Submitted Manuscript

Net-Metered Distributed Renewable Energy: A Peril for Utilities?

Nur Sunar
Kenan-Flagler Business School, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, Nur_Sunar@kenan-flagler.unc.edu

Jayashankar M. Swaminathan
Kenan-Flagler Business School, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, msj@unc.edu

Electricity end-users have been increasingly generating their own electricity via rooftop solar panels. Our paper studies the implications of such "distributed renewable energy" for utility profits and social welfare under net metering that has sparked heated debates in practice. The common belief is that such type of generation significantly decreases utility profits because (i) distributed generation reduces utility's market size, and (ii) under net metering, utilities must buy back the excess generation of their customers at a rate typically larger than their procurement cost. Based on this understanding, there have been various lobbying campaigns against the net-metered distributed solar energy. A distinctive feature of our paper is that it considers supply-side effects of distributed renewable energy on utilities by explicitly modeling the wholesale market dynamics, while also accounting for (i) and (ii). Our analysis shows that in contrast to the common belief, the presence of net-metered distributed renewable energy can strictly increase the expected profit for utilities (compared to the case with no such energy) when wholesale market dynamics are factored in. Specifically, we prove that the net-metered distributed renewable energy strictly improves the utility's expected profit if and only if the equilibrium wholesale electricity price is sufficiently sensitive to the changes in the wholesale demand and the utility's expected market-reliance level is above a threshold. Our numerical study uses data on distributed solar energy in California and the CAISO's wholesale electricity market, and demonstrates that our results continue to be valid under realistic parameters.

Key words: rooftop solar panel, distributed renewable energy, net metering, wholesale electricity market, utility, social welfare
History: This version: September, 2019

---

1. Introduction

Electricity end-users have been increasingly installing rooftop solar panels and small wind turbines to generate their own electricity. This small-scale decentralized renewable energy is called *distributed renewable energy*. The recent growth in distributed solar energy has been significant. For instance, in last six years, residential solar energy capacity has increased by more than 350% in the U.S. (U.S. EIA 2018a).

Distributed renewable energy (DRE) is changing the landscape of energy sector, and the implications of this disruptive generation model have recently been at the center of heated debates. In practice, the boost in distributed solar is perceived as a threat for electric utility companies (*utilities*) because allowing end-customers (e.g., homeowners) to generate their own electricity is assumed to decrease both sales and profits for utilities (The NYTimes 2017, The Washington Post 2015). In fact, the Edison Electric Institute (2012), which is a utility association in the U.S., classifies distributed solar as a prominent "challenge" for utilities. A presentation prepared by the Edison Electric Institute for utility executives in the U.S. emphasized that

Electronic copy available at: https://ssrn.com/abstract=3257925

rooftop solar panels could soon create serious problems for utilities, including “declining retail sales” and “loss of customers” (The Washington Post 2015).

The significant growth in distributed renewable energy can be attributed to the net metering policy, which is currently mandatory in 38 states, the District of Columbia and 3 territories of the U.S. (DSIRE 2017b). Under the net metering policy, electricity end-customers with DRE technology, i.e., *net-metered customers*, meet their electricity demand through their own generation. If these customers produce less than their demand, they meet their excess demand from the utility at the rate of retail electricity price. More importantly, if they produce more than their demand, they sell their excess generation back to the utility. Under the mandatory net metering policy, typically, the utility *must* purchase any generation surplus back from its net-metered customers at a certain rate.

The compensation rules for the generation surplus of net-metered customers significantly vary from one state to another, and have been subject to changes in the U.S. (see, e.g., Michigan Public Service Comission (2018), Vermont PUC (2017) and DSIRE (2017a)). Two widespread compensation rules in the U.S. have been *retail-based* and *market-based* rules. Under these two rules, the compensation rates are based on retail rate and wholesale market price of electricity, respectively. For example, per regulation, utilities in North Carolina, Iowa and Virginia must credit their net-metered customers for their excess generation based on the retail rate, whereas utilities in California have recently started to compensate the excess generation of their end-customers based on the wholesale market price (DSIRE 2017c, 2015, 2018, PG&E 2017). Among these two compensation rules, historically, the retail-based rule has been the more common one (DSIRE 2017a). Recently, there have been various lobbying campaigns by utilities for the market-based rule (Silverstein 2016). In this paper, we consider both retail-based and market-based rules.

Under the net metering policy, typically, utilities must pay more to buy back unit excess generation of their end-customers compared to obtaining the same amount of energy from traditional sources. These costly compensation requirements and the potential decline in retail sales due to distributed solar are believed to result in significant loss for utilities. Based on this understanding, there have been various lobbying efforts by utilities against the distributed renewable energy generation under net metering (The Washington Post 2015, The NYTimes 2017). Note that the aforementioned effects are the downstream implications of DRE for utilities.

Utilities’ upstream dynamics are as important as their downstream dynamics in understanding the implications of distributed solar for utilities. Our paper considers both these dynamics. In the U.S., numerous utilities operate in regions with regional transmission operators (RTOs) or independent system operators (ISOs), and these utilities typically benefit from wholesale markets (administered by RTOs/ISOs) in meeting

Electronic copy available at: https://ssrn.com/abstract=3257925

their customers' electricity demand (U.S. EIA 2018a).[1] These wholesale markets support two thirds of the electricity consumption in the U.S. (FERC 2017).[2] Despite the prominence of these markets, surprisingly, there is no theoretical study in the literature that accounts for the wholesale market dynamics in the analysis of distributed renewable energy under the net metering policy. Our paper provides such an analysis.

A wholesale electricity market typically operates as follows. There are multiple power generators in a wholesale market, and each generator bids a supply *curve* that represents the amount it is willing to supply at each possible wholesale market-clearing price. This bidding process occurs without observing the realized net market demand or any other generators' bids. After the net wholesale market demand is realized, the market-clearing price is set to match the aggregate committed wholesale supply and the aggregate net wholesale market demand. Consistent with the literature, we consider a supply function competition model to study the wholesale market. However, we also establish the robustness of our key insights with respect to the wholesale market formulation by considering more general wholesale market dynamics in Section 5.1.

In this context, our main research questions are as follows. (i) What are the implications of the distributed renewable energy (DRE) for utilities that are subject to the net metering policy? Does the presence of net-metered DRE hurt the profitability of utilities, as believed in practice? (ii) How does the adoption level of DRE affect utilities' expected profits? (iii) Among the net metering rules currently in effect, i.e., retail-based and market-based rules, which rule is more favorable to utilities, and under what conditions? Apart from these main research questions, our paper (i.e., Section 5.6) also studies (iv) social welfare implications of net-metered DRE and the two net metering rules.

1.1. Summary of Main Results and Insights

Considering wholesale electricity market dynamics while evaluating the impact of net-metered distributed renewable energy brings forth three important results for utilities. These results and their insights are new to the literature:

First, Theorem 1 proves that under certain conditions, the presence of net-metered distributed renewable energy strictly improves the expected profit of a utility, compared to the case with no such energy. This result is in contrast to the general understanding about the implications of net-metered DRE for utility profits. By Theorem 1, net-metered DRE strictly improves the expected profit of a utility if and only if (i)

[1] In 2017, 70% of the U.S. utilities listed in U.S. EIA (2018a) operated in regions with RTOs/ISOs such as MISO, CAISO and PJM.

[2] An important example of power suppliers in wholesale electricity markets is non-utility power producers. Utilities in many states sold off most of their generation assets due to the energy policy restructuring in the late 1990s (Blumsack et al. 2008). As a result, in various states, independent power producers or other non-utility power producers have been generating the majority of electricity power. For example, in 2017, generation of these entities constituted 98.3% of the electricity generation in Massachusetts while the corresponding percentage in Pennsylvania was 99.9% (U.S. EIA 2019). Non-utility power producers might not meet 100% of the wholesale demand because a utility can be a net seller in the wholesale market when it has excess power supply. Our formulation in Section 2 will take this into account.

Electronic copy available at: https://ssrn.com/abstract=3257925

the equilibrium wholesale price is not too insensitive to the changes in the (net) wholesale demand and (ii) the utility's expected *market-reliance* level is larger than a threshold, that is, the utility's existing energy resource is smaller than a critical size. This result identifies two factors that may drive a strict improvement in the utility profitability when net-metered DRE is introduced: the mix of the utility's energy resources and the sensitivity of wholesale price with respect to the wholesale demand. Moreover, Corollary 1 proves that the difference between the utility's expected profits with and without net-metered DRE strictly increases in the utility's expected market-reliance level. These conclusions hold regardless of the compensation rule. Sections 5.1 through 5.5 establish the robustness of Theorem 1 in various settings.

Theorem 1 and Corollary 1 provide three key insights for utilities: (i) In expectation, if a utility meets a portion of its demand through the wholesale market, which is common in practice, the utility should be extra prudent in its lobbying strategy about net-metered distributed solar. This is because in that case, the elimination of net-metered distributed solar might backfire by causing a profit loss for the utility. (ii) A more market-reliant utility benefits less from lobbying against net-metered distributed solar. In fact, utilities with a larger market-reliance are more exposed to the unexpected profit loss due to the elimination of net-metered distributed solar. (iii) As a general guideline, before lobbying, a utility should judiciously evaluate the following two key factors that determine if net-metered DRE boosts its expected profit: the composition of its energy resources and the characteristics of the wholesale market it operates in.

Second, by Theorem 2, the expected profit of a utility can strictly increase with the expected DRE generation in its serving area until that expected generation reaches a certain level. This means that utilities might benefit from motivating their customers to adopt DRE technology via their DRE assistance programs. However, such a benefit is relevant to utilities only until a certain cap is reached. Thus, for the emerging DRE assistance programs to serve their purposes, it is essential to have a carefully-set cap on them. Theorem 2 further suggests that it might be beneficial for utilities to lobby for a cap on the net metering programs rather than complete elimination of net-metered DRE.

Third, Theorem 3 proves that eventually, the retail-based rule results in strictly larger expected profit for a utility than the market-based rule under some conditions. Theorem 3 offers important insights to utilities: Utilities' current lobbying efforts for the implementation of the market-based rule, which compensates the generation surplus of customers at a lower rate than the retail-based rule in expectation, might eventually backfire. This is because lobbying for a net metering rule just based on its compensation rate may hurt the utility profitability. By Theorem 3, a utility should account for adoption level estimates and the wholesale market dynamics to identify the more favorable rule for itself.

Section 4 presents a numerical study based on the distributed solar energy in California, utilities in California and the wholesale electricity market operated by CAISO. Our numerical study demonstrates the

Electronic copy available at: https://ssrn.com/abstract=3257925

following key findings when parameters are set to realistic values: Under the net metering policy, (i) for a large range of realistic utility market-reliance levels, the presence of distributed solar strictly improves the utility's expected profit, compared to the case with no distributed solar, (ii) the aforementioned increase in the utility's expected profit can be considerable, and (iii) the utility's expected profit can strictly increase with the expected distributed solar generation for a wide range of distributed solar output levels.

Overall, a key message of our paper is that utilities' current lobbying efforts against net-metered distributed solar or the retail-based net metering rule might backfire as both net-metered DRE and retail-based rule can improve the profitability of utilities. As explained above, our results offer important guidelines to utilities regarding their lobbying efforts and emerging business strategies (e.g., DRE assistance programs). To our knowledge, there is no prior work that identifies these results and insights.

1.2. Literature Review

Our paper contributes to the renewable energy operations literature. To the best of our knowledge, we are the first to analyze the implications of net-metered DRE for utilities by considering a wholesale electricity market. The results and insights explained in Section 1.1 are new to the literature.

In renewable energy operations literature, Hu et al. (2015) analyze renewable capacity investments, and show that the granularity of the output and demand data significantly affects investments. Aflaki and Netessine (2017) find that an increase in the carbon price can discourage renewable energy investments. Sunar and Birge (2019) prove that imposing an undersupply penalty to large-scale renewable firms or increasing such a penalty can lead to larger equilibrium supply commitments by these firms and less reliability. Lobel and Perakis (2013) provide a framework to policy makers about how to subsidize customers' renewable technology adoption, and establish via an empirical study that current policies in Germany are not efficient. Alizamir et al. (2016) study the socially optimal design of a feed-in-tariff policy for renewable technologies, and prove that a policy providing constant profitability rarely achieves social optimality. Apart from these, this research stream study many other interesting topics, including energy storage (e.g., Zhou et al. (2018)), investment with operational flexibility (e.g., Kök et al. (2016)) and energy curtailment (e.g., Wu and Kapuscinski (2013)).

Despite the prominence of net-metered DRE in practice, the theoretical analysis of DRE under the net metering policy is very limited. Different from our paper, available papers on this topic typically focus on policymaking questions. Gautier et al. (2018) compare net metering in the U.S. with net purchasing, which is a support policy for DRE in some parts of Europe. The authors find that among the two systems, net metering results in more DRE adoption. Brown and Sappington (2017) study the optimal tariff and payment policy for customers to maximize a version of consumer welfare in the presence of DRE. They show that paying self-generating customers the welfare-maximizing tariff per their unit excess generation might not be welfare-optimal. Singh and Scheller-Wolf (2018) study the socially optimal design of tariff structures, and conclude

Electronic copy available at: https://ssrn.com/abstract=3257925

that a tiered tariff structure is necessary for social optimality. Our paper differs from these papers in various ways. First, our paper studies the utility's expected profit, which is a different performance metric than the ones considered in these papers. Second, we consider the interaction between utilities and the wholesale electricity market. This distinct feature requires us to model and analyze the wholesale electricity market, which is not considered in any of these papers. Third, we focus on common net metering rules currently in effect and their implications for utilities, which are not studied in these papers. To our knowledge, our paper is the first that theoretically analyzes the implications of the current net-metering rules for utilities by explicitly modeling a wholesale electricity market. In this context, our paper also analyzes social welfare.

There is a separate stream of energy economics literature that numerically studies the implications of the net metering policy. For example, Watts et al. (2015) present a case study to assess the impact of the net metering policy on solar PV in Chile. Similarly, Holdermann et al. (2014), Dufo-López and Bernal-Agustín (2015), Eid et al. (2014), and Jagruti and Basab (2018) present various case studies either to evaluate the economic feasibility of net-metered distributed generation or to identify its impact on customer bill savings in Brazil, Spain and India. Among these, Eid et al. (2014) numerically study a household in Spain to understand billing implications of net metering under potential network tariff structures. The authors demonstrate that customer bill decreases with net metering, and argue that in Europe, a capacity-based network tariff might better serve to customers and the system than an energy-based network tariff. Apart from these, Darghouth et al. (2014) conduct a case study to investigate the impact of net-metered solar PV on customer economics, considering a U.S. data set. Our paper is very different from these papers, as we provide a theoretical analysis of the net-metered distributed generation and we primarily focus on the utility's expected profit as a performance metric, as opposed to the typical focus on customers' bill savings in this stream of literature. Thus, the results explained in Section 1.1 are new to this literature.

There is also another stream of energy economics literature that qualitatively discusses potential alternatives that might ease utility's cost recovery in the presence of DRE generation. The alternative proposals in the literature consist of different tariff designs, demand and fixed charges and minimum bills (see, e.g., the discussion papers by Felder and Athawale (2014) and Borenstein (2016)). In contrast to this stream, our paper considers the current status in practice, and provides a theoretical analysis to understand the implications of net-metered DRE on utility's expected profit. Our analysis identifies two factors that can drive a strict improvement in the utility profitability when net-metered DRE is introduced: the mix in the utility's energy supply and the presence of a wholesale market. (See Theorem 1.) These factors have not been identified in the literature. Thus, the insights and results explained in Section 1.1 are new to this literature as well.

Electronic copy available at: https://ssrn.com/abstract=3257925

Finally, our paper also contributes to the sustainable operations literature that spans various topics including renewable energy, remanufacturing, emissions allocation and green product design (see, e.g., Kleindorfer et al. 2005, Corbett and Klassen 2006, Ferrer and Swaminathan 2006, Girotra and Netessine 2013, Caro et al. 2013, Cachon 2014, Guo et al. 2015, Sunar and Plambeck 2016, Gopalakrishnan et al. 2016, Agrawal and Bellos 2017, Orsdemir et al. 2017, Murali et al. 2018, Nguyen et al. 2019, Lee and Tang 2018).

Organization of the Paper: The remainder of our paper consists of Sections 2 through 6. Among those, Section 2 introduces the model. Section 3 includes our results and their interpretations. Sections 5.1 through 5.6 analyzes various extension of the base model in Section 2. Supplementary materials and the proofs of all formal results are presented in Appendices A through K of the Electronic Companion.

2. Model

Consider a wholesale electricity market that contains $N > 2$ power generators, indexed by $n = 1, 2, \ldots, N$, and $I \geq 1$ distributing companies, i.e., *utilities*, indexed by $i = 1, 2, \ldots, I$. Generators produce energy to sell in the wholesale electricity market. Each utility is responsible for meeting the electricity demand of its end-customers (e.g., residential customers). Utilities' requirement to meet end-customer demand is one of the drivers of the wholesale demand.

Wholesale Electricity Market. The wholesale market operates as follows. Each generator n submits its *supply function*

$$S_n : \mathbb{R} \to \mathbb{R},$$

without observing other generators' supply functions or the random net wholesale market demand $\mathcal{D}_w$. The supply function, which is allowed to be any twice differentiable function, represents how much energy the firm is willing to produce at each potential market-clearing price. The wholesale market-clearing price p_w^* is determined to match the aggregate supply commitment in the market and the realized net market demand:

$$\sum_{n=1}^{N} S_n(p_w^*) = \mathcal{D}_w. \tag{1}$$

Later, our analysis will establish the uniqueness of the market-clearing price in equilibrium. The clearing mechanism in (1) guarantees that the wholesale supply and the wholesale demand are matched at the minimum cost. This formulation of the wholesale electricity market is consistent with the literature (see, e.g., Johari and Tsitsiklis (2011), Holmberg and Newbery (2010) and Anderson and Philpott (2002)).

Electronic copy available at: https://ssrn.com/abstract=3257925

In the literature, it is common to consider a supply function equilibrium to capture the equilibrium dynamics in a wholesale electricity market.[3] Following the literature, our paper also considers a supply function equilibrium to do so. As will be explained later, Section 5.1 establishes the robustness of our analysis with respect to this wholesale market formulation. The concept of supply function equilibria is introduced by Klemperer and Meyer (1989). However, to our knowledge, no prior work has considered a supply function competition model in the context of distributed renewable energy as we do.

DEFINITION 1. (Supply Function Equilibrium) A supply function profile $(S_1, S_2, \ldots, S_N)$ is called a supply function equilibrium if and only if for every $n = 1, \ldots, N$, S_n satisfies

$$\pi_n(S_n; S_{-n}, \epsilon) \geq \pi_n(S; S_{-n}, \epsilon), \quad \text{for any} \quad S : \mathbb{R} \to \mathbb{R} \text{ and } \epsilon, \tag{2}$$

where $\pi_n(S; S_{-n}, \epsilon)$ is generator n's profit given that the generator n submits the supply function S, the supply function profile of other generators is $S_{-n} \doteq (S_1, \ldots, S_{n-1}, S_{n+1}, \ldots, S_N)$ and the net wholesale market demand is realized as ϵ.

In supply function equilibrium, each generator achieves the maximum profit it would achieve if it knew the realized net wholesale demand before submitting its supply function. Thus, a supply function equilibrium is an ex post equilibrium with respect to the random net market demand. Because (2) holds for every realization of net wholesale market demand, we also have $\mathbb{E}_\epsilon\big[\pi_n(S_n; S_{-n}, \epsilon)\big] \geq \mathbb{E}_\epsilon\big[\pi_n(S; S_{-n}, \epsilon)\big]$ for any S. This means that a supply function equilibrium is also an *ex ante* Nash equilibrium.

When the generator's output is q, production cost of generator n is cq^2 where the constant $c \in (\underline{c}, \bar{c})$, and $\underline{c}$ and $\bar{c}$ are allowed to be any finite constants such that $0 < \underline{c} < \bar{c}$. This form of cost function is common for power generators in the literature (see, e.g., Rudkevich (1999), Vives (2011) and Al-Gwaiz et al. (2017)). In this paper, we focus on a symmetric equilibrium where

$$S_1 = S_2 = \ldots = S_n = S. \tag{3}$$

The explicit analysis of asymmetric supply function equilibria with general production cost functions is well known to be intractable in the literature (Johari and Tsitsiklis 2011). That being said, Section 5.1 extends the wholesale market formulation by considering a general relation between the market-clearing price and the net wholesale demand, and shows that our key result and insights hold in that extension. Because Section 5.1 captures any form of realistic dynamics in the wholesale market, our results are robust with respect to the wholesale market formulation. An important advantage of the presented model over the one in Section

[3] See, e.g., Al-Gwaiz et al. (2017), Holmberg and Newbery (2010), Hortacsu and Puller (2008), Anderson and Philpott (2002), Wolak (2000), Rudkevich (1999), Green (1996) and Green and Newbery (1992), among many others. Note that this list includes both theoretical and empirical studies that explain the dynamics in wholesale electricity markets via a supply function competition model.

Electronic copy available at: https://ssrn.com/abstract=3257925

5.1 is its tractability: The former provides extension opportunities (e.g., Section 5.2), whereas the latter is not tractable in those extensions.

Utilities. Utility i sells electricity at the retail electricity price $p_{u,i}$, and must meet the electricity demand of its end-customers. In practice, the frequency at which the wholesale market is run is typically much higher than the frequency at which the retail electricity price is changed (see, e.g., Lazaar (2016) and the explanation of the wholesale market operated by the CAISO in Section 4). Thus, we consider a fixed $p_{u,i}$ in this section and Section 3. [4] Section 5.4 extends our analysis to allow for an endogenous retail electricity price, and establishes that our key result and insights hold in that extension.

The total electricity demand of utility i's end-customers is $\widehat{D}_i$, which is a general random variable defined on the support $[0, \widehat{Q}_i]$. Utilities are subject to the net metering policy, and operate in different regions. End-customers with DRE technology are called *net-metered customers* whereas the ones with no DRE technology are called regular customers. Then, $\widehat{D}_i$ is the sum of electricity demands of utility i's net-metered and regular customers. Under the net metering policy, utility i can meet its end-customer demand from three sources: (i) its net-metered customers, (ii) its existing resources and (iii) wholesale electricity market.

Under net metering, if a net-metered customer produces more electricity than its demand, the utility must purchase the customer's generation surplus at a particular rate. (This compensation rate will be explained later in this section.) If a net-metered customer produces less electricity than its demand, the customer meets its net demand from the utility at the retail electricity price. Utility i's net-metered customers generate Δ_i units of electricity in total. The generation quantity Δ_i is a random variable with a general differentiable distribution function $F_i : [0, Q_i] \to \mathbb{R}_+$, and it is independent of other regions' generation. Utility i's net-metered customers demand D_i units of electricity in total; D_i has a general differentiable distribution function G_i on the support $[0, Q_i]$. Based on these, the generation surplus of utility i's net-metered customers is $(\Delta_i - D_i)^+$. This paper considers a setting where $\widehat{D}_i = \beta D_i$ and β is a constant strictly larger than 1. This relation is only to ensure analytical tractability under the market-based rule; results and analysis under the retail-based rule hold as stated without this relation. Consistent with practice, $\mathbb{E}[\widehat{D}_i] \geq \mathbb{E}[\Delta_i]$. (Tables EC.1 and EC.3 in Appendix J verify this property for major utilities in California.)

Utility i has existing resources that can meet up to $K_i \geq 0$ units of electricity demand at a unit cost $\tilde{c} > 0$. For instance, this could be a long-term contract with an independent power producer, which is a common way to secure energy for many years (FERC 2007, California Energy Commission 2018a). Consistent with our formulation, in these contracts, the unit price of electricity is typically predetermined and fixed (Hausman et al. 2008). In fact, there are various utilities such that the vast majority of their existing

[4] The formulation in Section 2 does not imply any assumption on the retail price dynamics in the longer run. See Sections 5.3 and 5.4 for further discussion about this.

Electronic copy available at: https://ssrn.com/abstract=3257925

resources consist of fixed-price energy contracts (see, e.g., MCE (2018) and PCE (2017)). That being said, Section 5.2 establishes the robustness of our key results with respect to the form of this cost function.

We consider a scenario where

$$\text{(a) } p_{u,i} > \tilde{c} \ \text{ for } \ i = 1, \ldots, I \ \text{ and } \ \text{(b) } \mathbb{E}\big[\mathcal{D}_w\big] \geq \tilde{c}N/2c + \max_{i=1,\ldots,I} K_i. \tag{4}$$

The condition (4)-(a) ensures that utility i earns a non-negative profit by procuring electricity at rate $\tilde{c}$ and selling it at rate $p_{u,i}$. This condition is consistent with practice; see, for instance, CPUC (2017a) that verifies (4)-(a) for each of the three major utilities in California.

The condition (4)-(b) means that the expected wholesale demand is not small. This condition ensures that we study a meaningful setting where the market-clearing price is not extremely low, and utility prefers its existing resources over the wholesale market when there is a need for energy. In fact, it is easier to analyze the alternative scenario where the utility prioritizes the wholesale market over its existing resources to meet its demand. In that alternative scenario, our main results hold in stronger sense.[5]

Because utility i must buy back generation surplus of its net-metered customers, Δ_i of utility i's market is served via net-metered customers' generation.[6] Then, there are two possible scenarios for utility i. If the demand of utility i's end-customers exceeds $K_i + \Delta_i$, utility i meets its excess demand $\big(\widehat{D}_i - \Delta_i - K_i\big)^+$ from the wholesale market at the wholesale market-clearing price p_w^*. If the demand of utility i's end-customers is less than $K_i + \Delta_i$, the utility i sells its excess supply $\big(\Delta_i + K_i - \widehat{D}_i\big)^+$ to the wholesale market at price p_w^*. By doing so, utility i optimally gains additional profit from wholesale market sales by (4)-(b). The explained formulation of utility's excess supply is consistent with practice.[7] Let ξ be a random variable that represents the wholesale demand of market participants other than utilities (see, e.g., MISO (2018) and CAISO (2018)). As a result, total net demand in the wholesale market is

$$\mathcal{D}_w = \sum_{i=1}^{I} \big(\widehat{D}_i - K_i - \Delta_i\big)^+ - \sum_{i=1}^{I} \big(\Delta_i + K_i - \widehat{D}_i\big)^+ + \xi = \sum_{i=1}^{I} \big(\widehat{D}_i - K_i - \Delta_i\big) + \xi. \tag{5}$$

[5] In the explained alternative scenario, the key results are immediate corollaries of existing results. For example, in that alternative setting, Theorem 1 in Section 3 holds as stated with the exception that the first condition on K_j in (8) must be removed. The proof follows from the similar arguments as in the proof of Lemma EC.1 in Appendix C of the Electronic Companion.

[6] If $\Delta_i \leq D_i$, net-metered customers meet Δ_i of their demand through their production. If $\Delta_i > D_i$, Δ_i of utility i's customer demand is met through DRE as well because the utility receives the generation surplus $(\Delta_i - D_i)^+$ from its net-metered customers.

[7] In practice, it is common to observe that major utilities sell very small quantities of energy (if any) in wholesale markets (U.S. EIA 2018a, LCG Consulting 2018). For example, in 2017, the wholesale market sale of Southern California Edison, which was the largest utility in the CAISO's system, was less than 3.1% of the total sales in the CAISO's wholesale market (U.S. EIA 2018a, LCG Consulting 2018). Similarly, in 2017, the wholesale market sale of Connecticut Light & Power Co, which was the largest utility in the ISO-NE's system and is now called Eversource, was less than 0.55% of the total sales in the ISO-NE's wholesale market. In 2017, the average wholesale market sales percentage of a utility within CAISO and ISO-NE were less than 0.31% and 0.04%, respectively (U.S. EIA 2018a). Because the revenue stakes of such utilities are very little in the wholesale market, they are non-strategic in market competition, that is, they sell their excess power at the market-clearing price. There is also empirical evidence for the non-strategic behavior of utilities with small revenue stakes in the wholesale markets (see, e.g., Hortacsu and Puller (2008)), and our conversations with practitioners further validate this. Thus, our treatment of utility's excess supply is consistent with practice.

Electronic copy available at: https://ssrn.com/abstract=3257925

The random variable ξ has a general distribution function $\Phi : [\underline{\eta}, \bar{\eta}] \to \mathbb{R}_+$ with a mean η where η, $\underline{\eta}$ and $\bar{\eta}$ are some constants, and ξ is independent of Δ_i.

We analyze two common net metering rules for compensating the generation surplus of net-metered customers: retail-based rule (i.e., $\ell = r$) and market-based rule (i.e., $\ell = m$) (DSIRE 2015, 2018, PG&E 2017, NCSL 2016). Under the rule $\ell = r$, utility i buys back the generation surplus of its net-metered customers at the rate of retail electricity price $p_{u,i}$, whereas under the rule $\ell = m$, utility i does so at the rate of wholesale price p_w^*. Let $\mathbb{I}\{\cdot\}$ be the indicator function. Define p_ℓ such that $p_\ell \doteq p_{u,j}$ if $\ell = r$ and $p_\ell \doteq p_w^*$ if $\ell = m$. Then, the utility j's expected profit under the rule $\ell \in \{r, m\}$ is

$$\begin{aligned}
\Pi_j(\ell) = & \underbrace{\mathbb{E}\Big[\big(\widehat{D}_j - D_j + (D_j - \Delta_j)^+\big)p_{u,j}\Big]}_{\text{Revenue from selling to end-customers}} - \underbrace{\mathbb{E}\Big[(\Delta_j - D_j)^+ p_\ell\Big]}_{\text{Cost of buying from net-metered customers}} \\
& - \underbrace{\mathbb{E}\Big[\mathbb{I}\{\widehat{D}_j > \Delta_j + K_j\}\big(\big(\widehat{D}_j - \Delta_j - K_j\big)p_w^* + K_j\tilde{c}\big)\Big]}_{\text{Cost of meeting remaining demand when } \widehat{D}_j > \Delta_j + K_j} \\
& + \underbrace{\mathbb{E}\Big[\mathbb{I}\{\widehat{D}_j \le K_j + \Delta_j\}\big(\big(\Delta_j + K_j - \widehat{D}_j\big)p_w^* - K_j\tilde{c}\big)\Big]}_{\text{Extra profit from selling excess energy to the wholesale market when } \widehat{D}_j \le \Delta_j + K_j}. \qquad (6)
\end{aligned}$$

Here, by (1) and (5), p_w^* is a random variable that depends on $\widehat{D}_i - \Delta_i - K_i$ for $i = 1, \ldots, I$.

Let us explain the terms in (6). Utility j sells $\widehat{D}_j - D_j + (D_j - \Delta_j)^+$ units of electricity to its end-customers. This is because the demand of utility j's net-metered customers is $(D_j - \Delta_j)^+$ and the demand of utility j's other customers (with no DRE technology) is $\widehat{D}_j - D_j$. From this, the first (revenue) term in (6) follows. The logic behind the second line of (6) is as follows. Recall that Δ_j units of utility j's market is served with net-metered customers' generation. Then, by (4)-(b), utility j meets its remaining demand $\widehat{D}_j - \Delta_j$ from its existing resources. If the existing resources are not sufficient, i.e., if $\widehat{D}_j > \Delta_j + K_j$, utility j procures from the wholesale market to meet the remaining demand. Finally, the third line of (6) is because if $\widehat{D}_j \le \Delta_j + K_j$, utility j has an excess supply of $\Delta_j + K_j - \widehat{D}_j$, and it is favorable for utility j to gain additional profit by selling the excess supply in the wholesale market.

REMARK 1. The expression in (6) is equivalent to the utility j's expected profit in the following alternative formulation: (i) For any i, utility i's all existing supply K_i is sold in the wholesale market at the wholesale market-clearing price p_w^*. (ii) Utility i's end-customer demand and the retail price are as described in Section 2. To meet the demand, utility i buys (iii) $\widehat{D}_i - \Delta_i$ from the wholesale market at price p_w^* and (iv) $(\Delta_i - D_i)^+$ from its net-metered customers at price p_ℓ. The reason for the equivalence is as follows. By (ii), the utility j's expected retail revenue in this alternative formulation is the same as the first expectation term in (6). The utility j's expected payoff resulting from (i) and (iii) equals the sum of the second and third lines of (6). Lastly, the expected cost of (iv) is the same as the second expectation term in (6) for the utility j.

Electronic copy available at: https://ssrn.com/abstract=3257925

3. Analysis

We first establish the uniqueness of the equilibrium, and analyze the relation between distributed renewable energy (DRE) and the equilibrium market-clearing price.

PROPOSITION 1. **(a)** *There exists a unique supply function equilibrium that satisfies* (3)*. Furthermore, the equilibrium market-clearing price* $p_w^*(\mathcal{D}_w)$ *is unique for any realization of the net wholesale demand* $\mathcal{D}_w$*.* **(b)** *Under the net metering policy, an increase in the realization of distributed renewable energy* Δ_i *results in a strictly smaller* $p_w^*(\mathcal{D}_w)$ *for any* i *with probability 1.*

The rationale behind Proposition 1-(b) is as follows. Under the net metering policy, utility i has either a net demand of $(\widehat{D}_i - \Delta_i - K_i)^+$ or an excess supply of $(\Delta_i + K_i - \widehat{D}_i)^+$. Therefore, when the realization of Δ_i is larger, utility i has either a smaller net demand or a larger excess supply. Both of these scenarios imply a smaller net wholesale demand $\mathcal{D}_w$ by (5). Then, we have Proposition 1-(b) because by the proof of Proposition 1-(a), the equilibrium market-clearing price $p_w^*(\mathcal{D}_w)$ strictly increases in $\mathcal{D}_w$ with probability 1.

To focus on a realistic scenario, the remainder of this section considers a parameter set where the expected wholesale price is strictly smaller than the retail electricity price for utility $i = 1, \ldots, I$, that is,

$$\mathbb{E}\left[p_w^*(\mathcal{D}_w)\right] < p_{u,i} \tag{7}$$

both in the presence and absence of DRE. This condition is in line with practice. (See, e.g., CAISO (2017a) and U.S. EIA (2017a) to compare the average wholesale prices in the CAISO system and the average retail electricity price of each utility in California.)

It is widely believed that under the net metering policy, utilities would incur significant loss in presence of distributed solar, compared to the case with no distributed solar. Based on this belief, there are significant lobbying efforts by utilities for the latter case. (See the discussion in Section 1 for further details.) Theorem 1 below identifies *necessary and sufficient conditions* under which net-metered distributed renewable energy *strictly increases* expected profit of the utility, compared to the case with no DRE. Theorem 1 (and our numerical study in Section 4) shows that introducing net-metered DRE can strictly increase utility profits under plausible conditions. Before stating Theorem 1, Definition 2 formalizes the case with no DRE.

DEFINITION 2. No DRE corresponds to a scenario where there is no DRE technology in the end-customer market, and hence no end-customer generates its own electricity. This case will be represented by the rule $\ell = 0$.

THEOREM 1. *Consider utility* j*. There exist thresholds* $\bar{K}_\ell$ *and* γ_ℓ *such that in equilibrium, distributed renewable energy generation under the net metering rule* $\ell \in \{r, m\}$ *results in a strictly larger expected profit for the utility* j *compared to the case with no such generation if and only if*

$$K_j < \bar{K}_\ell \qquad \textit{and} \qquad \gamma_\ell < {p_w^*}'(\mathcal{D}_w). \tag{8}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

The constant γ_ℓ does not change with K_j for $\ell \in \{r,m\}$.

COROLLARY 1. *Under the net metering rule $\ell \in \{r,m\}$, we have $\partial(\Pi_j(\ell) - \Pi_j(0))/\partial K_j < 0$.*

Theorem 1 and Corollary 1 offer valuable insights to utilities. By (8), there are two factors that determine the implications of net-metered DRE for utilities: (i) The size of utility's existing resources K_j and (ii) $p_w^{*\prime}(\mathcal{D}_w)$, which can be interpreted as the sensitivity of the wholesale market-clearing price with respect to the net wholesale demand. Note that as K_j increases, utility j becomes less *market-reliant* because the utility's likelihood of buying from the wholesale market to meet its demand decreases. Thus, the factor (i) can also be expressed in terms of the utility's expected market-reliance level. Based on these interpretations, Theorem 1 proves that when the wholesale market-clearing price is considerably sensitive to the changes in the wholesale demand, there exists a critical market-reliance level that determines whether net-metered DRE generation improves the utility's expected profit, compared to the case with no such generation. If the utility's expected market-reliance is larger than the critical level (i.e., $K_j < \bar{K}_\ell$), net-metered DRE strictly increases the utility's expected profit. This result has an important implication for utilities: Lobbing against net-metered distributed solar can indeed hurt the profitability of utilities. Thus, before lobbying, utilities should judiciously evaluate the composition of their energy resources and characteristics of the wholesale market they operate in.

Apart from the explained insights, Corollary 1 suggests that a more market-reliant utility benefits less from lobbying against net-metered DRE. In fact, in light of Theorem 1, this finding implies that if a utility is more market-reliant, lobbying against net-metered DRE can incur even larger loss to the utility. Thus, utilities that are more likely to procure larger quantities from the wholesale market are more prone to the unexpected profit loss due to net-metered DRE elimination. These findings provide important guidelines to utilities for correctly directing their lobbying efforts about DRE.

Let us now explain the rationale behind Theorem 1. Compared to the case with no DRE, in the presence of DRE, customers buy less from the utility as some of them generate their own electricity. Thus, introducing DRE decreases the utility's retail-side sales revenue. Moreover, for the utility, buying unit excess DRE from its net-metered customers is typically costlier than obtaining unit energy from other sources. As a result, introducing net-metered DRE decreases the retail-side net revenue of the utility. These are the downstream impacts of net-metered DRE on the utility. Introducing net-metered DRE also affects the upstream interaction of the utility, which is overlooked in the literature. Upstream implications of net-metered DRE rely on Proposition 1-(b). But, the effect of reduced wholesale price on a utility is not straightforward because the utility can be a net seller or a net buyer of energy in the wholesale market. Theorem 1 essentially analyzes the trade-off between the explained downstream impacts versus the upstream impact of net-metered DRE on the utility, which will be detailed below.

Electronic copy available at: https://ssrn.com/abstract=3257925

Suppose that in the presence of net-metered DRE, the utility is a net buyer, that is, the utility meets a certain portion of its demand from the wholesale market. Then, if (8) holds, (i) the utility's expected procurement quantity from the wholesale market is considerable (i.e., $K_j < \bar{K}_\ell$) and (ii) when DRE is introduced, the equilibrium wholesale price considerably decreases.[8] Due to (i) and (ii), the utility's expected total procurement cost significantly decreases in the presence DRE compared to the case with no DRE. This positive upstream impact dominates the aforementioned negative downstream impact of net-metered DRE (i.e., the utility's reduced retail-side net revenue) on the utility's expected profit, resulting in an increase in the utility's expected profit. Note that the factor (ii) alone cannot guarantee such a significant decrease in the procurement cost; the other key driver of that decrease is the composition of the utility's energy resources.

Suppose now that utility j is a net seller in the wholesale market in the presence of DRE. Based on the explanation for Proposition 1-(b), introducing DRE reduces the equilibrium wholesale price in this case too. However, introducing DRE has another impact: Compared to case with no DRE, the presence of DRE results in larger excess supply and larger selling quantity for the utility in the wholesale market. Under (8), when DRE is introduced, the positive impact of the utility's increased wholesale market sales dominates the negative impact of decreased equilibrium wholesale price on the utility's expected profit.[9] Under (8), the resulting extra profit from the wholesale market due to net-metered DRE strictly improves the utility's expected profit compared to the case with no DRE.

The numerical example in Section 4, which is based on distributed solar in California and the CAISO's wholesale electricity market, demonstrates that the unexpected benefit of self-generating customers proved in Theorem 1 can be observed even when the utility's expected market-reliance is very small. Specifically, Section 4 shows that the self-supply threshold $\bar{K}_\ell$ in Theorem 1 can exceed 95.5% of a utility's expected market size under both rules $\ell \in \{r, m\}$. Thus, the unexpected benefit of DRE for the utility's expected profit can be observed even when a utility meets as small as 4.5% of its expected demand through the wholesale market in the absence of DRE. The following is an immediate corollary of Theorem 1.

COROLLARY 2. *Consider a market-reliant utility j, which means that $K_j = 0$. Then, in equilibrium, DRE generation under the net metering rule $\ell \in \{r, m\}$ results in a strictly larger expected profit for the utility j compared to the case with no such generation if and only if $\gamma_\ell < {p_w^*}'(\mathcal{D}_w)$ where γ_ℓ is as in Theorem 1.*

Thus, the result in Theorem 1 holds in stronger sense when the utility meets all of its net demand from the wholesale market in the absence of DRE.

[8] This follows from Proposition 1-(b), its explanation and the second condition in (8).

[9] When $K_j < \bar{K}_\ell$, the utility has limited excess supply, and hence limited sales in the wholesale market. This implies a considerably large equilibrium wholesale price even in the presence of DRE.

Electronic copy available at: https://ssrn.com/abstract=3257925

Theorem 2 investigates how DRE adoption level affects utility j's expected profit $\Pi_j(\ell,\mu)$, where μ is a parameter to be explained below. Hereafter, when we say an increase in the DRE adoption level in the utility j's service area, we refer to a positive shift in region j's DRE generation from Δ_j to $\widetilde{\Delta}_j \doteq \Delta_j + \mu$ where $\mu > 0$. The constant μ will be called the DRE *adoption parameter*. To state Theorem 2, we shall define

$$\nu \doteq \mathbb{E}\left[\sum_{i\neq j}\left\{\widehat{D}_i - \Delta_i - K_i\right\} + \xi\right]. \tag{9}$$

The notation ν represents the total expected net wholesale demand in the presence of DRE, except utility j's net wholesale demand.

THEOREM 2. (***DRE Adoption Level versus Utility's Expected Profit***) *Consider utility j with $K_j < \widehat{Q}_j$.* **(a)** *Under the net metering rule $\ell = r$, $\Pi_j(r,\mu)$ strictly increases with the DRE adoption parameter μ, i.e., $\partial\Pi_j(r,\mu)/\partial\mu > 0$, if and only if $\mathbb{E}[\widetilde{\Delta}_j] < \chi_r$ for some χ_r; otherwise, $\partial\Pi_j(r,\mu)/\partial\mu \le 0$.* **(b)** *Suppose that the expected wholesale demand is not small, i.e., $\nu > \bar{\nu}$ where ν is as in (9) and $\bar{\nu}$ is a constant. Then, under the net metering rule $\ell = m$, $\Pi_j(m,\mu)$ strictly increases with the DRE adoption parameter μ, i.e., $\partial\Pi_j(m,\mu)/\partial\mu > 0$, if and only if $\mathbb{E}[\widetilde{\Delta}_j\mathbb{I}(\widetilde{\Delta}_j < D_j)] < \chi_m$ for some χ_m; otherwise, $\partial\Pi_j(m,\mu)/\partial\mu \le 0$.*

Thus, contrary to the common belief, a utility's expected profit can strictly increase with the expected DRE generation in its service area.

By Theorem 2-(a), under the rule $\ell = r$, there exists a critical expected DRE generation level $\mathbb{E}[\Delta_j] + \mu_r^*$ that determines how utility j's expected profit is impacted by the DRE technology adoption in region j. If the expected DRE generation in region j is smaller than this critical level, utility j favors *more* adoption of DRE technology by its customers. After that critical level on, the utility's expected profit decreases with the adoption. By Theorem 2-(b), similar conclusions are also valid under the rule $\ell = m$ when the expected wholesale demand is not small. (See Figure 1 and its explanation below for a numerical example.) These observations offer the following two key insights for utilities.

The first insight is related to new business strategies innovated by utilities. An example of such innovations is the emerging distributed renewable energy assistance programs by utilities. In this recent business strategy, utilities supply information to their customers about the DRE technology. Basic educational information about rooftop panels or the list of technology suppliers are some examples of provided information in these programs (see, e.g., NREL (2013)). Such assistance programs increase awareness about distributed generation among customers, and drive more adoption of DRE technologies. In light of this, Theorem 2 suggests that utilities can increase their expected profits with the help of those assistance programs. However, motivating the adoption of DRE technologies in this way is favorable to a utility only until the expected generation from those technologies reaches a particular level; after that level on, such assistance programs

Electronic copy available at: https://ssrn.com/abstract=3257925

decreases the expected profit of the utility. Thus, utilities gain benefit from such assistance programs only by putting a *cap* on those programs.

The second insight is related to utilities' lobbying strategies. Theorem 2 suggests that it is more favorable for utilities to lobby for the implementation of caps on net metering programs rather than the complete elimination of net-metered DRE. With a net metering cap, whenever the adoption level reaches a certain level, a utility is typically not required to compensate the additional DRE adopters for their excess generation, which deters any DRE technology adoption beyond the cap. In fact, the conditions in Theorem 2 suggest that the aforementioned caps can be very large depending on the expected market size of each utility and generators' unit cost of production. Net metering caps have recently been implemented in some states (State of Vermont 2014, Felder and Athawale 2014).

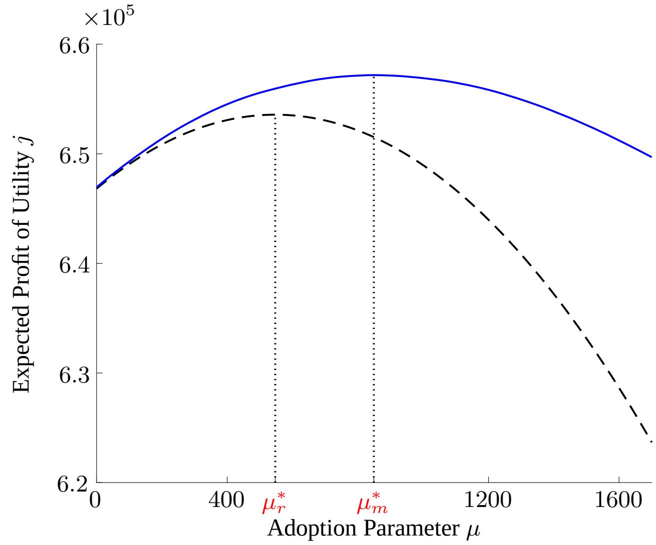

Figure 1 **Adoption parameter μ versus utility j's expected profit with the following parameters:** $p_{u,j} = 210$, $K_j = 6000$, $\nu = 5000$, $\tilde{c} = 3$, $N = 10$, $c = 0.1$, D_j **follows a gamma distribution with shape parameter 2.5 and mean 5000,** $\widehat{D}_j$ **satisfies** $\widehat{D}_j = \beta D_j$ **and its mean is** 9000, Δ_j **follows a truncated gamma distribution on support** $[0, 500]$ **with shape parameter 5 and mean 500. The dashed line represents the utility j's expected profit under the rule $\ell = r$ and the solid line represents the corresponding figure under the rule $\ell = m$.**

Figure 1 shows through a numerical example how utility j's expected profit changes with the adoption parameter μ. In this example, there exists a critical adoption parameter μ_ℓ^* for the utility j under each rule $\ell \in \{r, m\}$. There are three key observations related to Figure 1. First, as proved in Theorem 2, contrary to the common belief, an increase in the expected DRE generation can strictly increase the expected profit of the utility. Second, the increase in the utility's expected profit can be considerable: If the expected DRE generation increases from $\mathbb{E}[\Delta_j]$ to $\mathbb{E}[\Delta_j] + \mu_\ell^*$, the utility j's expected profit increases by 0.7% under the rule $\ell = r$ while the corresponding percentage is 1.6% under the rule $\ell = m$. Third, the critical adoption

Electronic copy available at: https://ssrn.com/abstract=3257925

parameters satisfy $\mu_r^* < \mu_m^*$. (One can easily formalize this observation; the formal result is omitted for brevity.) Our further numerical study suggests that μ_r^* decreases with N and K_i for $i = 1, \ldots, I$, but increases with the cost parameter c.

It is worth emphasizing that key results and insights established in Section 3 extend even when we consider a longer-term perspective than the one in Section 2. Sections 5.3 and 5.4 provide further details on this.

4. Numerical Example

We now present a numerical example based on distributed solar energy in California, utilities in California, and the wholesale electricity market operated by the CAISO. The main goal of this section is to demonstrate the following insights: When problem parameters are set to realistic values, (i) the unexpected benefit of distributed solar proved in Theorem 1 can be observed for a large range of utility market-reliance levels, (ii) introducing distributed solar can considerably increase the expected profit of a utility, and (iii) a utility's expected profit can strictly increase with the expected distributed solar energy for a large range of solar output.

In the CAISO system, a day in the wholesale market is divided into several trading time blocks. Each generator submits its supply function bid for any time block without observing the (net) wholesale demand and other generators' supply function bids in that time block. Supply bids and (net) wholesale demands are matched for each time block separately. This process produces a different wholesale price for each time block. Our numerical analysis considers 24 hourly time blocks in a day, i.e., 12:00am - 1:00am, 1:00am - 2:00am, $\ldots$, 11:00pm - 12:00am, which span an entire day. Given this setting, below we first explain how we obtain a realistic value for each problem parameter. Then, using these values, we calculate the expected profit for a utility based on our model in Section 2 to drive the aforementioned numerical insights.

Explanation of Parameters. We use several sources to obtain realistic values for parameters. Tables EC.1 through EC.3 in Appendix J of the Electronic Companion provide further details about data.

There are $I = 3$ major utilities in the CAISO system: Pacific Gas and Electric Company (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E) (U.S. EIA 2017a).[10] Our analysis requires us to estimate the distribution of net-metered solar production in each utility's serving area on an hourly basis. State of California (2018) provides 15-minute interval solar production data for some of the net-metered customers of each of the three big utilities in California during 2016. Using this, we construct the empirical distribution of hourly solar production in each utility's serving area in each month. Because this data set includes the data for only some of the net-metered customers, we take an additional step to account

[10] In 2016, these were the largest three utilities in California in terms of number of customers. The customers of these three utilities constituted around 81% of the electricity customers in California in 2016 (U.S. EIA 2017a). Consistent with this fact, in the literature, it is common to focus on these three utilities in numerical studies about California (see, e.g., Bollinger and Gillingham (2012)).

Electronic copy available at: https://ssrn.com/abstract=3257925

for all net-metered customers in the relevant region. Specifically, we utilize 2016 monthly net-metered solar capacity (i.e., maximum possible solar production by all net-metered customers) for each relevant region provided by U.S. EIA (2017a) and re-scale the aforementioned empirical distributions to find the empirical distribution of net-metered solar production $\Delta_{i,s,h}$ for each hour block $h = 1, 2, \ldots, 24$ of each month $s = 1, 2, \ldots, 12$ in each region $i = 1, 2, 3$. (Table EC.3 in Appendix J provides examples of $\mathbb{E}[\Delta_{i,s,h}]$ for July 2016 by representing each as a percentage of the expected end-customer demand in the relevant time block.)

U.S. EIA (2017a) provides end-customer demand and the average retail electricity price $p_{u,i,s}$ of each utility i for each month s of 2016. (See Table EC.1 in Appendix J for sample data.) To account for the demand fluctuations within a day, we calculate the average demand shares of each hour block in each month of 2016 based on U.S. EIA (2017b). Table EC.2 in Appendix J reports some of these shares for July 2016. Combining the aforementioned demand shares and monthly demand, we identify the average hourly end-customer demand $\mathbb{E}\big[\widehat{D}_{i,s,h}\big]$ of each utility i for each hour block h of month s in 2016. We assume that for each utility, end-customer demand in each hour block is uniformly distributed with the aforementioned average hourly end-customer demand. Moreover, based on U.S. EIA (2017a), we obtain an estimate of $\beta_{i,s}$, which is the ratio of average end-customer demand to average net-metered customer demand for each utility in month s. (See Table EC.1 in Appendix J to see examples of $\beta_{i,s}$.) This enables us to determine the average demand of each utility's net-metered customers in month s. We also identify each utility's cost $\tilde{c}_{i,s}$ of meeting unit demand through its existing resources for each month s based on the data provided by CPUC (2017a) and CPUC (2017b). In our study, we assume that $p_{u,i,s}$, $\tilde{c}_{i,s}$ and $\beta_{i,s}$ remain the same throughout a month.[11]

Appendix J in the Electronic Companion includes an explanation of how we obtained realistic values for N and the generator cost parameter c_s for each month s.

Calculating the expected profit of a utility in month s requires the average self-supply capacity $K_{i,s,h}$ of each utility i, and an estimate for the expected wholesale demand of market participants other than the three major utilities, i.e., $\mathbb{E}\left[\xi_{s,h}\right]$, in each hour block h. We calculate the monthly effective self-supply capacities of utilities in 2016 by using supply plans and the average monthly availability factor of each resource (California Energy Commission 2018b, U.S. EIA 2018c,d). We then convert the monthly self-supply capacity to hourly self-supply capacity by accounting for the number of days in a month and the fact that one day is 24 hours. To identify $\mathbb{E}\left[\xi_{s,h}\right]$, we use actual average wholesale market prices and the equilibrium relation between wholesale price and net wholesale demand implied by the proof of Proposition 1. In light of this, we determine $\mathbb{E}\left[\xi_{s,h}\right]$ by accounting for self-supply capacity of each utility, net-metered solar production in each hour block h of each month s, N and c_s. This calculation approach ensures that average wholesale

[11] In 2016, the vast majority of customers in California (e.g., around 97% of the residential customers) were subject to a flat retail electricity price (U.S. EIA 2018b,a). Thus, considering the average price $p_{u,i,s}$ throughout month s is consistent with practice.

Electronic copy available at: https://ssrn.com/abstract=3257925

prices calculated based on these parameters and our model are equal to actual average wholesale prices in the market. For example, in July 2016, average wholesale price was around \$34/MWh in the CAISO system (CAISO 2017b).

Numerical Results. Using the realistic values explained above, for various scenarios, we calculate the expected profit of the utility j that operates based on the PG&E's calibrated parameters.

Our numerical study shows that the net-metered distributed solar can *strictly increase* the utility's expected profit, compared to the case with no such energy, and this result can arise even when the utility's expected market-reliance is small. To make these points, we calculate the utility j's *critical self-reliance percentages* $\mathcal{P}_{h,\ell}$ for each hour block h of July 2016 under the rule $\ell \in \{r, m\}$. Formally, $\mathcal{P}_{h,\ell} \doteq \bar{K}_{\ell,h}/\mathbb{E}\big[\widehat{D}_{j,7,h}\big]$ where $\bar{K}_{\ell,h}$ is the self-supply threshold identified in Theorem 1 for the hour block h and rule ℓ.

Under both rules $\ell \in \{r, m\}$, the utility j's critical self-reliance percentage exceeds 95.5% for around 42% of hour blocks during July 2016. This means that the net-metered distributed solar can improve the utility's expected profit even when the utility only meets 4.5% of its expected demand through the wholesale market. Considering both rules $\ell \in \{r, m\}$, the utility's maximum and minimum critical self-reliance percentages across all hour blocks of July 2016 are respectively 98.43% and 57.51%, which are considerably large. We also calculate $\bar{\mathcal{P}}_{7,\ell}$, which is the utility's average critical self-reliance percentage in July under the rule ℓ, considering all hour blocks of July 2016. Our numerical analysis demonstrates that $\bar{\mathcal{P}}_{7,r} =$ 79.21% and $\bar{\mathcal{P}}_{7,m}$ is approximately 79.22%. Based on this, on average, if the utility meets as small as 20.79% or more of its demand from the wholesale market in the absence of distributed solar, the distributed solar strictly increases the utility's expected profit in July, compared to the case with no such energy. All of these suggest that the aforementioned unexpected benefit of net-metered distributed solar can be observed for a wide range of utility market-reliance levels.

Another key finding of our numerical study is that introducing distributed solar can considerably increase the utility's expected profit under the net metering policy. Considering different self-reliance percentages in July, i.e., $\mathcal{P} \doteq K_{j,7}/\mathbb{E}\big[\widehat{D}_{j,7}\big]$, Table 1 below displays the calculated increase in the utility j's expected profit in July as a result of introducing distributed solar under the rule $\ell = r$. Table 1 demonstrates that the presence of distributed solar can improve the utility's profit by hundreds of thousands of dollars in a month. (The results under the rule $\ell = m$ are very similar as the utility's expected profit difference under $\ell = m$ and $\ell = r$ is less than 0.01%. For brevity, we report the results under one rule.) Table EC.4 in Appendix J gives examples about the percentage contribution of each hour block h in some of the reported profit improvements in Table 1.

Theorem 2 suggests that under the rule $\ell \in \{r, m\}$, there exists a critical level of expected distributed solar (DS) generation that maximizes the utility's expected profit. In our numerical study, we express this level as

Electronic copy available at: https://ssrn.com/abstract=3257925

Table 1 The Utility's Expected Profit Increase in July Due to the Presence of Distributed Solar:

$\mathcal{P}=0\%$	$\mathcal{P}=10\%$	$\mathcal{P}=20\%$	$\mathcal{P}=30\%$	$\mathcal{P}=40\%$
\$960,498	\$824,162	\$687,826	\$551,490	\$415,000

a percentage of the utility's expected demand, and refer to it as the *critical DS adoption percentage* $\mathcal{A}$. For different self-reliance percentages, Table 2 below displays the critical DS adoption percentage for the utility j in July 2016 under the rule $\ell = r$. The percentages displayed in Table 2 suggest that the critical adoption percentage can be considerably large when the parameters are set to realistic values. By Theorem 2, these percentages further suggest that the utility j's expected profit strictly increases with the expected distributed solar energy for a large range of solar output.

Table 2 Examples of Critical Distributed Solar Adoption Percentage $\mathcal{A}$:

	$\mathcal{P}=35\%$	$\mathcal{P}=40\%$	$\mathcal{P}=45\%$	$\mathcal{P}=50\%$
$\mathcal{A}$	28.48%	23.47%	18.48%	13.47%

5. Extensions and Robustness Check

A key objective of this section is to establish the robustness of our key result, i.e., Theorem 1. Sections 5.1 through 5.4 prove the robustness of Theorem 1 in various settings.[12] Section 5.5 provides additional robustness discussions. Apart from these, Section 5.4 identifies (in Theorem 3) which rule among $\ell = r$ and $\ell = m$ is more favorable to utilities, and Section 5.6 provides social welfare analysis.

5.1. General Form of the Wholesale Electricity Price

Consistent with the literature, Section 3 considers a supply function competition model to analyze a wholesale electricity market. Therefore, the form of the equilibrium wholesale electricity price in Section 3 is a result of the supply function competition model described in Section 2. This section establishes the robustness of our key result with respect to the form of the wholesale electricity price.

Suppose that the wholesale electricity price is a general function of the net wholesale demand. Specifically, $g_w(\mathcal{D}_w)$ is the realized wholesale electricity price where (i) $g_w(\cdot)$ is twice continuously differentiable, (ii) $g_w'(\cdot) > 0$ and (iii) $g_w(0) = 0$. Property (i) is for tractability. Property (ii) suggests that the wholesale price strictly increases with the net wholesale demand with probability 1. Note that the equilibrium wholesale price structure in Section 3 is a special case of $g_w(\cdot)$ because the former satisfies properties (i) through (iii).

PROPOSITION 2. *When the wholesale electricity price is $g_w(\mathcal{D}_w)$ where g_w is a general function that satisfies the properties (i) through (iii) above, there exist some $\tilde{K}_\ell$ and $\tilde{\gamma}_\ell$ such that distributed renewable*

[12] Theorem 1 is analytically more challenging to extend than Theorem 2. Moreover, extending Theorem 2 drastically lengthens the paper without providing any new insights. Thus, in these sections, for brevity, we present the extensions of our key result, i.e., Theorem 1.

Electronic copy available at: https://ssrn.com/abstract=3257925

energy generation under the net metering rule $\ell \in \{r,m\}$ results in a strictly larger expected profit for utility j compared to the case with no such generation if $K_j < \tilde{K}_\ell$ and $\tilde{\gamma}_\ell < \left(\mathbb{E}\left[\sqrt{g'_w(\mathcal{D}_w)}\right]\right)^2$.

Thus, Theorem 1 and its insights extend even if we consider a general function of $\mathcal{D}_w$ rather than a supply function competition model to study the wholesale market-clearing price.

Note that this section allows for any convex $g_w(\cdot)$ that satisfies the properties (i) through (iii) above. The convexity of $g_w(\cdot)$ can be interpreted as a measure of wholesale electricity price spike. The stated condition in Proposition 2 and our numerical studies suggest that when $g_w(\cdot)$ is more convex, the result in Proposition 2 holds in stronger sense (i.e., under less-restrictive conditions).

Apart from the fact that supply function competition models are common in the literature to study wholesale electricity markets, an advantage of the formulation in Section 2 over this one is the following: The former offers other extension opportunities like Section 5.2 whereas the latter easily gets analytically intractable in further extensions.

5.2. Alternative Cost of Obtaining Electricity from Existing Resources

Section 2 considers a practical setting where utilities incur a constant cost to obtain unit electricity from their existing resources. To capture other possible practical settings, this section extends the model in Section 2 by considering a more general function $\bar{C}(\cdot)$ for the utility's cost of using its existing resources. Specifically, suppose that if utility i obtains q_i units of electricity from its existing resources, it incurs a total cost of $\bar{C}(q_i)$. Here, $\bar{C}'(\cdot)$ represents the utility's marginal cost of obtaining an additional unit of electricity from its existing resources. All other modeling elements are the same as in Section 2. Then, recalling the notation p_ℓ defined right before (6), when the utility j obtains q_j from its existing resources, the utility j's expected profit under the rule $\ell \in \{r,m\}$ is

$$\begin{aligned}\Pi_j(\ell) = &\underbrace{\mathbb{E}\big[\big(\widehat{D}_j - D_j + (D_j - \Delta_j)^+\big)p_{u,j}\big]}_{\text{Revenue from selling to end-customers}} - \underbrace{\mathbb{E}\big[\mathbb{I}\{\widehat{D}_j > \Delta_j + q_j\}\big(\big(\widehat{D}_j - \Delta_j - q_j\big)p_w^* + \bar{C}(q_j)\big)\big]}_{\text{Cost of meeting remaining demand when } \widehat{D}_j > \Delta_j + q_j} \\ &- \underbrace{\mathbb{E}\big[(\Delta_j - D_j)^+ p_\ell\big]}_{\text{Cost of buying from net-metered customers}} + \underbrace{\mathbb{E}\big[\mathbb{I}\{\widehat{D}_j \le q_j + \Delta_j\}\big(\big(\Delta_j + q_j - \widehat{D}_j\big)p_w^* - \bar{C}(q_j)\big)\big]}_{\text{Extra profit from selling excess energy to the wholesale market when } \widehat{D}_j \le \Delta_j + q_j} \quad . \qquad (10)\end{aligned}$$

Note that elements in (10) are similar to the ones in (6). Utility j chooses $q_j \le K_j$ to maximize its expected profit (10) under the rule $\ell \in \{r,m\}$. (In our base model in Section 2, the utility optimally uses all of its existing resources.)

In practice, the marginal cost of using existing resources could decrease with respect to the obtained quantity due to various reasons such as quantity discounts or other economies of scale. This case can be represented by total cost function $\bar{C}$ such that $\bar{C}(0) \ge 0$, $\bar{C}'(0) = \tilde{c} > 0$ and $\bar{C}''(\cdot) < 0$. With this cost function, all of our results in Section 3 hold as stated. The proofs of all results hold as stated with the

Electronic copy available at: https://ssrn.com/abstract=3257925

exception that the terms $\tilde{c}K_j$ and stand-alone $\tilde{c}$ in the proofs must be replaced with general terms $\bar{C}(K_j)$ and $\bar{C}'(K_j)$, respectively.

There could also be practical settings in which the marginal cost of using existing resources increases with respect to the obtained quantity. To capture such settings, consider the total cost function $\bar{C}(q_j) = \kappa_1 q_j + \kappa_2 q_j^2$ where κ_1 and κ_2 are positive constants. For example, if the utility produces its own electricity, convexity of $\bar{C}(\cdot)$ might reflect the necessity to use more expensive resources in the case of excessive demand. The following proposition verifies that our key result in Theorem 1 extends even if this variant of the base model is considered. For analytical tractability, Proposition 3 considers a case where the expected DRE generation is the same for each utility region. Our extensive numerical study suggests that the result extends when expected DRE generation levels differ across regions.

PROPOSITION 3. *Suppose that the utility j incurs a total cost of $\bar{C}(q_j) = \kappa_1 q_j + \kappa_2 q_j^2$ to obtain q_j units of electricity from its existing resources. Then, there exist constants $\bar{K}_{j,\ell}^{\bar{C}}$ and $\gamma_{j,\ell}^{\bar{C}}$ such that net-metered distributed renewable energy generation under the rule $\ell \in \{r, m\}$ results in a strictly larger expected profit for the utility j compared to the case with no such generation if $K_j < \bar{K}_{j,\ell}^{\bar{C}}$ and ${p_w^*}'(\mathcal{D}_w) > \gamma_{j,\ell}^{\bar{C}}$.*

5.3. Multi-Period Considerations

Consider a finite time horizon $t = 1, \ldots, T$ where a wholesale market is run in every period t. Suppose that the setting in each period t is the same as the one described in Section 2 with the following modification: Each parameter described in Section 2, except N, I and K_i, has a time index t (added as a subscript) to allow variation across time periods. Thus, the retail price of utility j is allowed to vary with t or it can be constant during T periods. Under the rule $\ell \in \{r, m, 0\}$, utility j's total expected profit during T periods is the sum of the utility's expected profit in each period t. Then, for each period t, Theorem 1 holds as stated with the exception that $\bar{K}_\ell$ and γ_ℓ must be replaced with period-specific thresholds $\bar{K}_{\ell,t}$ and $\gamma_{\ell,t}$. From this, it follows that the presence of net-metered DRE strictly increases utility j's total expected profit during T periods if $K_j < \min_{t=1,\ldots,T} \ \bar{K}_{\ell,t}$ and $\max_{t=1,\ldots,T} \ \gamma_{\ell,t} < \min_{t=1,2,\ldots,T} \ {p_{w,t}^*}'(\mathcal{D}_{w,t})$. Thus, our key result and its insights extend to this setting. It is perhaps worth noting that compared to the setting in Section 2, this extension adds significant notational complexity and length without providing any additional insights.

5.4. Long-Run Perspective with Endogenous Retail Electricity Price

This section takes a longer-term perspective where utility j sets its retail electricity price $p_{u,j}$. In practice, the frequency at which a wholesale electricity market is run is much higher than the frequency at which a new retail rate is determined (Lazaar 2016). In the U.S., most utilities do not file a rate change request for two to five years (Lazaar 2016). In light of this, we study the following model. Utility j sets its retail electricity price $p_{u,j} \in [\underline{p}, \bar{p}]$ in period $t = 1$. Let $t = 2, \ldots, T$ represent the time periods in which $p_{u,j}$ remains the same.

Electronic copy available at: https://ssrn.com/abstract=3257925

The term T can be interpreted as the time between two consecutive retail rate making dates, and correspond to a year or more in practice. A wholesale market is run in every period t, and the setting in each period t is the same as the one described in Section 2 with the following modification: Each parameter described in Section 2, except $p_{u,j}$, N, I and K_i, has a time index t (added as a subscript) to allow variation across time periods. For any $p_{u,j}$ and $\ell \in \{r,m,0\}$, utility j's expected total profit during the time horizon $[1,T]$ is $\bar{\Pi}_j(p_{u,j};\ell)$, which is the sum of the utility's expected profit in each period $t=1,2,\ldots,T$. Based on this, consistent with the endogenous retail price formulation in the literature (see, e.g., Kök et al. (2018)), the objective of the utility j is $\max_{p_{u,j}\in[\underline{p},\bar{p}]} \bar{\Pi}_j(p_{u,j};\ell)$. Total electricity demand of utility j's end-customers in period t is $\widehat{D}_{j,t} = A_{j,t} - B_{j,t}p_{u,j} + \omega_{j,t}$ where $\omega_{j,t}$ is a random variable with a general differentiable distribution function $H_{j,t} : [0, \bar{\Gamma}_{j,t}] \to [0,1]$, and $A_{j,t}$ and $B_{j,t}$ are constants that can vary with t. [13] To focus on a realistic scenario, consistent with (7), the expected wholesale price in period t is strictly smaller than the retail electricity price for utility $i=1,\ldots,I$ both in the presence and absence of the DRE, that is,

$$\mathbb{E}\left[p^*_{w,t}(\mathcal{D}_{w,t})\right] < p_{u,i}, \quad t=1,2,\ldots,T. \tag{11}$$

The condition (11) is guaranteed for example when $\underline{p}$ is not very close to zero.

In the long run, DRE generation levels are impacted by the following two key factors: (i) The retail electricity price and (ii) utilities' compensation rate for the excess DRE generation. Regarding (i), a larger retail electricity price is likely to increase the DRE adoption levels because in that case, an end-customer has to pay more to buy unit electricity from a utility (Felder and Athawale 2014). Regarding (ii), long-run DRE adoption levels are likely to be higher under the rule $\ell = r$ than under the rule $\ell = m$ because by (11), the rule $\ell = r$ provides a larger compensation rate per unit excess DRE generation than the rule $\ell = m$. Our formulation allows for these two long-run effects:

DEFINITION 3. (i) For any $p_{u,i}$, period-t DRE generation under the rule $\ell \in \{r,m\}$ in region $i=1,\ldots,I$ is $\widehat{\Delta}_{i,\ell,t} = \Delta_{i,t} + \mu_{i,\ell,t}(p_{u,i})$, where $\mu'_{i,\ell,t}(\cdot) \geq 0$ and $\Delta_{i,t}$ is a random variable with a general differentiable distribution function $F_{i,t}(\cdot)$. (ii) The expected DRE generation under the rule $\ell = r$ is strictly larger than the one under the rule $\ell = m$ for all t in each region i. Specifically, $\mu_{i,r,t}(p_1) > \mu_{i,m,t}(p_2) \geq 0$ for any two retail electricity prices p_1 and p_2.

Considering the described setting above, Proposition 4 below shows that Theorem 1 and its insights extend when we consider a long-term setting where the utility is allowed to set the price.

PROPOSITION 4. *There exist constants $\breve{K}_\ell$ and $\breve{\gamma}_\ell$ such that in equilibrium, distributed renewable energy generation under the net metering rule $\ell \in \{r,m\}$ results in a strictly larger optimal expected total profit for utility j compared to the case with no such generation, i.e.,* $\max_{p_{u,j}\in[\underline{p},\bar{p}]} \bar{\Pi}_j(p_{u,j};\ell) > \max_{p_{u,j}\in[\underline{p},\bar{p}]} \bar{\Pi}_j(p_{u,j};0)$, *if* $K_j < \breve{K}_\ell$ *and* $\breve{\gamma}_\ell < \min_{t=1,2,\ldots,T} {p^*_{w,t}}'(\mathcal{D}_{w,t})$.

[13] This formulation is based on the flat retail rate, which is the dominant form of retail rate in the U.S. (U.S. EIA 2018a,b).

Electronic copy available at: https://ssrn.com/abstract=3257925

The compensation rules for excess DRE are subject to various changes in practice (NC Clean Energy Technology Center 2018). For example, in Nevada, before 2016, the generation surplus of distributed solar was compensated based on the retail rate. However, by the beginning of 2016, the Nevada Public Utilities Commission changed the compensation rate to the wholesale price (PUNC 2015). Because the compensation rate for end-customers (per their unit excess DRE generation) is typically larger under the rule $\ell = r$ than under the rule $\ell = m$ as in (11), there have been significant lobbying efforts by utilities for the market-based net metering rule (Silverstein 2016). Theorem 3 below identifies which rule among $\ell = r$ and $\ell = m$ is more favorable to utility j. The remainder of the analysis focuses on a parameter set that induces a unique optimizer for utility j's total expected profit. To have tractability while capturing the effects in Definition 3, Theorem 3 considers the following adoption formulation: For utility j, there exists a time period $\underline{t} < T$ such that under the rule $\ell \in \{r, m\}$, $\widehat{\Delta}_{j,\ell,t} = \Delta_{j,t}$ for $t \leq \underline{t} - 1$ and $\widehat{\Delta}_{j,\ell,t} = \Delta_{j,t} + \mu_{j,\ell}(p_{u,j})$ for $t \geq \underline{t}$, where $0 \leq \mu_{j,m}(p_1) < \mu_{j,r}(p_2)$ for any two retail prices p_1 and p_2. To state Theorem 3, define $\underline{\kappa}_j \doteq \min_{t=1,\ldots,T} \mathbb{E}[\widehat{D}_{j,t}] - \mathbb{E}[\Delta_{j,t}]$.

THEOREM 3. *Consider utility j with $K_j \in [0, \underline{\kappa}_j)$, and suppose that the difference between DRE generations under rules $\ell \in \{r, m\}$ is not too large, i.e.,* $\max_{t=1,\ldots,T} \sqrt{\mathbb{E}\left[\left(\Sigma_{i\neq j}\, \mu_{i,r,t}(\bar{p}) - \mu_{i,m,t}(\underline{p})\right)^2\right]} < \tilde{v}$ *for some constant $\tilde{v}$.*[14] *Then, there exist constants $\widetilde{\mu}$, $\underline{\mu}$, $\bar{\mu}$, $\bar{\alpha}$ and $\bar{\bar{\mu}}$ such that $\widetilde{\mu} < \underline{\mu} < \bar{\mu} < \bar{\bar{\mu}}$ and the following results hold.* **(a)** *The rule $\ell = r$ results in a strictly larger optimal total expected profit for utility j than the rule $\ell = m$, i.e.,* $\max_{p_{u,j} \in [\underline{p}, \bar{p}]} \bar{\Pi}_j(p_{u,j}; r) > \max_{p_{u,j} \in [\underline{p}, \bar{p}]} \bar{\Pi}_j(p_{u,j}; m)$*, if*

$$\mu_{j,m}(\bar{p}) < \widetilde{\mu}, \;\; \mu_{j,r}(\underline{p}) > \underline{\mu}, \;\; \mu_{j,r}(\bar{p}) < \bar{\mu} \quad \textit{and} \quad \min_{t=1,\ldots,T} {p^*_{w,t}}'(\mathcal{D}_{w,t}) > \bar{\alpha}. \tag{12}$$

(b) *The rule $\ell = m$ results in a strictly larger optimal total expected profit for utility j than the rule $\ell = r$, i.e.,* $\max_{p_{u,j} \in [\underline{p}, \bar{p}]} \bar{\Pi}_j(p_{u,j}; m) > \max_{p_{u,j} \in [\underline{p}, \bar{p}]} \bar{\Pi}_j(p_{u,j}; r)$*, if*

$$\mu_{j,m}(\bar{p}) < \tilde{\mu}, \;\; \mu_{j,r}(\underline{p}) > \bar{\bar{\mu}} \quad \textit{and} \quad \min_{t=1,\ldots,T} {p^*_{w,t}}'(\mathcal{D}_{w,t}) > \bar{\alpha}. \tag{13}$$

Theorem 3 offers valuable insights to utilities. First, lobbying for a particular net-metering rule just based on its DRE compensation rate can be problematic for utilities in the long-run. Theorem 3-(a) and (11) show that, in contrast to the general understanding, a utility can be worse off under the rule that requires a smaller compensation rate to net-metered customers. Thus, utilities' current lobbying efforts for the implementation of the market-based rule instead of the retail-based rule can eventually hurt utilities' expected profits. Second insight is from (12) and (13). Specifically, each utility needs the following information to correctly direct its

[14] Note that when $K_j \in [0, \underline{\kappa}_j)$, there is still a positive probability for utility j to be a net seller in the wholesale market in any period t. The condition on K_j is commonly observed in practice (see, e.g., U.S. EIA (2018a)).

Electronic copy available at: https://ssrn.com/abstract=3257925

lobbying efforts for a particular rule: (i) good estimate of DRE technology adoption level in its serving area under each rule and (ii) good understanding of the wholesale electricity market it operates in.

Here is the rationale behind Theorem 3. Recall that a utility can be either a net buyer or a net seller of energy in the wholesale market. Consider a time period in which utility j is a net buyer in the wholesale market. Then, if DRE adoption levels under the two rules are moderately different than each other and the equilibrium market-clearing price is sufficiently sensitive to changes in the wholesale demand (as in (12)), compared to the rule $\ell = m$, the rule $\ell = r$ considerably decreases the equilibrium market-clearing price without excessively decreasing the utility's expected net market size. Thus, if (12) holds, under $\ell = r$, the positive effect of reduced equilibrium market-clearing price dominates the negative effects of the utility j's shrunk expected net market size and costlier net-metering compensation rate on its expected profit in the considered period. The upper bounds on the adoption parameters in (12) also imply that the fraction of time (in $[1, T]$) during which utility j is a net buyer is likely to be larger than the one during which it is a net seller in the wholesale market. Thus, the explained impact when utility j is a net buyer drives the result in part (a).

If the DRE adoption in region j increases too much as a result of implementing $\ell = r$ instead of $\ell = m$ (as in (13)), under the rule $\ell = r$, utility j's expected net market size shrinks too much. This leads to a loss for the utility j regardless of the utility being a net buyer or a net seller in the wholesale market, driving the result in Theorem 3-(b).

In 2017, around 95% of electricity customers in the U.S. were charged with a time-invariant (flat) retail electricity price that does not change with the hour of the day or the day of the week until the next rate making date is reached (U.S. EIA 2018a,b). Consistent with this prevalent strategy, this section considers a time-invariant retail electricity price for utility j. Note that the result in Proposition 4 further extends if we consider a time-of-use pricing strategy for the utility j. For further explanation on this, please see Note #1 in Appendix K of the Electronic Companion.

5.5. Additional Robustness Discussions

Our analysis considers two common net metering rules in practice, i.e., retail- and market-based rules. Because the results in Section 3 are proved under both rules, all of our results and insights in Section 3 remain unchanged under any intermediate net metering rule. Specifically, if the net metering compensation rate is equal to any convex combination of the retail electricity price and the wholesale price, our results and insights continue to hold. Moreover, if the net metering compensation rate is fixed (i.e., not dependent on the wholesale price) but smaller than the retail electricity price, the results obtained under the retail-based rule (in Section 3) would hold in stronger sense.

Our results and insights in Section 3 hold as stated if end-customers are segmented and each segment faces a different retail electricity price. Note that our formulation in Section 2 accommodates segmented end-customers because the retail electricity price in Section 2 can be interpreted as a certain weighted average

Electronic copy available at: https://ssrn.com/abstract=3257925

of retail electricity prices across customer segments. (For further details, see Note #2 in Appendix K in the Electronic Companion.)

It could also be of interest to analyze a modified setting where the DRE generation Δ_i causes an increase of $\rho\Delta_i$ in the electricity demand of utility i's net-metered customers where $\rho \in [0,1)$. In that case, all of our results and their proofs hold with the exception that Δ_i in the statements and proofs must be replaced with the term $(1-\rho)\Delta_i$.

Lastly, considering a fixed cost in the utility's expected profit does not change our main results and insights.

5.6. Social Welfare

Appendix A in the Electronic Companion analyzes the implications of introducing net-metered DRE and the two net metering rules for social welfare. Proposition EC.1 in Appendix A proves that under reasonable conditions, introducing net-metered DRE or implementing the rule $\ell = r$ instead of $\ell = m$ strictly improves social welfare compared to the case with no DRE if and only if the "social cost of carbon" is considerably large. There is a literature that estimates this cost and these estimates have been used in U.S. policy making (Sunar 2016). Given how consequential the social cost of carbon is for the social welfare, a social planner should put significant emphasis on accurately estimating it.

6. Concluding Remarks

In this paper, we study the implications of net-metered DRE for utilities' expected profits and the social welfare by considering a wholesale electricity market. To the best of our knowledge, our work is the first that theoretically analyzes this topic by explicitly modeling a wholesale market. Our paper offers key insights and guidelines to utilities. All of these are explained in Section 1.1.

In this paper, the wholesale electricity market is formulated as a supply function competition model, which is common in the literature. (Section 2 provides some examples from the literature.) The explicit analysis of a supply function competition model with full generality (e.g., with general asymmetric generation cost functions) is well-known to be analytically intractable. However, note that any extended wholesale market competition model yields a *particular* functional relation between the wholesale price and the net wholesale demand. Thus, to establish the robustness of our key results with respect to the wholesale market formulation, Section 5.1 extends our model to allow the wholesale price to be any general increasing function of the net wholesale demand. In this setting, Section 5.1 proves that our key insights continue to hold. Because the considered level of generality in Section 5.1 captures any reasonable wholesale market dynamics, Section 5.1 also captures the relation between the wholesale price and the net wholesale demand in any reasonable extension of the wholesale market formulation, e.g., with general asymmetric cost functions, or under any other notion of equilibrium.

Electronic copy available at: https://ssrn.com/abstract=3257925

References

Aflaki, S. and Netessine, S. (2017). Strategic investment in renewable energy sources: The effect of supply intermittency, *M&SOM* **19**(3): 489–507.

Agrawal, V. V. and Bellos, I. (2017). The potential of servicizing as a green business model, *Management Science* **63**(5): 1545–1562.

Al-Gwaiz, M., Chao, X. and Wu, O. Q. (2017). Understanding how generation flexibility and renewable energy affect power market competition, *M&SOM* **19**(1): 114–131.

Alizamir, S., de Véricourt, F. and Sun, P. (2016). Efficient Feed-In-Tariff Policies for Renewable Energy Technologies, *Operations Research* **64**(1): 52–66.

Anderson, E. J. and Philpott, A. B. (2002). Using supply functions for offering generation into an electricity market, *Operations Research* **50**(3): 477–489.

Blumsack, S., Lave, L. and Apt, J. (2008). Electricity prices and costs under regulation and restructuring, *2008 Industry Studies Conference Paper*.

Bollinger, B. and Gillingham, K. (2012). Peer effects in the diffusion of solar photovoltaic panels, *Marketing Science* **31**(6): 900–912.

Borenstein, S. (2016). The economics of fixed cost recovery by utilities, *The Electricity Journal* **29**(7): 5–12.

Brown, D. P. and Sappington, D. (2017). Designing compensation for distributed solar generation: Is net metering ever optimal?, *Energy Journal* **38**(3): 1–32.

Cachon, G. P. (2014). Retail store density and the cost of greenhouse gas emissions, *Management Science* **60**(8): 1907–1925.

CAISO (2017a). 2016 Annual Report on Market Issues and Performance. `www.caiso.com/Documents/2016AnnualReportonMarketIssuesandPerformance.pdf`, Accessed on 9/1/18.

CAISO (2017b). Q1 2017 Report on Market Issues and Performance. `www.caiso.com/Documents/2017FirstQuarterReport-MarketIssuesandPerformance.pdf`, Accessed on 7/7/19.

CAISO (2018). List of SCs, CRR Holders, Convergence Bidding Entities. `www.caiso.com/Documents/ListofSchedulingCoordinatorsCRRHoldersandConvergenceBiddingEntities.pdf`.

Caro, F., Corbett, C. J., Tan, T. and Zuidwijk, R. (2013). Double counting in supply chain carbon footprinting, *M&SOM* **15**(4): 545–558.

Corbett, C. J. and Klassen, R. D. (2006). Extending the horizons: Environmental excellence as key to improving operations, *M&SOM* **8**(1): 5–22.

CPUC (2017a). California Electric and Gas Utility Cost Report - Public Utilities Code Section 913 Annual Report to the Governor and Legislature. `www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/About_`

Electronic copy available at: https://ssrn.com/abstract=3257925

Us/Organization/Divisions/Office_of_Governmental_Affairs/Legislation/2017/AB67_Leg_Report_PDF_Final_5-5-17.pdf, Accessed on 8 /8/18.

CPUC (2017b). Historical electric cost data. www.cpuc.ca.gov/General.aspx?id=12056, Accessed on 8/10/18.

Darghouth, N. R., Barbose, G. and Wiser, R. H. (2014). Customer-economics of residential photovoltaic systems (part 1): The impact of high renewable energy penetrations on electricity bill savings with net metering, *Energy Policy* **67**: 290–300.

DSIRE (2015). Net Metering - Iowa. programs.dsireusa.org/system/program/detail/488, Accessed on 8/8/18.

DSIRE (2017a). Detailed summary maps - customer credits under net metering. ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2014/11/NEG-1.20161.pdf, Accessed on 7/23/18.

DSIRE (2017b). Detailed summary maps - net metering policies. ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2017/11/DSIRE_Net_Metering_November2017.pdf, Accessed on 7/23/18.

DSIRE (2017c). Net Metering - Program Overview for North Carolina. programs.dsireusa.org/system/program/detail/1246, Accessed on 9/5/17.

DSIRE (2018). Net Metering - Virginia. programs.dsireusa.org/system/program/detail/40, Accessed on 8/8/18.

Dufo-López, R. and Bernal-Agustín, J. L. (2015). A comparative assessment of net metering and net billing policies. Study cases for Spain, *Energy* **84**: 684–694.

Eid, C., Guillén, J. R., Marín, P. F. and Hakvoort, R. (2014). The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives, *Energy Policy* **75**: 244–254.

Felder, F. A. and Athawale, R. (2014). The life and death of the utility death spiral, *The Electricity Journal* **27**(6): 9–16.

FERC (2007). 18 CFR Part 35 - Wholesale Competition in Regions With Organized Electric Markets; Proposed Rule. www.gpo.gov/fdsys/pkg/FR-2007-07-02/pdf/E7-12550.pdf, Accessed on 8/8/18.

FERC (2017). Electric power markets: National overview. www.ferc.gov/market-oversight/mkt-electric/overview.asp, Accessed on 7/23/18.

Ferrer, G. and Swaminathan, J. M. (2006). Managing new and remanufactured products, *Management Science* **52**(1): 15–26.

Gautier, A., Jacqmin, J. and Poudou, J.-C. (2018). The prosumers and the grid, *Journal of Regulatory Economics* **53**(1): 100–126.

Girotra, K. and Netessine, S. (2013). OM Forum - Business Model Innovation for Sustainability, *M&SOM* **15**(4): 537–544.

Electronic copy available at: https://ssrn.com/abstract=3257925

Gopalakrishnan, S., Granot, D., Granot, F., Sosic, G. and Cui, H. (2016). Incentives and emission responsibility allocation in supply chains. Working Paper, UBC.

Green, R. (1996). Increasing Competition in the British Electricity Spot Market, *The Journal of Industrial Economics* **44**(2): pp. 205–216.

Green, R. J. and Newbery, D. M. (1992). Competition in the British Electricity Spot Market, *Journal of Political Economy* **100**(5): 929–953.

Guo, R., Lee, H. L. and Swinney, R. (2015). Responsible sourcing in supply chains, *Management Science* **62**(9): 2722–2744.

Hausman, E., Hornby, R. and Smith, A. (2008). Bilateral Contracting in Deregulated Electricity Markets - A Report to the American Public Power Association. Synapse Energy Economics Inc.,pg. 3.

Holdermann, C., Kissel, J. and Beigel, J. (2014). Distributed photovoltaic generation in Brazil: An economic viability analysis of small-scale photovoltaic systems in the residential and commercial sectors, *Energy Policy* **67**: 612–617.

Holmberg, P. and Newbery, D. (2010). The supply function equilibrium and its policy implications for wholesale electricity auctions, *Utilities Policy* **18**(4): 209–226.

Hortacsu, A. and Puller, S. L. (2008). Understanding strategic bidding in multi-unit auctions: a case study of the texas electricity spot market, *The RAND Journal of Economics* **39**(1): 86–114.

Hu, S., Souza, G. C., Ferguson, M. E. and Wang, W. (2015). Capacity investment in renewable energy technology with supply intermittency: Data granularity matters!, *M&SOM* **17**(4): 480–494.

Jagruti, T. and Basab, C. (2018). Impact of increased solar penetration on bill savings of net metered residential consumers in India, *Energy* **162**: 776–786.

Johari, R. and Tsitsiklis, J. N. (2011). Parameterized Supply Function Bidding: Equilibrium and Efficiency, *Operations Research* **59**(5): 1079–1089.

Kleindorfer, P. R., Singhal, K. and Van Wassenhove, L. N. (2005). Sustainable operations management, *Production and operations management* **14**(4): 482–492.

Klemperer, P. D. and Meyer, M. A. (1989). Supply Function Equilibria in Oligopoly under Uncertainty, *Econometrica* **57**(6): 1243–1277.

Kök, A. G., Shang, K. and Şafak Yücel (2016). Investments in Renewable and Conventional Energy: The Role of Operational Flexibility. Working Paper.

Kök, A. G., Shang, K. and Şafak Yücel (2018). Impact of electricity pricing policies on renewable energy investments and carbon emissions, *Management Science* **64**(1): 131–148.

Electronic copy available at: https://ssrn.com/abstract=3257925

Lazaar, J. (2016). Electricity Regulation In the US: A Guide. www.raponline.org/knowledge-center/electricity-regulation-in-the-us-a-guide-2/, pg. 40 and Figure 7.1 on pg. 41, Accessed on 7/8/19.

Lee, H. L. and Tang, C. S. (2018). Socially and environmentally responsible value chain innovations: New operations management research opportunities, *Management Science* **64**(3): 983–996.

Lobel, R. and Perakis, G. (2013). Consumer Choice Model for Forecasting Demand and Designing Incentives for Solar Technology. Working Paper, MIT.

MCE (2018). MCE 2019 Integrated Resource Plan. www.mcecleanenergy.org/wp-content/uploads/2019/01/MCE-2019-Integrated-Resource-Plan_11-8-2018_V_12-21-18.pdf, pg. 34, Accessed on 7/7/19.

MISO (2018). Certified Market Participant List. cdn.misoenergy.org/Certified%20Market%20Participant%20List68568.pdf, Accessed on 2/5/2019.

Murali, K., Lim, M. K. and Petruzzi, N. C. (2018). The effects of ecolabels and environmental regulation on green product development, *M&SOM* . Articles in Advance.

NCSL (2016). State Net Metering Policies: Program Overview. www.ncsl.org/research/energy/net-metering-policy-overview-and-state-legislative-updates.aspx, Accessed on 5/9/17.

Nguyen, J., Donohue, K. and Mehrotra, M. (2019). Closing a Supplier's Energy Efficiency Gap Through Assessment Assistance and Procurement Commitment, *Management Science* **65**(1): 122–138.

NREL (2013). Regulatory Considerations Associated with the Expanded Adoption of Distributed Solar. www.nrel.gov/docs/fy14osti/60613.pdf, Section 4.2.4 Value-Added Consulting Services, Accessed on 8/8/18.

Orsdemir, A., Deshpande, V. and Parlakturk, A. K. (2017). Is servicization a win-win strategy? profitability and environmental implications of servicization. Forthcoming in M&SOM.

PCE (2017). PCE 2018 Integrated Resource Plan. www.peninsulacleanenergy.com/wp-content/uploads/2018/01/PCE-FINAL-2017-IRP-Updated.pdf, pg. 19 and 20 ,Accessed on 7/7/19.

PG&E (2017). Frequently Asked Questions (FAQ) about the Net Surplus Compensation (NSC) program. www.pge.com/en_US/residential/solar-and-vehicles/green-energy-incentives/getting-credit-for-surplus-energy/getting-credit-for-surplus-energy.page, Accessed on 9/5/17.

PUNC (2015). PUNC to consider the revised rates for customers who participate in net energy metering. pucweb1.state.nv.us/PDF/AXImages/PRESS_RELEASES/300.pdf, Accessed on 5/31/18.

Rudkevich, A. (1999). Supply function equilibrium in power markets: Learning all the way, *TCA technical paper* **1299**: 1702.

Electronic copy available at: https://ssrn.com/abstract=3257925

Silverstein, K. (2016). Battle Over Rooftop Solar Surplus Power Rates Turns Into Political Hand-To-Hand Combat, *Forbes* . www.forbes.com/sites/kensilverstein/2016/01/21/rooftop-solar-battles-include-sniping-and-hand-to-hand-combat/#3a1fa82830e2, Accessed on 9/1/18.

Singh, S. P. and Scheller-Wolf, A. (2018). That's not fair: Tariff structures for electricity markets with rooftop solar. Working Paper, Tepper School of Business, Carnegie Mellon University.

State of Vermont (2014). Net Metering Law. publicservice.vermont.gov/renewable_energy/net_metering, Department of Public Service, Accessed on 8/8/18.

Sunar, N. (2016). Emissions allocation problems in climate change policies, *Environmentally Responsible Supply Chains*, Springer, pp. 261–282.

Sunar, N. and Birge, J. R. (2019). Strategic Commitment to a Production Schedule with Uncertain Supply and Demand: Renewable Energy in Day-Ahead Electricity Markets, *Management Science* **65**(2): 714–734.

Sunar, N. and Plambeck, E. (2016). Allocating emissions among co-products: Implications for procurement and climate policy, *M&SOM* **18**(3): 414–428.

California Energy Commission (2018a). Utility Energy Supply Plans, and Supply Contracts. www.energy.ca.gov/almanac/electricity_data/supply_forms.html, Accessed on 8/8/18.

California Energy Commission (2018b). Utility plans from 2017. www.energy.ca.gov/almanac/electricity_data/supply_forms_2017/, Accessed on 8/8/18.

Edison Electric Institute (2012). Board and chief executives meeting. www.documentcloud.org/documents/1374670-2012-eei-board-and-chief-executives-meeting.html#document/p48/a191712, Accessed on 5/9/17.

LCG Consulting (2018). Industry Data. www.energyonline.com/Data/, CAISO and ISO-NE, Actual Load, 2017, Accessed on 7/8/19.

Michigan Public Service Comission (2018). Order. www.michigan.gov/documents/mpsc/U-18383_4-18-18_620947_7.pdf, Accessed on 7/23/18.

NC Clean Energy Technology Center (2018). 50 States of Solar - Q1 2018 Quarterly Report. nccleantech.ncsu.edu/wp-content/uploads/Q1-18_SolarExecSummary_Final.pdf, Accessed on 8/22/18.

State of California (2018). California DG Statistics - Distributed Generation Incentive Program Data. www.californiadgstats.ca.gov/downloads/, Accessed on 8/8/18.

The NYTimes (2017). Rooftop solar dims under pressure from utility lobbyists. www.nytimes.com/2017/07/08/climate/rooftop-solar-panels-tax-credits-utility-companies-lobbying.html, Accessed on 5/9/17.

Electronic copy available at: https://ssrn.com/abstract=3257925

The Washington Post (2015). Utilities wage campaign against rooftop solar. www.washingtonpost.com/national/health-science/utilities-sensing-threat-put-squeeze-on-booming-solar-roof-ind 2015/03/07/2d916f88-c1c9-11e4-ad5c-3b8ce89f1b89_story.html?utm_term=.eb5a55703928, Accessed on 9/5/17.

U.S. EIA (2017a). Form eia-861m (formerly eia-826) detailed data. www.eia.gov/electricity/data/eia861m/, Accessed on 8 /8/18.

U.S. EIA (2017b). U.S. Electric System Operating Data. www.eia.gov/realtime_grid/#/data/graphs?end=20160616T00&start=20160609T00&bas=0&regions=g.

U.S. EIA (2018a). Annual Electric Power Industry Report, Form EIA-861 detailed data files for 2011 - 2017. www.eia.gov/electricity/data/eia861/, Utility Data 2017, Operational Data 2017, Dynamic Pricing 2016 and 2017, Net Metering Data, Accessed on 7/10/19.

U.S. EIA (2018b). Electric Sales, Revenue, and Average Price - 2016, 2017. www.eia.gov/electricity/sales_revenue_price/, Table 1 for 2016 and 2017, Accessed on 7/10/19.

U.S. EIA (2018c). Table 6.7.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels, January 2013-May 2018. www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a, Accessed on 8/8/18.

U.S. EIA (2018d). Table 6.7.B. Capacity Factors for Utility Scale Generators Not Primarily Using Fossil Fuels, January 2013-May 2018. www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b, Accessed on 8/8/18.

U.S. EIA (2019). Table 1. 2017 Summary Statistics. www.eia.gov/electricity/state/massachusetts/state_tables.php,www.eia.gov/electricity/state/pennsylvania/state_tables.php, Accessed on 7/8/19.

Vermont PUC (2017). Proposed changes to rule 5.100 - net-metering. puc.vermont.gov/about-us/statutes-and-rules/proposed-changes-rule-5100-net-metering, Accessed on 7/23/18.

Vives, X. (2011). Strategic supply function competition with private information, *Econometrica* **79**(6): 1919–1966.

Watts, D., Valdés, M. F., Jara, D. and Watson, A. (2015). Potential residential PV development in Chile: The effect of Net Metering and Net Billing schemes for grid-connected PV systems, *R&SER* **41**: 1037–1051.

Wolak, F. A. (2000). An empirical analysis of the impact of hedge contracts on bidding behavior in a competitive electricity market, *International Economic Journal* **14**(2): 1–39.

Wu, O. Q. and Kapuscinski, R. (2013). Curtailing intermittent generation in electrical systems, *M&SOM* **15**(4): 578–595.

Zhou, Y., Sheller-Wolf, A., Secomandi, N. and Smith, S. (2018). Managing Wind-Based Electricity Generation in the Presence of Storage and Transmission Capacity. Forthcoming at Production and Operations Management.

Electronic copy available at: https://ssrn.com/abstract=3257925

Electronic Companion for “Net-Metered Distributed Renewable Energy: A Peril for Utilities?”

Appendix A: Details on the Social Welfare Result and Formulation

This section studies the implications of net-metered DRE for social welfare in the long-run. The setting is based on the one described in Section 5.4. Utility i sets its retail electricity price $p_{u,i} \in [\underline{p}, \bar{p}]$ in period $t=1$. Let $t=2,\dots,T$ represent the time periods in which $p_{u,i}$ remains the same. A wholesale market is run in every period t. When utility i obtains $q_{i,t} \leq K_i$ units of electricity from its existing resources in period t, it incurs a total cost of $\bar{C}_t(q_{i,t}) = \tilde{c}_t q_{i,t}$. (Proposition EC.1 below and its proof hold as stated if $\bar{C}_t(\cdot)$ is such that $\bar{C}_t(0) \geq 0$, $\bar{C}_t'(0) = \tilde{c}_t > 0$ and $\bar{C}_t''(\cdot) \leq 0$. Thus, our insights hold as stated when utility i's marginal cost of using its existing resources is a general decreasing function of the obtained quantity.) Other than these, as explained in Section 5.4, the setting in each period t is the same as the one in Section 2 with the following exception: Each parameter described in Section 2, except $p_{u,i}$, N, I and K_i, has a time index t (added as a subscript) to allow variation across time periods. The DRE generation dynamics are as in Definition 3 with an additional property of continuously differentiable and bounded $\mu'_{i,\ell,t}(\cdot)$. (See Section 5.4 for more details about the overall set-up.)

Total social welfare during $t \in [1,T]$ is the sum of generators' expected profits, utilities' expected profits and expected consumer surplus minus the sum of social cost of emissions and generation cost of procured quantity (if any) during that time period. Let $\Pi_{i,t}(\ell, q_{i,t}; \vec{p}_u)$ represent utility i's expected profit in period t at the retail electricity price vector $\vec{p}_u \doteq (p_{u,1},\dots,p_{u,I})$ under the rule $\ell \in \{r,m,0\}$ when utility i obtains $q_{i,t} \leq K_i$ units of electricity from its existing resources in period t. Then, when utility i obtains $q_{i,t}$ units of electricity from its existing resources in period t and its retail electricity price is $p_{u,i}$, the equilibrium social welfare in the presence of distributed renewable energy under the rule $\ell \in \{r,m\}$ is

$$
\begin{aligned}
SW_\ell(\vec{p}_u,\vec{q}) \doteq\ & \underbrace{\sum_{t=1}^{T} \mathbb{E}\Big[S_t(p^*_{w,t})p^*_{w,t} - c_t(S_t(p^*_{w,t}))^2\Big]N}_{\text{Total Expected Profit of Generators}} + \underbrace{\sum_{t=1}^{T}\sum_{i=1}^{I} \Pi_{i,t}(\ell, q_{i,t}; \vec{p}_u)}_{\text{Total Expected Profit of Utilities}} \\
& \underbrace{-\,\delta \sum_{t=1}^{T} \mathbb{E}\left[\theta_g\left(S_t(p^*_{w,t})N\right) + \theta_e \sum_{i=1}^{I} q_{i,t}\right]}_{\text{Social Cost of Emissions}} - \underbrace{\sum_{t=1}^{T}\sum_{i=1}^{I} \bar{G}_t(\tilde{q}_{i,t})}_{\text{Cost of Generation for the Procured Energy}} \\
& \underbrace{+\sum_{t=1}^{T}\sum_{i}^{I} \mathbb{E}\Big[-\big(\widehat{D}_{i,t} - D_{i,t} + (D_{i,t} - \widehat{\Delta}_{i,\ell,t})^+\big)p_{u,i} + (\widehat{\Delta}_{i,\ell,t} - D_{i,t})^+ p_{\ell,t}\Big] - \sum_{i=1}^{I} V\Big(\sum_{t=1}^{T} \mathbb{E}[\widehat{\Delta}_{i,\ell,t}]\Big)}_{\text{Expected Consumer Surplus}}, \qquad \text{(EC.1)}
\end{aligned}
$$

where $p_{m,t} \doteq p^*_{w,t}$, $p_{r,t} \doteq p_{u,i}$, $\vec{q} \doteq (\{q_{1,t}\}_{t=1,\dots,T},\dots,\{q_{I,t}\}_{t=1,\dots,T})$, and $\widehat{\Delta}_{i,\ell,t}$ is as in Definition 3. Let us explain each component of social welfare as well as new notation appeared in (EC.1) such as $\tilde{q}_{i,t}$, $\bar{G}_t(\cdot)$, θ_g, θ_e and V.

Note that $p^*_{w,t}$ depends on the rule $\ell \in \{r,m\}$ as the DRE adoption levels are allowed to differ under different rules (See Definition 3). The random variable $S_t(p^*_{w,t})$ in (EC.1) represents a generator's cleared supply bid (i.e., sales) in the period-t wholesale market. Then, the expression in (EC.1) for generators' expected profit in period t follows from the facts that in period t, a generator earns $p^*_{w,t}$ per unit sales and incurs cost to generate $S_t(p^*_{w,t})$ units of energy.

Electronic copy available at: https://ssrn.com/abstract=3257925

The total energy production of $S_t(p^*_{w,t})N$ by generators results in $\theta_g\left(S_t(p^*_{w,t})N\right)$ units of emissions, where θ_g is a non-negative constant. Similarly, when utility i obtains $q_{i,t}$ units of electricity from its existing resources, $\theta_e q_{i,t}$ units of emissions are released to the atmosphere, where θ_e is another non-negative constant. The parameter δ represents "social cost of carbon," which is the monetary value of damage due to increasing emissions by 1 metric ton of carbon dioxide (or its equivalent) in the atmosphere (Sunar and Plambeck 2016). From these, we have the social cost of emissions as in (EC.1).

The rationale behind the expected consumer surplus expression in (EC.1) is as follows. In region i and period t, regular end-customers (with no distributed generation) purchase $\widehat{D}_{i,t} - D_{i,t}$ units of electricity and net-metered customers purchase $(D_{i,t} - \widehat{\Delta}_{i,\ell,t})^+$ units of electricity at the retail price $p_{u,i}$. In addition, net-metered customers in region i are compensated for their generation surplus $(\widehat{\Delta}_{i,\ell,t} - D_{i,t})^+$, and the compensation rate is $p_{u,i}$ under the rule $\ell = r$ and $p^*_{w,t}$ under the rule $\ell = m$. The term $V(Q)$ represents the cost of installing DRE technology that is eligible to generate Q units of electricity in expectation during $[1,T]$. Combining these and the installation cost $V(\cdot)$, we obtain the expected consumer surplus expression in (EC.1).

Note that (EC.1) already accounts for utility i's cost of obtaining electricity from its existing resources, i.e., $\bar{C}_t(\cdot)$, through the expected profit formulation for utilities. In the case of utilities' energy procurement via long-term contracts, it can also be valuable to account in the social welfare for the generation cost incurred by other parties for utilities' procured energy. The formulation (EC.1) allows for this. Specifically, in (EC.1), $\bar{G}_t(\cdot)$ is allowed to be any general function, and $\bar{G}_t(\tilde{q}_{i,t})$ represents the period-t generation cost of the energy $\tilde{q}_{i,t}$ procured by utility i (e.g., through a long-term contract). Because $\bar{G}_t(\cdot)$ is allowed to be zero, the formulation that excludes the generation cost of the procured energy from the social welfare is a special case of (EC.1).

In our analysis, we are interested in the equilibrium social welfare $SW_\ell(\vec{p}^*_u(\ell), \vec{q}^*(\ell))$ when utility i chooses $q_{i,t}$ in every $t = 1, \ldots, T$ and sets the retail electricity price $p_{u,i}$ at the beginning of the time horizon to maximize its expected profit under the rule $\ell \in \{r, m\}$. The condition $\bar{p} < \tilde{p}$ below prevents the retail electricity price to be excessively high.

PROPOSITION EC.1. *There exist constants $\bar{\bar{\delta}}_{r,0}$, $\bar{\bar{\delta}}_{m,0}$, $\bar{\bar{\delta}}_{r,m}$ and $\tilde{p}$ such that when the maximum feasible retail electricity price $\bar{p} < \tilde{p}$, in equilibrium,* **(a)** *the distributed renewable energy generation under the rule $\ell \in \{r, m\}$ results in strictly larger social welfare than in the absence of such generation, i.e., $SW_\ell(\vec{p}^*_u(\ell), \vec{q}^*(\ell)) > SW_0(\vec{p}^*_u(0), \vec{q}^*(0))$ if and only if the social cost of carbon is sufficiently large, i.e., $\delta > \bar{\bar{\delta}}_{\ell,0}$, and* **(b)** *the rule $\ell = r$ results in strictly larger social welfare than the rule $\ell = m$, i.e., $SW_r(\vec{p}^*_u(r), \vec{q}^*(r)) > SW_m(\vec{p}^*_u(m), \vec{q}^*(m))$, if and only if $\delta > \bar{\bar{\delta}}_{r,m}$; otherwise, the rule $\ell = m$ results in larger social welfare than the rule $\ell = r$.*

Let us now explain the rationale for Proposition EC.1. If the range for the retail price is moderate, the equilibrium retail prices under different rules are close to each other. Then, introducing distributed renewable energy or implementing the rule $\ell = r$ instead of $\ell = m$ results in a relatively small change in the expected end-customer demand $\mathbb{E}[\widehat{D}_{i,t}]$ because that change is driven by the difference in optimal retail prices. However, either of the two aforementioned changes also increases expected DRE generation. Because the change in expected end-customer demand is relatively small, the aforementioned increase in expected DRE generation translates into less net demand by utilities and hence

Electronic copy available at: https://ssrn.com/abstract=3257925

less net wholesale demand. This further implies less production by generators and hence less emissions by generators, resulting in less total emissions.

If the social cost of carbon is sufficiently large, a decrease in emissions results in an increase in the equilibrium social welfare. This is because under this condition, emissions have a relatively large weight in the social welfare, compared to the other elements of social welfare. As a result, when δ is sufficiently large, the option that results in less total emissions improves social welfare, as proved in Proposition EC.1.

Appendix B: Proof of Proposition 1

Consider any realization $\epsilon > 0$ of the net wholesale market demand. We now prove part (a). We first characterize generator n's best response supply function. Given any supply function profile of other generators, which is denoted by $S_{-n} \doteq (S_1, \ldots, S_{n-1}, S_{n+1}, \ldots, S_N)$, generator n's profit at price p is

$$\pi_n(p; S_{-n}, \epsilon) = \mathcal{R}_n(p; \epsilon, S_{-n})p - (\mathcal{R}_n(p; \epsilon, S_{-n}))^2 c. \tag{EC.2}$$

Here, $\mathcal{R}_n(p; \epsilon, S_{-n})$ is the residual net demand of generator n given S_{-n} and ϵ, and equal to:

$$\mathcal{R}_n(p; \epsilon, S_{-n}) = \epsilon - \sum_{k \neq n}^{N} S_k(p).$$

To achieve the maximum ex post profit with respect to the net market demand, generator n submits a supply function S_n that induces a profit-maximizing market-clearing price for itself. The price that maximizes (EC.2) satisfies the first order condition:

$$\mathcal{R}_n(p; \epsilon, S_{-n}) + (p - 2c\mathcal{R}_n(p; \epsilon, S_{-n}))\, \mathcal{R}_n'(p; \epsilon, S_{-n}) = 0. \tag{EC.3}$$

We claim and show at the end of this proof that if each generator $k \neq n$ submits a supply function $S_k(\cdot)$ that satisfies $S_k'(p) = S_k(p)/\left[\,(p - 2cS_k(p))\,(N-1)\right]$ for $p \geq 0$ subject to $S_k(0) = 0$, the best response of generator n satisfies

$$S_n(p) - \sum_{k \neq n} S_k'(p)\,(p - 2cS_n(p)) = 0 \quad \text{for } p \geq 0, \tag{EC.4}$$

subject to $S_n(0) = 0$. Then, combining (EC.4) and (3), the supply function equilibrium is characterized by the following ordinary differential equation (ODE)

$$S'(p) = S(p)/\left[\,(p - 2cS(p))\,(N-1)\right] \quad \text{for } p \geq 0, \tag{EC.5}$$

$$\text{subject to} \quad S(0) = 0. \tag{EC.6}$$

It follows from standard ODE arguments that the unique solution to the above relation is $S(p) = (N-2)p/((N-1)2c)$. Since there is a unique solution, the supply function equilibrium is unique, which completes the proof of the first sentence in part (a). The claim in the second sentence of part (a) follows from the form of $S(p)$, (1) and (3).

Part (b) immediately follows from the characterized supply function equilibrium, (1) and (5).

It only remains to show our claim that if each generator $k \neq n$ submits a supply function $S_k(\cdot)$ that satisfies $S_k'(p) = S_k(p)/\left[\,(p - 2cS_k(p))\,(N-1)\right]$ subject to $S_k(0) = 0$ for $p \geq 0$, then generator n's best response satisfies (EC.4) subject

Electronic copy available at: https://ssrn.com/abstract=3257925

to $S_n(0)=0$ for $p\geq 0$. To do so, we will first show that (EC.3) is sufficient to identify the optimal price for generator n by proving that $\pi_n(p;S_{-n},\epsilon)$ is strictly concave with respect to p. From (EC.2), we have

$$\frac{\partial^2\pi_n(p;S_{-n},\epsilon)}{\partial p^2}=2\mathcal{R}_n'(p;\epsilon,S_{-n})+(p-2c\mathcal{R}_n(p;\epsilon,S_{-n}))\,\mathcal{R}_n''(p;\epsilon,S_{-n})-2c(\mathcal{R}_n'(p;\epsilon,S_{-n}))^2. \tag{EC.7}$$

Because $\mathcal{R}_n'(p;\epsilon,S_{-n})=-\sum_{k\neq n}^N S_k'(p)=-(N-2)/2c<0$ and $\mathcal{R}_n''(p;\epsilon,S_{-n})=-\sum_{k\neq n}^N S_k''(p)=0$, it follows that $\partial^2\pi_n(p;S_{-n},\epsilon)/\partial p^2<0$. Thus, the optimal price for generator n is the unique p that satisfies (EC.3), and this implies that the best response supply function of generator n must satisfy (EC.4). Based on (EC.4), we also have $S_n(0)=0$. A strictly negative price is never optimal for generator n because by (EC.2), generator n earns a strictly negative profit at $p<0$. As a result, best response supply function should only be defined for price $p\in[0,\infty)$. $\square$

Appendix C: Proofs of Theorem 1 and Corollaries 1 and 2

First, we shall introduce some notation that will be used in the remainder of the Appendix:

$$\alpha\doteq 2c(N-1)/\left((N-2)N\right),\ D_j^{\text{reg}}\doteq\widehat{D}_j-D_j\quad\text{and}\quad \nu\doteq\mathbb{E}\Big[\sum_{i\neq j}\big\{\widehat{D}_i-\Delta_i-K_i\big\}+\xi\Big]. \tag{EC.8}$$

Throughout this proof, we will make the dependence of p_w^* on $\mathcal{D}_w$ explicit by including $\mathcal{D}_w$ as an argument of p_w^*. Note that

$$(D_j-\Delta_j)^+-(\Delta_j-D_j)^+=D_j-\Delta_j. \tag{EC.9}$$

Then, using the equilibrium identified in the proof of Proposition 1, (6) is equivalent to the following for $\ell=r$:

$$\begin{aligned}\Pi_j(r)&=\mathbb{E}\big[(\widehat{D}_j-\Delta_j)p_{u,j}\big]+\mathbb{E}\big[(\Delta_j+K_j-\widehat{D}_j)p_w^*(\mathcal{D}_w)\big]-K_j\tilde{c}\\&=\mathbb{E}\big[(\widehat{D}_j-\Delta_j)p_{u,j}\big]+\mathbb{E}\Big[\Big(\Delta_j+K_j-\widehat{D}_j\Big)\,\alpha\big(\widehat{D}_j-K_j-\Delta_j+\nu\big)\Big]-K_j\tilde{c}.\end{aligned} \tag{EC.10}$$

Similarly, using the equilibrium identified in the proof of Proposition 1, (6) is equivalent to the following for $\ell=m$:

$$\begin{aligned}&\Pi_j(m)\\&=p_{u,j}\mathbb{E}\big[D_j^{\text{reg}}+(D_j-\Delta_j)^+\big]-\mathbb{E}\big[(\Delta_j-D_j)^+p_w^*(\mathcal{D}_w)\big]+\mathbb{E}\big[(\Delta_j+K_j-\widehat{D}_j)p_w^*(\mathcal{D}_w)\big]-K_j\tilde{c}\\&=p_{u,j}\mathbb{E}\big[D_j^{\text{reg}}+(D_j-\Delta_j)^+\big]+\mathbb{E}\left[\Big((\Delta_j+K_j-\widehat{D}_j)-(\Delta_j-D_j)^+\Big)\,\alpha\big(\widehat{D}_j-K_j-\Delta_j+\nu\big)\right]-K_j\tilde{c}.\end{aligned} \tag{EC.11}$$

The utility j's expected profit under $\ell=0$, which refers to the case with no distributed generation, is

$$\Pi_j(0)=\mathbb{E}\Big[\widehat{D}_jp_{u,j}-(\widehat{D}_j-K_j)\alpha(\widehat{D}_j-K_j+\widehat{\nu})\Big]-K_j\tilde{c}, \tag{EC.12}$$

where

$$\widehat{\nu}\doteq\mathbb{E}\left[\sum_{i\neq j}\Big(\widehat{D}_i-K_i\Big)+\xi\right]. \tag{EC.13}$$

LEMMA EC.1. *Suppose that $K_j=0$. Then, net-metered distributed renewable energy generation under the rule $\ell\in\{r,m\}$ results in a strictly larger expected profit for utility j compared to the case with no such generation if and only if $\gamma_\ell<p_w^{*\prime}(\mathcal{D}_w)$.*

Electronic copy available at: https://ssrn.com/abstract=3257925

Proof of Lemma EC.1: We first prove the result for $\ell = r$. Based on (EC.10) and (EC.12), the difference in utility j's expected profits under the rules $\ell = r$ and $\ell = 0$ is

$$\Pi_j(r) - \Pi_j(0) = -\mathbb{E}[\Delta_j]\, p_{u,j} + \mathbb{E}\Big[\big(\Delta_j + K_j - \widehat{D}_j\big)\alpha\big(\widehat{D}_j - K_j - \Delta_j + \nu\big)\Big] + \mathbb{E}\Big[(\widehat{D}_j - K_j)\alpha(\widehat{D}_j - K_j + \widehat{\nu})\Big]. \tag{EC.14}$$

Based on (EC.11) and (EC.12), the difference in utility j's expected profits under the rules $\ell = m$ and $\ell = 0$ is

$$\begin{aligned}&\Pi_j(m) - \Pi_j(0)\\ &= p_{u,j}\mathbb{E}\big[D_j^{\text{reg}} + (D_j - \Delta_j)^+\big] + \mathbb{E}\left[\Big((\Delta_j + K_j - \widehat{D}_j) - (\Delta_j - D_j)^+\Big)\,\alpha\big(\widehat{D}_j - K_j - \Delta_j + \nu\big)\right]\\ &\quad - \mathbb{E}\Big[\widehat{D}_j p_{u,j} - (\widehat{D}_j - K_j)\alpha(\widehat{D}_j - K_j + \widehat{\nu})\Big].\end{aligned} \tag{EC.15}$$

Define γ_r and γ_m as

$$\gamma_r \doteq \frac{\mathbb{E}[\Delta_j]p_{u,j}}{\mathbb{E}\Big[2\Delta_j\widehat{D}_j - \Delta_j^2 + \nu\Delta_j + \widehat{D}_j(\widehat{\nu} - \nu)\Big]} \tag{EC.16}$$

$$\gamma_m \doteq \frac{\mathbb{E}[D_j - (D_j - \Delta_j)^+]p_{u,j}}{\mathbb{E}[2\Delta_j\widehat{D}_j - \Delta_j^2 + \nu\Delta_j + \widehat{D}_j(\widehat{\nu} - \nu) - (\Delta_j - D_j)^+(\widehat{D}_j - \Delta_j + \nu)]}. \tag{EC.17}$$

Then, when $K_j = 0$, $\Pi_j(\ell) - \Pi_j(0) > 0$ if and only if $\gamma_\ell < \alpha = p_w^{*\prime}(\mathcal{D}_w)$ for $\ell \in \{r, m\}$. □

LEMMA EC.2. *Suppose that utility j is self-reliant, that is, $K_j = \widehat{Q}_j$. Then, net-metered distributed renewable energy generation under the rule $\ell \in \{r, m\}$ strictly decreases the expected profit for the utility j compared to the case with no such generation.*

Proof of Lemma EC.2: We first prove the claim for $\ell = r$. Because $K_j = \widehat{Q}_j$, (EC.14) is equivalent to

$$\begin{aligned}&\Pi_j(r) - \Pi_j(0)\\ &= -\mathbb{E}[\Delta_j]\, p_{u,j} + \mathbb{E}\Big[\Big(\Delta_j + \widehat{Q}_j - \widehat{D}_j\Big)\,\alpha\big(\widehat{D}_j - \widehat{Q}_j - \Delta_j + \nu\big)\Big] - \mathbb{E}\Big[(\widehat{Q}_j - \widehat{D}_j)\alpha(\widehat{D}_j - \widehat{Q}_j + \widehat{\nu})\Big]\\ &= \mathbb{E}\left[\Delta_j\left(\alpha(\widehat{D}_j - \widehat{Q}_j - \Delta_j + \nu) - p_{u,j}\right)\right] + \mathbb{E}\left[(\widehat{Q}_j - \widehat{D}_j)\alpha(-\Delta_j + \nu - \widehat{\nu})\right] < 0.\end{aligned} \tag{EC.18}$$

The expression above is strictly negative because $\widehat{Q}_j \geq \widehat{D}_j$ with probability 1, $\widehat{\nu} > \nu$ and $p_{u,j} > \mathbb{E}[p_w^*(\mathcal{D}_w)]$. Similarly, when $K_j = \widehat{Q}_j$, (EC.15) is equivalent to

$$\begin{aligned}\Pi_j(m) - \Pi_j(0) &= p_{u,j}\mathbb{E}\left[(D_j - \Delta_j)^+ - D_j\right] + \mathbb{E}\left[\Delta_j\alpha(\widehat{D}_j - \widehat{Q}_j - \Delta_j + \nu)\right]\\ &\quad - \mathbb{E}\left[(\Delta_j - D_j)^+\alpha(\widehat{D}_j - \widehat{Q}_j - \Delta_j + \nu)\right] - \alpha\mathbb{E}\left[(\widehat{\nu} + \Delta_j - \nu)(\widehat{Q}_j - \widehat{D}_j)\right].\end{aligned} \tag{EC.19}$$

We claim and show below that (EC.19) is strictly negative. This completes the proof of our claim.

We now show that (EC.19) is strictly negative. If $D_j \geq \Delta_j$, (EC.19) is equal to

$$-p_{u,j}\mathbb{E}[\Delta_j] + \mathbb{E}\left[\Delta_j\alpha(\widehat{D}_j - \widehat{Q}_j - \Delta_j + \nu)\right] - \alpha\mathbb{E}\left[(\widehat{\nu} + \Delta_j - \nu)(\widehat{Q}_j - \widehat{D}_j)\right] < 0.$$

Electronic copy available at: https://ssrn.com/abstract=3257925

The expression above is strictly negative because $\widehat{Q}_j \geq \widehat{D}_j$ with probability 1, $\widehat{\nu} > \nu$ and $p_{u,j} > \mathbb{E}\left[p_w^*(\mathcal{D}_w)\right]$. Because of the same reasons, if $D_j < \Delta_j$, (EC.19) is equal to the following expression and it is strictly negative:

$$-p_{u,j}\mathbb{E}\left[D_j\right] + \mathbb{E}\left[D_j\alpha(\widehat{D}_j - \widehat{Q}_j - \Delta_j + \nu)\right] - \alpha\mathbb{E}\left[(\widehat{\nu} + \Delta_j - \nu)(\widehat{Q}_j - \widehat{D}_j)\right] < 0.$$

□

LEMMA EC.3. *Consider utility j. The following relation holds for $\ell \in \{r, m\}$:*

$$\partial\left(\Pi_j(\ell) - \Pi_j(0)\right)/\partial K_j < 0.$$

Proof of Lemma EC.3: Suppose that $K_j > 0$. Using (EC.14) and (EC.15), we have

$$\partial\left(\Pi_j(r) - \Pi_j(0)\right)/\partial K_j = \mathbb{E}\left[-2\alpha\Delta_j + \alpha(\nu - \widehat{\nu})\right] < 0,$$
$$\partial\left(\Pi_j(m) - \Pi_j(0)\right)/\partial K_j = \mathbb{E}\left[-\alpha\Delta_j + \alpha(\nu - \widehat{\nu})\right] + \alpha\mathbb{E}\left[-\Delta_j + (\Delta_j - D_j)^+\right] < 0.$$

The expressions above are both strictly negative because $\widehat{\nu} > \nu$. □

Proof of Theorem 1: Combining Lemmas EC.1 through EC.3, it follows that under the rule $\ell \in \{r, m\}$, there exists a threshold $\bar{K}_\ell$ such that $\Pi_j(\ell) - \Pi_j(0) > 0$ if and only if $K_j < \bar{K}_\ell$ and $\gamma_\ell < {p_w^*}'(\mathcal{D}_w)$. □

Proofs of Corollaries 1 and 2: Corollary 1 follows from Lemma EC.3, and Corollary 2 is proved in Lemma EC.1. □

Appendix D: Proof of Theorem 2

Recall the definitions of α, D_j^{reg} and ν from (EC.8). Suppose that the DRE generation of utility j's net-metered customers increases from Δ_j to $\widetilde{\Delta}_j \doteq \Delta_j + \mu$.

We first prove part (a). Based on (EC.10), under the rule $\ell = r$, the utility j's expected profit with the self-supply capacity K_j is

$$\Pi_j(r, \mu) = \mathbb{E}\left[(\widehat{D}_j - \widetilde{\Delta}_j)p_{u,j}\right] + \mathbb{E}\left[\left(\widetilde{\Delta}_j + K_j - \widehat{D}_j\right)\alpha\left(\widehat{D}_j - K_j - \widetilde{\Delta}_j + \nu\right)\right] - K_j\tilde{c}. \quad \text{(EC.20)}$$

Therefore, we have

$$\partial\Pi_j(r, \mu)/\partial\mu = -p_{u,j} + \alpha\nu + 2\alpha\mathbb{E}\left[\widehat{D}_j - K_j - \widetilde{\Delta}_j\right] \quad \text{and} \quad \partial^2\Pi_j(r, \mu)/\partial\mu^2 = -2\alpha < 0. \quad \text{(EC.21)}$$

These imply that $\partial\Pi_j(r, \mu)/\partial\mu > 0$ if and only if

$$\mathbb{E}[\widetilde{\Delta}_j] < \chi_r \doteq \frac{-p_{u,j} + 2\alpha\mathbb{E}[\widehat{D}_j - K_j] + \alpha\nu}{2\alpha}.$$

This and (EC.21) complete the proof of the claim in part (a).

We now prove the claim in part (b). Recall (EC.11). Then, if the DRE generation of utility j's net-metered customers increases from Δ_j to $\widetilde{\Delta}_j$, we have

$$\Pi_j(m, \mu) = p_{u,j}\mathbb{E}\left[D_j^{\text{reg}} + (D_j - \widetilde{\Delta}_j)^+\right] - K_j\tilde{c}$$
$$+ \mathbb{E}\left[\left((\widetilde{\Delta}_j + K_j - \widehat{D}_j) - (\widetilde{\Delta}_j - D_j)^+\right)\alpha\left(\widehat{D}_j - K_j - \widetilde{\Delta}_j + \nu\right)\right].$$

Electronic copy available at: https://ssrn.com/abstract=3257925

Recall that $\widehat{D}_j = \beta D_j$. Then, $D_j^{\text{reg}} = (\beta-1)D_j$, and hence the above expression for $\Pi_j(m,\mu)$ is equivalent to

$$\begin{aligned}\Pi_j(m,\mu) =& (\beta-1)\mathbb{E}[D_j]p_{u,j} + \int_0^{Q_j}\int_{y+\mu}^{\widehat{Q}_j/\beta}(x-y-\mu)p_{u,j}dG_j(x)dF_j(y) - K_j\tilde{c}\\ &-\int_0^{Q_j}\int_0^{y+\mu}(y+\mu-x)\alpha(\beta x - K_j - y - \mu + \nu)dG_j(x)dF_j(y)\\ &+\mathbb{E}\left[(\Delta_j+\mu+K_j-\beta D_j)\alpha(\nu+\widehat{D}_j-K_j-\Delta_j-\mu)\right]. \end{aligned} \tag{EC.22}$$

Based on this, we have

$$\begin{aligned}\partial\Pi_j(m,\mu)/\partial\mu =& (\alpha\nu - p_{u,j})\mathbb{P}\left(D_j > \widetilde{\Delta}_j\right) + 2\alpha(\beta\mathbb{E}[D_j]-K_j)\\ &-\int_0^{Q_j}\int_0^{y+\mu}\left(\alpha(\beta+1)x-\alpha K_j\right)dG_j(x)dF_j(y) - 2\alpha\mathbb{E}\left[\widetilde{\Delta}_j\left(1-\mathbb{I}(D_j\le\widetilde{\Delta}_j)\right)\right]. \end{aligned} \tag{EC.23}$$

and

$$\begin{aligned}\partial^2\Pi_j(m,\mu)/\partial\mu^2 =& 2\alpha\left(-1+\int_0^{Q_j}\int_0^{y+\mu}dG_j(x)dF_j(y)\right)\\ &+\int_0^{Q_j}\left(p_{u,j}-\alpha\big(\nu+(\beta-1)(y+\mu)-K_j\big)\right)g_j(y+\mu)dF_j(y).\end{aligned}$$

This implies that there exists a constant $\bar{\nu}$ such that when $\nu > \bar{\nu}$, $\partial^2\Pi_j(m,\mu)/\partial\mu^2 < 0$. Hence, by (EC.23), when $\nu > \bar{\nu}$, there exists some χ_m such that $\partial\Pi_j(m,\mu)/\partial\mu > 0$ if and only if $\mathbb{E}\left[\widetilde{\Delta}_j\mathbb{I}(\widetilde{\Delta}_j < D_j)\right] < \chi_m$. □

Appendix E: Proof of Proposition 2

LEMMA EC.4. *Consider utility j with $K_j = 0$. When the wholesale electricity price is equal to $g_w(\mathcal{D}_w)$ where g_w is a general function that satisfies the properties (i) through (iii) in Section 5.1, there exists some constant $\tilde{\gamma}_{1,\ell}$ such that distributed renewable energy generation under the net metering rule $\ell\in\{r,m\}$ results in a strictly larger expected profit for the utility j compared to the case with no such generation if $\tilde{\gamma}_{1,\ell} < \left(\mathbb{E}\left[\sqrt{g_w'(\mathcal{D}_w)}\right]\right)^2$.*

Proof of Lemma EC.4: Let $\widetilde{D}_i$ be such that $\widetilde{D}_i \doteq \widehat{D}_i - K_i$ for $i \ne j$ and $\widetilde{D}_j \doteq \widehat{D}_j$. Because g_w is a $\mathcal{C}^2$ function, by the Taylor expansion and the intermediate value theorem, we have the following for some $\tilde{x}_1 \in [0, \Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi]$ and $\tilde{x}_2 \in [\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi, \Sigma_{i=1}^I\widetilde{D}_i+\xi]$ with probability 1:

$$\begin{aligned}&g_w\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right) - \left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right)g_w'\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right) - \frac{1}{2}\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right)^2 g_w''(\tilde{x}_1)\\ &\quad = g_w(0) = 0,\end{aligned} \tag{EC.24}$$

$$g_w\left(\Sigma_{i=1}^I\widetilde{D}_i+\xi\right) - g_w\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right) = g_w'\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right)(\Sigma_{i=1}^I\Delta_i) + \frac{1}{2}g_w''(\tilde{x}_2)(\Sigma_{i=1}^I\Delta_i)^2. \tag{EC.25}$$

Let us first prove the result for $\ell = r$. Because $\Pi_j(r) = \mathbb{E}\left[(\widetilde{D}_j-\Delta_j)p_{u,j} + (\Delta_j-\widetilde{D}_j)g_w(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi)\right]$ and $\Pi_j(0) = \mathbb{E}\left[\widetilde{D}_j\left(p_{u,j}-g_w(\Sigma_{i=1}^I\widetilde{D}_i+\xi)\right)\right]$ when $K_j = 0$, $\Pi_j(r) > \Pi_j(0)$ if and only if

$$\mathbb{E}\big[\Delta_j g_w(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi)\big] + \mathbb{E}\big[\widetilde{D}_j\big(g_w(\Sigma_{i=1}^I\widetilde{D}_i+\xi) - g_w(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi)\big)\big] > \mathbb{E}\big[\Delta_j\big]p_{u,j}. \tag{EC.26}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

By (EC.24) and (EC.25), (EC.26) is equivalent to

$$\begin{aligned}&\mathbb{E}\left[\left[\Delta_j\big(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi\big)+\widehat{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)\right]g'_w\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right)\right]\\&\quad>\mathbb{E}[\Delta_j]p_{u,j}-\frac{1}{2}\mathbb{E}\big[\Delta_j\big(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi\big)^2g''_w(\tilde{x}_1)+\widetilde{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)^2g''_w(\tilde{x}_2)\big].\end{aligned}\tag{EC.27}$$

Because $g_w(\cdot)$ is $\mathcal{C}^2$ and both $\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi$ and $\Sigma_{i=1}^I\widetilde{D}_i+\xi$ have bounded supports, $g''_w(\tilde{x}_2)$ and $g''_w(\tilde{x}_1)$ are both bounded. Thus, there exists a constant $\bar{\kappa}_r$ such that $\bar{\kappa}_r$ is an upper bound on $\mathbb{E}[\Delta_j]p_{u,j}-\frac{1}{2}\mathbb{E}\big[\Delta_j\big(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi\big)^2g''_w(\tilde{x}_1)+\widetilde{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)^2g''_w(\tilde{x}_2)\big]$ in (EC.27). Moreover, by Cauchy-Schwartz inequality, we have

$$\begin{aligned}&\mathbb{E}\left[\left[\Delta_j\big(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi\big)+\widehat{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)\right]g'_w\left(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\right)\right]\\&\geq\left(\mathbb{E}\left[\sqrt{g'_w\big(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\big)}\right]\right)^2\left(\mathbb{E}\left[\left[\Delta_j\big(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi\big)+\widehat{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)\right]^{-1}\right]\right)^{-1}.\end{aligned}$$

This, the existence of $\bar{\kappa}_r$ and (EC.27) imply that $\Pi_j(r)>\Pi_j(0)$ if

$$\left(\mathbb{E}\left[\sqrt{g'_w\big(\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi\big)}\right]\right)^2\geq\tilde{\gamma}_{1,r}\doteq\bar{\kappa}_r\mathbb{E}\left[\left[\Delta_j\big(\Sigma_{i=1}^I\widetilde{D}_i-\Delta_i+\xi\big)+\widehat{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)\right]^{-1}\right].$$

To prove the result for the rule $\ell=m$, one can use similar arguments explained above. Let $\tilde{\mathcal{D}}_w\doteq\Sigma_{i=1}^I(\widetilde{D}_i-\Delta_i)+\xi$. In light of this, $\Pi_j(m)>\Pi_j(0)$ if and only if

$$\begin{aligned}&\mathbb{E}\big[\big(\Delta_j-(\Delta_j-D_j)^+\big)g_w(\tilde{\mathcal{D}}_w)\big]+\mathbb{E}\big[\big(\Sigma_{i=1}^I\Delta_i\big)\widehat{D}_jg'_w(\tilde{\mathcal{D}}_w)\big]\\&\quad>\mathbb{E}\big[D_j-(D_j-\Delta_j)^+\big]p_{u,j}-\frac{1}{2}\mathbb{E}\big[\big(\Sigma_{i=1}^I\Delta_i\big)^2\widehat{D}_jg''_w(\tilde{x}_2)\big].\end{aligned}\tag{EC.28}$$

Based on this, as $g''_w(\tilde{\mathcal{D}}_w)$ is bounded, there exists a constant $\bar{\kappa}_m$ such that $\bar{\kappa}_m$ is an upper bound on the right hand side of the above inequality. Then, because $\mathbb{E}\big[\big(\Delta_j-(\Delta_j-D_j)^+\big)g_w(\tilde{\mathcal{D}}_w)\big]>0$, a sufficient condition that guarantees (EC.28) is

$$\mathbb{E}\big[\big(\Sigma_{i=1}^I\Delta_i\big)\widehat{D}_jg'_w(\tilde{\mathcal{D}}_w)\big]>\bar{\kappa}_m.\tag{EC.29}$$

Moreover, from Cauchy-Schwartz inequality, we have $\mathbb{E}\big[\big(\Sigma_{i=1}^I\Delta_i\big)\widehat{D}_jg'_w(\tilde{\mathcal{D}}_w)\big]\mathbb{E}\big[\big(\big(\Sigma_{i=1}^I\Delta_i\big)\widehat{D}_j\big)^{-1}\big]\geq\left(\mathbb{E}\left[\sqrt{g'_w(\tilde{\mathcal{D}}_w)}\right]\right)^2$. Based on this and (EC.29), a sufficient condition for $\Pi_j(m)>\Pi_j(0)$ is

$$\left(\mathbb{E}\left[\sqrt{g'_w(\tilde{\mathcal{D}}_w)}\right]\right)^2>\tilde{\gamma}_{1,m}\doteq\bar{\kappa}_m\mathbb{E}\big[\big(\widehat{D}_j\big(\Sigma_{i=1}^I\Delta_i\big)\big)^{-1}\big].$$

This completes the proof of Lemma EC.4. □

LEMMA EC.5. *Consider utility j with existing resources of size K_j. When the wholesale electricity price is a general function of the net wholesale demand, i.e., $g_w(\mathcal{D}_w)$ with the explained properties in Section 5.1, for $\ell\in\{r,m\}$, $\partial(\Pi_j(\ell)-\Pi_j(0))/\partial K_j<0$ if $\tilde{\gamma}_{2,\ell}<\big(\mathbb{E}\big[\sqrt{g'_w(\mathcal{D}_w)}\big]\big)^2$ for some constant $\tilde{\gamma}_{2,\ell}$.*

Proof of Lemma EC.5: Let $\mathcal{D}_{w,0}\doteq\Sigma_{i=1}^I(\widehat{D}_i-K_i)+\xi$ and $\mathcal{D}_{w,d}\doteq\Sigma_{i=1}^I(\widehat{D}_i-\Delta_i-K_i)+\xi$. Note that

$$\Pi_j(m)=\mathbb{E}\big[\big(\widehat{D}_j-D_j+(D_j-\Delta_j)^+\big)p_{u,j}-K_j\tilde{c}\big]+\mathbb{E}\big[\big((\Delta_j+K_j-\widehat{D}_j)-(\Delta_j-D_j)^+\big)g_w(\mathcal{D}_{w,d})\big],\tag{EC.30}$$

$$\Pi_j(r)=\mathbb{E}\big[(\widehat{D}_j-\Delta_j)p_{u,j}-K_j\tilde{c}\big]+\mathbb{E}\big[(\Delta_j+K_j-\widehat{D}_j)g_w(\mathcal{D}_{w,d})\big]\tag{EC.31}$$

$$\Pi_j(0)=\mathbb{E}\big[\widehat{D}_jp_{u,j}-K_j\tilde{c}-(\widehat{D}_j-K_j)g_w(\mathcal{D}_{w,0})\big].\tag{EC.32}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

Then, $\Pi_j(r) - \Pi_j(0)$ is equal to

$$-\mathbb{E}\big[\Delta_j\big]p_{u,j} + \mathbb{E}\big[\Delta_j g_w(\mathcal{D}_{w,d})\big] + \mathbb{E}\big[(\widehat{D}_j - K_j)\big(g_w(\mathcal{D}_{w,0}) - g_w(\mathcal{D}_{w,d})\big)\big].$$

As a result, $\partial(\Pi_j(r) - \Pi_j(0))/\partial K_j$ is

$$-\mathbb{E}\big[\Delta_j g'_w(\mathcal{D}_{w,d})\big] - \mathbb{E}\big[g_w(\mathcal{D}_{w,0}) - g_w(\mathcal{D}_{w,d})\big] - \mathbb{E}\big[(\widehat{D}_j - K_j)\big(g'_w(\mathcal{D}_{w,0}) - g'_w(\mathcal{D}_{w,d})\big)\big]. \tag{EC.33}$$

From Taylor's expansion and the intermediate value theorem, with probability 1, we have the following for some $\tilde{y}_1 \in [\mathcal{D}_{w,d}, \mathcal{D}_{w,0}]$ and some $\tilde{y}_2 \in [\mathcal{D}_{w,d}, \mathcal{D}_{w,0}]$:

$$g'_w(\mathcal{D}_{w,0}) = g'_w(\mathcal{D}_{w,d}) + g''_w(\tilde{y}_1)\big(\Sigma_{i=1}^I \Delta_i\big) \tag{EC.34}$$

$$g_w(\mathcal{D}_{w,0}) = g_w(\mathcal{D}_{w,d}) + g'_w(\mathcal{D}_{w,d})\big(\Sigma_{i=1}^I \Delta_i\big) + \frac{1}{2} g''_w(\tilde{y}_2)\big(\Sigma_{i=1}^I \Delta_i\big)^2. \tag{EC.35}$$

Expressions in (EC.33), (EC.34) and (EC.35) imply that $\partial(\Pi_j(r) - \Pi_j(0))/\partial K_j < 0$ if and only if

$$-\mathbb{E}\big[\Delta_j g'_w(\mathcal{D}_{w,d})\big] - \mathbb{E}\big[g'_w(\mathcal{D}_{w,d})\big(\Sigma_{i=1}^I \Delta_i\big) + 0.5 g''_w(\tilde{y}_2)\big(\Sigma_{i=1}^I \Delta_i\big)^2\big] - \mathbb{E}\big[(\widehat{D}_j - K_j) g''_w(\tilde{y}_1)\big(\Sigma_{i=1}^I \Delta_i\big)\big] < 0,$$

which is equivalent to

$$-\mathbb{E}\big[0.5 g''_w(\tilde{y}_2)\big(\Sigma_{i=1}^I \Delta_i\big)^2 + (\widehat{D}_j - K_j) g''_w(\tilde{y}_1)\big(\Sigma_{i=1}^I \Delta_i\big)\big] < \mathbb{E}\big[\big(\Delta_j + \Sigma_{i=1}^I \Delta_i\big) g'_w(\mathcal{D}_{w,d})\big]. \tag{EC.36}$$

Because g''_w is a bounded function, there exists a constant $\tilde{\kappa}_r$ such that it is an upper bound on the left hand side of the above inequality and independent of K_j. Moreover, from an application of Cauchy-Schwartz inequality, we have

$$\left(\mathbb{E}\big[\sqrt{g'_w(\mathcal{D}_{w,d})}\big]\right)^2 \left(\mathbb{E}\big[\big(\Delta_j + \Sigma_{i=1}^I \Delta_i\big)^{-1}\big]\right)^{-1} \leq \mathbb{E}\big[\big(\Delta_j + \Sigma_{i=1}^I \Delta_i\big) g'_w(\mathcal{D}_{w,d})\big].$$

This, (EC.36) and the existence of $\tilde{\kappa}_r$ imply that $\partial(\Pi_j(r) - \Pi_j(0))/\partial K_j < 0$ if

$$\left(\mathbb{E}\left[\sqrt{g'_w(\mathcal{D}_{w,d})}\right]\right)^2 > \tilde{\gamma}_{2,r} \doteq \tilde{\kappa}_r \mathbb{E}\big[\big(\Delta_j + \Sigma_{i=1}^I \Delta_i\big)^{-1}\big].$$

We now prove the claim for $\ell = m$. From (EC.30) and (EC.32), $\Pi_j(m) - \Pi_j(0)$ is equal to

$$\mathbb{E}\big[(D_j - \Delta_j)^+ - D_j\big]p_{u,j} + \mathbb{E}\left[\big((\Delta_j + K_j - \widehat{D}_j) - (\Delta_j - D_j)^+\big) g_w(\mathcal{D}_{w,d})\right] + \mathbb{E}\left[(\widehat{D}_j - K_j) g_w(\mathcal{D}_{w,0})\right].$$

Then, $\partial(\Pi_j(m) - \Pi_j(0))/\partial K_j$ is equal to

$$\mathbb{E}\big[g_w(\mathcal{D}_{w,d}) - g_w(\mathcal{D}_{w,0})\big] - \mathbb{E}\left[\big((\Delta_j + K_j - \widehat{D}_j) - (\Delta_j - D_j)^+\big) g'_w(\mathcal{D}_{w,d})\right] - \mathbb{E}\left[(\widehat{D}_j - K_j) g'_w(\mathcal{D}_{w,0})\right].$$

Using this, (EC.34) and (EC.35), and applying similar steps as the ones explained for $\ell = r$ in this proof, it follows that there exists a constant $\tilde{\gamma}_{2,m}$ such that if $\tilde{\gamma}_{2,m} < \big(\mathbb{E}\big[\sqrt{g'_w(\mathcal{D}_{w,d})}\big]\big)^2$, $\partial(\Pi_j(m) - \Pi_j(0))/\partial K_j < 0$. Because $\mathcal{D}_{w,d} = \mathcal{D}_w$ by definition, the claim follows. $\square$

Define $\tilde{\gamma}_\ell \doteq \max\{\tilde{\gamma}_{1,\ell}, \tilde{\gamma}_{2,\ell}\}$ for $\ell \in \{r, m\}$. Then, under the rule $\ell \in \{r, m\}$, when $\tilde{\gamma}_\ell < \big(\mathbb{E}\big[\sqrt{g'_w(\mathcal{D}_w)}\big]\big)^2$, by Lemmas EC.4 and EC.5, there exists a constant $\tilde{K}_\ell \in (0, \widehat{Q}_j]$ such that $\Pi_j(\ell) - \Pi_j(0) > 0$ under the conditions in Proposition 2. $\square$

Electronic copy available at: https://ssrn.com/abstract=3257925

Appendix F: Proof of Proposition 3

Recall from (10) the utility j's expected profit under rule $\ell \in \{r, m\}$. In this proof, the notation $q_i^*(\ell)$ refers to the equilibrium self-supply quantity of utility $i = 1, 2, \ldots, I$ under the rule $\ell \in \{r, m, 0\}$.

Proof of the Claim for $\ell = r$: Note that for any q_j, (10) is equivalent to the following for $\ell = r$: $\Pi_j(r) = \mathbb{E}\big[(\widehat{D}_j - \Delta_j)p_{u,j} + (q_j + \Delta_j - \widehat{D}_j)\alpha(\Sigma_{i=1}^I \widehat{D}_i - \Delta_i - q_i + \xi) - \bar{C}(q_j)\big]$. Based on this, $\Pi_j(r)$ is strictly concave with respect to q_j because $\partial^2 \Pi_j(r)/\partial q_j^2 = -2\alpha - \bar{C}''(q_j) < 0$. As a result, for any given vector of self-supply quantities by other utilities $(q_1, \ldots, q_{j-1}, q_{j+1}, \ldots, q_I)$, the unconstrained optimal self-supply quantity for utility j is the unique q_j that satisfies $\partial \Pi_j(r; q_j)/\partial q_j = 0$, which is equivalent to $\iota q_j + \alpha \sum_{i \neq j} q_i = b_j$ where

$$\iota \doteq 2(\alpha + \kappa_2) \quad \text{and} \quad b_j \doteq \alpha \mathbb{E}\left[2(\widehat{D}_j - \Delta_j) + \sum_{i \neq j}(\widehat{D}_i - \Delta_i) + \xi\right] - \kappa_1. \tag{EC.37}$$

Then, under the rule $\ell = r$, utilities' unconstrained equilibrium self-supply quantities $(q_{1,\text{un}}^*(r), q_{2,\text{un}}^*(r), \ldots, q_{I,\text{un}}^*(r))$ satisfy the following relation:

$$\begin{bmatrix} \iota & \alpha & \alpha & \ldots & \alpha \\ \alpha & \iota & \alpha & \ldots & \alpha \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha & \alpha & \alpha & \ldots & \iota \end{bmatrix} \begin{bmatrix} q_{1,\text{un}}^*(r) & q_{1,\text{un}}^*(r) & q_{1,\text{un}}^*(r) & \ldots & q_{1,\text{un}}^*(r) \\ q_{2,\text{un}}^*(r) & q_{2,\text{un}}^*(r) & q_{2,\text{un}}^*(r) & \ldots & q_{2,\text{un}}^*(r) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ q_{I,\text{un}}^*(r) & q_{I,\text{un}}^*(r) & q_{I,\text{un}}^*(r) & \ldots & q_{I,\text{un}}^*(r) \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_I \end{bmatrix}$$

By linear algebra, we have

$$q_{j,\text{un}}^*(r) = \frac{\big(\iota + (I-2)\alpha\big)b_j - \big(\Sigma_{i \neq j}^I b_i\big)\alpha}{\iota^2 + (I-2)\alpha\iota - (I-1)\alpha^2}, \tag{EC.38}$$

where ι and b_j are as defined in (EC.37). By similar logic, in the absence of DRE, the unconstrained self-supply quantity of utility j in equilibrium is

$$q_{j,\text{un}}^*(0) = \frac{\big(\iota + (I-2)\alpha\big)\tilde{b}_j - \big(\Sigma_{i \neq j}^I \tilde{b}_i\big)\alpha}{\iota^2 + (I-2)\alpha\iota - (I-1)\alpha^2}, \tag{EC.39}$$

where $\tilde{b}_j \doteq \alpha \mathbb{E}\big[2\widehat{D}_j + \Sigma_{i \neq j}\widehat{D}_i + \xi\big] - \kappa_1$.

Suppose that $K_j = 0$. Then, because equilibrium self-supply quantities satisfy $q_j^*(\ell) \leq K_j$ for $\ell \in \{r, m, 0\}$, $q_j^*(0) = q_j^*(r) = 0$. As a result, by Lemma EC.1, $\Pi_j(r) > \Pi_j(0)$ if and only if $p_w^{*\prime}(\mathcal{D}_w) > \gamma_{j,r}^{\bar{C}} \doteq \gamma_r$ where γ_r is as in Lemma EC.1.

Using (EC.38), (EC.39) and that $\mathbb{E}\big[\Delta_1\big] = \mathbb{E}\big[\Delta_2\big] = \ldots = \mathbb{E}\big[\Delta_I\big]$, we conclude that $q_{j,\text{un}}^*(0) > q_{j,\text{un}}^*(r)$. We claim and show in the paragraph below that $\partial(\Pi_j(r) - \Pi_j(0))/\partial K_j < 0$ for $K_j \in (0, q_{j,\text{un}}^*(0))$ and $\partial(\Pi_j(r) - \Pi_j(0))/\partial K_j = 0$ for $K_j \geq q_{j,\text{un}}^*(0)$. This and the fact that when $K_j = 0$, $\Pi_j(r) > \Pi_j(0)$ if and only if $p_w^{*\prime}(\mathcal{D}_w) > \gamma_r$ immediately imply that $\Pi_j(r) > \Pi_j(0)$ if and only if $p_w^{*\prime}(\mathcal{D}_w) > \gamma_r$ and $K_j < K_{j,r}^{\bar{C}}$ for some constant $K_{j,r}^{\bar{C}}$.

We now prove the above claim about $\partial(\Pi_j(r) - \Pi_j(0))/\partial K_j$ under each of the following three cases. <u>Case I:</u> Suppose that $K_j \leq q_{j,\text{un}}^*(r)$. Then, the utility j's equilibrium self-supply quantity under the rule $\ell \in \{r, 0\}$ satisfies $q_j^*(0) = q_j^*(r) = K_j$, and $\Pi_j(r) - \Pi_j(0)$ is equal to

$$\begin{aligned} &\mathbb{E}\big[-\Delta_j\big]p_{u,j} + \mathbb{E}\big[(K_j + \Delta_j - \widehat{D}_j)\alpha\big(\Sigma_{i \neq j}\widehat{D}_i - \Delta_i - q_i^*(r) + \widehat{D}_j - \Delta_j - K_j + \xi\big)\big] \\ &\quad + \mathbb{E}\big[(\widehat{D}_j - K_j)\alpha\big(\Sigma_{i \neq j}\widehat{D}_i - q_i^*(0) + \widehat{D}_j - K_j + \xi\big)\big]. \end{aligned}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

Note from (EC.38) and (EC.39) that unconstrained equilibrium self-supply quantities $q^*_{i,\text{un}}(0)$ and $q^*_{i,\text{un}}(r)$ do not depend on K_j for $i \neq j$. Thus, both $q^*_i(0)$ and $q^*_i(r)$ are independent of K_j for $i \neq j$. Then,

$$\partial\big(\Pi_j(r) - \Pi_j(0)\big)/\partial K_j = \mathbb{E}\big[-\alpha\big(\Sigma^I_{i\neq j}\Delta_i + 2\Delta_j\big) + \alpha\Sigma^I_{i\neq j}\big(q^*_i(0) - q^*_i(r)\big)\big].$$

Plugging $\mathbb{E}[\Delta_1] = \mathbb{E}[\Delta_2] = \ldots = \mathbb{E}[\Delta_I]$ above and observing that $q^*_i(0) - q^*_i(r) \leq q^*_{i,\text{un}}(0) - q^*_{i,\text{un}}(r)$, we have

$$\partial\big(\Pi_j(r) - \Pi_j(0)\big)/\partial K_j \leq \mathbb{E}\big[-\alpha\big(\Sigma^I_{i\neq j}\Delta_i + 2\Delta_j\big) + \alpha\Sigma^I_{i\neq j}\big(q^*_{i,\text{un}}(0) - q^*_{i,\text{un}}(r)\big)\big] < 0.$$

Case II: Suppose that $q^*_{j,\text{un}}(r) < K_j \leq q^*_{j,\text{un}}(0)$. Then, the equilibrium self-supply quantities are $q^*_j(r) = q^*_{j,\text{un}}(r)$ and $q^*_j(0) = K_j$. As a result, $\Pi_j(r)$ does not depend on K_j while $\Pi_j(0)$ is a function of K_j. Based on this, $\partial\big(\Pi_j(r) - \Pi_j(0)\big)/\partial K_j = -\partial\Pi_j(0)/\partial K_j < 0$. Note that in this case, $\partial\Pi_j(0)/\partial q_j\big|_{\{q_j=K_j\}} > 0$ because $\Pi_j(0)$ is strictly concave in q_j and $K_j \leq q^*_{j,\text{un}}(0)$. Case III: Suppose that $q^*_{j,\text{un}}(0) < K_j$. Then, equilibrium self-supply quantities are $q^*_j(0) = q^*_{j,\text{un}}(0)$ and $q^*_j(r) = q^*_{j,\text{un}}(r)$. Because $q^*_i(0)$ and $q^*_i(r)$ are independent of K_j for $i = 1, 2, \ldots, I$, $\partial\big(\Pi_j(r) - \Pi_j(0)\big)/\partial K_j = 0$. Combining Cases I through III completes the proof of our claim for $\ell = r$.

Proof of the Claim for $\ell = m$**:** Note that for any q_j, (10) is equivalent to the following for $\ell = m$: $\Pi_j(m) = \mathbb{E}\big[\big((\widehat{D}_j - D_j) + (D_j - \Delta_j)^+\big)p_{u,j} + (q_j + \Delta_j - \widehat{D}_j)\alpha(\Sigma^I_{i=1}\widehat{D}_i - \Delta_i - q_i + \xi) - (\Delta_j - D_j)^+\alpha(\Sigma^I_{i=1}\widehat{D}_i - \Delta_i - q_i + \xi) - \bar{C}(q_j)\big]$. Based on this, $\Pi_j(m)$ is strictly concave in q_j because $\partial^2\Pi_j(r)/\partial q_j^2 = -2\alpha - \bar{C}''(q_j) < 0$. As a result, for any given vector of self-supply quantities of other utilities $(q_1, \ldots, q_{j-1}, q_{j+1}, \ldots, q_I)$, the unconstrained optimal self-supply quantity of utility j is the unique q_j that satisfies $\partial\Pi_j(m; q_j)/\partial q_j = 0$, which is equivalent to $\iota q_j + \alpha\sum_{i\neq j} q_i = \bar{b}_j$ where ι is as in (EC.37) and

$$\bar{b}_j \doteq \alpha\mathbb{E}\left[2(\widehat{D}_j - \Delta_j) + \sum_{i\neq j}(\widehat{D}_i - \Delta_i) + \xi\right] + \alpha\mathbb{E}\big[(\Delta_j - D_j)^+\big] - \kappa_1. \quad \text{(EC.40)}$$

Then, under the rule $\ell = m$, utilities' unconstrained equilibrium self-supply quantities $\big(q^*_{1,\text{un}}(m), q^*_{2,\text{un}}(m), \ldots, q^*_{I,\text{un}}(m)\big)$ satisfy $\iota q^*_{i,\text{un}} + \alpha\sum^I_{k\neq i} q^*_{k,\text{un}} = \bar{b}_i$ for $i = 1, \ldots, I$. Solving this system of linear equations, the utility j's unconstrained equilibrium self-supply quantity under the rule $\ell = m$ is

$$q^*_{j,\text{un}}(m) = \frac{\big(\iota + (I-2)\alpha\big)\bar{b}_j - \big(\Sigma^I_{i\neq j}\bar{b}_i\big)\alpha}{\iota^2 + (I-2)\alpha\iota - (I-1)\alpha^2}, \quad \text{(EC.41)}$$

where ι and $\bar{b}_j$ are respectively defined in (EC.37) and (EC.40).

Suppose that $K_j = 0$. Then, because equilibrium self-supply quantities must satisfy $q^*_j(\ell) \leq K_j$ for $\ell \in \{m, 0\}$, $q^*_j(0) = q^*_j(m) = 0$. Then, by the proof of Lemma EC.1, $\Pi_j(m) > \Pi_j(0)$ if and only if $p^*_w{}'(\mathcal{D}_w) > \gamma^{\bar{C}}_{j,m} \doteq \gamma_m$ where γ_m is as in Lemma EC.1.

By (EC.39) and (EC.41), $q^*_{j,\text{un}}(0) > q^*_{j,\text{un}}(m)$. We claim and show in the paragraph below that $\partial(\Pi_j(m) - \Pi_j(0))/\partial K_j < 0$ for $K_j \in (0, q^*_{j,\text{un}}(0))$ and $\partial(\Pi_j(m) - \Pi_j(0))/\partial K_j = 0$ for $K_j \geq q^*_{j,\text{un}}(0)$. This and the fact that when $K_j = 0$, $\Pi_j(m) > \Pi_j(0)$ if and only if $p^*_w{}'(\mathcal{D}_w) > \gamma_m$ immediately imply that $\Pi_j(m) > \Pi_j(0)$ if and only if $p^*_w{}'(\mathcal{D}_w) > \gamma_m$ and $K_j < K^{\bar{C}}_{j,m}$ for some constant $K^{\bar{C}}_{j,m}$.

We now prove the above claim about $\partial(\Pi_j(m) - \Pi_j(0))/\partial K_j$ under each of the following three cases. Case I: Suppose that $K_j \leq q^*_{j,\text{un}}(m)$. Then, because $q^*_j(\ell) \leq K_j$ for $\ell \in \{m, 0\}$, utility j's equilibrium self-supply quantities

Electronic copy available at: https://ssrn.com/abstract=3257925

under the rule $\ell \in \{m, 0\}$ satisfy $q_j^*(0) = q_j^*(m) = K_j$ Note from (EC.39) and (EC.41) that unconstrained equilibrium self-supply quantities $q_{i,\text{un}}^*(0)$ and $q_{i,\text{un}}^*(m)$ do not depend on K_j for $i \neq j$. Thus, both $q_i^*(0)$ and $q_i^*(r)$ are independent of K_j for $i \neq j$. Based on these, we have

$$\frac{\partial\big(\Pi_j(m) - \Pi_j(0)\big)}{\partial K_j} = -\alpha\mathbb{E}\big[\Sigma_{i\neq j}^I \Delta_i + 2\Delta_j\big] - \alpha\mathbb{E}\big[(\Delta_j - D_j)^+\big] + \alpha\Sigma_{i\neq j}^I\big(q_i^*(0) - q_i^*(m)\big).$$

Plugging $\mathbb{E}\big[\Delta_1\big] = \mathbb{E}\big[\Delta_2\big] = \ldots = \mathbb{E}\big[\Delta_I\big]$ and observing that $q_i^*(0) - q_i^*(m) \leq q_{i,\text{un}}^*(0) - q_{i,\text{un}}^*(m)$, we have

$$\frac{\partial\big(\Pi_j(m) - \Pi_j(0)\big)}{\partial K_j} \leq \frac{\big((I - I^2)\alpha^2 - 4I\kappa_2^2 + (-2I^2 - 2I + 2)\alpha\kappa_2\big)\mathbb{E}[\Delta_j]}{\iota^2 + (I-2)\alpha\iota - (I-1)\alpha^2} < 0.$$

Case II: Suppose that $q_{j,\text{un}}^*(m) < K_j \leq q_{j,\text{un}}^*(0)$. Then, the equilibrium self-supply quantities are $q_j^*(m) = q_{j,\text{un}}^*(m)$ and $q_j^*(0) = K_j$. As a result, $\Pi_j(m)$ does not depend on K_j while $\Pi_j(0)$ is a function of K_j. Based on this, from the same arguments as in Case II of the proof for $\ell = r$, it follows that $\partial\big(\Pi_j(m) - \Pi_j(0)\big)/\partial K_j < 0$. Case III: Suppose that $q_{j,\text{un}}^*(0) < K_j$. Then, equilibrium self-supply quantities under $\ell = 0$ and $\ell = m$ are $q_{j,\text{un}}^*(0)$ and $q_{j,\text{un}}^*(m)$, respectively. Thus, because $q_i^*(0)$ and $q_i^*(m)$ are independent of K_j for $i = 1, 2, \ldots, I$, $\partial\big(\Pi_j(m) - \Pi_j(0)\big)/\partial K_j = 0$. Combining Cases I through III completes the proof of the aforementioned claim. □

Appendix G: Proof of Proposition 4

For brevity, throughout this proof, we will use the notation p_j to represent the utility j's retail electricity price. Let $\bar{\Pi}_j(p_j;\ell)$ represent the utility j's total expected profit from $t = 1$ to $t = T$ when the retail price is p_j and the net metering rule is $\ell \in \{r, m, 0\}$. Define

$$\alpha_t \doteq 2c_t(N-1)/\left((N-2)N\right). \tag{EC.42}$$

Using the similar arguments as in the proof of Proposition 1, period-t equilibrium market-clearing price is $p_{w,t}^*(\mathcal{D}_{w,t}) = \alpha_t\mathcal{D}_{w,t}$ for any t. Note that the utility j's period-t expected profits under the rules $\ell = r$, $\ell = m$ and $\ell = 0$ are respectively equal to (EC.10), (EC.11) and (EC.12) with the following modification: Every parameter in (EC.10), (EC.11) and (EC.12), except N, I, K_j and p_j, has an additional subscript index t to indicate the time period under consideration, and DRE generation under the rule $\ell \in \{r, m\}$ is as in Definition 3. Based on these, we have

$$\bar{\Pi}_j(p_j;r) = \sum_{t=1}^{T}\Big(\mathbb{E}\big[(\widehat{D}_{j,t} - \widehat{\Delta}_{j,r,t})p_j\big] + \mathbb{E}\Big[\Big(\widehat{\Delta}_{j,r,t} + K_j - \widehat{D}_{j,t}\Big)\alpha_t\big(\widehat{D}_{j,t} - K_j - \widehat{\Delta}_{j,r,t} + \nu_t\big)\Big] - K_j\tilde{c}_t\Big), \tag{EC.43}$$

$$\begin{aligned}\bar{\Pi}_j(p_j;m) = &\sum_{t=1}^{T}\Big(\mathbb{E}\Big[\Big((\widehat{\Delta}_{j,m,t} + K_j - \widehat{D}_{j,t}) - (\widehat{\Delta}_{j,m,t} - D_{j,t})^+\Big)\alpha_t\big(\widehat{D}_{j,t} - K_j - \widehat{\Delta}_{j,m,t} + \nu_t\big)\Big]\Big) \\ &+ \sum_{t=1}^{T}\big(p_j\mathbb{E}\big[D_{j,t}^{\text{reg}} + (D_{j,t} - \widehat{\Delta}_{j,m,t})^+\big] - K_j\tilde{c}_t\big),\end{aligned} \tag{EC.44}$$

and

$$\bar{\Pi}_j(p_j;0) = \sum_{t=1}^{T}\Big(\mathbb{E}\Big[\widehat{D}_{j,t}p_j - (\widehat{D}_{j,t} - K_j)\alpha_t(\widehat{D}_{j,t} - K_j + \widehat{\nu}_t)\Big] - K_j\tilde{c}_t\Big). \tag{EC.45}$$

LEMMA EC.6. *When $K_j = 0$, under the net-metering rule $\ell \in \{r, m\}$, for any given p_j, there exists a constant $\underline{\gamma}_\ell(p_j)$ such that $\bar{\Pi}_j(p_j;\ell) > \bar{\Pi}_j(p_j;0)$ if $\underline{\gamma}_\ell(p_j) < \min_{t=1,2,\ldots,T}\ p_{w,t}^{*}{}'(\mathcal{D}_{w,t})$.*

Electronic copy available at: https://ssrn.com/abstract=3257925

Proof of Lemma EC.6: We first prove the claim for $\ell = m$. By (EC.44) and (EC.45), it follows that when $K_j = 0$, we have

$$\begin{aligned}\bar{\Pi}_j(p_j;m) - \bar{\Pi}_j(p_j;0) = \Sigma_{t=1}^T \mathbb{E}\left[\widehat{\Delta}_{j,m,t}\left(\alpha_t(\Sigma_{i=1}^I \widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t} + \xi_t) - p_j\right)\right] + \Sigma_{t=1}^T \mathbb{E}\left[\widehat{D}_{j,t}\alpha_t \Sigma_{i=1}^I \widehat{\Delta}_{i,m,t}\right] \\ - \Sigma_{t=1}^T \mathbb{E}\left[(\widehat{\Delta}_{j,m,t} - D_{j,t})^+ \left(\alpha_t(\Sigma_{i=1}^I \widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t} + \xi_t) - p_j\right)\right].\end{aligned}$$

Let $\tilde{\alpha} \doteq \alpha_t$ for some period $t \in \{1, 2, \ldots, T\}$. Then, because

$$\begin{aligned}&\partial\big(\bar{\Pi}_j(p_j;m) - \bar{\Pi}_j(p_j;0)\big)/\partial\tilde{\alpha} \\ &= \mathbb{E}\left[\left(\widehat{\Delta}_{j,m,t} - (\widehat{\Delta}_{j,m,t} - D_{j,t})^+\right)\left(\Sigma_{i=1}^I \widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t} + \xi_t\right)\right] + \mathbb{E}\left[\widehat{D}_{j,t}\Sigma_{i=1}^I \widehat{\Delta}_{i,m,t}\right] > 0, \qquad \text{(EC.46)}\end{aligned}$$

it follows that

$$\begin{aligned}\bar{\Pi}_j(p_j;m) - \bar{\Pi}_j(p_j;0) > \vartheta(\underline{\alpha}) \doteq \Sigma_{t=1}^T \mathbb{E}\left[\widehat{\Delta}_{j,m,t}\left(\underline{\alpha}(\Sigma_{i=1}^I \widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t} + \xi_t) - p_j\right)\right] + \Sigma_{t=1}^T \mathbb{E}\left[\widehat{D}_{j,t}\underline{\alpha}\Sigma_{i=1}^I \widehat{\Delta}_{i,m,t}\right] \\ - \Sigma_{t=1}^T \mathbb{E}\left[(\widehat{\Delta}_{j,m,t} - D_{j,t})^+ \left(\underline{\alpha}(\Sigma_{i=1}^I \widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t} + \xi_t) - p_j\right)\right],\end{aligned}$$

where $\underline{\alpha} \doteq \min_{t=1,2,\ldots,T}\ \alpha_t$. Note that

$$\vartheta'(\underline{\alpha}) = \Sigma_{t=1}^T \mathbb{E}\left[\left(\widehat{\Delta}_{j,m,t} - (\widehat{\Delta}_{j,m,t} - D_{j,t})^+\right)\left(\Sigma_{i=1}^I \widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t} + \xi_t\right)\right] + \Sigma_{t=1}^T\ \mathbb{E}\left[\widehat{D}_{j,t}\Sigma_{i=1}^I \widehat{\Delta}_{i,m,t}\right] > 0$$

and $\lim_{\underline{\alpha}\to\widehat{\alpha}} \vartheta(\underline{\alpha}) > 0$ where $\widehat{\alpha} \doteq p_j \Sigma_{t=1}^T \mathbb{E}\big[\widehat{\Delta}_{j,m,t} - (\widehat{\Delta}_{j,m,t} - D_{j,t})^+\big]/\mathbb{E}\big[\Sigma_{t=1}^T\big(\widehat{\Delta}_{j,m,t} - (\widehat{\Delta}_{j,m,t} - D_{j,t})^+\big)\big(\Sigma_{i=1}^I\big(\widehat{D}_{i,t} - \widehat{\Delta}_{i,m,t}\big) + \xi_t\big)\big]$. These, (EC.46) and the fact that $p^*_{w,t}(\mathcal{D}_{w,t}) = \alpha_t \mathcal{D}_{w,t}$ imply the existence of a constant $\underline{\gamma}_m(p_j)$ such that $\bar{\Pi}_j(p_j;m) - \bar{\Pi}_j(p_j;0) > 0$ if $\underline{\gamma}_m(p_j) < \min_{t=1,2,\ldots,T}\ {p^*_{w,t}}'(\mathcal{D}_{w,t})$.

We now prove the claim for $\ell = r$. By (EC.43) and (EC.45), it follows that when $K_j = 0$, we have

$$\bar{\Pi}_j(p_j;r) - \bar{\Pi}_j(p_j;0) = \Sigma_{t=1}^T \mathbb{E}\left[-\widehat{\Delta}_{j,r,t}p_j + \widehat{D}_{j,t}\alpha_t\left(\Sigma_{i=1}^I \widehat{\Delta}_{i,r,t}\right)\right] + \Sigma_{t=1}^T \mathbb{E}\left[\widehat{\Delta}_{j,r,t}\alpha_t\left(\Sigma_{i=1}^I(\widehat{D}_{i,t} - \widehat{\Delta}_{i,j,r}) + \xi_t\right)\right].$$

Based on this, using ideas similar to the ones explained for $\ell = m$ above, one can show the claim for $\ell = r$. □

LEMMA EC.7. **(a)** *Consider any utility j with $K_j > 0$. Then, for a given retail price p_j of utility j, $\partial\left(\bar{\Pi}_j(p_j;\ell) - \bar{\Pi}_j(p_j;0)\right)/\partial K_j < 0$ for $\ell \in \{r,m\}$.* **(b)** *Consider utility j with $K_j = \max_{t=1,2,\ldots,T}\ \widehat{Q}_{j,t}$. Then, $\bar{\Pi}_j(p_j;\ell) - \bar{\Pi}_j(p_j;0) < 0$ for $\ell \in \{r,m\}$.*

Proof of Lemma EC.7: Part (a): Lemma EC.3 implies that when the utility j's retail electricity price is p_j, $\partial\left(\Pi_{j,t}(\ell) - \Pi_{j,t}(0)\right)/\partial K_j < 0$ for each t and $\ell \in \{r,m\}$ where $\Pi_{j,t}(\ell)$ is the utility j's expected profit in period t under the rule $\ell \in \{r,m,0\}$. Because $\bar{\Pi}_j(p_j;\ell) = \Sigma_{t=1}^T \Pi_{j,t}(\ell)$ for $\ell \in \{r,m\}$, the claim immediately follows. Part (b): Lemma EC.2 implies that when the retail electricity price is p_j and the utility j is self-reliant, $\Pi_{j,t}(\ell) - \Pi_{j,t}(0) < 0$ for each t and $\ell \in \{r,m\}$. Because $\bar{\Pi}_j(p_j;\ell) = \Sigma_{t=1}^T \Pi_{j,t}(\ell)$ for $\ell \in \{r,m\}$, the claim immediately follows. □

Combining Lemmas EC.6 and EC.7, we conclude that for any given retail price p_j and under any rule $\ell \in \{r,m\}$, there exists a unique $\kappa_\ell(p_j)$ such that $\bar{\Pi}_j(p_j;\ell) > \bar{\Pi}_j(p_j;0)$ if $K_j < \kappa_\ell(p_j)$ and $\underline{\gamma}_\ell(p_j) < \min_{t=1,2,\ldots,T}\ {p^*_{w,t}}'(\mathcal{D}_{w,t})$. Define

$$\breve{K}_\ell \doteq \min_{p_j \in [\underline{p},\bar{p}]} \kappa_\ell(p_j) \quad \text{and} \quad \breve{\gamma}_\ell \doteq \max_{p_j \in [\underline{p},\bar{p}]} \underline{\gamma}_\ell(p_j).$$

Then, $\bar{\Pi}_j(p_j;\ell) > \bar{\Pi}_j(p_j;0)$ for any $p_j \in [\underline{p},\bar{p}]$ if $K_j < \breve{K}_\ell$ and $\breve{\gamma}_\ell < \min_{t=1,2,\ldots,T}\ {p^*_{w,t}}'(\mathcal{D}_{w,t})$.

Let $p^*_\ell = \arg\max_{p_j \in [\underline{p},\bar{p}]}\ \bar{\Pi}_j(p_j;\ell)$ for $\ell \in \{r,m,0\}$. Because p^*_0 is feasible but not necessarily the optimal retail price under the rule $\ell = r$ or $\ell = m$, the result follows. □

Electronic copy available at: https://ssrn.com/abstract=3257925

Appendix H: Proof of Theorem 3

H.1. Proof of Part (a):

Recall Definition 3 for $i \neq j$ and the notation α_t from (EC.42). Suppose that the vector of adoption levels in all regions except region j is given as $\vec{\mu}_{-j,\ell} \doteq (\vec{\mu}_{1,\ell}, \vec{\mu}_{2,\ell}, \ldots, \vec{\mu}_{j-1,\ell}, \vec{\mu}_{j+1,\ell}, \ldots, \vec{\mu}_{I,\ell})$ where $\vec{\mu}_{i,\ell} \doteq (\mu_{i,\ell,1}(p_{u,i}), \mu_{i,\ell,2}(p_{u,i}), \ldots, \mu_{i,\ell,T}(p_{u,i}))$. For brevity, the notations $\mu_{i,\ell,t}(p_{u,i})$ and $\mu_{j,\ell}(p_{u,j})$ will be simplified to $\mu_{i,\ell,t}$ and $\mu_{j,\ell}$, respectively, throughout the proof. Let $\mu^*_{j,\ell}$ be the adoption parameter that maximizes utility j's total expected profit under the rule $\ell \in \{r, m\}$ given $\vec{\mu}_{-j,\ell}$ and $p_{u,j}$. Hereafter, the utility j's retail price will be denoted by p_j for brevity. In light of these, we now state and prove a lemma, which will be used in the remainder of the proof. In this proof, we will include the utility j's adoption parameter $\mu_{j,\ell}$ as the first argument of $\bar{\Pi}_j(\cdot;\cdot)$ to make the dependence explicit.

LEMMA EC.8. *Consider a given retail electricity price p_j for utility j. For any given vector of adoption parameters $\vec{\mu}_{-j,\ell}$, if the difference between DRE generations under rules $\ell \in \{r, m\}$ is not too large, i.e., $\max_{t=1,\ldots,T} \sqrt{\mathbb{E}\left[\left(\Sigma_{i\neq j}\widehat{\Delta}_{i,r,t}(p_j) - \widehat{\Delta}_{i,m,t}(p_j)\right)^2\right]} < \upsilon(p_j)$ for some constant $\upsilon(p_j)$, the utility j's total expected profit under the rule $\ell \in \{r, m\}$ with the adoption parameter μ satisfies the following:*

$$\bar{\Pi}_j(\mu; m, \vec{\mu}_{-j,m}, p_j) > \bar{\Pi}_j(\mu; r, \vec{\mu}_{-j,r}, p_j) \tag{EC.47}$$

for any adoption parameter $\mu > 0$ in the region j.

Based on this lemma, define

$$\tilde{\upsilon} \doteq \min_{p_j \in [\underline{p}, \bar{p}]} \upsilon(p_j).$$

Then, the condition $\max_{t=1,\ldots,T} \sqrt{\mathbb{E}\left[\left(\Sigma_{i\neq j}\widehat{\Delta}_{i,r,t}(\bar{p}) - \widehat{\Delta}_{i,m,t}(\underline{p})\right)^2\right]} < \tilde{\upsilon}$, which is equivalent to $\max_{t=1,\ldots,T} \sqrt{\mathbb{E}\left[\left(\Sigma_{i\neq j}\mu_{i,r,t}(\bar{p}) - \mu_{i,m,t}(\underline{p})\right)^2\right]} < \tilde{\upsilon}$ in the statement of Theorem 3, implies that Lemma EC.8 holds for any retail price of utility j.

Proof of Lemma EC.8: Because Lemma EC.8 evaluates two profit functions at the same adoption parameter for utility j, i.e., $\mu_{j,r} = \mu_{j,m} = \mu$, $\widehat{\Delta}_{j,r,t} = \widehat{\Delta}_{j,m,t}$ for all t. Define $\widehat{\Delta}_{j,t} \doteq \widehat{\Delta}_{j,r,t} = \widehat{\Delta}_{j,m,t}$ for all t and note that period-t net wholesale electricity demand under the rule ℓ is

$$\mathcal{D}^{\ell}_{w,t} = \sum_{i=1}^{I} \left(\widehat{D}_{i,t} - \widehat{\Delta}_{i,\ell,t} - K_i\right) + \xi_t. \tag{EC.48}$$

From (EC.43), we have

$$\bar{\Pi}_j(\mu; r, \vec{\mu}_{-j,r}, p_j) = \sum_{t=1}^{T} \mathbb{E}\left[(\widehat{D}_{j,t} - \widehat{\Delta}_{j,t})p_j - K_j\tilde{c}_t\right] + \sum_{t=1}^{T} \mathbb{E}\left[(\widehat{\Delta}_{j,t} + K_j - \widehat{D}_{j,t})p^*_{w,t}(\mathcal{D}^r_{w,t})\right], \tag{EC.49}$$

where $p^*_{w,t}(\mathcal{D}^r_{w,t})$ is the equilibrium wholesale price under the rule $\ell = r$. From (EC.44), we have

$$\begin{aligned}\bar{\Pi}_j(\mu; m, \vec{\mu}_{-j,m}, p_j) = &\sum_{t=1}^{T} \left(p_j \mathbb{E}\left[\widehat{D}_{j,t} - D_{j,t} + (D_{j,t} - \widehat{\Delta}_{j,t})^+\right] - K_j\tilde{c}_t - (\widehat{\Delta}_{j,t} - D_{j,t})^+ p^*_{w,t}(\mathcal{D}^m_{w,t})\right) \\ &+ \sum_{t=1}^{T} \mathbb{E}\left[(\widehat{\Delta}_{j,t} + K_j - \widehat{D}_{j,t})p^*_{w,t}(\mathcal{D}^m_{w,t})\right].\end{aligned} \tag{EC.50}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

Then, $\bar{\Pi}_j(\mu; m, \vec{\mu}_{-j,m}, p_j) - \bar{\Pi}_j(\mu; r, \vec{\mu}_{-j,r}, p_j) > 0$ if and only if

$$\sum_{t=1}^{T} \mathbb{E}\left[\left((D_{j,t} - \widehat{\Delta}_{j,t})^+ - (D_{j,t} - \widehat{\Delta}_{j,t})\right)p_j - (\widehat{\Delta}_{j,t} - D_{j,t})^+ p^*_{w,t}(\mathcal{D}^m_{w,t})\right] + \sum_{t=1}^{T} \mathbb{E}\left[\left(\widehat{\Delta}_{j,t} + K_j - \widehat{D}_{j,t}\right)\left(p^*_{w,t}(\mathcal{D}^m_{w,t}) - p^*_{w,t}(\mathcal{D}^r_{w,t})\right)\right] > 0. \tag{EC.51}$$

Because $p^*_{w,t}(\mathcal{D}^m_{w,t}) - p^*_{w,t}(\mathcal{D}^r_{w,t}) = \alpha_t \sum_{i=1}^{I}\left(\widehat{\Delta}_{i,r,t} - \widehat{\Delta}_{i,m,t}\right) = \alpha_t \sum_{i\neq j}^{I}\left(\widehat{\Delta}_{i,r,t} - \widehat{\Delta}_{i,m,t}\right)$ and

$$\mathbb{E}\left[\left((D_{j,t} - \widehat{\Delta}_{j,t})^+ - (D_{j,t} - \widehat{\Delta}_{j,t})\right)p_j - (\widehat{\Delta}_{j,t} - D_{j,t})^+ p^*_{w,t}(\mathcal{D}^m_{w,t})\right] = \mathbb{E}\left[(\widehat{\Delta}_{j,t} - D_{j,t})^+ (p_j - p^*_{w,t}(\mathcal{D}^m_{w,t}))\right],$$

(EC.51) is equivalent to

$$\sum_{t=1}^{T} \mathbb{E}\left[\left(\widehat{\Delta}_{j,t} - D_{j,t}\right)^+ (p_j - p^*_{w,t}(\mathcal{D}^m_{w,t}))\right] > \sum_{t=1}^{T} \mathbb{E}\left[(\widehat{\Delta}_{j,t} + K_j - \widehat{D}_{j,t})\alpha_t\Big(\sum_{i\neq j}\left(\widehat{\Delta}_{i,m,t} - \widehat{\Delta}_{i,r,t}\right)\Big)\right]. \tag{EC.52}$$

Then, because $\mathbb{E}\left[(\widehat{\Delta}_{j,t} + K_j - \widehat{D}_{j,t})\alpha_t\Big(\Sigma_{i\neq j}\left(\widehat{\Delta}_{i,m,t} - \widehat{\Delta}_{i,r,t}\right)\Big)\right] < \mathbb{E}\left[\left|(\widehat{\Delta}_{j,t} + K_j - \widehat{D}_{j,t})\alpha_t\right|\left|\left(\Sigma_{i\neq j}\left(\widehat{\Delta}_{i,m,t} - \widehat{\Delta}_{i,r,t}\right)\right)\right|\right]$, it follows from the Cauchy-Schwarz inequality that there exists a constant $\upsilon(p_j)$ such that $\max_{t=1,\ldots,T} \sqrt{\mathbb{E}\left[\left(\Sigma_{i\neq j}\widehat{\Delta}_{i,r,t} - \widehat{\Delta}_{i,m,t}\right)^2\right]} < \upsilon(p_j)$ implies (EC.52), which is equivalent to $\bar{\Pi}_j(\mu; m, \vec{\mu}_{-j,m}, p_j) - \bar{\Pi}_j(\mu; r, \vec{\mu}_{-j,r}, p_j) > 0$. $\square$

To ensure the uniqueness of an optimizer of $\bar{\Pi}_j(\mu; m, \vec{\mu}_{-j,m}, p_j)$ in Lemma EC.9, this proof focuses on a setting where $\bar{p} < \tilde{p}$ for some constant $\tilde{p}$, which implies strict concavity of $\bar{\Pi}_j(\mu; m, \vec{\mu}_{-j,m}, p_j)$ with respect to μ.

LEMMA EC.9. *Consider a given retail electricity price p_j for the utility j. The optimal adoption parameters for the utility j satisfy*

$$\mu^*_{j,m} > \mu^*_{j,r}. \tag{EC.53}$$

Proof of Lemma EC.9: We first identify the adoption parameter $\mu^*_{j,r}$ that maximizes the utility j's total expected profit under the rule $\ell = r$ given that the adoption parameter vector of utility $i \neq j$ under the rule $\ell = r$ is $\vec{\mu}_{i,r} \doteq (\mu_{i,r,1}, \mu_{i,r,2}, \ldots, \mu_{i,r,T})$. Define

$$\nu_{r,t} \doteq \mathbb{E}\left[\sum_{i\neq j}^{I}\left(\widehat{D}_{i,t} - K_i - \Delta_{i,t} - \mu_{i,r,t}\right) + \xi_t\right] \quad \text{and} \quad \nu_{m,t} \doteq \mathbb{E}\left[\sum_{i\neq j}^{I}\left(\widehat{D}_{i,t} - K_i - \Delta_{i,t} - \mu_{i,m,t}\right) + \xi_t\right]. \tag{EC.54}$$

Recall that as explained right before Theorem 3, the adoption parameter $\mu_{j,r}$ is only relevant for $t \geq \underline{t}$. Then, by (EC.49), the optimal adoption parameter $\mu^*_{j,r}$ is the unique μ that satisfies

$$\bar{\Pi}'_j(\mu; r, \vec{\mu}_{-j,r}, p_j) = -(T - \underline{t} + 1)p_j + \sum_{t=\underline{t}}^{T} \alpha_t \mathbb{E}\left[\sum_{i\neq j}\left(\widehat{D}_{i,t} - \widehat{\Delta}_{i,\ell,t} - K_i\right) + \widehat{D}_{j,t} - \Delta_{j,t} - \mu - K_j + \xi_t\right] + \sum_{t=\underline{t}}^{T}(-\alpha_t)\mathbb{E}\left[\Delta_{j,t} + \mu + K_j - \widehat{D}_{j,t}\right] = 0.$$

which implies that

$$\mu^*_{j,r} = \frac{-(T - \underline{t} + 1)p_j + \sum_{t=\underline{t}}^{T}\alpha_t\left(\nu_{r,t} + 2\mathbb{E}[\widehat{D}_{j,t} - \Delta_{j,t} - K_j]\right)}{2\sum_{t=\underline{t}}^{T}\alpha_t}. \tag{EC.55}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

Define the function g as

$$g(\mu_{j,m}) \doteq \sum_{t=\underline{t}}^{T} \mathbb{E}\left[\left(\Delta_{j,t}+\mu_{j,m}-D_{j,t}\right)^{+}\left(p_j-\alpha_t\left(\nu_{m,t}+\widehat{D}_{j,t}-\Delta_{j,t}-\mu_{j,m}-K_j\right)\right)\right].$$

Because $\mathbb{E}\left[p_j\mathbb{I}(D_{j,t}<\Delta_{j,t}+\mu)\right]>\mathbb{E}\left[p_{w,t}(\mathcal{D}_{w,t}^{m})\mathbb{I}(D_{j,t}<\Delta_{j,t}+\mu)\right]$ and $\mathbb{E}\left[(\Delta_{j,t}+\mu-D_{j,t})\mathbb{I}(D_{j,t}<\Delta_{j,t}+\mu)\right]>0$,

$$g'(\mu_{j,m}) = \sum_{t=\underline{t}}^{T}\int_0^{Q_j}\int_0^{y+\mu_{j,m}}\left\{\left(p_j-\alpha_t(\nu_{m,t}+\beta x-y-\mu_{j,m}-K_j)\right)+\alpha_t(y+\mu_{j,m}-x)\right\}dG_{j,t}(x)dF_{j,t}(y)>0. \tag{EC.56}$$

By (EC.49) and (EC.50), $\bar{\Pi}_j(\mu;m,\vec{\mu}_{-j,m},p_j)=\bar{\Pi}_j(\mu;r,\vec{\mu}_{-j,m},p_j)+g(\mu)$. Combining this, (EC.56) and (EC.50), we have

$$\bar{\Pi}_j'(\mu;m,\vec{\mu}_{-j,m},p_j)=\bar{\Pi}_j'(\mu;r,\vec{\mu}_{-j,m},p_j)+g'(\mu)>\bar{\Pi}_j'(\mu;r,\vec{\mu}_{-j,m},p_j). \tag{EC.57}$$

Note that $\bar{\Pi}_j(\mu;m,\vec{\mu}_{-j,m},p_j)$ is strictly concave in μ when $\bar{p}<\tilde{p}$ for a constant $\tilde{p}$, and $\bar{\Pi}_j(\mu;r,\vec{\mu}_{-j,r},p_j)$ is strictly concave in μ. Then, it follows from (EC.57) that if $\vec{\mu}_{i,r}=\vec{\mu}_{i,m}$ for $i\neq j$, which suggests $\nu_{r,t}=\nu_{m,t}$, the optimal adoption parameters $\mu_{j,r}^*$ and $\mu_{j,m}^*$ for the utility j satisfy

$$\mu_{j,r}^*\Big|_{\vec{\mu}_{i,r}=\vec{\mu}_{i,m},i\neq j}<\mu_{j,m}^*\Big|_{\vec{\mu}_{i,r}=\vec{\mu}_{i,m},i\neq j}. \tag{EC.58}$$

From (EC.54) and because $\mu_{i,r,t}\geq\mu_{i,m,t}$ for $i\neq j$ and all t as in Definition 3, we have $\nu_{r,t}\leq\nu_{m,t}$. As a result, by (EC.55),

$$\begin{aligned}\mu_{j,r}^*\Big|_{\vec{\mu}_{i,r}=\vec{\mu}_{i,m},i\neq j}&=\frac{-(T-\underline{t}+1)p_j+\sum_{t=\underline{t}}^{T}\alpha_t\left(\nu_{m,t}+2(\widehat{D}_{j,t}-\Delta_{j,t}-K_j)\right)}{2\sum_{t=\underline{t}}^{T}\alpha_t}\\ \geq\mu_{j,r}^*\Big|_{\vec{\mu}_{i,r}>\vec{\mu}_{i,m},i\neq j}&=\frac{-(T-\underline{t}+1)p_j+\sum_{t=\underline{t}}^{T}\alpha_t\left(\nu_{r,t}+2(\widehat{D}_{j,t}-\Delta_{j,t}-K_j)\right)}{2\sum_{t=\underline{t}}^{T}\alpha_t}.\end{aligned} \tag{EC.59}$$

Combining (EC.58) and (EC.59), we get

$$\mu_{j,r}^*\Big|_{\vec{\mu}_{i,r}>\vec{\mu}_{i,m},i\neq j}\leq\mu_{j,r}^*\Big|_{\vec{\mu}_{i,r}=\vec{\mu}_{i,m},i\neq j}<\mu_{j,m}^*. \tag{EC.60}$$

This completes the proof of (EC.53). □

Let $p_{j,\ell}^*(\mu;\vec{\mu}_{-j,\ell})$ be the retail electricity price that maximizes the total expected profit for utility j under the rule $\ell\in\{r,m\}$ when the adoption parameter in utility j's service area is μ and the adoption vector of all other regions is $\vec{\mu}_{-j,\ell}$:

$$p_{j,\ell}^*(\mu;\vec{\mu}_{-j,\ell})\doteq\arg\max_{p_j\in[\underline{p},\bar{p}]}\bar{\Pi}_j(\mu;\ell,\vec{\mu}_{-j,\ell},p_j).$$

Using the facts that $\bar{\Pi}_j(\mu;m,\vec{\mu}_{-j,m},p_j)$ is strictly concave with respect to μ under the considered parameter set and $\mu_{j,\ell}'(\cdot)>0$ by the setting explained right before Theorem 3, it follows by (EC.47) and (EC.53) that when the utility j sets its retail price to maximize its total expected profit under each rule $\ell\in\{r,m\}$, the rule $\ell=r$ results in a strictly larger optimal total expected profit for utility j than the rule $\ell=m$ if

Electronic copy available at: https://ssrn.com/abstract=3257925

(i) $\bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j) < \bar{\Pi}_j(\mu^*_{j,r}; r, \vec{\mu}_{-j,r}, p_j)$ for any given retail price $p_j \in [\underline{p}, \bar{p}]$,

(ii) $\mu_{j,m}(\bar{p}) < \widetilde{\mu}$ for some constant $\widetilde{\mu}$,

(iii) $\mu_{j,r}(\underline{p}) > \underline{\mu}$ and $\mu_{j,r}(\bar{p}) < \bar{\mu}$ where $\underline{\mu}$ and $\bar{\mu}$ are constants that satisfy

$$\bar{\Pi}_j(\mu_{j,m}(\bar{p}); m, \vec{\mu}_{-j,m}, p^*_{j,m}(\mu_{j,m}(p_j); \vec{\mu}_{-j,m})) = \bar{\Pi}_j(\underline{\mu}; r, \vec{\mu}_{-j,r}, p^*_{j,r}(\mu^*_{j,r}; \vec{\mu}_{-j,r})) = \bar{\Pi}_j(\bar{\mu}; r, \vec{\mu}_{-j,r}, p^*_{j,r}(\mu^*_{j,r}; \vec{\mu}_{-j,r})).$$

The remainder of the proof will verify that (12) guarantees the conditions (i) through (iii) above, and provides more explanation about these conditions.

Condition (i): We now show that $\min_{t=1,\ldots,T} \ \alpha_t > \bar{\alpha}$, which is equivalent to the last condition in (12), is a sufficient condition for the condition (i) above, that is, $\bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j) < \bar{\Pi}_j(\mu^*_{j,r}; r, \vec{\mu}_{-j,r}, p_j)$ for any retail price $p_j \in [\underline{p}, \bar{p}]$. Recall that $\widehat{D}_{j,t} = A_{j,t} - B_{j,t}p_j + \omega_{j,t}$, and hence $\widehat{D}_{j,t}$ is dependent on the retail price p_j.

Under the rule $\ell = m$, when utility j's adoption parameter is zero and utility i's adoption parameter vector is $\vec{\mu}_{i,m}$ for $i \neq j$, we deduce from (EC.11) that utility j's total expected profit at any given p_j is

$$\begin{aligned}\bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j) = &\sum_{t=1}^{T} \mathbb{E}\big[(\widehat{D}_{j,t} - \Delta_{j,t})p_j - K_j \tilde{c}_t\big] \\ &+ \sum_{t=1}^{T} \mathbb{E}\left[(\Delta_{j,t} - D_{j,t})^+ \left(p_j - \alpha_t(\nu_{m,t} + \widehat{D}_{j,t} - \Delta_{j,t} - K_j)\right)\right] \\ &+ \sum_{t=1}^{T} \mathbb{E}\left[\left(\Delta_{j,t} + K_j - \widehat{D}_{j,t}\right) \alpha_t(\nu_{m,t} + \widehat{D}_{j,t} - \Delta_{j,t} - K_j)\right] \end{aligned} \tag{EC.61}$$

where $\nu_{m,t}$ is as in (EC.54). Moreover, by (EC.20) and the setting described right before Theorem 3, we have

$$\begin{aligned}\bar{\Pi}_j(\mu^*_{j,r}; r, \vec{\mu}_{-j,r}, p_j) = &\sum_{t=1}^{\underline{t}-1} \mathbb{E}\left[(\widehat{D}_{j,t} - \Delta_{j,t})p_j\right] + \sum_{t=\underline{t}}^{T} \mathbb{E}\left[(\widehat{D}_{j,t} - \Delta_{j,t} - \mu^*_{r,j})p_j\right] - \sum_{t=1}^{T} K_j \tilde{c}_t \\ &+ \sum_{t=1}^{\underline{t}-1} \mathbb{E}\left[(\Delta_{j,t} + K_j - \widehat{D}_{j,t})\alpha_t(\nu_{r,t} + \widehat{D}_{j,t} - \Delta_{j,t} - K_j)\right] \\ &+ \sum_{t=\underline{t}}^{T} \mathbb{E}\left[(\Delta_{j,t} + \mu^*_{j,r} + K_j - \widehat{D}_{j,t})\alpha_t(\nu_{r,t} + \widehat{D}_{j,t} - \Delta_{j,t} - \mu^*_{j,r} - K_j)\right], \end{aligned} \tag{EC.62}$$

where $\mu^*_{j,r}$ is as defined in (EC.55) for a given retail price p_j. Recall the definition of $\nu_{r,t}$ and $\nu_{m,t}$ from (EC.54). Define

$$d_{j,t} \doteq \nu_{r,t} - \nu_{m,t} = \sum_{i \neq j} \left(\mu_{i,m,t} - \mu_{i,r,t}\right) \leq 0 \quad \text{and} \quad \theta_{j,t} \doteq \widehat{D}_{j,t} - \Delta_{j,t} - K_j. \tag{EC.63}$$

Then, by (EC.61) and (EC.62),

$$\begin{aligned}\bar{\Pi}_j(\mu^*_{j,r}; r, \vec{\mu}_{-j,r}, p_j) - \bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j) = &-\sum_{t=\underline{t}}^{T} p_j \mu^*_{j,r} - \sum_{t=1}^{T} \mathbb{E}\Big[(\Delta_{j,t} - D_{j,t})^+ \big(p_j - \alpha_t(\nu_{m,t} + \theta_{j,t})\big)\Big] \\ &+ \sum_{t=1}^{T} \mathbb{E}\left[\alpha_t \theta_{j,t} \Big(\sum_{i \neq j} \mu_{i,r,t} - \mu_{i,m,t}\Big)\right] + \sum_{t=\underline{t}}^{T} \alpha_t \mu^*_{j,r} \mathbb{E}\left[2\theta_{j,t} + \nu_{t,r} - \mu^*_{j,r}\right] \\ = &-\sum_{t=\underline{t}}^{T} p_j \mu^*_{j,r} - \sum_{t=1}^{T} \mathbb{E}\left[(\Delta_{j,t} - D_{j,t})^+ (p_j - \alpha_t(\nu_{m,t} + \theta_{j,t}))\right] \end{aligned}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

$$+\mu_{j,r}^* \sum_{t=\underline{t}}^{T} \alpha_t \mathbb{E}\left[\nu_{m,t} + d_{j,t} - \mu_{j,r}^*\right] + 2\mu_{j,r}^* \sum_{t=\underline{t}}^{T} \alpha_t \mathbb{E}\left[\theta_{j,t}\right] - \sum_{t=1}^{T} \alpha_t \mathbb{E}\left[d_{j,t}\theta_{j,t}\right]. \tag{EC.64}$$

The equation (EC.64) follows from the definition of $d_{j,t}$ in (EC.63) and the fact that $\nu_{r,t} = \nu_{m,t} + d_{j,t}$. Note from (EC.55) and (EC.63) that

$$\mu_{j,r}^* = \frac{-(T-\underline{t}+1)p_j}{2\sum_{t=\underline{t}}^{T}\alpha_t} + \frac{\sum_{t=\underline{t}}^{T}\alpha_t\nu_{r,t}}{2\sum_{t=\underline{t}}^{T}\alpha_t} + \frac{2\sum_{t=\underline{t}}^{T}\alpha_t\mathbb{E}\left[\theta_{j,t}\right]}{2\sum_{t=\underline{t}}^{T}\alpha_t}.$$

Replacing this expression in place of $\mu_{j,r}^*$ in (EC.64) and rearranging terms, we get

$$\begin{aligned}&\bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_j) - \bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j)\\ &= \left(\mu_{j,r}^*\right)^2 \sum_{t=\underline{t}}^{T}\alpha_t - \sum_{t=1}^{T}\alpha_t d_{j,t}\mathbb{E}\left[\theta_{j,t}\right] - \sum_{t=1}^{T}\mathbb{E}\left[(\Delta_{j,t} - D_{j,t})^+(p_j - \alpha_t(\nu_{m,t} + \theta_{j,t}))\right].\end{aligned} \tag{EC.65}$$

Recall the definition in (EC.42) and the fact that generators' cost function parameter $c_t \in (\underline{c}_t, \bar{c}_t)$. Define $\underline{b}_t \doteq 2\underline{c}_t(N-1)/[N(N-2)]$, $\bar{b}_t \doteq 2\bar{c}_t(N-1)/[N(N-2)]$ and $\vec{\alpha} \doteq (\alpha_1, \alpha_2, \ldots, \alpha_T)$. Then, from (EC.65),

$$\begin{aligned}&\bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_j) - \bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j)\\ &> \zeta(\vec{\alpha}) \doteq \sum_{t=\underline{t}}^{T}\alpha_t \min\left\{\left(\frac{-(T-\underline{t}+1)p_j}{2\sum_{t=\underline{t}}^{T}\underline{b}_t} + \frac{\min_{t=\underline{t},\ldots,T}\{\nu_{r,t} + 2\mathbb{E}[\theta_{j,t}]\}}{2}\right)^2, \left(\frac{-(T-\underline{t}+1)p_j}{2\sum_{t=\underline{t}}^{T}\bar{b}_t} + \frac{\min_{t=\underline{t},\ldots,T}\{\nu_{r,t} + 2\mathbb{E}[\theta_{j,t}]\}}{2}\right)^2\right\}\\ &\quad - \sum_{t=1}^{T}\alpha_t d_{j,t}\mathbb{E}\left[\theta_{j,t}\right] - \sum_{t=1}^{T}\mathbb{E}\left[(\Delta_{j,t} - D_{j,t})^+(p_j - \alpha_t(\nu_{m,t} + \theta_{j,t}))\right].\end{aligned} \tag{EC.66}$$

Because $d_{j,t} \le 0$ and $\mathbb{E}[\theta_{j,t}] \ge 0$ as $K_j < \underline{\kappa}_j$, by (EC.42) and (EC.66), it follows that $\partial\zeta(\vec{\alpha})/\partial c_t > 0$ for all t. Thus, by (EC.42) and (EC.66), there exists a constant $s(p_j)$ such that if $\min_{t=1,\ldots,T}\ \alpha_t > s(p_j)$, $\bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_j) - \bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_j) > 0$ for the retail price p_j. Define $\bar{\alpha} \doteq \max_{p_j\in[\underline{p},\bar{p}]}\ s(p_j)$. Then, because $\alpha_t = p_{w,t}^{*}{}'(\mathcal{D}_{w,t})$, $\min_{t=1,\ldots,T}\ \alpha_t > \bar{\alpha}$ is equivalent to the last condition in (12). Note that condition (i) implies that

$$\bar{\Pi}_j(0; m, \vec{\mu}_{-j,m}, p_{j,m}^*(\mu_{j,m}; \vec{\mu}_{-j,m})) < \bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_{j,m}^*(\mu_{j,m}; \vec{\mu}_{-j,m})) < \bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_{j,r}^*(\mu_{j,r}^*; \vec{\mu}_{-j,r})), \tag{EC.67}$$

which guarantees the existence of constants that will be defined below.

Condition (ii): The first condition in (12) is the same as the condition (ii). Let us provide more explanation about this condition. Let $\widehat{\mu}_{j,m}(p_j)$ be the smallest adoption level that satisfies the following under the rule $\ell = m$ at the retail price p_j:

$$\bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_j) = \bar{\Pi}_j(\widehat{\mu}_{j,m}(p_j); m, \vec{\mu}_{-j,m}, p_j).$$

The existence of $\widehat{\mu}_{m,j}(p_j)$ follows from Lemmas EC.8 and EC.9 and the condition (i). Define

$$\widetilde{\mu} \doteq \min_{p_j\in[\underline{p},\bar{p}]}\ \widehat{\mu}_{m,j}(p_j). \tag{EC.68}$$

Thus, the first condition in (12) implies that when $\mu_{j,m}(\bar{p}) < \tilde{\mu}$,

$$\bar{\Pi}_j(\mu_{j,r}^*; r, \vec{\mu}_{-j,r}, p_1) > \bar{\Pi}_j(\mu_{j,m}; m, \vec{\mu}_{-j,m}, p_2) \quad \text{for any} \quad p_1, p_2 \in [\underline{p}, \bar{p}].$$

Condition (iii): The second and third conditions in (12) are equivalent to condition (iii). The existence of $\underline{\mu}$ and $\bar{\mu}$ follows from (EC.67) and the fact that $\mu_{j,m}(\bar{p}) < \tilde{\mu}$ implies $\mu_{j,m}(p_j) < \tilde{\mu}$ for all p_j.

Electronic copy available at: https://ssrn.com/abstract=3257925

H.2. Proof of Part (b):

Suppose the first and third conditions in (13) hold. From the proof of part (a), these conditions imply the existence of a constant $\check{\mu}_{r,j}(p_j)$ such that $\check{\mu}_{r,j}(p_j)$ is the largest adoption level that satisfies the following under the rule $\ell = r$ at the retail price p_j:

$$\bar{\Pi}_j(\check{\mu}_{j,r}(p_j); r, \vec{\mu}_{-j,r}, p_j) = \bar{\Pi}_j(\mu_{j,m}(p_j); m, \vec{\mu}_{-j,m}, p_j).$$

Because $\bar{\Pi}_j(\mu; r, \vec{\mu}_{-j,r}, p_j)$ is concave with respect to μ, by definition, $\check{\mu}_{j,r}(p_j) > \mu^*_{j,r}$ when the utility j's retail electricity price is p_j. This implies that

$$\bar{\Pi}_j(\mu; r, \vec{\mu}_{-j,r}, p_j) < \bar{\Pi}_j(\mu_{j,m}; m, \vec{\mu}_{-j,m}, p_j) \quad \text{for} \quad \mu > \check{\mu}_{j,r}(p_j).$$

Define

$$\bar{\bar{\mu}} \doteq \max_{p_j \in [\underline{p}, \bar{p}]} \check{\mu}_{j,r}(p_j).$$

Then, $\mu_{j,r}(\underline{p}) > \bar{\bar{\mu}}$ implies that $\mu_{r,j}(p_j) > \bar{\bar{\mu}}$ for all p_j, and thus when (13) holds,

$$\bar{\Pi}_j(\mu_{j,r}; r, \vec{\mu}_{-j,r}, p_j) < \bar{\Pi}_j(\mu_{j,m}; m, \vec{\mu}_{-j,m}, p_j) \quad \text{for} \quad p_j \in [\underline{p}, \bar{p}].$$

Based on this, because $p^*_{j,r}(\mu_{j,r}; \vec{\mu}_{-j,r}) \in [\underline{p}, \bar{p}]$, when (13) holds, we have

$$\bar{\Pi}_j(\mu_{j,r}; r, \vec{\mu}_{-j,r}, p^*_{j,r}(\mu_{j,r}; \vec{\mu}_{-j,r})) < \bar{\Pi}_j(\mu_{j,m}; m, \vec{\mu}_{-j,m}, p^*_{j,r}(\mu_{j,r}; \vec{\mu}_{-j,r})). \tag{EC.69}$$

Note also that $\bar{\Pi}_j(\mu_{j,m}; m, \vec{\mu}_{-j,m}, p^*_{j,r}(\mu_{j,r}; \vec{\mu}_{-j,r})) \leq \bar{\Pi}_j(\mu_{j,m}; m, \vec{\mu}_{-j,m}, p^*_{j,m}(\mu_{j,m}; \vec{\mu}_{-j,m}))$ because $p^*_{j,r}(\mu_{j,r}; \vec{\mu}_{-j,r})$ is a feasible but not necessarily an optimal retail price for utility j under the rule $\ell = m$. Combining this inequality and (EC.69) completes the proof of part (b). □

Appendix I: Proof of Proposition EC.1

When utility i obtains $q_{i,t}$ units of electricity from its existing resources and its retail price is $p_{u,i}$ for $i = 1, 2, \ldots, I$ and $t = 1, \ldots, T$, the social welfare under the rule $\ell \in \{r, m\}$ is (EC.1), and period-t net wholesale market demand under the rule $\ell \in \{r, m\}$ is $\mathcal{D}^{\ell}_{w,t} = \sum_{i=1}^{I} \widehat{D}_{i,t} - \widehat{\Delta}_{i,\ell,t}(p_{u,i}) - q_{i,t} + \xi_t$ whereas period-t net wholesale market demand in the absence of DRE is $\mathcal{D}^{0}_{w,t} = \sum_{i=1}^{I} \widehat{D}_{i,t} - q_{i,t} + \xi_t$. Among different elements of social welfare (EC.1), utility i's period-t expected profit under the rule ℓ (with the obtained quantity $q_{i,t}$ and the retail price $p_{u,i}$) is

$$\begin{aligned}\Pi_{i,t}(\ell, q_{i,t}; \vec{p}_u) =& \mathbb{E}\big[\big(\widehat{D}_{i,t} - D_{i,t} + (D_{i,t} - \widehat{\Delta}_{i,\ell,t}(p_{u,i}))^+\big)p_{u,i}\big] - \mathbb{E}\big[\big(\widehat{\Delta}_{i,\ell,t}(p_{u,i}) - D_{i,t}\big)^+ p_{\ell,t}\big] \\ &- \mathbb{E}\big[\mathbb{I}\{\widehat{D}_{i,t} > \widehat{\Delta}_{i,\ell,t}(p_{u,i}) + q_{i,t}\}\big(\big(\widehat{D}_{i,t} - \widehat{\Delta}_{i,\ell,t}(p_{u,i}) - q_{i,t}\big)p^*_{w,t} + \bar{C}_t(q_{i,t})\big)\big] \\ &+ \mathbb{E}\big[\mathbb{I}\{\widehat{D}_{i,t} \leq q_{i,t} + \widehat{\Delta}_{i,\ell,t}(p_{u,i})\}\big(\big(\widehat{\Delta}_{i,\ell,t}(p_{u,i}) + q_{i,t} - \widehat{D}_{i,t}\big)p^*_{w,t} - \bar{C}_t(q_{i,t})\big)\big],\end{aligned} \tag{EC.70}$$

where $p_{\ell,t} \doteq p_{u,i}$ if $\ell = r$ and $p_{\ell,t} \doteq p^*_{w,t}(\mathcal{D}^m_{w,t})$ if $\ell = m$ where $p^*_{w,t}(\mathcal{D}^m_{w,t})$ is period-t wholesale price under $\ell = m$. The interpretation of each expectation term in (EC.70) is the same as the corresponding term in (10) for period t. The structural properties of the cost function $\bar{C}_t(\cdot)$ implies that regardless of the retail price $p_{u,i}$ and the rule $\ell \in \{r, m, 0\}$,

Electronic copy available at: https://ssrn.com/abstract=3257925

the utility i optimally obtains K_i units of electricity from existing resources. Given other utilities' retail prices $\vec{p}_{u,-j}$, the optimal retail price for utility j is the one that maximizes its total expected profit, i.e.,

$$\breve{p}_{u,j}(\ell) = \underset{p_{u,j}\in[\underline{p},\bar{p}]}{\arg\max}\ \bar{\Pi}_j(p_{u,j};\ell,\vec{p}_{u,-j}) \doteq \sum_{t=1}^{T} \Pi_{j,t}(\ell, K_j; \vec{p}_u), \tag{EC.71}$$

where $\Pi_{j,t}(\cdot,\cdot;\cdot)$ is as defined in (EC.70). Then, in equilibrium, for any i, utility i's price $p^*_{u,i}(\ell)$ satisfies (EC.71) given other utilities' prices $(p^*_{u,1}(\ell),\ldots,p^*_{u,i-1}(\ell),p^*_{u,i+1}(\ell),\ldots,p^*_{u,I}(\ell))$.

In the remainder of our proof, we will explicitly express the dependence of $p^*_{w,t}$ and $\widehat{D}_{i,t}$ on the rule $\ell\in\{r,m,0\}$ by including ℓ as an argument of $p^*_{w,t}$ and $\widehat{D}_{i,t}$. Then, period-t total demand of utility i's end-customers is

$$\widehat{D}_{i,t}(\ell) = A_{i,t} - B_{i,t}p^*_{u,i}(\ell) + \omega_{i,t}, \quad i=1,\ldots,I \text{ and } t=1,\ldots,T, \tag{EC.72}$$

where $A_{i,t}$, $B_{i,t}$ and $\omega_{i,t}$ are as defined in Section 5.4. Moreover, defining $\vec{p}^*_u(\ell) \doteq (p^*_{u,1}(\ell),\ldots,p^*_{u,I}(\ell))$, $p^*_{w,t}(\ell)$ represents the period-t equilibrium wholesale price under the rule ℓ (with period-t net wholesale demand $\mathcal{D}^{\ell}_{w,t}(\vec{p}^*_u(\ell))$).

Define $h_m \doteq \max_{t=1,\ldots,T}|1-\alpha_t(\beta_t-1)\bar{k}|$ where $\bar{k}$ is the upper bound on $\mu'_{j,m,t}(\cdot)$. Then, there exists a constant $U_{\max}$ such that

$$\tilde{p} \doteq \min\left\{\frac{U_{\max}}{h_m}, \frac{\sum_{t=1}^{T}\sum_{i=1}^{I}\min\left\{\mathbb{E}\big[\widehat{\Delta}_{i,m,t}(\underline{p})\big],\mathbb{E}\big[\widehat{\Delta}_{i,r,t}(\underline{p})-\widehat{\Delta}_{i,m,t}(\bar{p})\big]\right\}}{\sum_{t=1}^{T}\sum_{i=1}^{I}B_{i,t}}\right\},$$

and when $\bar{p}<\tilde{p}$, $\bar{\Pi}_j(p_{u,j};m,\vec{p}_{u,-j})$ is strictly concave with respect to $p_{u,j}$ for any $\vec{p}_{u,-j}$.

Denote by $E(\ell)$, the total expected emissions under the rule $\ell\in\{r,m,0\}$ in equilibrium. We first prove the following lemma, the result of which will be used in the remainder of the proof.

LEMMA EC.10. *When $\bar{p}<\tilde{p}$, in equilibrium, expected total emissions under rules $\ell\in\{r,m,0\}$ satisfy the following:*

$$\textit{(i) } E(0)-E(\ell)>0, \quad \ell\in\{r,m\} \quad \textit{and} \quad \textit{(ii) } E(m)-E(r)>0. \tag{EC.73}$$

Proof of Lemma EC.10: In equilibrium, wholesale supply and wholesale demand must match in each period t under the rule $\ell\in\{r,m\}$, that is, $S_t(p^*_{w,t}(\ell))N = \sum_{i=1}^{I}\big(\widehat{D}_{i,t}(\ell)-\widehat{\Delta}_{i,\ell,t}(p^*_{u,i}(\ell))-K_i\big)+\xi_t$. Thus, by (EC.72), in equilibrium, expected total emission under the rule $\ell\in\{r,m\}$ is

$$\begin{aligned}E(\ell) &= \sum_{t=1}^{T}\mathbb{E}\left[\theta_g S_t(p^*_{w,t}(\ell))N + \theta_e\sum_{i=1}^{I}K_i\right]\\ &= \sum_{t=1}^{T}\mathbb{E}\left[\theta_g\Big(\sum_{i=1}^{I}\big(A_{i,t}-B_{i,t}p^*_{u,i}(\ell)+\omega_{i,t}-\widehat{\Delta}_{i,\ell,t}(p^*_{u,i}(\ell))-K_i\big)+\xi_t\Big)+\theta_e\sum_{i=1}^{I}K_i\right].\end{aligned}$$

Moreover, in equilibrium, expected total emission in the absence of DRE is

$$E(0) = \sum_{t=1}^{T}\mathbb{E}\left[\theta_g\Big(\sum_{i=1}^{I}\big(A_{i,t}-B_{i,t}p^*_{u,i}(0)+\omega_{i,t}-K_i\big)+\xi_t\Big)+\theta_e\sum_{i=1}^{I}K_i\right].$$

Then, in equilibrium, the difference between the expected total emission in the absence of DRE and the expected total emission in the presence of DRE under the rule $\ell\in\{r,m\}$ is

$$E(0)-E(\ell) = \theta_g\sum_{t=1}^{T}\Big(\sum_{i=1}^{I}\mathbb{E}\big[\widehat{\Delta}_{i,\ell,t}(p^*_{u,i}(\ell))\big]-\sum_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(0)-p^*_{u,i}(\ell)\big)\Big). \tag{EC.74}$$

Electronic copy available at: https://ssrn.com/abstract=3257925

Similarly, we have

$$E(m)-E(r)=\theta_g\sum_{t=1}^{T}\Big(\sum_{i=1}^{I}\mathbb{E}\big[\widehat{\Delta}_{i,r,t}(p^*_{u,i}(r))-\widehat{\Delta}_{i,m,t}(p^*_{u,i}(m))\big]-\sum_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(m)-p^*_{u,i}(r)\big)\Big). \tag{EC.75}$$

Let us first prove (EC.73)-(i) by using (EC.74). There could be two cases related to the sign of $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(0)-p^*_{u,i}(\ell)\big)$. *Case 1*: Suppose that $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(0)-p^*_{u,i}(\ell)\big)\le 0$. Then, by (EC.74), (EC.73)-(i) immediately follows. *Case 2*: Suppose that $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(0)-p^*_{u,i}(\ell)\big)>0$. Then, because $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(0)-p^*_{u,i}(\ell)\big)\le\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\bar{p}$, $\bar{p}<\tilde{p}$ implies that (EC.74) is strictly positive. From this, (EC.73)-(i) follows.

Let us now prove (EC.73)-(ii). Recall from Definition 3 that $\mathbb{E}\left[\widehat{\Delta}_{i,r,t}(p_1)-\widehat{\Delta}_{i,m,t}(p_2)\right]>0$ for any two prices $p_1,\,p_2\in[\underline{p},\bar{p}]$. There could be two cases related to the sign of $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(m)-p^*_{u,i}(r)\big)$. *Case 1*: Suppose that $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(m)-p^*_{u,i}(r)\big)\le 0$. Then, by (EC.75), (EC.73)-(ii) immediately follows. *Case 2*: Suppose that $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(m)-p^*_{u,i}(r)\big)>0$. Then, because $\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\big(p^*_{u,i}(m)-p^*_{u,i}(r)\big)\le\Sigma_{t=1}^{T}\Sigma_{i=1}^{I}B_{i,t}\bar{p}$, $\bar{p}<\tilde{p}$ implies that (EC.75) is strictly positive. From this, (EC.73)-(ii) follows. $\square$

Based on (EC.73), we now prove the claims in parts (a) and (b). Recall that $\vec{p}^*_u(\ell)\doteq(p^*_{u,1}(\ell),\ldots,p^*_{u,I}(\ell))$. Denote by $\tilde{q}_{i,\ell,t}$, utility i's equilibrium procurement quantity (from an independent power producer) under the rule $\ell\in\{r,m,0\}$ in period t and define

$$\begin{aligned}
&\widehat{\pi}(\ell)\doteq\sum_{t=1}^{T}\mathbb{E}\Big[S_t(p^*_{w,t}(\ell))p^*_{w,t}(\ell)-c_t(S_t(p^*_{w,t}(\ell)))^2\Big]N,\quad \ell\in\{r,m,0\},\\
&p^{\text{net-meter}}_{i,r,t}\doteq p^*_{u,i}(r),\quad p^{\text{net-meter}}_{i,m,t}\doteq p^*_{w,t}(m),\\
&Z(\ell)\doteq\sum_{t=1}^{T}\sum_{i}^{I}\mathbb{E}\Big[-\big(\widehat{D}_{i,t}(\ell)-D_{i,t}+(D_{i,t}-\widehat{\Delta}_{i,\ell,t}(p^*_{u,i}(\ell)))^+\big)p^*_{u,i}(\ell)\Big]\\
&\qquad+\sum_{t=1}^{T}\sum_{i}^{I}\mathbb{E}\big[(\widehat{\Delta}_{i,\ell,t}(p^*_{u,i}(\ell))-D_{i,t})^+p^{\text{net-meter}}_{i,\ell,t}\big]-\sum_{i=1}^{I}V\Big(\Sigma_{t=1}^{T}\mathbb{E}\big[\widehat{\Delta}_{i,\ell,t}(p^*_{u,i}(\ell))\big]\Big),\quad \ell\in\{r,m\},\\
&\Pi^*_{i,t}(\ell,K_i)\doteq\Pi_{i,t}(\ell,K_i;\vec{p}^*_u(\ell)),\quad \ell\in\{r,m,0\},\\
&\mathcal{A}_{\ell,0}\doteq(\widehat{\pi}(0)-\widehat{\pi}(\ell))+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(\Pi^*_{i,t}(0,K_i)-\Pi^*_{i,t}(\ell,K_i)\right)+Z(0)-Z(\ell)+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(\bar{G}_t(\tilde{q}_{i,\ell,t})-\bar{G}_t(\tilde{q}_{i,0,t})\right),\quad \ell\in\{r,m\},\\
&\mathcal{A}_{r,m}\doteq(\widehat{\pi}(m)-\widehat{\pi}(r))+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(\Pi^*_{i,t}(m,K_i)-\Pi^*_{i,t}(r,K_i)\right)+Z(m)-Z(r)+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(\bar{G}_t(\tilde{q}_{i,r,t})-\bar{G}_t(\tilde{q}_{i,m,t})\right),\\
&\bar{\delta}_{\ell,0}\doteq\big[E(0)-E(\ell)\big]^{-1}\mathcal{A}_{\ell,0},\quad \ell\in\{r,m\}\quad\text{and}\quad \bar{\delta}_{r,m}\doteq\big[E(m)-E(r)\big]^{-1}\mathcal{A}_{r,m}.
\end{aligned}$$

In light of these, by (EC.1), the equilibrium social welfare under the rule $\ell\in\{r,m,0\}$ is

$$SW_\ell(\vec{p}^*_u(\ell),\vec{q}^*(\ell))=\widehat{\pi}(\ell)+\sum_{t=1}^{T}\sum_{i=1}^{I}\Pi^*_{i,t}(\ell,K_i)+Z(\ell)-\delta E(\ell)-\sum_{t=1}^{T}\sum_{i=1}^{I}\bar{G}_t(\tilde{q}_{i,\ell,t}).$$

Then, by elementary analysis, $SW_\ell(\vec{p}^*_u(\ell),\vec{q}^*(\ell))-SW^*_0(\vec{p}^*_u(0),\vec{q}^*(0))>0$ if and only if $\delta>\bar{\delta}_{\ell,0}$ for $\ell\in\{r,m\}$. Similarly, $SW_r(\vec{p}^*_u(r),\vec{q}^*(r))-SW^*_m(\vec{p}^*_u(m),\vec{q}^*(m))>0$ if and only if $\delta>\bar{\delta}_{r,m}$. $\square$

Electronic copy available at: https://ssrn.com/abstract=3257925

Table EC.1 Various Parameters for Each Utility in July:

	$i = $ PG&E	$i = $ SCE	$i = $ SDG&E
Expected End-Customer Demand in July, i.e., $\mathbb{E}[\widehat{D}_{i,7}]$ (MWh)	6,601,602	7,013,885	1,201,664.6
$\beta_{i,7}$	19.52	26.15	15.60
Average Retail Price in July ($/KWh)	0.2127	0.1599	0.2140
$\mathbb{E}[\Delta_{i,7}]/\mathbb{E}[\widehat{D}_{i,7}]$	0.037%	0.023%	0.059%

Table EC.2 Share of End-Customer Demand in the Hour Block h Within Total Daily End-Customer Demand - July 2016

$h=8$	$h=9$	$h=10$	$h=11$	$h=12$	$h=13$	$h=14$	$h=15$	$h=16$	$h=17$
3.2%	3.1%	3.2%	3.3%	3.4%	3.6%	3.8%	4.0%	4.2%	4.3%

Table EC.3 $\mathbb{E}[\Delta_{i,7,h}]/\mathbb{E}[\widehat{D}_{i,7,h}]$ in Various Hour Blocks h for Each Utility i

	$h=8$	$h=9$	$h=10$	$h=11$	$h=12$	$h=13$	$h=14$	$h=15$	$h=16$	$h=17$
PG&E	0.037%	0.068%	0.092%	0.107%	0.112%	0.109%	0.100%	0.087%	0.069%	0.047%
SCE	0.025%	0.042%	0.057%	0.066%	0.068%	0.065%	0.059%	0.050%	0.038%	0.024%
SDG&E	0.071%	0.124%	0.164%	0.182%	0.184%	0.175%	0.158%	0.133%	0.100%	0.060%

Appendix J: More Details on Section 4

Let us explain how we obtain N and the generators' cost parameter c_s for each month s. In the CAISO system, flexible generators (specifically natural gas fired power plants) dominate the production mix (Galiteva 2017). There are $N = 12$ such major generators in the CAISO system (U.S. EIA 2018e). Using the 2016 U.S. power plant database (U.S. EIA 2018e) and 2016 fuel costs in the U.S. (U.S. EIA 2018f), we identify the total generation and total production cost for each generating company in California. Based on these and considering the production cost function of the form $c_s q^2$ at quantity $q > 0$ for each month s, we determine the variable cost of a generator. We assume that the production cost parameter is the same for each hour block in a month.

Tables EC.1 through EC.4 include more details about Section 4. In Table EC.4, $h = k$ corresponds to an hour block between $k-1$ and k. Naturally, there is significant hourly variation in percentage contributions. The majority of profit improvements due to distributed solar comes from $h = 11$ to $h = 17$; the maximum profit improvement is achieved at $h = 15$.

Table EC.4 Percentage Contribution of Different Hour Blocks in Monthly Utility Profit Improvement

	$h=8$	$h=9$	$h=10$	$h=11$	$h=12$	$h=13$	$h=14$	$h=15$	$h=16$	$h=17$
$\mathcal{P} = 30\%$	2.40%	3.76%	5.38%	7.27%	9.28%	11.68%	13.10%	13.29%	11.83%	8.88%
$\mathcal{P} = 40\%$	1.93%	2.78%	4.12%	6.05%	8.39%	11.49%	13.53%	14.15%	12.87%	9.82%

Electronic copy available at: https://ssrn.com/abstract=3257925

Appendix K: Additional Notes

Note #1: Under the time-of-use pricing strategy, a day is typically divided into $z = 2$ or $z = 3$ time blocks and the utility charges a fixed but different retail electricity price during each of these time blocks until the next rate making date T is reached. In this setting, the utility j would choose z prices at $t = 1$, and each price would be valid for T_k periods $k = 1, \dots, z$ such that $T_1 + \dots + T_z = T$. Because the optimal value of each retail price can be determined by solving a flat-rate pricing problem with a modified time horizon, Proposition 4 extends by replacing the current thresholds in Proposition 4 with new ones.

Note #2: The proof of the extended Theorem 1 in the setting with customer segments is the same as the existing one with the following exceptions: Under the rule $\ell = r$, $p_{u,j}$ in the proofs must be replaced with $\frac{\Sigma_{z=1}^{\bar{z}} p_{u,j,z}\mathbb{E}[\Delta_{j,z}]}{\Sigma_{z=1}^{\bar{z}}\mathbb{E}[\Delta_{j,z}]}$ where $\bar{z}$ is the number of customer segments, $p_{u,j,z}$ is the utility j's retail electricity price for the customer segment z, and $\Delta_{j,z}$ is the DRE generation of utility j's net-metered customers in segment z. Similarly, under the rule $\ell = m$, $p_{u,j}$ in the proofs must be replaced with $\frac{\Sigma_{z=1}^{\bar{z}} p_{u,j,z}\mathbb{E}[D_{j,z} - (D_{j,z} - \Delta_{j,z})^+]}{\Sigma_{z=1}^{\bar{z}}\mathbb{E}[D_{j,z} - (D_{j,z} - \Delta_{j,z})^+]}$ where $D_{j,z}$ is the electricity demand of the utility j's net-metered customers in segment z.

References for the Electronic Companion

Galiteva, A. (2017), H2@Scale: The Role of Storage and DER for California. `www.energy.gov/sites/prod/files/2017/11/f46/fcto_nov17_h2_scale_session_galiteva.pdf`, Accessed on 7/7/19.

U.S. EIA (2018e), Form EIA-923 detailed data with previous form data (EIA-906/920) - 2016. `www.eia.gov/electricity/data/eia923/`, Accessed on 8/8/18.

U.S. EIA (2018f), Refiner Petroleum Product Prices by Sales Type. `www.eia.gov/dnav/pet/pet_pri_refoth_dcu_nus_m.htm`, Accessed on 8/8/18.

Electronic copy available at: https://ssrn.com/abstract=3257925