = 2$. Using (13), (16), and that $\delta_1 \in [0,1]$:

$$\frac{\partial q_{1t}^*}{\partial \theta_{1t}R_1} = \frac{(2\beta_t + c_{2t})(\beta_t\delta_1 + c_{1t})}{A_t} < 1 \quad \Leftrightarrow \quad -\beta_t^2\,(3 - 2\delta_1) - \beta_t c_{2t}(2 - \delta_1) < 0;$$

$$\frac{\partial q_{1t}^*}{\partial \theta_{2t} R_2} \;=\; -\frac{\beta_t\,(\beta_t \delta_2 + c_{2t})}{A_t} > -1 \quad \Leftrightarrow \quad -\beta_t^2 (3-\delta_2) - \beta_t c_{2t} - 2\beta_t c_{1t} - c_{1t} c_{2t} \;<\; 0;$$

$$\frac{\partial q_{1t}^*}{\partial q_{1t}^f} \;=\; \frac{\beta_t\,(2\,\beta_t + c_{2t})}{A_t} \;<\; 1 \quad \Leftrightarrow \quad -\beta_t^2 - 2\beta_t c_{1t} - \beta_t c_{2t} \;<\; 0;$$

$$\frac{\partial q_{1t}^*}{\partial q_{2t}^f} \;=\; -\frac{\beta_t^2}{A_t} \in (-1, 0) \quad \Leftrightarrow \quad -2\beta_t^2 - 2\beta_t c_{1t} - 2\beta_t c_{2t} - c_{1t} c_{2t} \;<\; 0. \quad \blacksquare$$

**Proof of Lemma 2**. It is without loss of generality to assume $i = 1$ and $j = 2$. For any $\delta_1 \in [0, 1]$ and $\delta_2 \in [0, 1]$, using (13) and (14) and holding forward quantities constant:

$$\frac{\partial q_{1t}^* - \theta_{1t} R_1}{\partial \theta_{1t} R_1} \;=\; \frac{(2\beta_t + c_{2t})(\beta_t\,\delta_1 + c_{1t})}{A_t} - 1 \;=\; -\frac{1}{A_t}\left[\beta_t^2 (3 - 2\delta_1) + \beta_t\, c_{2t}\,(2-\delta_1)\right] < 0; \tag{17}$$

$$\frac{\partial q_{1t}^* - \theta_{1t} R_1}{\partial \theta_{2t} R_2} \;=\; -\frac{1}{A_t}\left[\beta_t^2 \delta_2 + \beta_t c_{2t}\right] < 0. \tag{18}$$

Suppose $\delta_1 = \delta_2 = 1$. Using (17) and (18), it can readily be shown that $\frac{\partial q_{1t}^* - \theta_{1t} R_1}{\partial \theta_{1t} R_1} = \frac{\partial q_{1t}^* - \theta_{1t} R_1}{\partial \theta_{2t} R_2}$. Suppose $\delta_1 < 1$ or $\delta_2 < 1$. Using (17) and (18):

$$\left|\frac{\partial q_{it}^* - \theta_{it} R_i}{\partial \theta_{it} R_i}\right| \;>\; \left|\frac{\partial q_{it}^* - \theta_{it} R_i}{\partial \theta_{jt} R_j}\right| \quad \Leftrightarrow \quad \beta_t^2 (3 - 2\delta_1 - \delta_2) + \beta_t\, c_{2t}\,(1-\delta_1) \;>\; 0. \quad \blacksquare$$

**Proof of Proposition 1**. Using (13), and (16):

$$\frac{\partial q_{it}^*}{\partial \theta_{it} R_i} \gtreqless \frac{\partial q_{it}^*}{\partial q_{it}^f} \quad \Leftrightarrow \quad \frac{(2\beta_t + c_{jt})(\beta_t \delta_i + c_{it})}{A_t} \gtreqless \frac{\beta_t\,(2\,\beta_t + c_{jt})}{A_t} \quad \Leftrightarrow \quad c_{it} \gtreqless (1-\delta_i)\beta_t. \quad \blacksquare$$

**Proof of Lemma 3**. Using (3) and assuming an interior solution:

$$\frac{\partial \pi_{it}(\cdot)}{\partial q_{it}^f} \;=\; P_t'(Q_t^*)[q_{it}^*(q_{1t}^f, q_{2t}^f) - \theta_{it} R_i]\left(\frac{\partial q_{it}^*(\cdot)}{\partial q_{it}^f} + \frac{\partial q_{jt}^*(\cdot)}{\partial q_{it}^f}\right) + P_t(Q_t^*)\frac{\partial q_{it}^*(\cdot)}{\partial q_{it}^f}$$

$$- C_{it}'(q_{it}^*)\frac{\partial q_{it}^*(\cdot)}{\partial q_{it}^f} + P_t'(Q_t^*)(1-\delta_i)\,\theta_{it} R_i \left(\frac{\partial q_{it}^*(\cdot)}{\partial q_{it}^f} + \frac{\partial q_{jt}^*(\cdot)}{\partial q_{it}^f}\right) \;=\; 0. \tag{19}$$

Adding and subtracting $P_t'(Q_t^*)\, q_{it}^f \frac{\partial q_{it}^*}{\partial q_{it}^f}$ and recognizing that $P_t'(Q_t^*)[q_{it}^*(q_{1t}^f, q_{2t}^f) - \delta_i\,\theta_{it}\,R_i - q_{it}^f] + P_t(Q_t^*) - C_{it}'(q_{it}^*) = 0$ from (2), (19) can be rewritten as:

$$P_t'(Q_t^*)\, q_{it}^f \frac{\partial q_{it}^*}{\partial q_{it}^f} + \; P_t'(Q_t^*)[q_{it}^*(q_{1t}^f, q_{2t}^f) - \delta_i\,\theta_{it}\,R_i]\frac{\partial q_{jt}^*(\cdot)}{\partial q_{it}^f} \;=\; 0. \quad \blacksquare$$

**Proof of Proposition 2**. Using (14), (15), and Lemma 1, $S_{it} \equiv \frac{\beta_t^3}{A_t}[q_{it}^* - \delta_i\,\theta_{it} R_i]$. Consequently, using (13) and (16):

$$\frac{\partial S_{it}}{\partial \theta_{it} R_i} \;=\; \frac{\beta_t^3}{A_t}\left[\frac{\partial q_{it}^*}{\partial \theta_{it} R_i} - \delta_i\right] \;=\; \frac{\beta_t^3}{A_t^2}\left[-\beta_t^2 \delta_i - \beta_t \delta_i c_{jt} + c_{it}\, c_{jt}\,(1-\delta_i) + 2\beta_t\, c_{it}\,(1-\delta_i)\right]. \quad (20)$$

From (20) and that $\beta_t > 0$ and $A_t > 0$ from (13), $\frac{\partial S_{it}}{\partial \theta_{it} R_i}$ is monotonically decreasing in $\delta_i$, $\frac{\partial S_{it}}{\partial \theta_{it} R_i}\big|_{\delta_i=1} < 0$, and $\frac{\partial S_{it}}{\partial \theta_{it} R_i}\big|_{\delta_i=0} > 0$. Consequently, using (20), there is a $\delta_i = \widetilde{\delta}_{it} \in (0,1)$ where:

$$-\beta_t^2 \widetilde{\delta}_{it} - \beta_t \widetilde{\delta}_{it} c_{jt} + c_{it}\, c_{jt}\,(1-\widetilde{\delta}_{it}) + 2\beta_t\, c_{it}\,(1-\widetilde{\delta}_{it}) \;=\; 0 \quad \Rightarrow \quad \widetilde{\delta}_{it} \equiv \frac{c_{it}(2\beta_t + c_{jt})}{\beta_t(\beta_t + c_{jt}) + c_{it}(2\beta_t + c_{jt})}. \quad \blacksquare$$

**Proof of Proposition 3**. Using (4), (14), (15), (16), and Lemma 1, the optimal forward contract position set by firm $i$ satisfies:

$$-\beta_t\, q_{it}^{f\,*} \frac{\partial q_{it}^*}{\partial q_{it}^f} - \beta_t[q_{it}^* - \delta_i\, \theta_{it}\, R_i] \frac{\partial q_{jt}^*}{\partial q_{it}^f} \;=\; 0 \quad \Leftrightarrow \quad \frac{q_{it}^{f\,*}}{q_{it}^* - \delta_i\, \theta_{it}\, R_i} \;=\; \frac{\beta_t}{2\beta_t + c_{jt}}. \quad (21)$$

An increase in $\delta_i\, \theta_{it} R_i$ increases the left-hand side of equation (21), holding $q_{it}^{f\,*}$ and $q_{it}^*$ constant. Because the right-hand side of equation (21) does not vary with respect to $\delta_i\, \theta_{it} R_i$ , then either $q_{it}^{f\,*}$ must decrease and/or $q_{it}^*$ must increase when $\delta_i\, \theta_{it} R_i$ increases in order for condition (21) to hold. This implies that the ratio $\frac{q_{it}^{f\,*}}{q_{it}^*}$ is strictly decreasing in $\delta_i \theta_{it} R_i$. $\blacksquare$

**Proof of Proposition 4**. Using (4), and (16), firm $i$'s optimal forward quantity satisfies:

$$-\beta_t\, q_{it}^{f\,*} \frac{\partial q_{it}^*}{\partial q_{it}^f} - \beta_t[q_{it}^* - \delta_i\, \theta_{it}\, R_i] \frac{\partial q_{jt}^*}{\partial q_{it}^f} \;=\; 0 \quad \Leftrightarrow \quad q_{it}^{f\,*} \;=\; \left(\frac{\beta_t}{2\beta_t + c_{jt}}\right)[q_{it}^* - \delta_i\, \theta_{it}\, R_i]. \quad (22)$$

Define:

$$k_{3t} \;\equiv\; \left(\frac{\beta_t}{2\beta_t + c_{2t}}\right)\left[\frac{1}{(2\beta_t + c_{1t})(2\beta_t + c_{2t}) - 2\beta_t^2}\right] \;>\; 0; \quad (23)$$

$$k_{4t} \;\equiv\; \alpha_t(\beta_t + c_{2t}) + \theta_{1t} R_1[(2\beta_t + c_{2t})(\beta_t \delta_1 + c_{1t}) - A_t \delta_1] - \beta_t \theta_{2t} R_2(\beta_t \delta_2 + c_{2t}); \quad (24)$$

$$k_{5t} \;\equiv\; \left(\frac{\beta_t}{2\beta_t + c_{1t}}\right)\left[\frac{1}{(2\beta_t + c_{1t})(2\beta_t + c_{2t}) - 2\beta_t^2}\right] \;>\; 0; \text{and} \quad (25)$$

$$k_{6t} \;\equiv\; \alpha_t(\beta_t + c_{1t}) + \theta_{2t} R_2[(2\beta_t + c_{1t})(\beta_t \delta_2 + c_{2t}) - A_t \delta_2] - \beta_t \theta_{1t} R_1(\beta_t \delta_1 + c_{1t}). \quad (26)$$

Using (13), (14), (23), (24) and defining $i = 1$ and $j = 2$, (22) can be rewritten as:

$$q_{1t}^{f\,*} \;=\; \left(\frac{\beta_t}{2\beta_t + c_{2t}}\right)\left[\frac{\alpha_t\,(\beta_t + c_{2t}) + k_{1t}\,(2\beta_t + c_{2t}) - \beta_t\, k_{2t}}{A_t} - \delta_1\, \theta_{1t}\, R_1\right]$$

$$\Leftrightarrow \quad q_{1t}^{f\,*} \;=\; k_{3t}\left\{k_{4t} - \beta_t^2 q_{2t}^{f\,*}\right\}. \quad (27)$$

Using (13), (15), (23), (24), and defining $i = 2$ and $j = 1$, (22) can be rewritten as:

$$\begin{aligned} q_{2t}^{f\,*} &= \left(\frac{\beta_t}{2\beta_t + c_{1t}}\right)\left[\frac{\alpha_t\,(\beta_t + c_{1t}) + k_{2t}\,(2\beta_t + c_{1t}) - \beta_t\,k_{1t}}{A_t} - \delta_2\,\theta_{2t}\,R_2\right] \\ \Leftrightarrow\quad q_{2t}^{f\,*} &= k_{5t}\left\{k_{6t} - \beta_t^2 q_{1t}^{f\,*}\right\}. \end{aligned} \tag{28}$$

Using (28), (27) can be rewritten as:

$$q_{1t}^{f\,*} = k_{3t}\left\{k_{4t} - \beta_t^2 k_{5t}\left[k_{6t} - \beta_t^2 q_{1t}^{f\,*}\right]\right\} \quad \Leftrightarrow \quad q_{1t}^{f\,*} = \left(\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\left[k_{4t} - \beta_t^2\,k_{5t}\,k_{6t}\right]. \tag{29}$$

Using (27), (28) can be rewritten as:

$$q_{2t}^{f\,*} = k_{5t}\left\{k_{6t} - \beta_t^2 k_{3t}\left[k_{4t} - \beta_t^2 q_{2t}^{f\,*}\right]\right\} \quad \Leftrightarrow \quad q_{2t}^{f\,*} = \left(\frac{k_{5t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\left[k_{6t} - \beta_t^2\,k_{3t}\,k_{4t}\right]. \tag{30}$$

It is without loss of generality to focus on player 1. Using (23) - (26) and (29):

$$\frac{\partial q_{1t}^{f\,*}}{\partial \theta_{1t} R_1} = \left(\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\left[(2\beta_t + c_{2t})(\beta_t\delta_1 + c_{1t}) - A_t\delta_1 + \beta_t^2\,k_{5t}\left\{\beta_t(\beta_t\delta_1 + c_{1t})\right\}\right]. \tag{31}$$

Using (23) and (25):

$$\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}} > 0 \quad \Leftrightarrow \quad 1 - \beta_t^4\,k_{3t}\,k_{5t} > 0$$

$$\begin{aligned} \Leftrightarrow \quad & 15\beta_t^6 + 40\beta_t^5[c_{1t} + c_{2t}] + \beta_t^4[32c_{1t}^2 + 84c_{1t}c_{2t} + 32c_{2t}^2] + \beta_t^3[8c_{1t}^3 + 56c_{1t}^2c_{2t} + 56c_{1t}c_{2t}^2 + 8c_{2t}^3] \\ & + \beta_t^2[12c_{1t}^3c_{2t} + 32c_{1t}^2c_{2t}^2 + 12c_{1t}c_{2t}^3] + 6\beta_t[c_{1t}^3c_{2t}^2 + c_{1t}^2c_{2t}^3] + c_{1t}^3c_{2t}^3 > 0. \end{aligned} \tag{32}$$

Using (13), (25), (31), and (32):

$$\frac{\partial q_{1t}^{f\,*}}{\partial \theta_{1t} R_1} \overset{s}{=} (2\beta_t + c_{2t})(\beta_t\delta_1 + c_{1t}) - [3\beta_t^2 + 2\beta_t c_{1t} + 2\beta_t c_{2t} + c_{1t}c_{2t}]\delta_1 + \beta_t^3\,k_{5t}\,(\beta_t\delta_1 + c_{1t}) \equiv B_t. \tag{33}$$

Using (25), (33) is monotonically decreasing in $\delta_1$

$$\begin{aligned} \frac{\partial B_t}{\partial \delta_1} &= \beta_t(2\beta_t + c_{2t}) - [3\beta_t^2 + 2\beta_t c_{1t} + 2\beta_t c_{2t} + c_{1t}c_{2t}] + \beta_t^4\,k_{5t} < 0 \\ \Leftrightarrow \quad & 3\beta_t^5 + \beta_t^4[14c_{1t} + 8c_{2t}] + \beta_t^3[14c_{1t}^2 + 22c_{1t}c_{2t} + 4c_{2t}^2] \\ & + \beta^2[4c_{1t}^3 + 17c_{1t}^2c_{2t} + 8c_{1t}c_{2t}^2] + \beta_t[4c_{1t}^3 + c_{2t} + 5c_{1t}^2c_{2t}^2] + c_{1t}^3c_{2t}^2 > 0. \end{aligned}$$

Evaluating (33) at $\delta_1 = 0$:

$$B_t\big|_{\delta_1=0} \;=\; (2\beta_t + c_{2t})c_{1t} + \beta_t^3\, k_{5t}\, c_{1t} \;>\; 0.$$

Using (25) and evaluating (33) at $\delta_1 = 1$:

$$B_t\big|_{\delta_1=1} \;=\; (2\beta_t + c_{2t})(\beta_t + c_{1t}) - [3\beta_t^2 + 2\beta_t c_{1t} + 2\beta_t c_{2t} + c_{1t}c_{2t}] + \beta_t^3\, k_{5t}\,(\beta_t + c_{1t}) \;<\; 0$$

$$\Leftrightarrow \quad 3\beta_t^5 + \beta_t^4[5c_{1t} + 8c_{2t}] + \beta_t^3[2c_{1t}^2 + 10c_{1t}c_{2t} + 4c_{2t}^2] + \beta_t^2[3c_{1t}^2 c_{2t} + 4c_{1t}c_{2t}^2] + \beta_t c_{1t}^2 c_{2t}^2 \;>\; 0.$$

Consequently, because (33) is monotonically decreasing in $\delta_1$, negative when $\delta_1 = 1$, and positive when $\delta_1 = 0$, then there exists a $\widehat{\delta}_{1t} \in (0,1)$ where (33) equals zero. Using (25) and (33):

$$(2\beta_t + c_{2t})(\beta_t\widehat{\delta}_{1t} + c_{1t}) - [3\beta_t^2 + 2\beta_t c_{1t} + 2\beta_t c_{2t} + c_{1t}c_{2t}]\widehat{\delta}_{1t} + \beta_t^3\, k_{5t}\,(\beta_t\widehat{\delta}_{1t} + c_{1t}) \;=\; 0$$

$$\Rightarrow \quad \widehat{\delta}_{1t} \;=\; \frac{(2\beta_t + c_{2t})c_{1t} + \beta_t^3 k_{5t} c_{1t}}{\beta_t^2 + 2\beta_t c_{1t} + \beta_t c_{2t} + c_{1t}c_{2t} - \beta_t^4 k_{5t}} \in (0,1).$$

Using (13), (23) - (26), (29), and (32):

$$\frac{\partial {q_{1t}^f}^*}{\partial \theta_{2t} R_2} \;=\; \left(\frac{k_{3t}}{1 - \beta_t^4\, k_{3t}\, k_{5t}}\right)\left[-\beta_t(\beta_t\delta_2 + c_{2t}) - \beta_t^2 k_{5t}\{(2\beta_t + c_{1t})(\beta_t\delta_2 + c_{2t}) - A\delta_2\}\right] \tag{34}$$

$$\stackrel{s}{=} \; -\beta_t(\beta_t\delta_2 + c_{2t}) - \beta_t^2 k_{5t}\{[1-\delta_2](2\beta_t c_{2t} + c_{1t}c_{2t}) - \delta_2\,\beta_t(\beta_t + c_{1t})\} \equiv D_t. \tag{35}$$

Using (25), (34), and (35):

$$\frac{\partial {q_{1t}^f}^*}{\partial \theta_{2t} R_2}\bigg|_{\delta_2=0} \;\stackrel{s}{=}\; -\beta_t c_{2t} - \beta_t^2 k_{5t}\{(2\beta_t c_{2t} + c_{1t}c_{2t})\} \;<\; 0.$$

Using (25), (35), and the $\beta_t > 0$, $c_{1t} \geq 0$, and $c_{2t} \geq 0$:

$$\frac{\partial D_t}{\partial \delta_2} \;=\; -\beta_t^2 + \beta_t^2 k_{5t}\{2\beta_t c_{2t} + c_{1t}c_{2t} + \beta_t^2 + \beta_t c_{1t}\} \;<\; 0$$

$$\Leftrightarrow \quad 3\beta_t^3 + \beta_t^2(5c_{1t} + 2c_{2t}) + \beta_t(2c_{1t}^2 + 3c_{1t}c_{2t}) + c_{1t}^2\, c_{2t} \;>\; 0.$$

Because $\frac{\partial {q_{1t}^f}^*}{\partial \theta_{2t} R_2}$ is decreasing in $\delta_2$ and $\frac{\partial {q_{1t}^f}^*}{\partial \theta_{2t} R_2}\big|_{\delta_2=0}$ implies that $\frac{\partial {q_{1t}^f}^*}{\partial \theta_{2t} R_2} < 0$ for all $\delta_2 \in (0,1]$. ■

**Proof of Propositon 5**. Using (14) and (15):

$$Q_{t,m}{}^* \;=\; \frac{1}{A}\Big\{\alpha_t\,(2\beta_t + c_{1t} + c_{2t}) + \theta_{1t}R_1 c_{1t}(\beta_t + c_{2t}) + \theta_{2t}R_2 c_{2t}(\beta_t + c_{1t})$$

$$+\beta_t {q_{1,t,m}^f}^*(\beta_t + c_{2t}) + \beta_t {q_{2,t,m}^f}^*(\beta_t + c_{1t})\Big\}; \tag{36}$$

$$Q_{t,\overline{P}}{}^{*} = \frac{1}{A_t}\Big\{\alpha_t\,(2\beta_t + c_{1t} + c_{2t}) + \theta_{1t}R_1(\beta_t + c_{1t})(\beta_t + c_{2t}) + \theta_{2t}R_2(\beta_t + c_{1t})(\beta_t + c_{2t})$$

$$+ \beta_t\, q^f_{1,t,\overline{P}}{}^{*}(\beta_t + c_{2t}) + \beta_t\, q^f_{2,t,\overline{P}}{}^{*}(\beta_t + c_{1t})\Big\}. \quad (37)$$

Using (13), (36), and (37):

$$Q_{t,\overline{P}}{}^{*} - Q_{t,m}{}^{*} \overset{s}{=} \theta_{1t}R_1\,\beta_t\,(\beta_t + c_{2t}) + \theta_{2t}R_2(\beta_t + c_{1t})\,\beta_t - \beta_t(\beta_t + c_{2t})\,[q^f_{1,t,m}{}^{*} - q^f_{1,t,\overline{P}}{}^{*}]$$

$$- \beta_t(\beta_t + c_{1t})\,[q^f_{2,t,m}{}^{*} - q^f_{2,t,\overline{P}}{}^{*}]. \quad (38)$$

$$= \left(\frac{\theta_{1t}R_1}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right) Z_{1t} + \left(\frac{\theta_{2t}R_2}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right) Z_{2t} \quad (39)$$

where

$$Z_{1t} \equiv (\beta_t + c_{2t} - (\beta_t + c_{1t})\,k_{5t}\,\beta_t^2)\left[1 - k_{3t}\,[\beta_t^2 + 2\beta_t c_{1t} + \beta_t c_{2t} + c_{1t}c_{2t}]\right]; \quad (40)$$

$$Z_{2t} \equiv (\beta_t + c_{1t} - (\beta_t + c_{2t})\,k_{3t}\,\beta_t^2)[1 - k_{5t}\,[\beta_t^2 + \beta_t c_{1t} + 2\beta_t c_{2t} + c_{1t}c_{2t}]]. \quad (41)$$

Using (23) and (25), it can be shown that $Z_{1t} > 0$ and $Z_{2t} > 0$. See Brown and Eckert (2018) for a detailed proof. Consequently, $Q_{t,\overline{P}}{}^{*} - Q_{t,m}{}^{*}$ defined in (39) is positive. ∎

**Proof of Lemma 4**. Suppose $\delta_1 = \delta_2 = 1$. It is without loss of generality to focus on firm 1. Using (24), (26), and (29), in period $t = L, H$:

$$q^{f*}_{1,t,R1} = \left(\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\Big[\alpha_t(\beta_t + c_{2t}) + \theta_t R[(2\beta_t + c_{2t})(\beta_t + c_{1t}) - A_t]$$

$$- \beta_t^2\,k_{5t}\,[\alpha_t(\beta_t + c_{1t}) - \beta_t\theta_t R(\beta_t + c_{1t})]\Big]; \quad (42)$$

$$q^{f*}_{1,t,R2} = \left(\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\Big[\alpha_t(\beta_t + c_{2t}) - \beta_t\theta_t R(\beta_t + c_{2t})$$

$$- \beta_t^2\,k_{5t}\,[\alpha_t(\beta_t + c_{1t}) + \theta_t R[(2\beta_t + c_{1t})(\beta_t + c_{2t}) - A_t]]\Big]. \quad (43)$$

Using (13), (42), and (43):

$$q^{f*}_{1,t,R1} - q^{f*}_{1,t,R2} = \left(\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\Big\{\theta_t R\left[2\beta_t^2 + 2\beta_t c_{1t} + \beta_t c_{2t} + c_{1t}c_{2t} - 3\beta_t^2 - 2\beta_t c_{1t}\right.$$

$$\left. - 2\beta_t c_{2t} - c_{1t}c_{2t} + \beta_t^2 + \beta_t c_{2t}\right] + \beta_t^2\,k_{5t}\,\theta_t\,R[2\beta_t^2 + 2\beta_t c_{2t} + \beta_t c_{1t}$$

$$+ c_{1t}c_{2t} - 3\beta_t^2 - 2\beta_t c_{1t} - 2\beta_t c_{2t} - c_{1t}c_{2t} + \beta_t^2 + \beta_t c_{1t}]\Big\} = 0. \quad (44)$$

Using (11), (12), and (14):

$$q^*_{1,t,R1} = \frac{1}{A_t}\left[\alpha_t\,(\beta_t + c_{2t}) + (2\beta_t + c_{2t})\,[\theta_t R(\beta_t + c_{1t}) + \beta_t q^{f*}_{1,t,R1}] - \beta_t\,[\beta_t q^{f*}_{2,t,R1}]\right]; \tag{45}$$

$$q^*_{1,t,R2} = \frac{1}{A_t}\left[\alpha_t\,(\beta_t + c_{2t}) + (2\beta_t + c_{2t})[\beta_t q^{f*}_{1,t,R2}] - \beta_t\,[\theta_t R(\beta_t + c_{2t}) + \beta_t q^{f*}_{2,t,R2}]\right]. \tag{46}$$

Using (13), (45), (46), and that $q^{f*}_{i,t,R2} = q^{f*}_{i,t,R1}$ for $i = 1, 2$ from (42) - (44):

$$q^*_{1,t,R1} - q^*_{1,t,R2} = \frac{1}{A_t}\left[\theta_t R[3\beta_t^2 + 2\beta_t c_{1t} + 2\beta_t c_{2t} + c_{1t}c_{2t}]\right] = \theta_t R.$$

Consequently, because $q^*_{1,t,R1} = q^*_{1,t,R2} + \theta_t R$ and $q^*_{2,t,R2} = q^*_{2,t,R1} + \theta_t R$:

$$Q^*_{t,R1} - Q^*_{t,R2} = q^*_{1,t,R1} + q^*_{2,t,R1} - (q^*_{1,t,R2} + q^*_{2,t,R2}) = \theta_t R - \theta_t R = 0. \quad \blacksquare$$

**Proof of Lemma 5**. Suppose $\delta_1 = \delta_2 = 1$. Using (1), firm $i$ is indifferent between receiving the renewable capacity and its rival receiving the renewable capacity when $\sum_{t=L,H} \pi_{it}(q^*_{i,t,Ri}, q^*_{j,t,Ri}) = \sum_{t=L,H} \pi_{it}(q^*_{i,t,Rj}, q^*_{j,t,Rj})$ implying:

$$\overline{P}_i^{min}\left(\sum_{t=L,H}\theta_t R\right) = F - \sum_{t=L,H}\{P_t(Q^*_{t,Ri})\,[q^*_{i,t,Ri} - \theta_t R] - C_{it}(q^*_{i,t,Ri})$$

$$- [P_t(Q^*_{t,Rj})\,q^*_{i,t,Rj} - C_{it}(q^*_{i,t,Rj})]\}. \quad \blacksquare$$

**Proof of Proposition 6**. Suppose $\delta_1 = \delta_2 = 1$. It is without loss of generality to focus on firm 1. From Lemma 4, $Q^*_{t,R1} = Q^*_{t,R2}$, $q^*_{1,t,R1} - \theta_t R = q^*_{1,t,R2}$. Consequently, (7) can be rewritten:

$$\overline{P}_1^{min}\left(\sum_{t=L,H}\theta_t R\right) = F - \sum_{t=L,H}\left\{\frac{c_{1t}}{2}([q^*_{1,t,R2}]^2 - [q^*_{1,t,R1} - \theta_t R]^2)\right\} = F. \quad \blacksquare$$

**Proof of Proposition 7**. Suppose $\delta_1 = \delta_2 = 1$. Using (7) and that $\sum\limits_{t=L,H} \theta_{1t} R = \sum\limits_{t=L,H} \theta_{2t} R$ under Assumption 1, $\overline{P}_1^{min} < \overline{P}_2^{min}$ implies:

$$\sum_{t=L,H}\left\{P_t(Q^*_{t,R1})\,[q^*_{1,t,R1} - \theta_{1t}R] - C_{1t}(q^*_{1,t,R1}) + [P_t(Q^*_{t,R1})\,q^*_{2,t,R1} - C_{2t}(q^*_{2,t,R1})]\right\}$$

$$> \sum_{t=L,H}\left\{[P_t(Q^*_{t,R2})\,q^*_{1,t,R2} - C_{1t}(q^*_{1,t,R2})] + P_t(Q^*_{t,R2})\,[q^*_{2,t,R2} - \theta_{2t}R] - C_{2t}(q^*_{2,t,R2})\right\}. \tag{47}$$

Using (11), (12), (14), (15), (23) - (26), (29) and (30), the equilibrium values of ($q^{f*}_{1,t,R1}, q^{f*}_{1,t,R2}, q^{f*}_{2,t,R2}, q^{f*}_{2,t,R1}, q^{*}_{1,t,R1}, q^{*}_{1,t,R2}, q^{*}_{2,t,R2}, q^{*}_{2,t,R1}$) when $\delta_1 = \delta_2 = 1$ can be characterized. Utilizing these spot and forward quantities in equilibrium and *Mathematica* to simplify the analytical expression, under the specified conditions (47) can be rewritten as:

$$\left(\frac{1}{(5\beta^2+5\beta c+c^2)^2}\right)\left\{\left[2\,(2\beta+c)(\beta^2+3\beta c+c^2)-c\,(2\beta+c)^2\right]\times\right.$$

$$\left.\left[\,(\alpha_H-\beta\theta_{1H}R)^2-(\alpha_H-\beta\theta_{2H}R)^2+(\alpha_L-\beta\theta_{1L}R)^2-(\alpha_L-\beta\theta_{2L}R)^2\,\right]\right\}\;>\;0$$

$$\Leftrightarrow\quad 2\alpha_H[\theta_{2H}-\theta_{1H}]+2\alpha_L[\theta_{2L}-\theta_{1L}]+\beta R[\theta_{1H}^2-\theta_{2H}^2+\theta_{1L}^2-\theta_{2L}^2]\;>\;0. \qquad (48)$$

Under Assumption 1, $\theta_{1H}^2-\theta_{2H}^2=(\theta_{1H}+\theta_{2H})(\theta_{1H}-\theta_{2H})$, $\theta_{1L}^2-\theta_{2L}^2=(\theta_{1L}+\theta_{2L})(\theta_{1L}-\theta_{2L})$, $\theta_{1L}+\theta_{1H}=\theta_{2L}+\theta_{2H}$ such that $\theta_{2L}-\theta_{1L}=\theta_{1H}-\theta_{2H}$. (48) can be rewritten as:

$$[\theta_{2H}-\theta_{1H}]\,\{\,(\alpha_H-\beta R\,\theta_{1H})-(\alpha_L-\beta R\,\theta_{1L})+(\alpha_H-\beta R\,\theta_{2H})-(\alpha_L-\beta R\,\theta_{2L})\,\}\;>\;0. \qquad (49)$$

(49) holds because $\theta_{2H} > \theta_{1H}$ and $\alpha_H - \beta_H\,\theta_{iH}R > \alpha_L - \beta_L\,\theta_{jL}R$ for both $i, j = 1, 2$. ■

**Proof of Lemma 6**. The proof parallels the Proof of Lemma 4. For a detailed Proof of Lemma 6, see Brown and Eckert (2018). ■

**Proof of Lemma 7**. Suppose $\delta_1 = \delta_2 = 0$. Using (1), firm $i$ is indifferent between receiving the renewable capacity and its rival $j$ when $\sum_{t=L,H} \pi_{it}(q^*_{1,t,Ri}, q^*_{2,t,Ri}) \;=\; \sum_{t=L,H} \pi_{it}(q^*_{1,t,Rj}, q^*_{2,t,Rj})$:

$$\sum_{t=L,H}\{P_t(Q^*_{t,Ri})\,q^*_{i,t,Ri}-C_{it}(q^*_{i,t,Ri})+m_i^{min}\theta_t R\}-F\;=\;P_t(Q^*_{t,Rj})\,q^*_{i,t,Rj}-C_{it}(q^*_{i,t,Rj})$$

$$\Leftrightarrow\quad m_i^{min}\;=\;\frac{F}{\sum_{t=L,H}\theta_t R}-\left(\frac{1}{\sum_{t=L,H}\theta_t R}\right)\sum_{t=L,H}\Delta\Pi^{Spot}_{i,t}.\quad ■$$

**Proof of Proposition 8**. Using (51), when the renewable resources are homogeneous, $\theta_{2H} = \theta_{2L}$ and $\theta_{2H}\theta_{2L} = \theta_{1H}\theta_{1L}$, then $m_1^{min} = m_2^{min}$. ■

**Proof of Proposition 9**. Suppose $\delta_1 = \delta_2 = 0$. Using (8) and Assumption 1:

$$m_2^{min}\;<\;m_1^{min}\quad\Leftrightarrow\quad\sum_{t=L,H}\left\{P_t(Q^*_{t,R2})\,q^*_{2,t,R2}-C_{2t}(q^*_{2,t,R2})-(P_t(Q^*_{t,R1})\,q^*_{2,t,R1}-C_{2t}(q^*_{2,t,R1}))\right.$$

$$\left.-\;\left[P_t(Q^*_{t,R1})\,q^*_{1,t,R1}-C_{1t}(q^*_{1,t,R1})-(P_t(Q^*_{t,R2})\,q^*_{1,t,R2}-C_{1t}(q^*_{1,t,R2}))\right]\right\}\;>\;0. \qquad (50)$$

Using (11), (12), (14), (15), (23) - (26), (29) and (30), the equilibrium values of $(q^{f*}_{1,t,R1}, q^{f*}_{1,t,R2}, q^{f*}_{2,t,R2}, q^{f*}_{2,t,R1}, q^{*}_{1,t,R1}, q^{*}_{1,t,R2}, q^{*}_{2,t,R2}, q^{*}_{2,t,R1})$ when $\delta_1 = \delta_2 = 0$ can be characterized. Utilizing these spot and forward quantities in equilibrium and *Mathematica* to simplify the analytical expression, under the specified conditions (50) can be rewritten as:

$$\left(\frac{c\,R}{(\beta^2+\beta c+\frac{1}{5}c^2)^2}\right)\left(\frac{1}{(\beta^2+\frac{4}{3}\beta c+\frac{1}{3}c^2)^2}\right)\left(\frac{1}{225\,(\beta^2+3\beta c+c^2)^2}\right)\times\Big\{[\alpha_H-\alpha_L][\theta_{2H}-\theta_{1H}]\times\Big[$$
$$8453\beta^6c^5+8024\beta^7c^4+5946\beta^5c^6+4959\beta^8c^3+2810\beta^4c^7+1894\beta^9c^2+880\beta^3c^8+402\beta^{10}c$$
$$+175\beta^2c^9+36\beta^{11}+20\beta c^{10}+c^{11}\Big]+\beta R\,[\theta_{2H}\theta_{2L}-\theta_{1H}\theta_{1L}]\Big[22438\beta^6c^5+23537\beta^7c^4$$
$$+14593\beta^5c^6+16518\beta^8c^3+6484\beta^4c^7+7414\beta^9c^2+1934\beta^3c^8+1932\beta^{10}c$$
$$+370\beta^2c^9+225\beta^{11}+41\beta c^{10}+2c^{11}\Big]\;>\;0. \tag{51}$$

The inequality in (51) holds because $\alpha_H > \alpha_L$, $\theta_{2H} > \theta_{1H}$, and $\theta_{2H}\theta_{2L} \geq \theta_{1H}\theta_{1L}$ (or if $\alpha_H$ is sufficiently large) under the specified conditions. ■

**Proof of Proposition 10**. Under the specified conditions, firm 2 wins the renewable auction when $\delta_1 = \delta_2 = 0$ and firm 1 wins the renewable auction when $\delta_1 = \delta_2 = 1$. Define $(Q^*_{t,R1}, q^*_{1,t,R1}, q^*_{2,t,R1})$ and $(Q'_{t,R2}, q'_{1,t,R2}, q'_{2,t,R2})$ to be the equilibrium aggregate and firm-specific quantities under the fixed-priced FIT and the premium-priced FIT, respectively. Define $W = \sum_{t=L,H}\{CS_t + \pi_{1t}(\cdot) + \pi_{2t}(\cdot) - G_t\}$ to be aggregate welfare, where $\pi_{1t}(\cdot)$ and $\pi_{2t}(\cdot)$ reflects firms' profits, $CS_t = \int_0^{Q_t} P_t(Q_t)\,d\,Q_t$ reflects consumer surplus, and $G_t$ reflects government spot market payments for renewable generation. Using (1), welfare is higher under the premium-priced FIT if:

$$\Delta W = W_{\delta_1=\delta_2=0} - W_{\delta_1=\delta_2=1} \;>\; 0 \;\;\Leftrightarrow\;\; \sum_{t=L,H}\Big\{\int_0^{Q'_{t,R2}} P_t(Q_t)\,d\,Q_t - C_{1t}(q'_{1,t,R2}) - C_{2t}(q'_{2,t,R2})$$
$$-\Big[\int_0^{Q^*_{t,R1}} P_t(Q_t)\,d\,Q_t - C_{1t}(q^*_{1,t,R1}) - C_{2t}(q^*_{2,t,R1})\Big]\Big\}\;>\;0. \tag{52}$$

Using (11), (12), (14), (15), (23) - (26), (29) and (30) to solve for $(Q^*_{t,R1}, q^*_{1,t,R1}, q^*_{2,t,R1})$ and $(Q'_{t,R2}, q'_{1,t,R2}, q'_{2,t,R2})$, we utilize *Mathematica* to simplify the analytical expression of (52). See Brown and Eckert (2018) for a detailed presentation. Differentiating (52) with respect to $\alpha_H$:

$$\frac{\partial\Delta\widetilde{W}}{\partial\alpha_H} \;=\; c^{12}(\theta_{2H}-\theta_{1H}) + 22\,c^{11}\beta(\theta_{2H}-\theta_{1H}) + c\,\beta^{11}(108\,\theta_{2H} - 204\,\theta_{1H})$$
$$+\,c^{10}\beta^2(211\,\theta_{2H}-212\,\theta_{1H}) + c^2\beta^{10}(1098\,\theta_{2H}-1528\,\theta_{1H}) + c^9\beta^3(1162\,\theta_{2H}-1178\,\theta_{1H})$$
$$+\,c^8\beta^4(4070\,\theta_{2H}-4180\,\theta_{1H}) + c^3\beta^9(4656\,\theta_{2H}-5722\,\theta_{1H}) + c^7\beta^5(9482\,\theta_{2H}-9908\,\theta_{1H})$$

$$+c^4\beta^8(10899\,\theta_{2H} - 12524\,\theta_{1H}) + c^6\beta^6(14921\,\theta_{2H} - 15946\,\theta_{1H})$$
$$+c^5\beta^7(15770\,\theta_{2H} - 17366\,\theta_{1H}) - 9\,\beta^{12}\theta_{1H} \;>\; 0. \tag{53}$$

When $\theta_{2H} - \theta_{1H}$ and $c$ are sufficiently large, the inequality in (53) is satisfied. Consequently, $\Delta W$ is positive if $\alpha_H$, $\theta_{2H} - \theta_{1H}$, and $c$ are sufficiently large and positive. ■

**Proof of Proposition 11**. Suppose $\delta_1 = \delta_2 = \delta_3 = 1$. $\overline{P}_1^{minRj}$ and $\overline{P}_2^{minRj}$ for $j = 1, 2, 3$ follows directly from the Proof of Proposition 6. Firm 3 is indifferent between receiving the renewable capacity and its rival $j = 1, 2$ when:

$$\sum_{t=L,H} \pi_{3t}(q^*_{1,t,R3}, q^*_{2,t,R3}) \;=\; 0 \quad \Leftrightarrow \quad \overline{P}_3^{minRj} = \frac{F}{\sum_{t=L,H} \theta_t R}. \;\blacksquare \tag{54}$$

**Proof of Proposition 12**. Suppose $\delta_1 = \delta_2 = \delta_3 = 0$. For $i = 1, 2$, $m_i^{minRj}$ follows directly from Proposition 8. Firm 3 is indifferent between receiving the renewable capacity and an incumbent rival receiving the renewable capacity when:

$$\sum_{t=L,H} \pi_{3t}(q^*_{1,t,R3}, q^*_{2,t,R3}) \;=\; 0 \quad \Leftrightarrow \quad \sum_{t=L,H} \left\{ [P_t(Q^*_{t,R3}) + m_3^{min}]\,\theta_{3t}R_3 \right\} - F \;=\; 0$$

$$\Leftrightarrow \quad m_3^{min} \;=\; \frac{F}{\sum\limits_{t=L,H} \theta_{3t}R_3} - \frac{1}{\sum\limits_{t=L,H} \theta_{3t}R_3} \left( \sum_{t=L,H} P_t(Q^*_{t,R3})\,\theta_{3t}R_3 \right).$$

Using Proposition 8, under the specified conditions:

$$m_1^{minR3} - m_3^{min} \;=\; \sum_{t=L,H} \left\{ P_t(Q^*_{t,R1})q^*_{1,t,R1} - C_{1t}(q^*_{1,t,R1}) - (P_t(Q^*_{t,R3})q^*_{1,t,R3} - C_{1t}(q^*_{1,t,R3})) \right\}$$
$$- \sum_{t=L,H} P_t(Q^*_{t,R3})\,\theta_{3t}R_3. \tag{55}$$

Using (11), (12), (14), (24), (26), (29), and that the fringe's renewable output adjusts residual demand to be served by the incumbents by $P_t(Q_t) \;=\; \alpha_t - \beta_t\,Q_t = \alpha_t - \beta_t\theta_{3t}R_3 - \beta_t(q_{1t} + q_{2t})$:

$$q^{f*}_{1,t,R3} \;=\; \left( \frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}} \right) \left[ (\alpha_t - \beta_t\theta_{3t}R_3)(\beta_t + c_{2t}) - \beta_t^2\,k_{5t}\,(\alpha_t - \beta_t\theta_{3t}R_3)(\beta_t + c_{1t}) \right]; \tag{56}$$

$$q^{f*}_{2,t,R3} \;=\; \left( \frac{k_{5t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}} \right) \left[ (\alpha_t - \beta_t\theta_{3t}R_3)(\beta_t + c_{1t}) - \beta_t^2\,k_{3t}\,(\alpha_t - \beta_t\theta_{3t}R_3)(\beta_t + c_{2t}) \right]. \tag{57}$$

$$q^*_{1,t,R3} \;=\; \frac{1}{A_t} \left[ (\alpha_t - \beta_t\theta_{3t}R_3)\,(\beta_t + c_{2t}) + (2\beta_t + c_{2t})[\beta_t q^{f*}_{1,t,R3}] - \beta_t\,[\beta_t q^{f*}_{2,t,R3}] \right]; \tag{58}$$

$$q^*_{2,t,R3} \;=\; \frac{1}{A_t}\Big[(\alpha_t - \beta_t\theta_{3t}R_3)\,(\beta_t + c_{1t}) + (2\beta_t + c_{1t})[\beta_t q^{f*}_{2,t,R3}] - \beta_t\,[\beta_t q^{f*}_{1,t,R3}]\Big]. \tag{59}$$

Using (11), (12), (14), (15), (23) - (26), (29) and (30) to solve for $(Q^*_{t,R1}, q^*_{1,t,R1}, q^*_{2,t,R1}, q^{f*}_{1,t,R1}, q^{f*}_{2,t,R1})$, (56) – (59), and utilizing *Mathematica* to simplify the analytical expression, under the specified conditions (55) can be rewritten as:

$$\begin{aligned} m_1^{minR3} - m_3^{min} \;=\; & \left[\frac{1}{\beta^2 + \beta c + 0.2c^2}\right]^2 \left[\frac{1}{\beta^2 + \frac{4}{3}\beta c + \frac{1}{3}c^2}\right]^2 \left[\frac{1}{\beta^2 + 3\beta c + c^2}\right]^2 \left[\frac{\beta^2\, R}{225}\right] \\ & \times\Big\{\beta^{10}\,\theta_H[9\alpha_H - 27\beta\theta_H R] + \beta^9\,c\,\theta_H[60\alpha_H - 256.5\beta\theta_H R] \\ & +\beta^8\,c^2\,\theta_H[154\alpha_H - 1089\beta\theta_H R] + \beta^7\,c^3\,\theta_H[201\alpha_H - 2669.5\beta\theta_H R] \\ & +\beta^6\,c^4\,\theta_H[145\alpha_H - 4153\beta\theta_H R] + \beta^5\,c^5\,\theta_H[58\alpha_H - 4284\beta\theta_H R] \\ & +\beta^4\,c^6\,\theta_H[12\alpha_H - 2985\beta\theta_H R] + \beta^3\,c^7\,\theta_H[\alpha_H - 1406\beta\theta_H R] \\ & +\beta^{10}\,\theta_L[9\alpha_L - 27\beta\theta_L R] + \beta^9\,c\,\theta_L[60\alpha_L - 256.5\beta\theta_L R] \\ & +\beta^8\,c^2\,\theta_L[154\alpha_L - 1089\beta\theta_L R] + \beta^7\,c^3\,\theta_L[201\alpha_L - 2669.5\beta\theta_L R] \\ & +\beta^6\,c^4\,\theta_L[145\alpha_L - 4153\beta\theta_L R] + \beta^5\,c^5\,\theta_L[58\alpha_L - 4284\beta\theta_L R] \\ & +\beta^4\,c^6\,\theta_L[12\alpha_L - 2985\beta\theta_L R] + \beta^3\,c^7\,\theta_L[\alpha_L - 1406\beta\theta_L R] \\ & -87.5\beta^2 c^9 R[\theta_H^2 + \theta_L^2] - 10\beta c^{10} R[\theta_H^2 + \theta_L^2] \\ & -\frac{1}{2}c^{11} R[\theta_H^2 + \theta_L^2] - 440\beta^3 c^8 R[\theta_H^2 + \theta_L^2]\Big\}. \end{aligned} \tag{60}$$

Using (60), as $c \to 0$, under the specified conditions:

$$\lim_{c\to 0} m_1^{minR3} - m_3^{min} \;=\; \left[\frac{1}{\beta^{12}}\right]\left[\frac{\beta^{12}\,R}{225}\right]\sum_{t=L,H}\theta_t[9\alpha_t - 27\beta\theta_t R] \;>\; 0. \quad \blacksquare$$

**Proof of Proposition 13**. Suppose $\delta_1 = \delta_2 = \delta_3 = 1$. It is without loss of generality to focus on firm 1. Using (1), firm 1 is indifferent between receiving the renewable capacity and firm 3 when:

$$\begin{aligned} \overline{P}_1^{minR3} \;=\; & \frac{F}{\sum\limits_{t=L,H}\theta_{1t}R} - \left(\frac{1}{\sum\limits_{t=L,H}\theta_{1t}R}\right)\sum_{t=L,H}\{P_t(Q^*_{t,R1})\,[q^*_{1,t,R1} - \theta_{1t}R] - C_{1t}(q^*_{1,t,R1}) \\ & - [P_t(Q^*_{t,R3})\,q^*_{1,t,R3} - C_{1t}(q^*_{1,t,R3})]\}. \end{aligned} \tag{61}$$

Using (54) and (61), under Assumption 2:

$$\overline{P}_3^{min} - \overline{P}_1^{minR3} \stackrel{s}{=} \sum_{t=L,H} \{P_t(Q^*_{t,R1})\,[q^*_{1,t,R1} - \theta_{1t}R] - C_{1t}(q^*_{1,t,R1})$$

$$- [P_t(Q^*_{t,R3})\,q^*_{1,t,R3} - C_{1t}(q^*_{1,t,R3})]\}. \tag{62}$$

Using (23) – (30), and and that the fringe's renewable output adjusts residual demand to be served by the incumbents by $P_t(Q_t) = \alpha_t - \beta_t Q_t = \alpha_t - \beta_t\theta_{3t}R_3 - \beta_t(q_{1t} + q_{2t})$:

$$q^{f*}_{1,t,R3} = \left(\frac{k_{3t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\left[(\alpha_t - \beta_t\theta_{3t}R)(\beta_t + c_{2t}) - \beta_t^2\,k_{5t}\,(\alpha_t - \beta_t\theta_{3t}R)(\beta_t + c_{1t})\right]; \tag{63}$$

$$q^{f*}_{2,t,R3} = \left(\frac{k_{5t}}{1 - \beta_t^4\,k_{3t}\,k_{5t}}\right)\left[(\alpha_t - \beta_t\theta_{3t}R)(\beta_t + c_{1t}) - \beta_t^2\,k_{3t}\,(\alpha_t - \beta_t\theta_{3t}R)(\beta_t + c_{2t})\right]. \tag{64}$$

Using (11) – (15):

$$q^*_{1,t,R3} = \frac{1}{A_t}\left[(\alpha_t - \beta_t\theta_{3t}R)\,(\beta_t + c_{2t}) + (2\beta_t + c_{2t})[\beta_t q^{f*}_{1,t,R3}] - \beta_t\,[\beta_t q^{f*}_{2,t,R3}]\right]; \tag{65}$$

$$q^*_{2,t,R3} = \frac{1}{A_t}\left[(\alpha_t - \beta_t\theta_{3t}R)\,(\beta_t + c_{1t}) + (2\beta_t + c_{1t})[\beta_t q^{f*}_{2,t,R3}] - \beta_t\,[\beta_t q^{f*}_{1,t,R3}]\right]. \tag{66}$$

Using (11), (12), (14), (15), (23) - (26), (29) and (30) to solve for $(Q^*_{t,R1}, q^*_{1,t,R1}, q^*_{2,t,R1}, q^{f*}_{1,t,R1}, q^{f*}_{2,t,R1})$, (63) - (66), and utilizing *Mathematica* to simplify the analytical expression, under the specified conditions (62) can be rewritten as:

$$\sum_{t=L,H} \{P_t(Q^*_{t,R1})\,[q^*_{1,t,R1} - \theta_{1t}R] - C_{1t}(q^*_{1,t,R1}) - [P_t(Q^*_{t,R3})\,q^*_{1,t,R3} - C_{1t}(q^*_{1,t,R3})]\}$$

$$\stackrel{s}{=} [\alpha_H - \alpha_L][\theta_{3H} - \theta_{1H}] + \beta R[\theta_{1H}^2 - \theta_{1H}\theta_{3H} - \theta_{1H}\theta_{3L} + \theta_{3H}\theta_{3L}]$$

$$= [\theta_{3H} - \theta_{1H}]\left[(\alpha_H - \beta R\theta_{1H}) - (\alpha_L - \beta R\theta_{3L})\right] \stackrel{s}{=} \theta_{3H} - \theta_{1H}. \tag{67}$$

Under Assumption 2, $\theta_{3H} > \theta_{1H}$ such that $\overline{P}_3^{min} > \overline{P}_1^{minR3}$. Similarly, it can be readily shown that $\overline{P}_3^{min} > \overline{P}_2^{minR3}$ under Assumption 2 because $\theta_{3H} > \theta_{2H}$. ■

**Proof of Proposition 14**. Suppose $\delta_1 = \delta_2 = \delta_3 = 1$. Using (62) - (67), under Assumption 3 $\theta_{3H} < \theta_{1H}$ such that $\overline{P}_3^{min} < \overline{P}_1^{minR3}$. Similarly, it can be readily shown that $\overline{P}_3^{min} < \overline{P}_2^{minR3}$ because $\theta_{3H} < \theta_{2H}$ under Assumption 3. ■

**Proof of Proposition 15**. Suppose $\delta_1 = \delta_2 = \delta_3 = 0$. It is without loss of generality to focus on firm 1. Using (11), (12), (14), (15), (23) - (26), (29) and (30) to solve for $(Q^*_{t,R1}, q^*_{1,t,R1}, q^*_{2,t,R1}, q^{f*}_{1,t,R1}, q^{f*}_{2,t,R1})$, (56) – (59), we utilizing *Mathematica* to simplify the analytical expression in (55).

See Brown and Eckert (2018) for a detailed presentation. Differentiating (55) with respect to $\eta$:

$$\begin{aligned}\frac{\partial(m_1^{minR3}-m_3^{min})}{\partial\,\eta} \;\stackrel{s}{=}\; & \beta^4c^8\big[3550(\alpha_H-\alpha_L)-7980\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^3c^9\big[1037(\alpha_H-\alpha_L)-2249\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^2c^{10}\big[194(\alpha_H-\alpha_L)-408\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta c^{11}\big[21(\alpha_H-\alpha_L)-43\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+c^{12}\big[(\alpha_H-\alpha_L)-2\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^5c^7\big[8140(\alpha_H-\alpha_L)-19090\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^{12}\big[9(\alpha_H-\alpha_L)-54\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^6c^6\big[12712(\alpha_H-\alpha_L)-31370\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^7c^5\big[13493(\alpha_H-\alpha_L)-35439\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^{11}c\big[168(\alpha_H-\alpha_L)-738\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^8c^4\big[9554(\alpha_H-\alpha_L)-27132\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^{10}c^2\big[1180(\alpha_H-\alpha_L)-4254\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]\\
&+\beta^9c^3\big[4341(\alpha_H-\alpha_L)-13641\beta R(2\eta+\theta_{1H}-\theta_{1L})\big]. \qquad (68)\end{aligned}$$

Condition (68) depends critically on the sign of $A_1(\alpha_H-\alpha_L)-A_2\beta R(2\eta+\theta_{1H}-\theta_{1L})$ where $A_1, A_2$ are positive constants, the largest differential between $A_1$ and $A_2$ arises when $A_1=9$ and $A_2=54$, and $2\eta+\theta_{1H}-\theta_{1L}=\theta_{1H}+\eta-(\theta_{1L}-\eta)=\theta_{3H}-\theta_{3L}$, then (68) is strictly positive when:

$$9(\alpha_H-\alpha_L)-54\beta R(2\eta+\theta_{1H}-\theta_{1L}) \;=\; 9\alpha_H-54\beta R\theta_{3H}-(9\alpha_L-54\beta R\theta_{3L}) \;>\; 0. \qquad (69)$$

(69) holds when demand in the high demand period is sufficiently large compared to the low demand period when the fringe wins the renewable auction (i.e., $\alpha_H$ is sufficiently large).

In addition, differentiating (55) with respect to $\alpha_H$:

$$\begin{aligned}\frac{\partial(m_1^{minR3}-m_3^{min})}{\partial\,\alpha_H} \;\stackrel{s}{=}\; & \beta^4c^8 3550\eta+\beta^3c^9 1037\eta+\beta^2c^{10}194\eta+\beta c^{11}21\eta+c^{12}\eta+\beta^5c^7[8140\eta+\theta_{1H}]\\
&+9\beta^{12}[\eta+\theta_{1H}]+\beta^6c^6[12712\eta+12\theta_{1H}]+\beta^7c^5[13494\eta+58\theta_{1H}]\\
&+\beta^{11}c[168\eta+60\theta_{1H}]+\beta^8c^4[9554\eta+145\theta_{1H}]+\beta^{10}c^2[1180\eta+154\theta_{1H}]\\
&+\beta^9c^3[4341\eta+201\theta_{1H}] \;>\; 0. \quad \blacksquare\end{aligned}$$

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