The Effect of Subsidized Entry in Multi-Unit Capacity Auctions with Allocation Externalities

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Abstract

This paper examines the effect of subsidized entry of electricity generation capacity on the outcome of centralized capacity auctions. Subsidized entry suppresses capacity prices and induces an inefficient allocation of capacity. Subsidized entry also alters the generation portfolio determined by the capacity auction, leading to lower expected electricity prices in subsequent market interactions. These effects reduce total industry profit, but may increase consumer surplus. Consequently, the effect of subsidized entry on the overall level of short-term expected social welfare is ambiguous. Subsidized entry has long-term adverse impacts. The suppressed capacity and electricity prices reduce unsubsidized firms' incentives to undertake generation capacity investments. The long-term resource adequacy issues associated with insufficient capacity investment may dominate the potential short-term benefits of subsidized entry.

Keywords: Multi-unit auctions; Allocation externalities; Subsidized entry; Electricity markets; Regulation.

JEL Classifications: D44, L13, L50, L94.

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1 Introduction

Ensuring sufficient electricity generation resources is a central concern of regulators and policy-makers. Inadequate electricity generation capacity can result in cascading outages (blackouts) causing billions of dollars in economic damages. Further, blackouts can have significant adverse impacts on providing critical infrastructure such as communication, health services, heating, cooling, and water supply. These disruptive events have occurred in California in 2000-2001, the Northeastern United States in 2003, and more recently in India in 2012 where over 620 million people were affected (9% of the world's population) (Romero, 2012), along with many others.[1] In the face of growing demand and an aging fleet of generation, it is essential that electricity markets are designed to ensure that there is adequate generation capacity.

Capacity payment mechanisms have been adopted world-wide to promote generation capacity investment. In the United States, these capacity mechanisms have taken the form of centralized capacity auctions. The objective of these capacity mechanisms is to provide additional revenue to supplement earnings in subsequent energy markets.[2] These capacity auctions aim to ensure resource adequacy and provide a long-term transparent price signal for generation capacity investment.

Some industry experts argue that capacity procurement auctions have helped to ensure reliability by attracting capacity investment (Pfeifenberger et al., 2011). Others contend that capacity auctions provide windfall profits to existing generators and argue that capacity auctions do not provide sufficient incentives for new generation investments (Wilson, 2008; APPA, 2011). These criticisms have led several state governments to subsidize new potential capacity investments. For example, the States of New Jersey and Maryland implemented plans to establish contracts that secure long-term payments in excess of those determined by the wholesale electricity markets to induce the construction of new gas-fired generation units in their States (NJBPU, 2011; MPSC, 2011). The governments that provide such out-of-market (OOM) payments argue that these subsidies are necessary in order to ensure resource adequacy and lower prices for consumers in their regions. However, regulators view these subsidies as an execution of buyer-side market power. This article examines the short-run and long-run system-wide impacts of such capacity subsidies.

Prior to the deliver-year, load-serving entities (LSEs) who provide electricity to end-users are required to secure capacity obligations that ensure that there are sufficient generation resources available to supply all of the electricity demanded during the highest (peak) period (PJM, 2011). In centralized capacity auctions, the

[1] The black outs in California and Northeastern United States were not due to inadequate generation resources. Alternatively, the outages in India were largely caused by insufficient generation capacity. However, all of these large-scale outages provide an illustration of the negative impacts of blackouts.

[2] Regulatory policies aimed at limiting market power execution in electricity markets has resulted in insufficient revenues necessary to promote capacity expansion. This is often referred to as the "missing money" problem (Joskow, 2007, 2008).

demand function is the summation of all of the buyers' (LSEs') capacity obligations. The LSEs are obligated to pay the market-clearing capacity auction price for each unit of capacity in their capacity obligation.[3]

Regulators have viewed subsidized entry as an attempt to suppress capacity prices and hence, as an execution of buyer-side market power. Since buyers (LSEs) of capacity are obligated to pay the prevailing capacity prices determined by the capacity auction, they may have an incentive to subsidize new generation capacity investment if the benefits from reducing the equilibrium capacity prices exceeds the costs of the subsidy.[4] Regulators are concerned that subsidized entry will undermine the central objectives of capacity auctions by distorting the price signal indicating where and when new capacity investment is needed. Regulatory policies aimed at restricting subsidized entry of new generation capacity have been considered or adopted in regions with centralized capacity auctions. In particular, Pennsylvania-New Jersey-Maryland Interconnection (PJM) has implemented the Minimum Offer Pricing Rule (MOPR) with the objective of eliminating subsidized entry (Pfeifenberger et al., 2011).[5] The MOPR precludes units who have been identified to have received an OOM payment from submitting a bid to supply capacity below an estimate of the unit's underlying unsubsidized cost of new capacity investment.[6]

I find that subsidized entry suppresses the capacity price and results in an inefficient allocation of capacity as a more efficient resource is replaced by the less efficient subsidized unit. Further, subsidized entry suppresses expected electricity prices in subsequent delivery-year electricity markets under plausible conditions. Therefore, total industry profits are reduced in the presence of subsidized entry because firms receive a lower capacity price, capacity is allocated to a less efficient resource, and firms' expected earnings in subsequent interactions are reduced. These effects are more pronounced as the subsidized unit becomes less efficient.

I find that the effect of subsidized entry on expected short-run social welfare is ambiguous. Subsidized entry reduces the capacity price and expected electricity prices in subsequent energy markets. Hence, if the benefits to consumers through reduced expected electricity prices and capacity payments exceeds the reduction in industry profits and the social cost of raising the subsidy, then expected short-run social welfare increases in the presence of subsidized entry. However, if these benefits are not sufficiently large, then

[3]On the supply side, firms submit bids into the auction for each of their installed and/or new potential capacity investments to supply a portion of the capacity demand. These bids reflect the price at which the firm is willing to make its installed or new potential generation capacity available in subsequent delivery-year electricity markets. If a firm's bid is accepted, then it is obligated to make its capacity for the dispatched generation unit available in the subsequent delivery-year energy markets.

[4]Attempts by the states of New Jersey and Maryland to provide capacity subsidizes have been viewed as attempts to exercise buyer-side market power to suppress capacity prices. The states can be thought of as central planners which are aggregating the preferences of all buyers (LSEs) in their regions (PJM, 2013). However, these states argue that they provide these subsidies to reduce electricity prices and increase reliability in their regions.

[5]PJM is an independent system operator (ISO) that manages and coordinates electricity markets in its region. Policies similar to PJM's MOPR have been adopted or are being considered by ISOs in New England, New York, and the Midwest.

[6]PJM has several categorical exemptions from the MOPR that allows certain resources to receive OOM payments. For a detailed account of the proposed exemptions see PJM (2012).

subsidized entry reduces short-run expected social welfare. If the entry of the subsidized unit occurs in a region with a high (low) degree of generation and/or transmission capacity scarcity, the electricity price suppressing effect is amplified (dampened) and hence, it is more (less) likely that short-run expected welfare will increase in the presence of subsidized entry.

Subsidized entry also reduces the incentives of firms not receiving OOM payments to undertake new capacity investments. Therefore, while subsidized entry has the potential to increase short-term expected welfare, the resulting long-term issues associated with insufficient generation capacity expansion may more than offset the potential gains identified in the short-run welfare analysis. The negative long-run impacts of capacity scarcity due to reduced participation incentives are magnified (lessened) in regions with a high degree of aging coal units and/or renewable generation technologies (demand-response). In these settings, the overall impact of subsidized entry on expected long-run welfare is more likely to be negative (positive) because the resource adequacy concerns associated with reduced capacity investment are larger (smaller).

The current analysis is closely related to the work of von der Fehr and Harbord (1993), García-Díaz and Marin (2003), and Crawford et al. (2007), which analyze bidding behavior in uniform price multi-unit auctions. These studies criticize the assumed continuity of bid functions used in previous multi-unit auction literature (Wilson, 1979; Klemperer and Meyer, 1989).[7] Kremer and Nyborg (2004) and Kastl (2011) reveal that taking into account the discreteness inherent in multi-unit auctions in practice has important effects on firms' bidding behavior. However, unlike the current analysis, this discrete multi-unit auction literature focuses on isolated auctions with no allocation externalities.

Auctions are often followed by subsequent interactions such that bidders' expected payoffs are affected by the allocation of goods in the auction. Such auctions with allocation externalities have been the subject of several recent articles. Das Varma (2002) and Das Varma and Lopomo (2010) find that bidders change their behavior in order to alter the resulting allocation of goods in the auction. However, these authors focus on single-unit auctions. Alternatively, Aseff and Chade (2008) and Jehiel and Moldovanu (2001) analyze the revenue-maximizing and efficient mechanism in a multi-unit auction with allocation externalities, respectively. Aseff and Chade assume bidders have unit-demands. Jehiel and Moldovanu allow for the case where firms demand multiple units.[8] I explicitly model bidding behavior in a multi-unit auction with allocation externalities and reveal how subsidized entry affects firms' bidding behavior in this environment.[9]

The current analysis complements several studies on subsidies and set-asides in single-unit government

[7]For a detailed literature review on multi-unit auctions see Schone (2009).

[8]Jehiel and Moldovanu reveal that the efficient mechanism only exists in certain non generic cases.

[9]The basic model considers a setting where firms have unit supplies. However, section A in the Technical Appendix derives necessary and sufficient conditions for a Pure Strategy Nash Equilibrium when bidders are willing to supply multiple units.

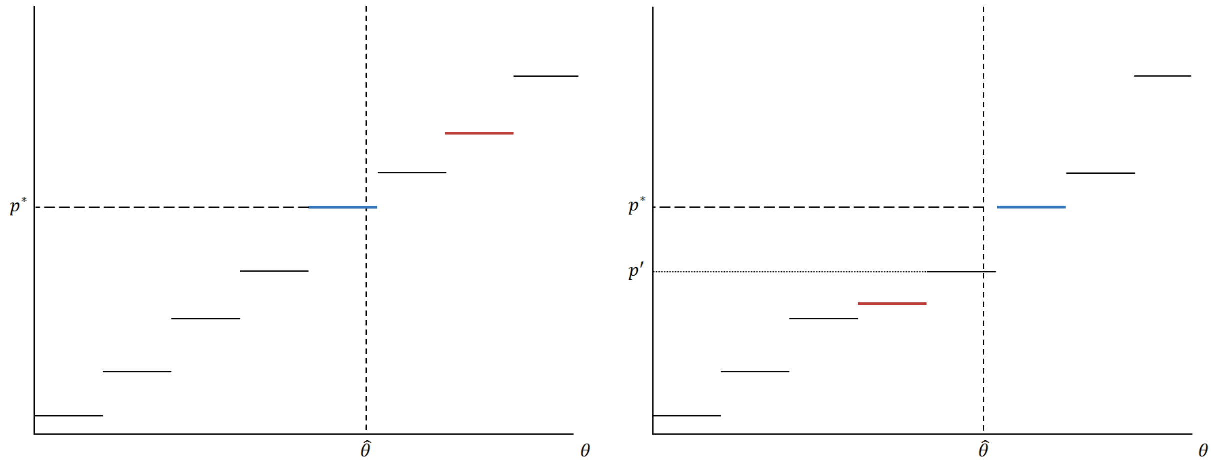
procurement auctions (Krasnokutskaya and Seim, 2011; Athey et al., 2013). These studies find that bid subsidies and set-asides have an overall ambiguous effect on revenue and efficiency that depends upon their impacts on bidder participation. In the current article, bidder participation is analogous to a firm's decision to undertake a new capacity investment. Similar to these studies, I find that the overall expected effect of capacity subsidies is ambiguous because it depends upon the magnitude of the long-run impact of reduced participation incentives on resource adequacy and the change in the short-run expected welfare. In contrast to this literature, I consider a multi-unit auction with allocation externalities that takes into account the effect of subsidies on subsequent market interactions.

2 Subsidized Entry

Subsidized entry occurs when an entrant, E_s, receives an OOM payment that reduces its cost of constructing a new generation unit. Figure 1 illustrates a potential bid function in the capacity auction with and without subsidized entry for a given level of realized capacity demand $\widehat{\theta}$. These functions are formed by arranging the bids submitted by firms for each of their installed and/or new potential generation units from least to greatest. Each bid reflects the price at which a firm is willing to make its installed and/or new capacity investment available in the subsequent deliver-year's energy markets. Figure 1 (a) considers a setting in which there are no capacity subsidies leading to the market-clearing price p^*. Alternatively, Figure 1 (b) provides an illustration of a setting in which an entrant, E_s, is receiving an OOM payment to subsidize its new potential capacity investment resulting in its unit being procured and the market-clearing price $p' < p^*$. Subsidized entry reduces the market-clearing price and a unit which was procured without subsidized entry (in blue) is displaced by the subsidized unit (in red). Without this subsidy, E_s's new capacity investment is too costly to procure profitably in the capacity auction. Because the auction is a uniform price auction, the market-clearing price is paid to the price-setting bidder (marginal bidder) and all bidders whose bids are below the market-clearing price (inframarginal bidders).

The analysis proceeds as follows. Section 3 describes the multi-unit capacity auction model. Section 4 presents the benchmark setting with no subsidized entry. Section 5 analyzes how capacity subsidies affects the outcome of the capacity auction. The effect of capacity subsidies on short-run welfare and subsequent energy auctions are presented in sections 6 and 7. The long-run welfare implications of subsidized entry are considered in section 8. Lastly, section 9 concludes. The Appendix contains proofs of all formal conclusions.[10]

[10]As noted in detail in the conclusion, the Technical Appendix provides several extensions to the basic model.



(a) No OOM Payments (b) OOM Payments

Figure 1: Comparison of Capacity Auction Outcomes with and without OOM Payments

3 The Model

Two incumbents ($\mathbf{I} = \{I_1, I_2\}$) and M potential entrants ($\mathbf{E} = \{E_1, E_2, ..., E_M\}$) compete to supply capacity in a sealed-bid, uniform-priced, multi-unit auction. Each incumbent has a set of installed generation units. In contrast, each entrant has a single potential new capacity investment.[11] Denote the set of generation units by U and firm j's set of generation units by $U_j \subset U \ \forall \ \ j \in \{\mathbf{I}, \mathbf{E}\}$. Capacity is assumed to be perfectly divisible. Both installed and new potential capacity investments have capacity limits. Define k_j^u as the capacity limit of firm j's u^{th} unit $\forall \ \ u \in U_j$ and $\forall \ \ j \in \{\mathbf{I}, \mathbf{E}\}$. It is assumed that the entrants have homogeneous capacity limits (i.e., $k_{E_i}^u = k_E^u \ \forall \ i = 1, 2, ..., M$).[12] Denote I_j's total installed capacity by $K_{I_j} = \sum_{u \in U_{I_j}} k_{I_j}^u$ and the incumbents' aggregate installed capacity by $K_I = K_{I_1} + K_{I_2}$.

Capacity demand, which is announced by the auctioneer prior to the capacity auction, is characterized by the following assumption.

Assumption 1. *Capacity demand is a random variable θ with a known probability distribution $f(\theta)$ on the region $[\underline{\theta}, \overline{\theta}] \subset \mathbb{R}_+$ where $K_I < \underline{\theta} < \overline{\theta} < K_I + Mk_E$. $\widehat{\theta}$ denotes the realization of θ where $K_I + (l-1)k_E < \widehat{\theta} \leq K_I + lk_E$ for some $2 < l < M$.*

The capacity demand realization range detailed in Assumption 1 specifies a setting in which installed capacity is insufficient to supply all of the capacity demanded (i.e., $\widehat{\theta} > K_I$). Rather, l units of new capacity

[11] The analysis can be extended to allow the incumbents to have a new potential capacity investment in addition to their installed capacity units. See Section A in the Technical Appendix for details.

[12] García-Díaz and Marin (2003) characterize how firms' behavior changes when there are heterogeneous capacity limits. Section B in the Technical Appendix analyzes a setting in which the subsidized entrant E_s's capacity $k_{E_s} > k_E = k_{E_i} \ \forall \ \ i \neq s$.

investment are needed in addition to the installed capacity to satisfy the capacity demanded.

Each generation unit has marginal cost of capacity c_j^u up to its capacity limit $\forall\, u \in U_j$ and $\forall\, j \in \{\mathbf{I}, \mathbf{E}\}$. The marginal cost of an installed capacity unit, $c_{I_j}^u$, reflects the ongoing costs of making a unit of installed capacity available.[13] Alternatively, the marginal cost of new capacity investment, $c_{E_i}^u$, reflects both the marginal capital and ongoing cost of a new capacity investment.[14]

If a firm's capacity bid is accepted (dispatched) by the auctioneer, it is obligated to make the capacity procured in the auction available in the subsequent delivery-year's energy markets.[15] Therefore, prior to making bidding decisions, each firm forms expectations about its expected per-unit earnings in subsequent energy markets for each of its units. Firm j's expected per-unit earnings for a unit $u \in U_j$ depends on two important factors. First, the market characteristics in the subsequent energy markets such as energy demand, fuel input prices, and environmental and regulatory policies. These factors are uncertain *ex ante*. Define η to be a random variable reflecting the uncertainties in these market characteristics with probability density function $g(\eta)$ on the support $[\underline{\eta}, \overline{\eta}] \subset \mathbb{R}$. Second, the portfolio of generation competing in the delivery-year's energy markets has important affects on firms' expected payoffs. For instance, the entry of a certain mix of new generation capacity may lower the cost of supplying electricity in subsequent market interactions and increase competition, resulting in lower prices in energy markets (see Section 7). Denote ψ to be a particular portfolio of generation units determined by the allocation of capacity in the capacity auction and denote Ψ to be the set of all potential generation portfolios. The expected per-unit earnings from energy markets for firm j's u^{th} unit with a generation portfolio ψ is:

$$\bar{\pi}_j^u(\psi) = E[\pi_j^u(\eta, \psi)] = \int_{\underline{\eta}}^{\overline{\eta}} \pi_j^u(\eta, \psi)\, g(\eta)\, d\eta \quad \text{where } u \in U_j,\ j \in \{\mathbf{I}, \mathbf{E}\},\ \text{and } \psi \in \Psi. \tag{1}$$

If a firm does not procure its generation unit in the capacity auction, it is not able to compete in subsequent energy market interactions. Hence, in making its bidding decisions, a firm considers both the physical costs, c_j^u, and the forgone payoff if its unit(s) are not dispatched in the capacity auction, $\bar{\pi}_j^u(\psi)$. Define $c_j^u - \bar{\pi}_j^u(\psi)$ to be firm j's net marginal cost of capacity for its u^{th} unit given some generation portfolio $\psi \in \Psi$. For notational simplicity, the superscript u will be suppressed for the entrants because the entrants have a single new capacity unit (i.e., $|U_{E_i}| = 1\ \forall\, i = 1, 2, ..., M$). Throughout the analysis, the following assumptions play an important role.

[13] More formally, the marginal cost of an installed capacity resource reflects the per-unit (MW-day) operating expenses that would be avoided if the unit were not to operate for a year.

[14] These costs reflect the marginal (MW-day) costs of constructing and operating a new generation unit levelized over the life of the plant. For more details on the marginal (MW-Day) cost of new capacity investment see Spees et al. (2011).

[15] In practice, in addition to participating in energy markets, firms can procure their generation resources in ancillary service markets. For simplicity I abstract away from this multiple market setting. The results are robust to this specification.

Assumption 2. Using expected per-unit earnings from energy markets defined in (1):

2.1 $\bar{\pi}^u_j(\psi) \geq 0 \;\; \forall \;\; u \in U_j, \, \psi \in \Psi$, and $j \in \{\mathbf{I}, \mathbf{E}\}$.

2.2 $c_{E_i} - \bar{\pi}_{E_i}(\psi) > 0 \; \forall \;\; i = 1, 2, ..., M$.

2.3 There exists a $\psi \neq \psi'$ with $\psi, \psi' \in \Psi$ such that $\bar{\pi}^u_j(\psi) > \bar{\pi}^u_j(\psi')$ for some $u \in U_j \; \forall \; j \in \{\mathbf{I}, \mathbf{E}\}$.

2.4 The set of entrants $\mathbf{E}$ is ordered such that $c_{E_1} - \bar{\pi}_{E_1}(\psi) < c_{E_2} - \bar{\pi}_{E_2}(\psi) < ... < c_{E_M} - \bar{\pi}_{E_M}(\psi) \; \forall \; \psi \in \Psi$.

Assumption 2.1 states that the expected per-unit earnings from subsequent energy markets are non-negative for any firm $j \in \{\mathbf{I}, \mathbf{E}\}$. Assumption 2.2 states that the net marginal cost of new capacity is positive for each potential entrant. Both of these assumptions are supported empirically because firms earn sufficient revenues in energy markets to cover the costs of energy procurement, but insufficient funds to cover the cost of capacity (Joskow, 2007; PJM, 2011). Assumption 2.3 indicates that there exists an allocation externality. That is, there are certain portfolio allocations that adversely affect firm j's expected per-unit earnings in subsequent energy markets because of its impact on the nature of competition in these subsequent electricity market interactions (see Section 7). Lastly, Assumption 2.4 implies that the portfolio effect on each entrant's expected earnings from energy markets identified in Assumption 2.3 are sufficiently small.[16]

Firms compete by submitting a single bid to the auctioneer for each of their generation units.[17] These bids reflect the price at which the firm is willing to make the entire capacity of its u^{th} unit available in subsequent market interactions. Each bid must fall below a reserve price $\overline{P}$ set *ex ante* by the auctioneer. To avoid the trivial case where there is insufficient new capacity investment at the reserve price, assume that $\overline{P} > c_{E_{l+2}} - \bar{\pi}_{E_{l+2}}(\psi)$ for any $\psi \in \Psi$ where l is characterized in Assumption 1. Each entrant submits a single bid $b_{E_i} \in [0, \overline{P}]$ for its sole potential new capacity investment. Alternatively, the incumbents submit a single price-quantity pair $(b^u_{I_j}, q^u_{I_j})$ for each of their units $u \in U_{I_j}$. The incumbents' bid functions can be represented by the following non-decreasing left-continuous step functions:

$$B_{I_j} = \{(b^u_{I_j}, q^u_{I_j})\}_{\forall \, u \in U_{I_j}}, \; b^u_{I_j} \in [0, \overline{P}], \; b^u_{I_j} \leq b^{u+1}_{I_j}, \text{ and } q^u_{I_j} = k^u_{I_j} \qquad \forall \; u \in U_{I_j} \text{ and } j = 1, 2. \tag{2}$$

Let $\boldsymbol{\beta} = (B_{I_1}, B_{I_2}, b_{E_1}, ..., b_{E_M})$ denote the aggregate bid profile. In order to limit the incumbents' abilities to exercise market power, the auctioneer requires that the incumbents' bids for each of their installed generation units must not exceed an offer-cap, $\bar{b}^u_{I_j}$, set *ex ante* (i.e., $b^u_{I_j} \leq \bar{b}^u_{I_j} \; \forall \; u \in U_{I_j}$ and $\forall \; j = 1, 2$). These offer-caps are based upon estimates of the net marginal cost of each installed unit $u \in U_{I_j} \; \forall \; j = 1, 2$.

[16] Section C in the Technical Appendix derives the necessary and sufficient conditions for a Pure Strategy Nash Equilibrium without this assumption.

[17] This follows the literature established by von der Fehr and Harbord (1993).

Define $\bar{b}_{I_j} = \max_{u \in U_{I_j}} \{\bar{b}^u_{I_j}\}$ to be I_j's maximum bid offer-cap for $j = 1, 2$. Assume that $\max\{\bar{b}_{I_1}, \bar{b}_{I_2}\} < c_{E_1} - \bar{\pi}_{E_1}(\psi)\ \forall\ \psi \in \Psi$. This implies that the most efficient new capacity investment (in terms of net marginal cost) exceeds the estimated net marginal cost of the least efficient installed unit.[18]

Once the bids are submitted to the auctioneer, the auctioneer orders the bids and their corresponding capacities in order of least-cost to form a non-decreasing left-continuous supply function $S(p; \boldsymbol{\beta})$. The market-clearing (stop-out) price is set where the aggregate supply is just sufficient to meet capacity demand:

$$p^* = \min\{p : S(p; \boldsymbol{\beta}) \geq \widehat{\theta}\}. \tag{3}$$

Define the firm(s) whose bid(s) set the stop-out price as the marginal bidder(s) and the market-clearing bid(s) as the marginal bid(s). Denote the marginal bid(s) by b_m. Once the stop-out price is determined, the auctioneer accepts all bids up to p^*. All of the units that are accepted by the auctioneer are paid the stop-out price p^*. The marginal bid(s) are typically rationed. Rationing is assumed to be efficient. Therefore, if there is a single marginal bidder, then residual demand is rationed fully to this bidder. If there are multiple marginal bidders, then residual demand is rationed equally to the most efficient marginal bidder(s).

Throughout the analysis it is assumed that firms' costs, capacity limits, expected earnings from energy markets, and offer-caps are common knowledge.

Supplier are risk-neutral. Therefore, each firm chooses its bid(s) to maximize the sum of its payoff from the capacity payment plus the subsequent discounted expected earnings from energy market interactions.[19] I normalize the discount rate δ to 1. Using (1)-(3), Incumbent I_j's profit function for a given bid profile $\boldsymbol{\beta}$ and resulting portfolio allocation ψ is:[20]

$$\Pi_{I_j} = \sum_{u \in U_{I_j}} [p^* - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi))] X^u_{I_j}(\widehat{\theta}; \boldsymbol{\beta}) \qquad \forall\ j = 1, 2 \tag{4}$$

where the output of I_j's u^{th} unit is:

[18]It is possible that the net marginal cost of an installed generation unit may exceed the net marginal cost of a new capacity investment. For example, with increasing environmental restrictions, the cost of operating an existing coal plant can exceed the cost of constructing a new natural gas combustion turbine or combined cycle unit. In such settings, an incumbent's bid for such an installed unit may set the market-clearing price or not be procured by the auctioneer. Section A in the Technical Appendix allows the incumbents to undertake new capacity investments and hence, restores the potential for an incumbent to submit a price-setting bid.

[19]In the current environment, the incumbents' choose their bid functions to maximize their payoffs subject to the offer-caps. Section A in the Technical Appendix considers the setting in which the incumbents can submit an unconstrained bid for a new capacity investment.

[20]For brevity, the profit functions below assume that there is a single marginal bidder. If there are multiple marginal bidders, then the presumed efficient ration occurs as follows. Residual demand for firm j's u^{th} unit defined in (6) now equals $R(\widehat{\theta}, p^*; \boldsymbol{\beta}) = (\widehat{\theta} - X_-(\widehat{\theta}, p^*; \boldsymbol{\beta}))\rho^u_j$ where $X_-(\widehat{\theta}, p^*; \boldsymbol{\beta})$ is defined by (7). The rationing rule is determined by $\rho^u_j = 0$ if $u \notin z \cap \underline{c}$, and $\rho^u_j = \frac{1}{|z \cap \underline{c}|}$ if $u \in z \cap \underline{c}$ where $z = \{u \in U : b^u_j = b_m\}$ is the set of units whose bids are among the marginal bids and $\underline{c} = \min\{c^u_j - \bar{\pi}^u_j(\cdot) : u \in z \text{ and } u \in U)\}$ is the set of the most efficient units in the set z.

$$X^u_{I_j}(\widehat{\theta};\boldsymbol{\beta}) = \begin{cases} 0 & \text{if } b^u_{I_j} > b_m \\ k^u_{I_j} & \text{if } b^u_{I_k} < b_m \\ R(\widehat{\theta}, p^*; \boldsymbol{\beta}) & \text{if } b^u_{I_j} = b_m. \end{cases} \tag{5}$$

If I_j's bid $b^u_{I_j}$ is the marginal bid, then $R(\widehat{\theta}, p^*; \boldsymbol{\beta})$ represents the residual demand on-the-margin and is characterized as follows:

$$R(\widehat{\theta}, p^*; \boldsymbol{\beta}) = \widehat{\theta} - X_-(\widehat{\theta}, p^*; \boldsymbol{\beta}) \tag{6}$$

where

$$X_-(\widehat{\theta}, p^*; \boldsymbol{\beta}) = \sum_{j\in\{\mathbf{I},\mathbf{E}\}} \sum_{u\in\mathcal{F}_j} k^u_j, \text{and} \tag{7}$$

$$\mathcal{F}_j = \{u \in U_j : b^u_j < b_m = p^* \text{ and } b^u_j \in \boldsymbol{\beta}\}. \tag{8}$$

$X_-(\widehat{\theta}, p^*; \boldsymbol{\beta})$ denotes the total inframarginal capacity given the bid profile $\boldsymbol{\beta}$ and $\mathcal{F}_j$ denotes the set of firm j's inframarginal units given the marginal bid $b_m = p^*$.

Entrant E_i's profit for a given bid profile $\boldsymbol{\beta}$ and resulting portfolio allocation ψ is:

$$\Pi_{E_i} = [p^* - (c_{E_i} - \bar{\pi}_{E_i}(\psi))]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}) \qquad \forall \;\; i = 1, 2, ..., M \tag{9}$$

where the output of E_i's new capacity investment is:

$$X_{E_i}(\widehat{\theta};\boldsymbol{\beta}) = \begin{cases} 0 & \text{if } b_{E_i} > b_m \\ k_{E_i} & \text{if } b_{E_i} < b_m \\ R(\widehat{\theta}, p^*; \boldsymbol{\beta}) & \text{if } b_{E_i} = b_m. \end{cases} \tag{10}$$

If E_i's bid is a marginal bid, then $R(\widehat{\theta}, p^*; \boldsymbol{\beta})$ in (6) represents the residual demand allocated to E_i.

Throughout the analysis, superscripts NS and S denote the cases where there is and is not a capacity subsidy, respectively. For example, $(\boldsymbol{\beta}^{NS}, p^{NS}, \psi^{NS})$ denotes the equilibrium bid profile, stop-out price, and generation portfolio when there is no subsidized entry. Lastly, the portfolio in which the first extramarginal entrant undercuts the marginal bidder will play an important role. Denote this generation portfolio by ψ^{EM}. The first extramarginal entrant is the entrant whose bid is the first bid to exceeds the marginal bidder.

4 Benchmark Setting

Initially consider the benchmark setting in which there are no OOM payments. In particular, I characterize the Pure Strategy Nash Equilibrium (PSNE) in weakly-undominated strategies. Lemma 1 reveals that it is a strictly-dominated strategy for an entrant to procure positive capacity if it expects to earn a negative payoff.[21] Further, Lemma 1 shows that it is a weakly-dominated strategy for an entrant to forgo procuring capacity for a non-negative payoff.

Lemma 1. In any Nash Equilibrium, $b_{E_i} \leq p^*$ if and only if $p^* \geq c_{E_i} - \bar{\pi}_{E_i}(\psi)$ where $\psi \in \Psi \; \forall \; i = 1, 2, ..., M$.

The incumbents' installed capacities are fully procured because their bids are constrained by bid offer-caps. Therefore, the entrants compete over residual demand $\widehat{\theta} - K_I$. From Assumption 1, l units of new capacity investment are needed in addition to all of the incumbents' installed capacities. Lemma 1 implies that in any Nash Equilibrium the l least-costly new capacity investments in terms of net marginal cost will be undertaken to serve residual demand $\widehat{\theta} - K_I$. If this were not the case, then an entrant would be foregoing a positive payoff on its new capacity investment and hence, would find it profitable to deviate unilaterally.

Proposition 1 characterizes the PSNE outcome of this benchmark setting. The proposition reveals that the price-setting firm (i.e., marginal bidder) and non price-setting firms undertake distinct bidding strategies.[22]

Proposition 1. Let E_k denote the marginal bidder who sets the stop-out price p^{NS} for some $k \leq l$. E_k sets the stop-out price p^{NS} with its bid $b_{E_k} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$, while all other entrants $E_i \; \forall \; i = 1, 2, ..., l$ bid sufficiently low to make undercutting unprofitable with $i \neq k$.

Proposition 1 reveals that in the setting with no OOM payments the l most efficient (in terms of net marginal cost) new capacity investments are procured in addition to the incumbents' installed units resulting in the generation portfolio $\psi^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_l}\}$. The non price-setters which procure their entire new capacities have weakly higher output than the price-setter because the price-setter's capacity is rationed (i.e., $X_{E_k}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \leq k_E$). Because firms are all paid the same uniform price, firms prefer to be non price-setters. The non price-setters behave as price-takers and bid sufficiently low to ensure that the marginal bidder has no incentive to unilaterally deviate, become a non price-setter, and lower the stop-out price.[23]

[21] Notice that the incumbents are constrained to submit their bids below the bid offer-caps (i.e., $b^u_{I_j} \leq \bar{b}^u_{I_j} \;\; \forall \; u \in U_{I_j}$ and $j = 1, 2$). Therefore, there may be units $u \in U_{I_j}$ where $b^u_{I_j} \leq \bar{b}^u_{I_j} < p^* < c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi)$. In practice, such an environment would signal that incumbent I_j may want to retire its u^{th} unit. Such considerations are out of the scope of this article and are left for future research.

[22] This is a well established result in this literature (García-Díaz and Marin, 2003; Crawford et al., 2007).

[23] This distinct bidding behavior is observed in practice. Inframarginal generation units bid near zero to ensure that their entire capacity is procured, while the bidders near the margin bid to maximize their payoff facing residual demand.

Conditional on the inframarginal entrants bidding sufficiently low, the price-setter E_k maximizes its payoff facing residual demand $(\widehat{\theta} - X_-(\widehat{\theta}, p^{NS}; \boldsymbol{\beta}^{NS})$ defined in (6)-(8)) by charging the most efficient extramarginal firm's net marginal cost of new capacity investment, $c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$.[24] From Lemma 1, no extramarginal entrant will deviate because such an action would result in procuring new capacity for a loss. This PSNE is unique up to the identity of the price-setting and non price-setting firms.

5 Effects of Subsidized Entry

In this section I investigate the effect of subsidized entry on the capacity auction. Assume an entrant, E_s with $s > l$, receives an OOM payment (i.e., a subsidy) $\tau > 0$ per-unit of capacity procured in the auction. When E_s receives the OOM payment its adjusted net marginal cost of capacity is $c_{E_s} - \bar{\pi}_{E_s}(\psi) - \tau$.[25] Assume that E_s has a capacity limit $k_{E_s} = k_E$. Further, assume that if E_s receives a subsidy that is sufficient large (as defined below), it bids into the capacity auction to ensure that its subsidized unit is fully dispatched.[26]

From Lemma 1 and Assumption 2.4, given $s > l$, if E_s did not receive the subsidy it would not procure its new capacity in the capacity auction. Alternatively, if $\tau > c_{E_s} - \bar{\pi}_{E_s}(\psi') - (c_{E_l} - \bar{\pi}_{E_l}(\psi)) = \widetilde{\tau}$, then E_s's adjusted (by τ) net marginal cost for its new capacity unit is sufficiently low such that it is now among the l least-cost new capacity investments.[27] For now, assume that the buyer provides a subsidy $\tau > \widetilde{\tau}$.[28]

If the subsidy is provided and E_s's unit is dispatched, then this unit displaces another new capacity investment which would have otherwise been procured in the capacity auction. In practice, OOM payments have been given to potential new capacity investments in regions with constrained generation and/or transmission capacity. Therefore, if E_s's unit is dispatched in the capacity auction, the construction of this unit puts downward pressure on subsequent energy procurement prices as the generation and transmission scarcity is eased. That is, the marginal cost function of electricity production in subsequent energy procurement auctions shifts weakly downward (see Section 7). This is referred to as the energy portfolio effect. Hence, it is assumed that if the subsidized entrant's new capacity investment is dispatched, all other firms who dispatch capacity in the auction have weakly lower expected earnings from the energy procurement auctions

[24] The portfolio $\psi^{EM} = \{\psi^{NS} \backslash U_{E_k}, U_{E_{l+1}}\}$ for any $k = 1, 2, ..., l$ represents the portfolio in the setting where the first extramarginal firm undercuts the marginal bidder. The marginal bidder E_k ensures that the extramarginal firm, E_{l+1}, has no incentive to unilaterally deviate and undercut its bid b_{E_k} by pricing at E_{l+1}'s net marginal cost with the portfolio ψ^{EM}.

[25] For illustrative purposes, capacity subsidies are assumed to be linear. However, the intuition behind the effects of subsidized entry identified in this article are robust to other non-linear subsidy schemes.

[26] It is assumed that the subsidized firms' objectives are aligned with the buyer providing the subsidy. As show in Proposition 2, subsidized entry suppresses the capacity price. The buyer benefits from a lower capacity price and hence, prefers that E_s behaves a non price-setter and bids sufficiently low to induce the maximum price suppression.

[27] The portfolio $\psi' = \{\psi \backslash U_{E_l}, U_{E_s}\}$ represents the portfolio where E_s displaces E_l's unit.

[28] The buyer's incentives to provide such a subsidy are investigated below.

compared to the generation portfolio without E_s's unit.[29] Assumption 3 formalizes this statement.

Assumption 3. Define ψ^{NS} and ψ^S to be the equilibrium generation portfolios with $U_{E_s} \notin \psi^{NS}$ and $\psi^S = \{\psi^{NS} \backslash U_{E_i}, U_{E_s}\}$ where U_{E_i} is the unit displaced by E_s's unit for some $i = 1, 2, ..., M$ with $i \neq s$. Then, $\bar{\pi}_j^u(\psi^{NS}) \geq \bar{\pi}_j^u(\psi^S)$ $\forall$ $u \in \psi^{NS} \cap \psi^S$ where $u \in U_j$ and $j \in \{\mathbf{I}, \mathbf{E}\}$.

By assumption the incumbents' installed capacities are fully procured such that the entrants compete over residual demand $\widehat{\theta} - K_I$. Proposition 2 characterizes the PSNE of the capacity auction when entrant E_s is receiving an OOM payment $\tau > \widetilde{\tau}$.

Proposition 2. Suppose $\tau > \widetilde{\tau} = c_{E_s} - \bar{\pi}_{E_s}(\psi^S) - (c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS}))$. The PSNE involves the marginal bidder E_k for some $k = 1, 2, ..., l-1$ setting the stop-out price p^S with its bid $b_{E_k} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$, while all other entrants E_i $\forall$ $i = 1, 2, ..., l-1, s$ bid sufficiently low to make undercutting unprofitable with $i \neq k$.

Proposition 2 reveals that in addition to the incumbents' installed capacities, the $l-1$ most efficient entrants' capacity investments and entrant E_s's new capacity investment are procured to serve $\widehat{\theta}$, i.e., the resulting generation portfolio is $\psi^S = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l-1}}, U_{E_s}\}$. Similar to Proposition 1, the price-setter (E_k) and non price-setters (E_i $\forall$ $i = 1, 2, ..., l-1, s$ with $i \neq k$) undertake distinct bidding strategies. The non price-setters behave as price-takers and bid sufficiently low to ensure that the marginal bidder has no incentive to deviate and become a non price-setter, while the marginal bidder maximizes its payoff facing residual demand by bidding at the most efficient extramarginal entrant's net marginal cost.[30] The PSNE characterized in Proposition 2 is unique up to the identity of the price-setter and the non price-setters.

In the benchmark setting, Proposition 1 reveals that the l most efficient new capacity investments are undertaken. Alternatively, Proposition 2 shows that subsidized entry induces allocative inefficiencies because the subsidized unit, U_{E_s}, displaces a more efficient new capacity investment, U_{E_l}. Further, OOM payments suppress the capacity price because the most efficient extramarginal entrant's net marginal cost is less than its counterpart in the benchmark setting (i.e., $l < l+1$). Proposition 3 summarizes these conclusions.

Proposition 3. Subsidized entry reduces the capacity price and induces allocative inefficiencies.

Now, I investigate the buyer's incentives to provide a subsidy $\tau > \widetilde{\tau}$. The buyer who provides the subsidy is required to purchase some fraction $\alpha \in (0, 1)$ of the total capacity demand $\widehat{\theta}$ (i.e., their capacity obligation) at the capacity price determined by the auction. A buyer's utility function is of the form:

[29] Throughout the analysis the results when Assumption 3 does not hold will be discussed.

[30] E_k ensures that the extramarginal firm, E_l, has no incentive to unilaterally deviate and undercut its bid b_{E_k} to dispatch its capacity by pricing at the net marginal cost of the first extramarginal firm with the portfolio $\psi^{EM} = \{\psi^S \backslash U_{E_k}, U_{E_l}\}$.

$$U^B(p, \tau, \alpha\widehat{\theta}, V_\alpha(p, \alpha\widehat{\theta}, \psi)) \tag{11}$$

where p is the capacity price and $V_\alpha(p, \alpha\widehat{\theta}, \psi)$ reflects the aggregate surplus of consumers the buyer is obligated to serve in its region. Assume that $\frac{\delta U^B(\cdot)}{\delta V_\alpha(p,\alpha\widehat{\theta},\psi)} = U^B_{V_\alpha(p,\alpha\widehat{\theta},\psi)} \geq 0$. As shown in Propositions 1 and 2, because certain threshold levels of p and τ can shift the equilibrium outcome of the game, the relationship between $U^B(\cdot)$ and a change in τ and p is nonmonotonic. In order to investigate the buyer's choice to provide a subsidy, I focus the discussion on the relationship between $U^B(\cdot)$ and τ.

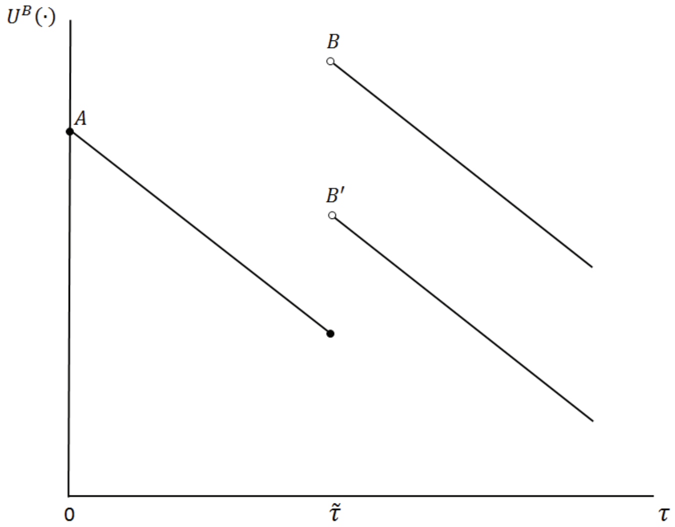


Figure 2: Buyer's Equilibrium Utility as the Subsidy τ Varies.

Figure 2 illustrates the relationship between the buyer's equilibrium utility ($U^B(\cdot)$) and the subsidy (τ). Propositions 1 and 2 imply that there is a critical subsidy level $\widetilde{\tau} = c_{E_s} - \bar{\pi}_{E_s}(\psi^S) - (c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS}))$. For any $\tau \in [0, \widetilde{\tau}]$, E_s is not among the l most efficient new capacity investments and the resulting PSNE is characterized in Proposition 1. Alternatively, for any $\tau > \widetilde{\tau}$, E_s's new capacity is procured in the auction resulting in the PSNE characterized in Proposition 2. Therefore, at $\widetilde{\tau}$ there is a shift in the equilibrium outcome resulting in a discontinuous change in the buyer's equilibrium utility. Within the interior region consistent with a single equilibrium (i.e., regions $[0, \widetilde{\tau}] \cap (\widetilde{\tau}, \infty)$) the utility is monotonically decreasing in τ because the buyer is providing a costly subsidy without altering the outcome of the capacity auction.

The buyer chooses among two potential levels of τ: (1) $\tau = 0$ or (2) $\tau = \widetilde{\tau} + \epsilon$.[31] In Figure 2, the buyer's equilibrium utility when $\tau = 0$ is represented by point A and when $\tau = \widetilde{\tau} + \epsilon$ is represented by B

[31] Formally, no local maximum exists for the buyer's equilibrium utility around the neighborhood of $\widetilde{\tau}$. Rather, there is a supremum. However, it is without loss of generality to assume that in this region the buyer maximizes its payoff by choosing $\widetilde{\tau} + \epsilon$ for some infinitesimally small $\epsilon > 0$.

and B'. If the benefits to the buyer from providing the subsidy, which affects the consumers' utility $V_\alpha(\cdot)$ and suppresses the capacity price, more than offsets the cost of providing the subsidy, then the buyer will provide the subsidy $\tau = \widetilde{\tau} + \epsilon$. Otherwise, $\tau = 0$. In the former case, $U_B(\cdot)$ at $\tau = \widetilde{\tau} + \epsilon$ is represented by B'. In the latter, $U_B(\cdot)$ at $\tau = \widetilde{\tau} + \epsilon$ is represented by B. Proposition 4 summarizes the conclusions.[32]

Proposition 4. $\tau = \widetilde{\tau} + \epsilon$ for some $\epsilon > 0$ if and only if $U^B(p^S, \tau = \widetilde{\tau} + \epsilon, \alpha\widehat{\theta}, V_\alpha(p^S, \alpha\widehat{\theta}, \psi^S)) \geq U^B(p^{NS}, \tau = 0, \alpha\widehat{\theta}, V_\alpha(p^{NS}, \alpha\widehat{\theta}, \psi^{NS}))$. Otherwise, $\tau = 0$.

Using Propositions 1 and 2, Lemma 2 identifies the effects of subsidized entry on industry profit.

Lemma 2. $\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v = \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Pi_v|_{\tau=0} - \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Pi_v|_{\tau>\widetilde{\tau}} \gtreqless 0$ as:

$$\sum_{j=1}^{2} \Delta\Pi_{I_j} + \sum_{i=1}^{l-1} \Delta\Pi_{E_i} + \Pi_{E_l}\Big|_{\tau=0} - \Pi_{E_s}\Big|_{\tau>\widetilde{\tau}} \gtreqless \tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S). \tag{12}$$

The first term on the left-hand side of inequality (12) reflects the difference between the incumbents' profits in the unsubsidized and subsidized outcomes. The second term reflects the change in the profits of the entrants who are procured under both settings. The third term is the profit of the l^{th} entrant who is no longer procured in the setting with OOM payments, and the fourth term is the subsidized entrant's profit net of the subsidy. The right-hand side of inequality (12) reflects the total subsidy given to entrant E_s. Recall from Proposition 3, that subsidized entry reduces the stop-out price and induces allocative inefficiencies. Inequality (12) reveals that subsidized entry reduces the total industry profit unless the subsidy is so large that it offsets the reduction in firms' profit due to the lower stop-out price, allocation of capacity to a less efficient unit, and reduced expected earnings in subsequent market interactions due to the entry of E_s's unit per Assumption 3.

Proposition 5. Suppose Assumption 3 holds. Then subsidized entry strictly reduces the level of aggregate industry profit (i.e., $\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v > 0$).

From Lemma 2, subsidized entry reduces aggregate industry profit unless τ is sufficiently large. Proposition 5 reveals that the highest potential subsidy value chosen by the buyer, $\widetilde{\tau} + \epsilon$ identified in Proposition 4, will never increase industry profits.[33]

[32] As noted in the conclusion, a more detailed analysis of buyers' incentives to provide subsidies warrants further research. However, such an analysis is beyond the scope of this article.

[33] Assumption 3 can be relaxed further. The necessary condition for Proposition 5 to hold is that $\sum_{j\in\mathbf{H}} \sum_{u\in U_j} \bar{\pi}_j^u(\psi^{NS}) - \bar{\pi}_j^u(\psi^S)$ with $\mathbf{H} = \{I_1, I_2, E_1, ..., E_{l-1}\}$ can not be sufficiently negative. If the entry of E_s's unit (instead of E_l's unit) increases firms' expected earnings from energy markets sufficiently such that this necessary condition fails, then $\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v \leq 0$.

The impact on the capacity auction varies with the efficiency of the generation technology that is subsidized. As the net marginal cost of E_s's unit increases, the critical subsidy threshold $\widetilde{\tau}$ increases. Propositions 3 and 5 reveal that a rise in E_s's net marginal cost increases the degree of allocative inefficiency and further reduces the level of aggregate industry profit. Therefore, the negative effects of subsidized entry on the capacity auction outcome is amplified as the subsidized unit's net marginal costs rise.

6 Short-Run Welfare Analysis

Having characterized the key outcomes of the capacity auction with and without subsidized entry, I can now assess the impact of capacity subsidies on short-run expected welfare. In particular, I compare the level of expected welfare in the benchmark setting to the environment with subsidized entry, taking into account the effect that the allocation of capacity has on the subsequent delivery-year electricity market interactions (i.e., the energy portfolio effect).

The benchmark setting is analogous to a framework in which a regulatory policy prevents an entrant from receiving an OOM payment. For instance, PJM's MOPR removes the entrant's ability to use the subsidy to lower its net marginal cost such that its new capacity investment can be procured for a profit.[34] (Recall Proposition 2.) Therefore, the welfare comparison in this section can also be interpreted as evaluating the performance of such a regulatory policy.

For a given bid profile $\boldsymbol{\beta}$ and the resulting generation portfolio ψ, expected short-run social welfare equals $E[W] = E[V + \Pi - S]$ where V denotes the surplus enjoyed by the consumers, $\Pi = \sum_{v \in \{\mathbf{I},\mathbf{E}\}} \Pi_v$ is the total rent of all firms in the industry, and S is the societal cost of raising the subsidy. When there are no OOM payments $S = 0$. When $\tau > \widetilde{\tau}$, $S = (1+\lambda)\tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta})$ where λ reflects the social costs of raising public funds and $X_{E_s}(\widehat{\theta}; \boldsymbol{\beta})$ is E_s's allocation of capacity in the auction defined in (10).[35]

There are $T < \infty$ subsequent energy market interactions during the delivery-year. Therefore, V reflects the aggregate surplus consumers derived from all energy market interactions. The capacity market determines the resulting generation portfolio in the subsequent energy market interactions and the capacity price passed onto consumers. For a given bid profile $\boldsymbol{\beta}$ and portfolio ψ, consumer surplus is characterized as follows:

$$V(\psi, \boldsymbol{\beta}) = \sum_{t=1}^{T} \int_{P_t}^{P_t^{max}} \phi(t, \mu) dP \tag{13}$$

[34] Since the regulator has imperfect information about firms' net marginal costs, the mitigated offer-floor is an imperfect estimate. However, in the current analysis the regulator's information requirement is weak. It is assumed that the regulator has sufficient information to know that the subsidized entrant's new capacity investment is receiving an OOM payment and is not among the l most efficient new capacity investments.

[35] λ reflects the distortions created by taxing consumers/taxpayers to raise funds for the subsidy.

where for a given market interaction t: P_t equals the aggregate price consumers pay; P_t^{max} represents the consumers' maximum willingness to pay;[36] and $\phi(t,\mu)$ is the price-inelastic energy demand function. The energy demand function for each interaction t is uncertain *ex ante* because characteristics such as weather conditions and consumption patterns are not known with certainty. μ is a random variable representing these uncertainties where μ has a known distribution $h(\mu)$ on the support $[\underline{\mu},\overline{\mu}] \subset \mathbb{R}$. The aggregate price for market t is decomposed into two terms: $P_t = P_t^E + P_t^C$ where P_t^E represents the cost of consuming a unit of energy and P_t^C reflects the capacity payment passed onto consumers in market t.[37] Using the results in Propositions 1 and 2, the capacity prices are known. However, the energy prices P_t^E are uncertain *ex ante* because these prices are determined by the interaction among generation units in subsequent energy procurement auctions which depend on the realization of fuel input costs, unexpected unit deactivations, and environmental and regulatory policies. Further, the resulting energy prices are affected by the nature of competition in the subsequent energy procurement markets. Therefore, the distribution of energy prices is conditional on the generation portfolio resulting from the allocation of capacity in the capacity auction. More formally, $P_t^E = P_t^E(\sigma)$ is a random variable with a conditional probability distribution $g(\sigma|\psi)$ on the support $[\underline{\sigma},\overline{\sigma}] \subset \mathbb{R}$ for a given portfolio allocation $\psi \in \Psi$ where σ reflects energy market uncertainties.

For a given bid function $\boldsymbol{\beta}$ and the resulting generation portfolio ψ, the expected short-run welfare function is:

$$E[W(\boldsymbol{\beta},\psi)] = \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Pi_v + E\left[\sum_{t=1}^{T}\int_{P_t}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi\right] - (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}). \tag{14}$$

Using the equilibrium outcomes in Propositions 1 and 2, Lemma 3 characterizes the change in expected short-run welfare by comparing the welfare levels with $(\tau > \widetilde{\tau})$ and without $(\tau = 0)$ subsidized entry.

Lemma 3. $E[\Delta W] = E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^{S},\psi^{S})|_{\tau>\widetilde{\tau}}]$ equals:

$$\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) + \sum_{t=1}^{T}\Big(E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right]\Big) + (p^S - p^{NS})\widehat{\theta}. \tag{15}$$

The first term in (15) is the change in total industry profit. The second term is the social costs of raising the subsidy. The third term represents the expected energy portfolio effect. The fourth term reflects the difference in the capacity payments with and without subsidized entry. From Proposition 5, the change in total industry profit term is positive. The social cost of subsidizing the entrant is also positive. Since the

[36] P_t^{max} is often referred to as the value of lost load (VOLL) (Joskow and Tirole, 2007).

[37] For each unit of energy consumed by consumers, they must pay a capacity price charge. This charge reflects the cost of capacity procurement. Therefore, $P_t^C = f(p^*,\widehat{\theta},T,\phi(t,\mu))$. It is without loss of generality to assume that the capacity payment scheme is constructed such that $E[\sum_{t=1}^{T} P_t^C\phi(t,\mu)] = p^*\widehat{\theta}$ to ensure that the capacity procurement costs are fully recovered.

existence of subsidized entry depresses the capacity price (i.e., $p^{NS} > p^S$), the capacity payment effect on consumer surplus is negative. The expected energy portfolio effect reflects the change in expected energy procurement costs due to a change in the generation portfolio. That is, because the allocation of capacity determines the portfolio of generation units, it affects the nature of competition in subsequent market interactions and hence, affects the resulting distribution of energy prices. Suppose Assumption 3 holds. The energy portfolio effect is negative because the expected energy procurement costs under the portfolio ψ^{NS} exceed those under ψ^S $\left(\text{i.e., } \sum_{t=1}^T E\left[P_t^E \phi(t,\mu) \middle| \psi^{NS}\right] > \sum_{t=1}^T E\left[P_t^E \phi(t,\mu) \middle| \psi^S\right]\right)$.[38]

Using Lemma 3, Proposition 6 evaluates the effect of subsidized entry on expected short-run welfare.

Proposition 6. $E[\Delta W] = E[W(\boldsymbol{\beta}^{NS}, \psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^S, \psi^S)|_{\tau>\tilde{\tau}}] \gtreqless 0$ as:

$$\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S) \gtreqless \sum_{t=1}^T \left(E\left[P_t^E \phi(t,\mu) \middle| \psi^{NS}\right] - E\left[P_t^E \phi(t,\mu) \middle| \psi^S\right]\right) + (p^{NS} - p^S)\widehat{\theta}. \quad (16)$$

The components in both the right-hand and left-hand sides of inequality (16) are non-negative.[39] Therefore, Proposition 6 reveals that subsidized entry may be welfare-enhancing (i.e., $E[\Delta W] < 0$) if the benefit to consumers through reduced expected energy procurement costs (E_s's energy portfolio effect) and capacity payments ($p^* > p'$) exceed the reduction in total industry profit and the social cost of raising the subsidy. This implies that there are certain settings in which regulatory policies such as the MOPR may be welfare-reducing in the short-run. Alternatively, if the capacity payment effect and E_s's energy portfolio effect are sufficiently limited, then subsidized entry reduces expected short-run social welfare because the negative aspects of allowing OOM payments detailed in Propositions 3 and 5 outweigh the benefits to consumers from suppressed capacity and energy procurement prices. In these settings, regulatory policies such as the MOPR are welfare-enhancing.

Corollary 1. Suppose Assumption 3 holds. If E_s's expected energy portfolio effect is zero, then $E[\Delta W] > 0$.

Corollary 1 reveals that the capacity payment effect induced by the OOM payment is not sufficiently large to solely offset the welfare-reducing effects of subsidized entry. This implies that subsidized entry enhances short-run expected welfare if and only if E_s's energy portfolio effect is sufficiently positive as defined in (16).

[38] That is, because E_s's unit is constructed in a region with scarce generation and transmission capacity and shifts the energy supply function down (see Assumption 3), the energy portfolio effect is negative as the expected energy market prices are lower with portfolio ψ^S compared to portfolio ψ^{NS}.

[39] If Assumption 3 fails to hold, then the expected energy portfolio effect term is negative. In this setting, subsidized entry is likely to reduce expected welfare (i.e., $E(\Delta W) > 0$) unless the benefits to consumers through lower capacity payments and the firms' higher expected earnings in subsequent energy markets under portfolio ψ^S compared to ψ^{NS} are sufficiently large to more than offset the social cost of raising the subsidy and the higher expected energy procurement prices passed onto consumers.

7 Energy Portfolio Effect

To illustrate the nature of the energy portfolio effect identified in the short-run welfare analysis, this section provides a basic model that characterizes the outcome of the subsequent delivery-year's energy procurement auctions given the generation portfolio determined by the allocation of capacity in the capacity auction.

Assume that each firm has a constant marginal cost of supplying electricity $\gamma_j^u \geq 0$ up to its capacity limit $\forall\, u \in \psi$ where $j \in \{\mathbf{I}, \mathbf{E}\}$. Define $\gamma(q|\psi) : \mathbb{R}_+ \to \mathbb{R}_+$ to be the non-decreasing aggregate marginal cost step-function that is formed by arranging the units in increasing order of their marginal cost of electricity generation given the portfolio $\psi \in \Psi$. For each market interaction t, energy demand is assumed to be a perfectly price-inelastic deterministic demand function $\phi(t)$.[40]

Similar to the capacity auction, energy procurement auctions are sealed-bid, uniform-priced, multi-unit auctions. However, for illustrative purposes it is assumed that firms are non-strategic in these energy procurement auctions and hence, they bid their marginal costs for each of their units. Further, assume that there are two demand realizations where $t = 1$ is a low-demand state, $\phi(L)$, and $t = 2$ is a high-demand state, $\phi(H)$. For a given portfolio $\psi \in \Psi$, the auctioneer sets the stop-out price:

$$P_t^E(\psi) = \min\{\gamma(\phi(t)|\psi), \bar{P}^E\} \text{ for each } t = L, H \tag{17}$$

where $\bar{P}^E$ is the price cap announced *ex ante* by the auctioneer. That is, $P_t^E(\psi)$ is the minimum of the price cap and the point where the aggregate marginal cost step-function intersects electricity demand, $\gamma(\phi(t)|\psi)$ (see Figure 3). For each market interaction t, generation units whose marginal costs do not exceed the stop-out price are called upon to supply electricity and are paid $P_t^E(\psi)$.

Suppose Assumption 3. Then, for any quantity of electricity demanded, q, the aggregate marginal cost step-function with portfolio ψ^S is weakly less than that with portfolio ψ^{NS} (i.e., $\gamma(q|\psi^{NS}) \geq \gamma(q|\psi^S)\ \forall\, q \geq 0$) because a change from portfolio ψ^{NS} to ψ^S shifts the function $\gamma(q|\cdot)$ weakly down.[41]

Lemma 4. For the generation portfolios ψ^{NS}, if $\gamma(q|\psi^{NS}) \geq \gamma(q|\psi^S)\ \forall\, q \geq 0$, then $P_t^E(\psi^{NS}) \geq P_t^E(\psi^S)$ for any $t = 1, 2, ..., T$.

Lemma 4 reveals that subsidized entry weakly reduces the market-clearing electricity procurement price for any level of energy demand. Figure 3 illustrates how altering the generation portfolio can shift the aggregate marginal cost function and its potential price reducing effects for both demand states.

[40] In Section 6 energy demand was stochastic. However, the current environment focuses on the setting in which energy demand has been realized and firms compete in energy procurement auctions.

[41] If Assumption 3 fails to hold, then $\gamma(q|\psi^{NS}) \leq \gamma(q|\psi^S)\ \forall\, q \geq 0$ such that the function $\gamma(q|\cdot)$ shifts weakly upward, weakly increasing energy procurement costs.

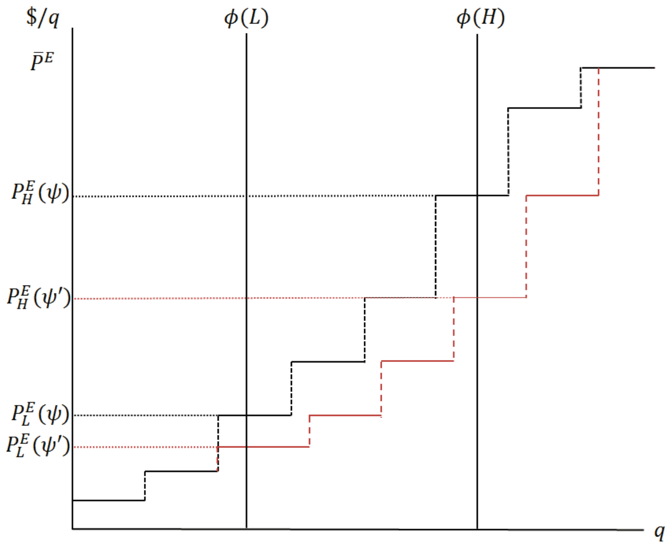


Figure 3: The Marginal Cost Functions $\gamma(q|\psi^{NS})$ and $\gamma(q|\psi^{S})$ with $\gamma(q|\psi^{NS}) \geq \gamma(q|\psi^{S})\ \forall\ q \geq 0$.

The total energy procurement costs with portfolios ψ^{NS} and ψ^{S} are $P_L^E(\psi^{NS})\phi(L) + P_H^E(\psi^{NS})\phi(H)$ and $P_L^E(\psi^{S})\phi(L) + P_H^E(\psi^{S})\phi(H)$, respectively. From Lemma 4, it is readily verified that $P_L^E(\psi^{NS})\phi(L) + P_H^E(\psi^{NS})\phi(H) \geq P_L^E(\psi^{S})\phi(L) + P_H^E(\psi^{S})\phi(H)$. This reflects the realization of the energy portfolio effect. Proposition 7 substitutes the realization of the energy portfolio effect into the expected short-run welfare analysis detailed in Proposition 6 to demonstrate when subsidized entry is welfare-enhancing or -reducing.

Proposition 7. Suppose Assumption 3 holds, $T = 2$, and firms bid non-strategically in the energy auctions. Then, $E[\Delta W] = E[W(\boldsymbol{\beta}^{NS}, \psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^{S}, \psi^{S})|_{\tau>\tilde{\tau}}] < 0$ if and only if:

$$P_L^E(\psi^{NS})\phi(L)+P_H^E(\psi^{NS})\phi(H)-\big(P_L^E(\psi^{S})\phi(L) + P_H^E(\psi^{S})\phi(H)\big) > \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v+(1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})-(p^{NS}-p^{S})\widehat{\theta}. \tag{18}$$

Proposition 7 provides an illustration of when the energy portfolio effect is sufficiently large (positive) enough to cause short-run welfare to increase in the presence of subsidized entry. The reduction in electricity prices induced by the change in the generation portfolio must exceed the reduction in total industry profits and cost of the subsidy adjusted by the reduced capacity price consumers pay.[42]

As the degree of generation and/or transmission capacity scarcity in the region in which E_s's unit is constructed increases (decreases), the electricity price suppressing effect is magnified (reduced) because the shift in the marginal cost function shown above is more (less) pronounced. In particular, $(P_H^E(\psi^{NS}) -$

[42]From Corollary 1, the right-hand side of inequality (18) is positive.

$P_H^E(\psi^S))\phi(H)$ will be more (less) positive in regions with a higher (lower) degree of generation and/or transmission capacity scarcity making it more (less) likely that inequality (18) will hold. For example, in New Jersey and Maryland, generation and transmission capacity is scarce during high-demand periods, leading to the need for these states to import electricity from other regions resulting in high electricity prices, congestion of their transmission lines, and concerns over potential outages. Alternatively, almost all other states in the Northeastern United States have sufficient generation capacity to ensure very few periods of capacity scarcity. Therefore, short-run expected social welfare is more (less) likely to increase in the presence of subsidized entry if the subsidized unit enters into a region with a high (low) degree of generation and/or transmission capacity scarcity.

8 Long-Run Effects of Subsidized Entry

The analysis to this point has assumed that there is a fixed set of new capacity investments. However, when evaluating the impacts of subsidized entry it is critical to investigate how subsidized entry affects firms' long-run generation investment incentives. This section derives the Subgame Perfect Nash Equilibrium (SPNE) of a sequential move game to illustrate the effect of subsidized entry on firms' investment decisions.

Consider the following two-stage game. In the first-stage an entrant E_i chooses a strategy $a \in A = \{a_1, a_2\} = \{\text{Invest}, \text{Do Not Invest}\}$ for some $i = 1, 2, ..., l-1$, while all other entrants choose invest with certainty.[43] If E_i chooses to invest, then it is making its new capacity investment available to be bid into the subsequent capacity auction. Otherwise, E_i is not able to bid into the capacity auction. Further, assume there is a cost $\zeta > 0$ of making a potential investment available to be bid into the capacity auction.[44] Define $\widetilde{U} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., \widetilde{U}_{E_i}, ..., U_{E_M}\}$ to be the set of generation units available to bid into the capacity auction where $\widetilde{U}_{E_i} = \mathbb{I}\{a = a_1\}U_{E_i} + \mathbb{I}\{a = a_2\}\emptyset$ and $\mathbb{I}\{\cdot\}$ is an indicator function which equals one if the interior statement is true, and zero otherwise. In the second-stage, after observing the set of available generation units, $\widetilde{U}$, firms compete to supply capacity by submitting bids into the capacity auction.

This game is solved by first characterizing the PSNE outcomes in the second-stage capacity auction with and without subsidized entry for any $\widetilde{U}$ determined by the first-stage, i.e., for each $a \in A$ chosen by E_i. Lemma 5 summarizes the outcome of the capacity auction for each $a \in A$ and $\tau \in \{0, \widetilde{\tau} + \epsilon\}$.

[43] A more detailed model which considers a setting in which each of the entrants choose a strategy $a \in A$ simultaneously in the first-stage warrants further attention. However, such an analysis is left for future research.

[44] If a firm's new capacity investment is procured in the subsequent capacity auction, the firm is obligated to make that capacity available in the energy procurement auctions for upcoming delivery-year. Therefore, ζ reflects the planning and licensing costs associated with preparing a potential new capacity investment to be bid into an upcoming capacity auction.

Lemma 5. The PSNE of the second-stage capacity auction involves:

(i) If $a = a_1$ and $\tau = 0$, then $p_{a_1}^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\cdot)$ and $\psi_{a_1}^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_i}, ..., U_{E_l}\}$;

(ii) If $a = a_1$ and $\tau = \widetilde{\tau} + \epsilon$, then $p_{a_1}^{S} = c_{E_l} - \bar{\pi}_{E_l}(\cdot)$ and $\psi_{a_1}^{S} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_i}, ..., U_{E_{l-1}}, U_{E_s}\}$;

(iii) If $a = a_2$ and $\tau = 0$, then $p_{a_2}^{NS} = c_{E_{l+2}} - \bar{\pi}_{E_{l+2}}(\cdot)$ and $\psi_{a_2}^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l+1}}\}$; and

(iv) If $a = a_2$ and $\tau = \widetilde{\tau} + \epsilon$, then $p_{a_2}^{S} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\cdot)$ and $\psi_{a_2}^{S} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_l}, U_{E_s}\}$.

Lemma 5 reveals that the Nash Equilibrium of the second-stage capacity auction involves the procurement of the l least-cost new capacity investments available in addition to the incumbents' installed generation units. Cases (i) and (ii) in Lemma 5 are equivalent to the outcomes in Propositions 1 and 2, respectively. However, if $a = a_2$ (cases (iii) and (iv)), then an additional, more costly, new capacity investment must be undertaken to replace E_i's forgone capacity investment. This increases the resulting stop-out price for a given τ value. For any given $a \in A$, subsidized entry suppresses the capacity price and alters the generation portfolio because E_s's capacity investment displaces the least-efficient new capacity investment that was dispatched in the absence of subsidized entry. The equilibrium outcome for each case is unique up to the identity of the price-setting and non price-setting firms.

Lemma 6 provides the necessary condition for E_i to choose to invest in the first-stage given its beliefs about the outcome of the subsequent capacity auction for any $\tau \in \{0, \widetilde{\tau} + \epsilon\}$.

Lemma 6. Define p_{a_1}, ψ_{a_1}, and $X_{E_i}(\widehat{\theta}; \boldsymbol{\beta})$ to be the equilibrium stop-out price, generation portfolio, and E_i's output in the subsequent capacity auction when strategy a_1 is chosen. E_i chooses a_1 if and only if:

$$[p_{a_1} + \bar{\pi}_{E_i}(\psi_{a_1})] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) \geq c_{E_i} X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) + \zeta. \tag{19}$$

Lemma 6 reveals that E_i will choose a_1 if and only if the revenue from the capacity payment and expected earnings in subsequent energy auctions exceeds the cost of capacity plus the upfront planning/licensing costs, ζ. Therefore, the SPNE of this two-stage game entails E_i choosing a_1 in the first-stage if and only if inequality (19) holds. This analysis illustrates the important implications that the magnitude of the capacity price and expected earnings in energy markets can have on a firm's investment decisions. Proposition 8 investigates the impact of subsidized entry on E_i's investment decision.

Proposition 8. Suppose Assumption 3 holds. Subsidized entry strictly reduces E_i's incentive to undertake a new capacity investment.

As illustrated in Lemma 5, subsidized entry suppresses the capacity auction price and alters the generation portfolio for any $a \in A$ chosen in the first-stage. From Assumption 3, the entry of the subsidized unit weakly reduces all of the firms' expected earnings in the subsequent deliver-year energy auctions. Therefore, because subsidized entry suppresses the capacity and expected electricity prices, E_i has reduced incentives to invest in new capacity in the presence of subsidized entry.

Reduced participation in capacity auctions has the potential to have substantial long-term impacts on resource adequacy and social welfare. First, reduced investment increases the expected capacity prices in future capacity auctions, ceteris paribus. Second, reduced investment increases the scarcity of generation capacity as electricity demand grows and aging units retire. This increases the likelihood of rolling blackouts or wide-spread cascading outages which have substantial social and economic costs. Further, a rise in capacity scarcity increases expected electricity prices in future electricity market interactions because during periods of high-demand costly generation units are called upon to meet electricity demanded.[45] This can be viewed as a shift upward in the long-run marginal cost function of supplying electricity.

I construct a long-run welfare analysis to illustrate the effects of reduced participation due to subsidized entry in capacity auctions. Long-run expected welfare equals:

$$E[W_{LR}] = E[\Pi_{LR}] + E\left[\sum_{t=1}^{T_{LR}} \left(\int_{\widetilde{p}_t}^{p_t^{max}} \phi(t,\mu_{LR})dp\right)(1-\rho_o(\tau)) + \left(\int_{\widetilde{p}_t}^{p_t^{max}} \phi(t,\mu_{LR})dp\right)(1-\omega)\rho_o(\tau)\right] \quad (20)$$

where $E[\Pi_{LR}] = E[\Pi_{LR}^E] + E[\Pi_{LR}^C]$ equals expected long-run industry profit from energy and capacity auctions, respectively. The second term in (20) reflects the long-run expected consumer surplus for T_{LR} future electricity market interactions. As in Section 6, for each market interaction t: p_t^{max} reflects the consumers' maximum willingness to pay for electricity, $\widetilde{p}_t = \widetilde{p}_t^E + \widetilde{p}_t^C$ reflects the aggregate payment separated into a capacity and energy procurement cost component, and $\phi(t,\mu_{LR})$ is the level of electricity demanded.[46] To investigate the long-run impact of local and system-wide outages, $\rho_o(\tau) \in (0,1)$ reflects the probability of an outage for a given subsidy $\tau \in \{0, \widetilde{\tau}+\epsilon\}$ and $\omega \in (0,1]$ represents the percentages of consumers who do not receive electricity if a blackout occurs. An increase in capacity scarcity implies that $\rho_o(\tau = 0) < \rho_o(\tau > \widetilde{\tau})$.

In the presence of subsidized entry, there are two important cases to consider: (i) the system-wide long-run expected energy price increases due to reduced capacity investment dominates the regional short-run electricity price suppressing effect identified in Sections 6 and 7 (i.e., E_s's energy portfolio effect) and (ii) the system-wide long-run expected energy price effects do not exceed the short-run energy portfolio effect.

[45] Also, firms are more likely to exercise market power during periods of high-demand when capacity is scarce resulting in higher electricity prices (Crawford et al., 2007). The occurrence of such high-demand periods increases as capacity scarcity rises.

[46] As in Section 6, $\phi(t,\mu_{LR})$ is a random variable where μ_{LR} has some distribution $h_{LR}(\mu_{LR})$ on the support $[\underline{\mu}_{LR}, \bar{\mu}_{LR}] \subset \mathbb{R}$. Further, $\widetilde{p}_t^E$ is a random variable with conditional probability distribution $g(\sigma|\psi)$ on the support $[\underline{\sigma}, \bar{\sigma}] \subset \mathbb{R}\ \forall\ \psi \in \Psi$.

In case (i), subsidized entry increases the expected long-run energy price (i.e., $E[\widetilde{p}_t^E|\psi^{NS}] < E[\widetilde{p}_t^E|\psi^S]$). In case (ii), $E[\widetilde{p}_t^E|\psi^{NS}] \geq E[\widetilde{p}_t^E|\psi^S]$.

Proposition 9. $E[\Delta W_{LR}] = E[W_{LR}|_{\tau=0}] - E[W_{LR}|_{\tau>\widetilde{\tau}}] \gtreqless 0$ as $E[\Delta\Pi_{LR}^C] + E[\Delta\Pi_{LR}^E] + E[\Delta CS_{LR}] \gtreqless 0$ where:

$$
\begin{aligned}
E[\Delta CS_{LR}] \quad &= \quad E\Bigg[\sum_{t=1}^{T_{LR}} \phi(t,\mu_{LR})\big\{[p_t^{max} - \widetilde{p}_t^{NS}]\,(1-\rho_o(\tau=0) + \rho_o(\tau=0)(1-\omega)) \\
&- \quad [p_t^{max} - \widetilde{p}_t^{S}]\,(1-\rho_o(\tau>\widetilde{\tau}) + \rho_o(\tau>\widetilde{\tau})(1-\omega))\,\big\}\Bigg]. \qquad (21)
\end{aligned}
$$

Proposition 9 characterizes the impact of reduced capacity investment associated with subsidized entry on long-run expected welfare. $E[\Delta\Pi_{LR}^C]$ and $E[\Delta\Pi_{LR}^E]$ reflect the change in expected industry profits from capacity and energy auctions, respectively. For a market t and $\tau \in \{0, \widetilde{\tau}+\epsilon\}$, $[p_t^{max} - \widetilde{p}_t^j]\phi(t,\mu_{LR})$ reflects the surplus consumers obtain from consuming energy $\forall\, j \in \{NS, S\}$ weighted by: (1) the probability that there is no black-out, $(1-\rho_o(\tau))$, and (2) the probability of an outage, $\rho_o(\tau)$, times the number of consumers served if an outage occurs, $(1-\omega)$.

The change in expected industry profit is ambiguous. In case (i) subsidized entry increases long-run expected electricity prices resulting in an increase in expected future profits from electricity auctions (i.e., $E[\Delta\Pi_{LR}^E] < 0$). Alternatively, in case (ii), E_s's energy portfolio effect dominates the expected system-wide electricity price increases induced by reduced participation such that $E[\Delta\Pi_{LR}^E] \geq 0$. In either case, subsidized entry and reduced investment incentives increases expected capacity prices resulting in higher expected profits from capacity auctions (i.e., $E[\Delta\Pi_{LR}^C] < 0$).

Long-run expected consumer surplus strictly decreases in the presence of reduced participation in capacity auctions unless E_s's energy portfolio effect is large enough to more than offset the system-wide expected electricity price increases and the increased probability of blackouts due to a higher degree of capacity scarcity (i.e. $\rho_o(\tau > \widetilde{\tau}) > \rho_o(\tau = 0)$). This implies that expected long-run consumer surplus strictly falls ($E[\Delta CS] > 0$) in case (i) and weakly increases ($E[\Delta CS] \leq 0$) in case (ii) when subsidized entry occurs if and only if E_S's energy portfolio effect is sufficiently large.[47]

Long-run expected welfare increases in the presence of reduced participation in case (i) if and only if the increase in expected industry profit more than offsets the reduction in expected consumer surplus.[48]

[47] That is, $E[\sum_{t=1}^{T_{LR}} \widetilde{p}_t^S \phi(t,\mu_{LR}) W_{\tau>\widetilde{\tau}}] \leq E[\sum_{t=1}^{T_{LR}} \widetilde{p}_t^{NS} \phi(t,\mu_{LR}) W_{\tau=0}] - p_t^{max}(W_{\tau=0} - W_{\tau>\widetilde{\tau}})$ where $W_\tau = (1-\rho_o(\tau) + (1-\omega)\rho_o(\tau))\ \forall\ \tau \in \{0, \widetilde{\tau}+\epsilon\}$. This reflects the fact that the expected energy price with subsidized entry must be below the expected energy price without subsidized entry adjusted by the reduced consumer payoff due to a higher propensity of blackouts.

[48] If expected long-run welfare rises in this case, it reflects a substantial redistribution of surplus from consumers to the producers of electricity. If the long-run expected welfare function puts more weight on consumer surplus, then it is less likely the change in long-run expected social welfare will be positive.

Similarly, in case (ii), long-run expected welfare rises if and only if the higher expected profits from capacity markets and the local consumers' benefits from E_s's energy portfolio effect is sufficiently large to more than offset the firms' lower expected profits from electricity markets and the reduction in consumer surplus from system-wide expected electricity price increases and the increased probability of blackouts.

Proposition 9 reveals that capacity scarcity has major implications on the level of expected long-run consumer surplus.[49] During periods of black-outs, there are substantial losses to consumer surplus as the surplus $(p_t^{max} - \widetilde{p}_t)$ is lost for the $\omega \in (0, 1]$ percent of consumers affected. Reduced participation increases the probability of black-outs (i.e., $\rho_o(\tau > \widetilde{\tau}) > \rho_o(\tau = 0)$). Further, the higher degree of capacity scarcity due to reduced participation increases the expected energy prices in future market interactions (i.e., $E[\widetilde{p}_t^{NS}] < E[\widetilde{p}_t^{S}]$). As these two forces increase (decrease), it is more (less) likely that expected long-run consumer surplus falls (rise) due to reduced participation and hence, it is more (less) likely that expected long-run welfare decreases when capacity is subsidized. Several market characteristics amplify or dampen these negative effects of capacity scarcity identified in Proposition 9. First, the wide-spread retirement of aging coal units due to stricter environmental regulations and cheaper alternative fuels such as natural gas has accelerated the need for new capacity investments. Reduced participation is more likely to raise capacity scarcity and resource adequacy concerns in regions with higher concentrations of coal generation.

Second, increasing penetration of renewable generation technologies, which provide an intermittent supply of electricity, increases the need for an adequate reserve of natural gas-fired generation units which can start and stop producing electricity relatively quickly. For example, in regions with a large presence of solar (wind) generation resources, if the sun (wind) is unexpectedly blocked (stops), then electricity markets rely on quick-response generation units to offset the decline in supply. Therefore, reduced investment incentives of new natural gas-fired units due to subsidized entry can result in periods where there is an unexpected interruption in the supply of renewable resources and no reserve quick-response resources to call upon to meet demand. Such events can lead to regional and system-wide outages. Hence, reduced investment incentives in regions with considerable and/or growing renewable portfolios are likely to observe an increase in the occurrence of periodic capacity scarcity due to the dynamic nature of electricity markets.

Third, demand-response resources provide regulators with a tool to adjust demand to reduce the degree of capacity scarcity. Demand-response resources can be viewed as a substitute for electricity generation during periods of high-demand. Therefore, regions with a high penetration of demand-response resources

[49]The expected loss of consumer surplus due capacity scarcity induced by reduced participation increases as the probability of a blackout ($\rho_o(\tau > \widetilde{\tau})$), the consumers' maximum willingness to pay (p_t^{max}) that is foregone when an outage occurs, or the percentage of consumers who do not receive electricity if a blackout occurs (ω) increase.

will limit the degree of capacity scarcity associated with lower investment incentives due to subsidized entry.

9 Conclusion

I have constructed a model that evaluates the effect of subsidized entry on capacity market outcomes. I have shown that such OOM payments reduce the market-clearing capacity price and induce allocative inefficiencies. The capacity price suppression and allocative inefficiencies become more pronounced as the subsidized unit becomes less efficient. These effects reduce the level of total industry profits compared to a setting with no OOM payments and may increase consumer surplus under plausible conditions. This implies that the effect of subsidized entry on the overall level of expected short-run welfare is ambiguous. Subsidized entry has the potential to increase expected short-run welfare if the increase in consumer surplus via the energy portfolio and capacity price effects more than offset the reduction in total industry profits and the social cost of raising the subsidy. Otherwise, expected short-run welfare is reduced in the presence of subsidized entry. This result stresses the importance of taking a system-wide modeling approach that accounts for the effect of the allocation of capacity in the capacity auction on subsequent market interactions.

In addition to these short-run effects, subsidized entry reduces firms' incentives to undertake new capacity investments. Reduced participation increases the degree of capacity scarcity which has adverse impacts on the level of long-run expected consumer surplus due to higher expected long-run electricity prices and an increased probability of local and system-wide blackouts. Therefore, reduced participation can increase expected system-wide electricity prices and undo the price-reducing effects of E_s's energy portfolio effect. However, reduced capacity investment has the potential to increase expected long-run industry profits and hence, the overall effect on long-run social welfare is ambiguous.

These results provide important insights into how subsidized entry should be regulated in centralized capacity auctions. A uniform mandate that restricts all OOM payments may not be the optimal policy.[50] Rather, it is important to consider the effects that the entry of subsidized resources will have on subsequent market interactions. (Recall Section 7.) It is also critical to consider the potential adverse long-term impacts of capacity subsidies on participation incentives.

This paper provides a framework to assess the system-wide short-term and long-term impacts of subsidized entry. The properties of the ideal capacity subsidy policy vary with the impact of subsidized entry on consumer surplus through reduced capacity and expected electricity prices, the social cost of capacity subsi-

[50] Currently, PJM has several proposed exemptions from their MOPR bid offer-floors which restrict OOM payments. However, these exemptions focus on allowing LSEs to provide capacity subsidies that are operating under longstanding business models that predate the capacity auction (PJM, 2012)

dization, the change in aggregate firm profits, and the long-term adverse impacts on investment incentives. The impact of each of these factors depends largely upon the characteristics of the electricity market under consideration. For instance, E_s's energy portfolio effect will be more pronounced in a region with a high degree of capacity and/or transmission scarcity. Alternatively, the negative long-term aspects associated with capacity scarcity due to reduced participation incentives are magnified (dampened) in regions with a considerable portfolio of aging coal units and/or renewables generation technologies (demand-response).

For illustrative purposes, the analysis has considered a simple setting. However, the key qualitative conclusions are not an artifact of simplifying assumptions.[51] In particular, allowing the incumbents' to undertake new capacity investments does not affect the short-run or long-run effects of subsidized entry.[52] In this setting, the incumbents may procure their new capacity investments for a loss to avoid allocation externalities induced by the entry of certain units. Alternatively, E_s may have a heterogeneous capacity limit (i.e., $k_{E_s} > k_E$).[53] As the capacity limit of the subsidized unit's new capacity investment expands, the capacity price suppression and the extent of the inefficient allocation of capacity increase. Lastly, Assumption 2.4 states that the allocation externalities are sufficiently small such that the set of entrants ($\mathbf{E}$) can be ordered in terms of their net marginal cost for any portfolio $\psi \in \Psi$. Relaxing this assumption complicates the analysis substantially.[54] However, in any potential PSNE, the effect of capacity subsidies is identical to those presented in the simplified analysis.

Further research is required to investigate other aspects of subsidized entry in order to assist in directing the regulatory policy. This article provides a framework to assess such considerations. First, the potential indirect impacts that subsidized entry has on firms' retirement incentives for their installed generation units also warrants attention. Subsidized entry reduces capacity payments to firms procured in the auction and has the potential to have a large impact on subsequent energy markets via the energy portfolio effect. Therefore, the potentially lower expected energy market payoffs may induce a firm to retire an installed unit. Second, future research might also investigate alternative regulatory policies aimed at preventing subsidized entry such as the Alternative Price Rule (APR) which has been considered in ISO-New England (FERC, 2011). Using the current framework the APR can be evaluated and compared to the MOPR adopted by PJM. This will contribute to the contentious debate over which regulatory policy performs better. Third, a more robust

[51] For a detailed discussion and analysis of these extensions, see the Technical Appendix.

[52] However, in this setting, the critical threshold $\widetilde{\tau}$ weakly decreases, weakly increasing the social cost of subsidization.

[53] García-Díaz and Marin (2003) and Crawford et al. (2007) characterize how heterogeneous capacity limits affects firms' bidding behavior in electricity procurement auctions.

[54] This analysis is closely related to Jehiel and Moldovanu's 2001 characterization of an efficient mechanism in multi-unit auctions with allocation externalities. In the current setting, necessary and sufficient conditions for a PSNE can be derived. Further, existence can be ensured under certain settings.

model that characterizes the buyers' incentives to provide a subsidy should be considered. Regulators have imperfect information about the cost of providing new capacity investments and hence, they have problems identifying which resources are receiving OOM payments. Therefore, this would help characterize what types of resources are most likely to receive subsidies limiting the large costs associated with investigating each resource's underlying cost of capacity.[55]

[55] Recently, PJM used data on their capacity auction to empirically investigate when buyers have an incentive to provide an OOM payment to a resource (PJM, 2013). However, a more robust analysis warrants further attention.

APPENDIX

Proof of Lemma 1: The proof proceeds in two steps. Prove that: (1) $b_{E_i} \leq p^* \Rightarrow c_{E_i} - \bar{\pi}_{E_i}(\psi) \leq p^*$ and (2) $b_{E_i} \leq p^* \Leftarrow c_{E_i} - \bar{\pi}_{E_i}(\psi) \leq p^*$.

Part (1): Assume there exists a bid profile $\boldsymbol{\beta}$ with $b_{E_i} \leq p^*$ and $p^* < c_{E_i} - \bar{\pi}_{E_i}(\psi)$ for some $i = 1, 2, ..., M$ and $\psi \in \Psi$ with $U_{E_i} \in \psi$. Assume that E_i unilaterally deviates to $b^{'}_{E_i} = c_{E_i} - \bar{\pi}_{E_i}(\psi)$ resulting in the stop-out price $p' \geq p^*$. Define this new bid profile as $\boldsymbol{\beta}'$. There are two potential outcomes: (i) $p^* < b^{'}_{E_i} = p'$ and (ii) $p^* < p' < b^{'}_{E_i}$.

Case (i): E_i was earning a negative payoff under the bid profile $\boldsymbol{\beta}$. However, by deviating to $b^{'}_{E_i}$ the stop-out price increases and E_i earns a payoff of zero on each unit of capacity procured.

Case (ii): E_i goes from procuring capacity for a loss to earning a payoff of zero because its capacity is no longer procured.

Part (2): Assume there exists a bid profile $\boldsymbol{\beta}$ with $b_{E_i} > p^*$ and $c_{E_i} - \bar{\pi}_{E_i}(\psi) \leq p^*$ for some $i = 1, 2, ..., M$ where $\psi \in \Psi$ with $U_{E_i} \in \psi$ such that E_i procures no output and earns a payoff of zero.[56] Assume that E_i unilaterally deviates to $b^{'}_{E_i} = p^* - \epsilon$ resulting in E_i's capacity being at least partially procured for some $\epsilon \geq 0$.[57] Define this new bid profile as $\boldsymbol{\beta}'$ and the resulting stop-out price as $p' \in \{p^* - \epsilon, p^*\}$. Using (1), (3), (9), and (10), because $p' \geq c_{E_i} - \bar{\pi}_{E_i}(\psi)$ and $X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}') \geq 0$ the following inequality holds:[58]

$$\begin{aligned} \Delta\Pi_{E_i} &= \Pi_{E_i}|_{b'_{E_i}} - \Pi_{E_i}|_{b_{E_i}} \geq 0 \\ &\Leftrightarrow [p' - (c_{E_i} - \bar{\pi}_{E_i}(\psi))]X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}') - 0 \geq 0. \end{aligned} \tag{22}$$

□

Proof of Proposition 1: The incumbents are restricted to bid $b^u_{I_j} \leq \bar{b}^u_{I_j}$. By assumption $\max\{\bar{b}_{I_1}, \bar{b}_{I_2}\} < c_{E_1} - \bar{\pi}_{E_1}(\psi) \; \forall \;\; \psi \in \Psi$ such that the incumbents' installed units are always procured and the entrants compete over residual demand $\widehat{\theta} - K_I$ where $K_I = \sum_{j=1}^{2} \sum_{u \in U_{I_j}} k^u_{I_j}$. Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ with $\max\{b_{E_i} \; \forall \; i = 1, 2, ..., l \text{ with } i \neq k\} < b_{E_k} = p^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM}) = b_{E_{l+1}}$ where $\psi^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_l}\}$, $\psi^{EM} = \{\psi \backslash U_{E_k}, U_{E_{l+1}}\}$, and $i, k = 1, 2, ..., l$ with $i \neq k$. Under the bid profile $\boldsymbol{\beta}^{NS}$, Π_{E_j} defined in (9) is positive $\forall \; j \leq l$ and zero $\forall \; j > l$.

[56] The portfolio ψ is the resulting portfolio if E_i chooses to deviate and procure positive capacity.

[57] $\epsilon > 0$ if $p^* > c_{E_i} - \bar{\pi}_{E_i}(\psi)$ and $\epsilon = 0$ if $p^* = c_{E_i} - \bar{\pi}_{E_i}(\psi)$.

[58] Inequality (22) holds with strict inequality when $p^* > c_{E_i} - \bar{\pi}_{E_i}(\psi)$ where $p' = p^* - \epsilon$ and $\epsilon > 0$ because the non-infinitesimally small output increase ($X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}') > 0$) dominates the infinitesimally small price reduction. Alternatively, if $p^* = c_{E_i} - \bar{\pi}_{E_i}(\psi)$, then $p' = p^*$ and inequality (22) holds with equality. However, it is assumed that the entrant prefers the potential to procure positive capacity for a payoff of zero, rather than procure no capacity with certainty.

The non price-setters ($\forall\ i = 1, 2, .., l$ with $i \neq k$) bid sufficiently low to ensure that the price-setter (k) does not have an incentive to unilaterally deviate to become a non price-setter. Define $\bar{b}_E = \max\{b_{E_i}\ \forall\ i = 1, 2, ..., l \text{ with } i \neq k\}$. Assume E_k unilaterally deviates to $b'_{E_k} < \bar{b}_E$ such that it becomes inframarginal resulting in stop-out price $p^{NS'} = \bar{b}_E$. Using (1)-(8), the non price-setters' bids are sufficiently low if:

$$\begin{aligned}
\Delta\Pi_{E_k} &= \Pi_{E_k}|_{b'_{E_k}} - \Pi_{E_k}|_{b_{E_k}} \leq 0 \\
&\Leftrightarrow\ [p^{NS'} - (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS}))]k_E - [p^{NS} - (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS}))]X_{E_k}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \leq 0 \\
&\Leftrightarrow\ [\bar{b}_E - (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS}))]k_E \leq [c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM}) - (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS}))]X_{E_k}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \\
&\Leftrightarrow\ \bar{b}_E \leq (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS})) + [c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM}) - (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS}))]\left(\frac{X_{E_k}(\widehat{\theta}; \boldsymbol{\beta}^{NS})}{k_E}\right). \quad (23)
\end{aligned}$$

If inequality (23) is satisfied, then E_k has no incentive to unilaterally deviate to become a non price-setter. Next, I show that the non price-setters have no incentive to deviate from bidding sufficiently low (as defined in (23)). Assume E_j unilaterally deviates from $b_{E_j} \leq \bar{b}_E$ to $b'_{E_j} > \bar{b}_E$ for some $j \leq l$ with $j \neq k$. There are three potential outcomes: (i) $b'_{E_j} < p^{NS}$; (ii) $b'_{E_j} = p^{NS}$; and (iii) $b'_{E_j} > p^{NS}$.

Case (i): There is no change in E_j's payoff because the stop-out price and E_j's output remains unchanged.

Case (ii): E_j's payoff weakly decreases because the stop-out price is unchanged, while E_j's output weakly decreases because it is now rationed.

Case (iii): E_j's payoff falls to zero because its capacity is no longer procured.

Lastly, I show that the price-setter E_k and first extramarginal firm E_{l+1} have no incentive to unilaterally deviate from the bid profile $\boldsymbol{\beta}$. If E_k unilaterally deviates to $b'_{E_k} \neq b_{E_k}$ there are three possible outcomes: (i) $b'_{E_k} < \bar{b}_E$; (ii) $\bar{b}_E < b'_{E_k} < b_{E_k}$; and (iii) $b_{E_k} < b'_{E_k}$.

Case (i): Conditional on the non price-setters' bids satisfying inequality (23), it is not profitable for entrant E_k to make such a deviation as shown above.

Case (ii): E_k's payoff decreases because the resulting stop-out price $p^{NS'} < p^{NS}$, while E_k's output is unchanged.

Case (iii): E_k's payoff falls to zero because its capacity is replaced in the dispatch order by E_{l+1}'s capacity.

From Lemma 1, no extramarginal firms $j \geq l + 1$ have an incentive to unilaterally deviate to procure positive capacity because doing so would result in procuring capacity for a loss.[59] This PSNE is unique up to the identity of the price-setter and non price-setting firms.

$\square$

[59] By bidding $b_{E_k} = p^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$, E_k ensures that the extramarginal firm, E_{l+1}, has no incentive to unilaterally deviate and undercut its bid b_{E_k}.

Proof of Proposition 2: Is analogous to the proof of Proposition 1. □

Proof of Proposition 3: Follows directly from Propositions 1 and 2. □

Proof of Proposition 4: $U^B(p, \alpha\widehat{\theta}, V_\alpha(p, \alpha\widehat{\theta}, \psi))$ is monotonically decreasing in τ in the intervals $[0, \widetilde{\tau})$ and $[\widetilde{\tau}, \infty)$ with a jump discontinuity at $\tau = \widetilde{\tau}$. Therefore, the buyer chooses among two values: (1) $\tau = 0$ or (2) $\tau = \widetilde{\tau} + \epsilon$ for some infinitesimally $\epsilon > 0$ which results in the PSNE characterized in Propositions 1 and 2, respectively. The buyer chooses $\tau = \widetilde{\tau} + \epsilon$ if and only if the equilibrium outcome in Proposition 2 yields a higher utility than the equilibrium from Proposition 1. Otherwise, $\tau = 0$. □

Proof of Lemma 2: Using (4)-(10) and the PSNE characterized in Proposition 1, the total industry profit for the setting without OOM payments ($\tau = 0$) is:

$$\sum_{v \in \{\mathbf{I}, \mathbf{E}\}} \Pi_v|_{\tau=0} = \sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{NS} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{NS}))\right] k^u_{I_j} + \sum_{i=1}^{l} \left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \quad (24)$$

Similarly, using (4)-(10) and the PSNE characterized in Proposition 2, the total industry profit for the setting with OOM payments ($\tau > \widetilde{\tau}$) is:

$$\begin{aligned} \sum_{v \in \{\mathbf{I}, \mathbf{E}\}} \Pi_v|_{\tau>\widetilde{\tau}} &= \sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{S} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{S}))\right] k^u_{I_j} + \sum_{i=1}^{l-1} \left[p^{S} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{S}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{S}) \\ &+ \left[p^{S} - (c_{E_s} - \bar{\pi}_{E_s}(\psi^{S}) - \tau)\right] X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^{S}) \end{aligned} \quad (25)$$

Using (24) and (25):

$$\begin{aligned} &\sum_{v \in \{\mathbf{I}, \mathbf{E}\}} \Delta\Pi_v = \sum_{v \in \{\mathbf{I}, \mathbf{E}\}} \Pi_v|_{\tau=0} - \sum_{v \in \{\mathbf{I}, \mathbf{E}\}} \Pi_v|_{\tau>\widetilde{\tau}} \gtreqless 0 \\ \Leftrightarrow\ & \sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{NS} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{NS}))\right] k^u_{I_j} + \sum_{i=1}^{l} \left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \\ -\ & \Bigg(\sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{S} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{S}))\right] k^u_{I_j} + \sum_{i=1}^{l-1} \left[p^{S} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{S}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{S}) \\ +\ & \left[p^{S} - (c_{E_s} - \bar{\pi}_{E_s}(\psi^{S}) - \tau)\right] X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^{S})\Bigg) \gtreqless 0 \end{aligned}$$

$$\Leftrightarrow \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\Big[p^{NS}-p^{S}+\bar{\pi}^{u}_{I_j}(\psi^{NS})-\bar{\pi}^{u}_{I_j}(\psi^{S})\Big]\,k^{u}_{I_j}+\sum_{i=1}^{l-1}\Bigg\{\left[p^{NS}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{NS}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})$$
$$-\ \left[p^{S}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{S}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S})\Bigg\}+\left[p^{NS}-(c_{E_l}-\bar{\pi}_{E_l}(\psi^{NS}))\right]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})$$
$$-\ [p^{S}-(c_{E_s}-\bar{\pi}_{E_s}(\psi^{S}))]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})\gtreqless\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S}). \tag{26}$$

□

Proof of Proposition 5: As characterized in Proposition 4, the buyer will provide one of two subsidy values $\tau\in\{0,\widetilde{\tau}+\epsilon\}$ for some $\epsilon>0$. There is a critical subsidy value τ^{*} at which (12) holds with equality:

$$\tau^{*}X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})=\sum_{j=1}^{2}\sum_{u\in U_{I_j}}\Big[p^{NS}-p^{S}+\bar{\pi}^{u}_{I_j}(\psi^{NS})-\bar{\pi}^{u}_{I_j}(\psi^{S})\Big]\,k^{u}_{I_j}+\sum_{i=1}^{l-1}\Bigg\{\left[p^{NS}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{NS}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})$$
$$-\ \left[p^{S}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{S}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S})\Bigg\}+\left[p^{NS}-(c_{E_l}-\bar{\pi}_{E_l}(\psi^{NS}))\right]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})$$
$$-\ [p^{S}-(c_{E_s}-\bar{\pi}_{E_s}(\psi^{S}))]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})$$
$$=\ p^{NS}\left(K_I+\sum_{i=1}^{l-1}X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})+X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})\right)-p^{S}\left(K_I+\sum_{i=1}^{l-1}X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S})+X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})\right)$$
$$+\ \sum_{j=1}^{2}\sum_{u\in U_{I_j}}[\bar{\pi}^{u}_{I_j}(\psi^{NS})-\bar{\pi}^{u}_{I_j}(\psi^{S})]k^{u}_{I_j}+\sum_{i=1}^{l-1}[c_{E_i}-\bar{\pi}_{E_i}(\psi^{S})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S})+[c_{E_s}-\bar{\pi}_{E_s}(\psi^{S})]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})$$
$$-\ \sum_{i=1}^{l-1}[c_{E_i}-\bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})-[c_{E_l}-\bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}). \tag{27}$$

Under the bid profiles $\boldsymbol{\beta}^{NS}$ and $\boldsymbol{\beta}^{S}$, capacity demand $\widehat{\theta}$ is served by the generation portfolios ψ^{NS} and ψ^{S}, respectively. Therefore, $\widehat{\theta}=K_I+\sum_{i=1}^{l-1}X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})+X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})=K_I+\sum_{i=1}^{l-1}X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S})+X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})$. (27) simplifies to:

$$(p^{NS}-p^{S})\widehat{\theta}+\sum_{j=1}^{2}\sum_{u\in U_{I_j}}[\bar{\pi}^{u}_{I_j}(\psi^{NS})-\bar{\pi}^{u}_{I_j}(\psi^{S})]k^{u}_{I_j}+\sum_{i=1}^{l-1}[c_{E_i}-\bar{\pi}_{E_i}(\psi^{S})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S})$$
$$+\ [c_{E_s}-\bar{\pi}_{E_s}(\psi^{S})]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})-\sum_{i=1}^{l-1}[c_{E_i}-\bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})-[c_{E_l}-\bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}). \tag{28}$$

The maximum potential subsidy is $\widetilde{\tau}+\epsilon$. If $\widetilde{\tau}+\epsilon<\tau^{*}$ for some $\epsilon>0$, then $\sum_{v\in\{\mathbf{I},\mathbf{E}\}}\Delta\Pi_v>0$. As $\epsilon\to 0$, using (28) and $\widetilde{\tau}=c_{E_s}-\bar{\pi}_{E_s}(\psi^{S})-(c_{E_l}-\bar{\pi}_{E_l}(\psi^{NS}))$:

$$(\widetilde{\tau}+\epsilon)X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})<\tau^{*}X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S})$$

$$\Leftrightarrow \quad (\widetilde{\tau}+\epsilon)X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) < (p^{NS}-p^S)\widehat{\theta} + \sum_{j=1}^{2}\sum_{u\in U_{I_j}} [\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} + [c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)$$

$$+\sum_{i=1}^{l-1}\Big([c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})$$

$$\Leftrightarrow \quad (p^{NS}-p^S)\widehat{\theta} + \sum_{i=1}^{l-1}\Big([c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big)$$

$$- \quad [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]\Big(X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) - X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)\Big) + \sum_{j=1}^{2}\sum_{u\in U_{I_j}} [\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} > 0. \tag{29}$$

$p^{NS} > p^S$, Assumption 2.2 implies that $c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}) \geq 0 \;\forall\; i = 1, 2, ..., M$, and Proposition 2 revealed that $X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) = k_E \geq X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})$. This implies that the first and last terms in (29) are positive and non-negative, respectively. From Assumption 3, $\bar{\pi}^u_j(\psi^{NS}) - \bar{\pi}^u_j(\psi^S) \geq 0 \;\forall\; j \in \{I_1, I_2, E_1, ..., E_{l-1}\}$. This implies that the second and third terms are non-negative because the net marginal cost of the firms' procured under both settings weakly increase. Hence, inequality (29) holds.

□

Proof of Lemma 3: Using Proposition 1, (13), (14), and (24), the expected short-run social welfare function with no OOM payments is:

$$E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}] = \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\Big[p^{NS} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{NS}))\Big]k^u_{I_j} + \sum_{i=1}^{l}\big[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\big]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})$$
$$+ \quad E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}}\phi(t,\mu)dP\,\middle|\,\psi^{NS}\right] \tag{30}$$

where $p^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM1})$; $\psi^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_l}\}$; $\psi^{EM1} = \{\psi^{NS}\backslash U_{E_k}, U_{E_{l+1}}\}$; and $P_t^{NS} = P_t^E + P_t^{C^{NS}}$.[60] $P_t^{C^{NS}} = f(p^{NS},\widehat{\theta},T,\phi(t,\mu))$ reflects the capacity payment passed onto consumers for each market interaction. It is without loss of generality to assume that the capacity payment scheme is constructed such that $E\left[\sum_{t=1}^{T}P_t^{C^{NS}}\phi(t,\mu)\right] = p^{NS}\widehat{\theta}$ to ensure that the capacity procurement costs are fully recovered.

Similarly, using Proposition 2, (13), (14), and (25), the expected short-run social welfare function when there is a resource receiving an OOM payments is:

$$E[W(\boldsymbol{\beta}^S,\psi^S)|_{\tau>\widetilde{\tau}}] \;=\; \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\Big[p^S - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^S))\Big]k^u_{I_j} + \sum_{i=1}^{l-1}\big[p^S - (c_{E_i} - \bar{\pi}_{E_i}(\psi^S))\big]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S)$$
$$+ \quad \big[p^S - (c_{E_s} - \bar{\pi}_{E_s}(\psi^S) - \tau)\big]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) + E\left[\sum_{t=1}^{T}\int_{P_t^S}^{P_t^{max}}\phi(t,\mu)dP\,\middle|\,\psi^S\right]$$
$$- \quad (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \tag{31}$$

[60] Recall, P_t^E is a random variable whose distribution is affected by the equilibrium generation portfolio. Hence, $E[P_t^E|\psi^{NS}] \neq E[P_t^E|\psi^S]$.

where $p^S = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM2})$; $\psi^S = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l-1}}, U_{E_s}\}$; $\psi^{EM2} = \{\psi^S \backslash U_{E_k}, U_{E_l}\}$; $P_t^S = P_t^E + P_t^{C^S}$; and $P_t^{C^S} = f(p^S, \widehat{\theta}, T, \phi(t,\mu))$ is constructed such that $E\left[\sum_{t=1}^T P_t^{C^S}\phi(t,\mu)\right] = p^S\widehat{\theta}$.

Using (30) and (31):

$$\begin{aligned}
E[\Delta W] &= E[W(\boldsymbol{\beta}^{NS}, \psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^S, \psi^S)|_{\tau>\tilde{\tau}}] \\
&= \sum_{j=1}^{2}\sum_{u\in U_{I_j}} \left[p^{NS} - (c_{I_j}^u - \bar{\pi}_{I_j}^u(\psi^{NS}))\right] k_{I_j}^u + \sum_{i=1}^{l}\left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \\
&+ E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi^{NS}\right] - \left\{\sum_{j=1}^{2}\sum_{u\in U_{I_j}} \left[p^S - (c_{I_j}^u - \bar{\pi}_{I_j}^u(\psi^S))\right] k_{I_j}^u\right. \\
&+ \sum_{i=1}^{l-1}\left[p^S - (c_{E_i} - \bar{\pi}_{E_i}(\psi^S))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^S) + \left[p^S - (c_{E_s} - \bar{\pi}_{E_s}(\psi^S))\right] X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S) \\
&+ \left. E\left[\sum_{t=1}^{T}\int_{P_t^S}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi^S\right] - (1+\lambda)\tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S)\right\} \\
&= \sum_{j=1}^{2}\sum_{u\in U_{I_j}} \left(p^{NS} + \bar{\pi}_{I_j}^u(\psi^{NS})) - \left[p^S + \bar{\pi}_{I_j}^u(\psi^S)\right]\right) k_{I_j}^u + \sum_{i=1}^{l}\left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \\
&- \sum_{i=1}^{l-1}\left[p^S - (c_{E_i} - \bar{\pi}_{E_i}(\psi^S))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^S) - \left[p^S - (c_{E_s} - \bar{\pi}_{E_s}(\psi^S))\right] X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S) \\
&+ E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi^{NS}\right] - E\left[\sum_{t=1}^{T}\int_{P_t^S}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi^S\right] + (1+\lambda)\tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S). \qquad (32)
\end{aligned}$$

The first four terms in (32) represent the change in total industry profits ($\sum_{v\in\{\mathbf{I},\mathbf{E}\}}\Delta\Pi_v$), the fifth and sixth terms reflect the change in expected consumer surplus ($E[\Delta V]$), and the last term is the social cost of subsidizing E_s's new capacity investment ($(1+\lambda)\tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S)$). The change in expected consumer surplus in (32) can be simplified further:

$$\begin{aligned}
E[\Delta V] &= E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi^{NS}\right] - E\left[\sum_{t=1}^{T}\int_{P_t^S}^{P_t^{max}} \phi(t,\mu)dP \middle| \psi^S\right] \\
&= E\left[\sum_{t=1}^{T}(P_t^{max} - P_t^{NS})\phi(t,\mu) \middle| \psi^{NS}\right] - E\left[\sum_{t=1}^{T}(P_t^{max} - P_t^S)\phi(t,\mu) \middle| \psi^S\right] \qquad (33)
\end{aligned}$$

The maximum consumers are willing-to-pay for electricity is unaffected by the portfolio allocation (i.e., $E\left[\sum_{t=1}^T P_t^{max}\phi(t,\mu)\middle|\psi\right] = E\left[\sum_{t=1}^T P_t^{max}\phi(t,\mu)\right]$ for any $\psi \in \Psi$). Further, recall that P_t^{NS} and P_t^S can be decomposed into two components: an energy price and capacity payment. (33) simplifies to:

$$\sum_{t=1}^{T}\left(\left[(P_t^E + P_t^{C^S})\phi(t,\mu)\Big|\psi^S\right] - E\left[(P_t^E + P_t^{C^{NS}})\phi(t,\mu)\Big|\psi^{NS}\right]\right)$$
$$= \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\big|\psi^S\right] - E\left[P_t^E\phi(t,\mu)\big|\psi^{NS}\right] + E\left[P_t^{C^S}\phi(t,\mu)\Big|\psi^S\right] - E\left[P_t^{C^{NS}}\phi(t,\mu)\Big|\psi^{NS}\right]\right). \tag{34}$$

By assumption, the capacity payment schedule is such that the total capacity procurement costs are recovered over all t market interactions (e.g., $E\left[\sum_{t=1}^{T} P_t^C\phi(t,\mu)\Big|\psi^{NS}\right] = p^{NS}\widehat{\theta}$). (34) simplifies to:

$$\sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\big|\psi^S\right] - E\left[P_t^E\phi(t,\mu)\big|\psi^{NS}\right]\right) + p^S\widehat{\theta} - p^{NS}\widehat{\theta}. \tag{35}$$

Using (35), (32) can be rewritten as:

$$\begin{aligned}
E[\Delta W] &= E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^S,\psi^S)|_{\tau>\widetilde{\tau}}] \\
&= \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\left(p^{NS} + \bar{\pi}_{I_j}^u(\psi^{NS}) - \left[p^S + \bar{\pi}_{I_j}^u(\psi^S)\right]\right)k_{I_j}^u + \sum_{i=1}^{l}\left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) \\
&- \sum_{i=1}^{l-1}\left[p^S - (c_{E_i} - \bar{\pi}_{E_i}(\psi^S))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - \left[p^S - (c_{E_s} - \bar{\pi}_{E_s}(\psi^S))\right]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \\
&+ \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\big|\psi^S\right] - E\left[P_t^E\phi(t,\mu)\big|\psi^{NS}\right]\right) + (p^S - p^{NS})\widehat{\theta} + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S).
\end{aligned} \tag{36}$$

Recognizing that the first four components in (36) reflect the change in total industry profit, (36) can be further simplified into:

$$E[\Delta W] = \sum_{v\in\{\mathbf{I},\mathbf{E}\}}\Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) + \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\big|\psi^S\right] - E\left[P_t^E\phi(t,\mu)\big|\psi^{NS}\right]\right) + (p^S - p^{NS})\widehat{\theta}. \tag{37}$$

□

Proof of Proposition 6: Using (37), $E[\Delta W] \gtreqless 0$ as:

$$\sum_{v\in\{\mathbf{I},\mathbf{E}\}}\Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \gtreqless \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\big|\psi^{NS}\right] - E\left[P_t^E\phi(t,\mu)\big|\psi^S\right]\right) + (p^{NS} - p^S)\widehat{\theta}. \tag{38}$$

□

Proof of Corollary 1: Suppose Assumption 3 holds. Further, assume that $\sum_{t=1}^{T} E\left[P_t^E\phi(t,\mu)\big|\psi^{NS}\right] = \sum_{t=1}^{T} E\left[P_t^E\phi(t,\mu)\big|\psi^S\right]$. Denote the change in total industry profits net of the subsidy by $\sum_{v\in\{\mathbf{I},\mathbf{E}\}}\Delta\widetilde{\Pi}_v$. Denote the change in capacity price as $\Delta p^C = (p^{NS} - p^S)\widehat{\theta}$. Using (37), $E[\Delta W] > 0$ as:

$$
\begin{aligned}
& \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v - \tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \Delta p^C > \sum_{t=1}^{T} E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^{S}\right] \\
\Leftrightarrow & \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v + \lambda\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \Delta p^C > 0 \\
\Leftarrow & \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v > \Delta p^C. \qquad (39)
\end{aligned}
$$

Using $\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v$ defined in (28), (39) can be written as:

$$
\begin{aligned}
& \Delta p^C + \sum_{j=1}^{2}\sum_{u\in U_{I_j}} [\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} + \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) \\
+ \quad & [c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) > \Delta p^C \\
\Leftrightarrow \quad & \sum_{j=1}^{2}\sum_{u\in U_{I_j}} [\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} + \sum_{i=1}^{l-1}\Big([c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) \\
+ \quad & \Big([c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) > 0. \qquad (40)
\end{aligned}
$$

From Assumption 3, the first term in (40) is non-negative and the second and third terms are positive because subsidized entry increases the aggregate net marginal cost of supplying capacity demand.[61] □

Proof of Lemma 4: If $\gamma(q|\psi^{NS}) \geq \gamma(q|\psi^S)\ \forall\ q \geq 0$, then $\gamma(\phi(t)|\psi^{NS}) \geq \gamma(\phi(t)|\psi^S)$. Using (17), this implies that $P_t^E(\psi^{NS}) = \min\{\gamma(\phi(t)|\psi^{NS}), \bar{P}^E\} \geq P_t^E(\psi^S) = \min\{\gamma(\phi(t)|\psi^S), \bar{P}^E\}$. □

Proof of Proposition 7: Assume that $T = 2$ and firms bid non-strategically in the electricity auctions. Using (37) and substituting $\sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]\right) = P_L^E(\psi^{NS})\phi(L) + P_H^E(\psi^{NS})\phi(H) - \left(P_L^E(\psi^S)\phi(L) + P_H^E(\psi^S)\phi(H)\right)$ which represents the realization of the energy portfolio effect, then $E[\Delta W] = E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^S,\psi^S)|_{\tau>\widetilde{\tau}}] < 0$ if and only if:

$$
P_L^E(\psi^{NS})\phi(L) + P_H^E(\psi^{NS})\phi(H) - \left(P_L^E(\psi^S)\phi(L) + P_H^E(\psi^S)\phi(H)\right) > \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - (p^{NS} - p^S)\widehat{\theta}.
$$

□

Proof of Lemma 5: There are four cases to consider: (i) $a = a_1$ and $\tau = 0$; (ii) $a = a_1$ and $\tau = \widetilde{\tau} + \epsilon$; (iii) $a = a_2$ and $\tau = 0$; and (iv) $a = a_2$ and $\tau = \widetilde{\tau} + \epsilon$. Cases (i) and (ii) are identical to the settings in

[61] This is the case because when E_s's new capacity is procured in place of E_l more efficient new capacity investment, aggregate capacity costs rise and firms' have weakly lower expected earnings in subsequent energy market interactions per Assumption 3.

Propositions 1 and 2. Firms' bidding incentives in cases (iii) and (iv) are analogous to those identified in the proof of Proposition 1. However, in cases (iii) and (iv), the l least-cost new capacity investments which are procured in the capacity auction involve the sets $(U_{E_1}, ..., U_{E_{l+1}})$ if $\tau = 0$ and $(U_{E_1}, ..., U_{E_l}, U_{E_s})$ if $\tau = \widetilde{\tau} + \epsilon$ because $U_{E_i} = \emptyset$.[62] In each of these settings, a single marginal bidder sets the stop-out price at the first extra-marginal firm's net marginal cost, while all non price-setters bid sufficiently low. The stop-out price and resulting generation portfolio for each of these cases is provided in the Lemma.[63] □

Proof of Lemma 6: For any value $\tau \in \{0, \widetilde{\tau} + \epsilon\}$, given its beliefs about the outcome of the subsequent capacity auction summarized in Lemma 5 $\forall\, a \in A$, entrant E_i will choose a_1 if and only if $\Pi_{E_i}(a_1)|_\tau \geq \Pi_{E_i}(a_2)|_\tau$.[64] If $a = a_2$, then E_i procures no capacity in the second-stage capacity auction and hence, $\Pi_{E_i}(a_2)|_\tau = 0$. Alternatively, if $a = a_1$, then E_i is receiving the capacity payment defined in Lemma 5 for each $\tau \in \{0, \widetilde{\tau} + \epsilon\}$. Define p_{a_1}, ψ_{a_1}, and $X_{E_i}(\widehat{\theta}; \boldsymbol{\beta})$ to be the equilibrium capacity price, generation portfolio, and E_i's output in the capacity auction when $a = a_1$.[65] Using (9) and (10) and Lemma 5, E_i will choose a_1 if and only if:

$$\begin{aligned} & \Pi_{E_i}(a_1)|_\tau \geq \Pi_{E_i}(a_2)|_\tau = 0 \\ \Leftrightarrow \quad & [p_{a_1} - (c_{E_i} - \bar{\pi}_{E_i}(\psi_{a_1}))] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) - \zeta \geq 0 \\ \Leftrightarrow \quad & [p_{a_1} + \bar{\pi}_{E_i}(\psi_{a_1})] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) \geq c_{E_i} X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) + \zeta. \end{aligned} \tag{41}$$

□

Proof of Proposition 8: Using the Nash Equilibrium outcomes summarized in Lemma 5, (9), and (10), E_i has reduced incentive to invest in new capacity in the presence of subsidized entry if:

$$\begin{aligned} & \Pi_{E_i}(a_1)|_{\tau=0} > \Pi_{E_i}(a_1)|_{\tau=\widetilde{\tau}+\epsilon} \\ \Leftrightarrow \quad & [p_{a_1}^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi_{a_1}^{NS}))] X_{E_i}(\cdot) - \zeta > [p_{a_1}^{S} - (c_{E_i} - \bar{\pi}_{E_i}(\psi_{a_1}^{S}))] X_{E_i}(\cdot) - \zeta \\ \Leftrightarrow \quad & p_{a_1}^{NS} - p_{a_1}^{S} + \bar{\pi}_{E_i}(\psi_{a_1}^{NS}) - \bar{\pi}_{E_i}(\psi_{a_1}^{S}) > 0. \end{aligned} \tag{42}$$

From Lemma 5, $p_{a_1}^{NS} > p_{a_1}^{S}$ and from Assumption 3 $\bar{\pi}_{E_i}(\psi_{a_1}^{NS}) \geq \bar{\pi}_{E_i}(\psi_{a_1}^{S})$ such that inequality (42) holds. □

Proof of Proposition 9: $E[W_{LR}] = E[\Pi_{LR}^E] + E[\Pi_{LR}^C] + E[CS_{LR}]$. Using (20), for any $\tau \in \{0, \widetilde{\tau} + \epsilon\}$:

[62] Recall, due to bid offer-caps, all of the installed generation units are also dispatched.

[63] For notational simplicity, in the Lemma for each of the stop-out prices I left the interior argument of the first extra-marginal bidder's expected earnings in energy markets blank. Recall from Proposition 1, the marginal bidder charges at the first extramarginal firm's net marginal cost $c_{E_j} - \bar{\pi}_{E_j}(\psi^{EM})$ for some $j \geq l$ where ψ^{EM} represents the generation portfolio in the setting in which the first extramarginal firm undercuts the marginal bidder.

[64] It is assumed that E_i chooses a_1 if it is indifferent between a_1 and a_2.

[65] As defined in Lemma 5, for each value of τ the notation (superscripts) on the price and generation portfolio varies. However, the result in inequality (41) applies for each value of $\tau \in \{0, \widetilde{\tau} + \epsilon\}$.

$$
\begin{aligned}
E[CS_{LR}] &= E\left[\sum_{t=1}^{T_{LR}}\left(\int_{\widetilde{p}_t}^{p_t^{max}}\phi(t,\mu_{LR})dp\right)(1-\rho_o(\tau))+\left(\int_{\widetilde{p}_t}^{p_t^{max}}\phi(t,\mu_{LR})dp\right)(1-\omega)\rho_o(\tau)\right] \\
&= E\left[\sum_{t=1}^{T_{LR}}\phi(t,\mu_{LR})\left\{[p_t^{max}-\widetilde{p}_t](1-\rho_o(\tau))+[p_t^{max}-\widetilde{p}_t](1-\omega)\rho_o(\tau)\right\}\right]. \qquad (43)
\end{aligned}
$$

Denote $\widetilde{p}_t^{NS}$ and $\widetilde{p}_t^{S}$ to be the aggregate prices consumers pay without and with subsidized entry, respectively. $E[\Delta W_{LR}] = E[W_{LR}|_{\tau=0}] - E[W_{LR}|_{\tau>\widetilde{\tau}}] \gtreqless 0$ as $E[\Pi_{LR}^C|_{\tau=0}] - E[\Pi_{LR}^C|_{\tau>\widetilde{\tau}}] + E[\Pi_{LR}^E|_{\tau=0}] - E[\Pi_{LR}^E|_{\tau>\widetilde{\tau}}] + E[\Delta CS_{LR}] \gtreqless 0$. Using (43), $E[\Delta CS_{LR}]$ is detailed in (21). $\square$

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