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The Effect of Subsidized Entry on Capacity Auctions and the Long-Run Resource Adequacy of Electricity Markets

David Brown
University of Alberta

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Abstract

Motivated by recent government interventions in the form of mandated subsidies for new generation capacity, I examine the impact of subsidized entry of electricity generation capacity on the performance of centralized capacity auctions. Subsidized entry suppresses capacity prices and induces an inefficient allocation of capacity. It also alters the equilibrium generation portfolio determined by the capacity auction. In the short-run, altering the generation portfolio through subsidized entry may lead 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 short-run expected welfare is ambiguous. However, subsidized entry also has adverse long-run impacts. The suppressed capacity and electricity prices reduce the incentives of unsubsidized firms to invest in generation capacity. Further, subsidized entry may induce welfare-reducing boom and bust investment cycles and/or may be self-reinforcing. Regulatory policies such as PJM's Minimum Offer Pricing Rule (MOPR) attempt to eliminate subsidized entry. Under plausible conditions, the long-run resource adequacy issues associated with insufficient capacity investment dominate the potential short-run benefits of subsidized entry such that the MOPR is welfare-enhancing.

Keywords: Electricity market design; Subsidized entry; Resource adequacy; Regulatory policy, Multi-unit auctions.

JEL Classifications: D44, L13, L50, L94.

*Department of Economics, University of Alberta, 8-14 HM Tory Building, Edmonton Alberta, Canada T6G 2H4
Email: dpbrown@ualberta.ca

1 Introduction

It is essential that electricity markets are designed to ensure adequate, reliable generation capacity. 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 critical infrastructure such as communication, health services, heating, cooling, and water supply.

Electricity market restructuring has occurred world-wide and in many regions of the United States. In these restructured electricity markets, generation units participate in competitive energy markets where they must recover not only their costs to produce electricity, but also their large costs of capacity investment. Concerns that generation units are unable to recover their cost of capacity investment in these energy-only markets has led to the development of capacity payment mechanisms.[1] In the United States, these capacity mechanisms have typically take the form of centralized capacity auctions. The objective of these capacity auctions is to provide additional revenue to supplement earnings in subsequent energy markets in order to induce adequate investment in generation resources. Recently, in addition to the capacity payments from these capacity auctions, the state governments of New Jersey and Maryland have provided capacity subsidies to further induce the entry of base-load generation units in their regions. This intervention has raised considerable debate over the impacts of such out-of-market (OOM) payments on the performance of the capacity auction and long-run resource adequacy. The objective of this paper is to investigate both the short-run and the long-run impacts of such OOM payments.

The capacity product is not the electricity itself, but the ablity to generate electricity on demand in the future. Capacity auctions often occur three-to-five years prior to the delivery-year in which the capacity must be made available to compete in subsequent energy markets. In these capacity auctions, load-serving entities (LSEs) who provide electricity to end-users are required to contract for generation capacity that ensures that sufficient generation resources will be available to meet the demand for electricity during the highest (peak) period (PJM, 2011). The LSEs pay the prevailing capacity auction price for these capacity contracts. Generation units bid into these capacity auctions to make their generation capacity available in the future delivery-year for both existing generation units and new capacity investments. These capacity auctions largely determine the configuration of generation capacity in the subsequent delivery-year energy markets, i.e., they determine the generation portfolio.[2] This market design has been adopted by the Pennsylvania-New Jersey-Maryland (PJM) and New England (ISONE) Independent System Operators (ISOs) who

[1] Energy-only markets are suspected to provide insufficient investment incentives for two main reasons. First, inefficiently low price-caps in energy markets restrict revenues (Joskow, 2007). Second, system-wide reliability is viewed as a public good. Therefore, generation units underinvest relative to the socially optimal capacity level.

[2] Capacity may also be contracted for through bilateral contracts. However, an analysis of both bilateral contracts and centralized capacity auctions are out of the scope of the current analysis.

are in charge of coordinating these regional electricity markets.[3]

Some industry experts argue that centralized capacity 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 deliver payments to generation units to supplement the revenues they receive in the capacity and energy markets. These payments are intended to encourage the construction of base-load generation units in their states (NJBPU, 2011; MPSC, 2011). The governments that provide these OOM payments argue that these capacity subsidies are necessary to ensure resource adequacy and lower prices for consumers in their states. However, regulators have viewed subsidized entry as an attempt to suppress capacity prices and hence, as an execution of buyer-side market power. Since buyers of capacity are obligated to pay the prevailing capacity prices, 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.

Regulators are concerned that subsidized entry will undermine the central objectives of capacity auctions by distorting the price signals they generate which provide valuable information about where and when capacity investment is needed. Regulatory policies that restrict subsidized entry of generation capacity have been considered or adopted in regions with capacity auctions. In particular, PJM has implemented the Minimum Offer Pricing Rule (MOPR) with the objective of eliminating subsidized entry (Pfeifenberger et al., 2011).[4] 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.[5] This paper aims to address several important policy questions. How does subsidized entry affect the performance of capacity auctions and the long-run resource adequacy of electricity markets? How do electricity market characteristics impact the effect of subsidized entry? Do regulatory policies such as PJM's MOPR increase expected welfare?

To address these important policy questions, I establish a model of centralized capacity auctions accounting for the impact that the allocation of capacity in the capacity auction has on the nature of competition in the subsequent energy markets. I find that subsidized entry reduces the equilibrium price paid for capacity and encourages an inefficient allocation of capacity by allowing a less-efficient subsidized unit to replace a more efficient resource. Further, subsidized entry often suppresses expected electricity prices in the subsequent delivery-year electricity markets. Therefore,

[3]The forward centralized capacity auction design is being considered in several other markets in the US and world-wide. For a detailed discussion on PJM's Reliability Pricing Model and ISONE's Forward Capacity Market, see PJM (2011) and Pfeifenberger et al. (2009).

[4]Policies similar to PJM's MOPR have been adopted or are being considered by ISOs in New England, New York, and the Midwest.

[5]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 total industry profits 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 become more pronounced as the subsidized unit becomes less efficient.

The impact of subsidized entry on expected short-run 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 subsidized entry increases expected short-run welfare. If the entry of the subsidized unit occurs in a region with a low degree of generation and/or transmission capacity scarcity, the energy price suppressing effect of subsidized entry is dampened. Further, if the expected electricity price benefits are limited (or nonexistent), then subsidized entry strictly reduces short-run expected welfare.

Subsidized entry also has long-run adverse impacts. Subsidized entry reduces the incentives of firms that do not receive OOM payments to undertake new capacity investments. Therefore, while subsidized entry has the potential to increase short-run expected welfare, the resulting long-run issues associated with insufficient generation capacity expansion more than offset the potential short-run welfare gains under plausible conditions. If subsidized entry increases long-run expected welfare, it does so by transferring substantial rents from consumers to producers. The negative long-run effects are magnified in regions with a high degree of aging coal units and/or renewable generation technologies. Further, subsidized entry may cause a self-reinforcing cycle as more capacity subsidies are needed to counteract the reduce participation in the capacity auction and/or OOM payments may induce welfare-reducing boom and bust investment cycles.

The current analysis extends the important work of Briggs and Kleit (2013). Similar to their analysis, I find that subsidized entry suppresses capacity auction prices, generates allocative inefficiencies, and reduces the investment incentives of the generation units that do not receive capacity subsidies. The current analysis extends their analysis by explicitly modeling the bidding behavior in centralized capacity auction with and without subsidized entry, taking into account the effect the allocation of capacity has on subsequent market interactions (i.e., the energy portfolio effect). This modeling allows me to demonstrate that the net effects (short- and long-run) of subsidized entry depend on the magnitudes of the countervailing forces.[6] However, under plausible conditions, the associated adverse long-run impacts of subsidized entry dominate the potential short-term gains, lending further credence to Briggs and Kleit's (2013) findings and PJM's MOPR used to prevent OOM payments.

Procurement auctions are often followed by subsequent market interactions. In these settings, bidders' expected

[6] Briggs and Kleit (2013) consider an environment with two energy markets to account for transmission congestion considerations. The current analysis accounts for the effect of subsidized entry on transmission constraints implicitly through its effect on expected energy prices in subsequent energy markets which contain congestion costs (i.e., the energy portfolio effect).

payoffs are affected by whose bid(s) are accepted in the auction (i.e., by the allocation of goods in the auction). Such auctions with allocation externalities have been the subject of several recent articles (Jehiel and Moldovanu (2001); Das Varma (2002); Aseff and Chade (2008); Das Varma and Lopomo (2010)). These authors reveal that firms change their behavior in order to alter the resulting allocation of goods in the auction. I explicitly model bidding behavior in a multi-unit auction with allocation externalities and focus on the effect of the allocation of goods on welfare.[7]

The current analysis complements several studies of subsidies and set-asides in single-unit procurement auctions (Krasnokutskaya and Seim, 2011; Athey et al., 2013). Similar to these studies, I find that subsidized entry reduces participation incentives of those bidders not receiving subsidies. 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.

The analysis proceeds as follows. Section 2 illustrates the impact of subsidies on capacity auctions. 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 markets are presented in sections 6 and 7. The long-run welfare implications are considered in section 8. Section 9 concludes. The Appendix contains proofs of all formal conclusions.

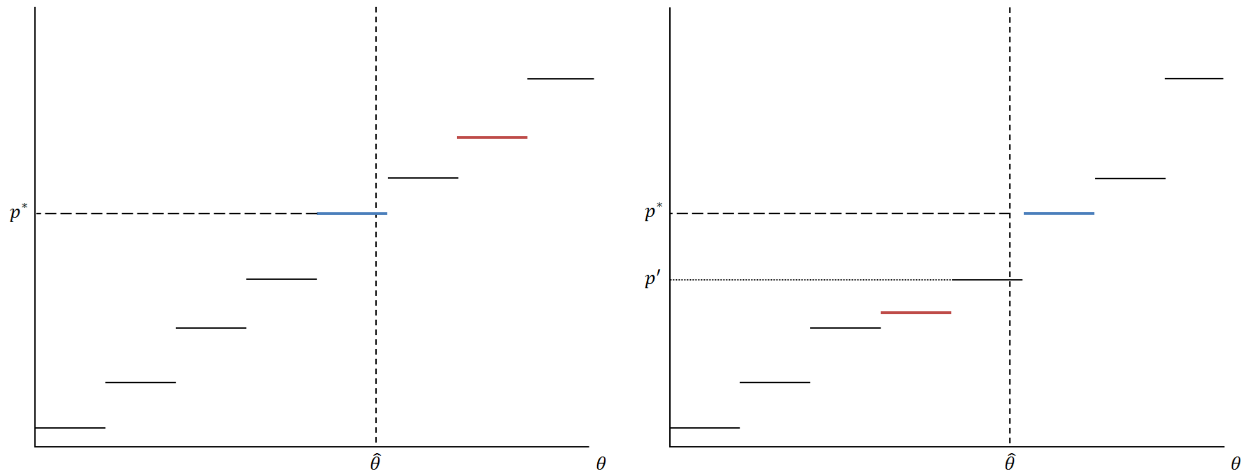
2 Subsidized Entry

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 $\widehat{\theta}$.[8] 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 1a considers a setting in which there are no capacity subsidies leading to the market-clearing price p^*. Alternatively, Figure 1b 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

[7] In particular, the current analysis is closely related to the work of von der Fehr and Harbord (1993), García-Díaz and Marin (2003), Fabra et al. (2006), and Crawford et al. (2007), which analyze bidding behavior in uniform price multi-unit auctions where firms submit discrete bid functions. However, unlike the current analysis, this literature focuses on isolated auctions with no allocation externalities.

[8] For illustrative purposes, capacity demand is assumed to be inelastic. However, as discussed in the conclusion and shown in the Appendix, the results of this article are robust to an environment with price-elastic capacity demand.

price is paid to the price-setting bidder (marginal bidder) and all bidders whose bids are below the market-clearing price (inframarginal bidders).



(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.[9] In contrast, each entrant has a single potential new capacity investment. 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., $k_{E_i}^u = k_E^u$ $\forall \, i = 1, 2, ..., M$).[10] 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 price-inelastic 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 $K_I + (l-1)k_E <$

[9]For illustrative purposes, I have assumed that the incumbents only have installed generation units. The Appendix reveals that the qualitative conclusions of this article are robust to the setting where the incumbent(s) also have new capacity investment(s). Further, I focus on two incumbents for notational simplicity. The results are robust to a setting with N incumbents.

[10]The Appendix reveals that the qualitative results are robust to an environment where the entrants' capacity limits are heterogeneous.

$\widehat{\theta} \leq K_I + lk_E$ for some $2 < l < M$.[11]

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 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.[12] 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.[13]

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. 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 an entrant does not procure its generation unit in the capacity auction, it is not able to compete in subsequent energy market interactions.[14] 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

[11] For the extension with price-elastic capacity demand, see the Appendix.

[12] 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.

[13] 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).

[14] It is assumed that an entrant can not profitably enter without earning the capacity payments from the capacity auction. Entry by resources through payments outside of the capacity auction are out of the scope of the current analysis.

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.

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

2.1 $\bar{\pi}_j^u(\psi) \geq 0\ \forall\ \ u \in U_j, \psi \in \Psi$, 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 $\bar{\pi}_j^u(\psi) > \bar{\pi}_j^u(\psi')$ for some $u \in U_j\ \forall\ j \in \{\mathbf{I}, \mathbf{E}\}$.

2.4 The set of entrants **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 allocative externalities (portfolio effects) are sufficiently small such that the entrants can be ranked in terms of their net marginal cost.[15]

Firms compete by submitting a single bid to the auctioneer for each of their generation units.[16] 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 $(b_{I_j}^u, q_{I_j}^u)$ 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:

$$B_{I_j} = \{(b_{I_j}^u, q_{I_j}^u)\}_{\forall\, u \in U_{I_j}},\ b_{I_j}^u \in [0, \overline{P}],\ b_{I_j}^u \leq b_{I_j}^{u+1},\ \text{and}\ q_{I_j}^u = k_{I_j}^u \qquad \forall\ u \in U_{I_j}\ \text{and}\ j = 1, 2. \tag{2}$$

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, $\bar{b}_{I_j}^u$, set *ex ante* (i.e., $b_{I_j}^u \leq \bar{b}_{I_j}^u\ \forall\ u \in U_{I_j}$ and $\forall\ j = 1, 2$). These offer-caps are based

[15]The Appendix reveals that the findings of this article hold when Assumption 2.4 is relaxed.

[16]This follows the multi-unit auction literature established by von der Fehr and Harbord (1993).

upon estimates of the net marginal cost of each installed unit $u \in U_{I_j}\ \forall\ j = 1, 2$.[17] 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.[19] Throughout the analysis it is assumed that firms' costs, capacity limits, and expected earnings from energy markets 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. 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:

$$X^u_{I_j}(\widehat{\theta}; \boldsymbol{\beta}) = \begin{cases} 0 & \text{if } b^u_{I_j} > b_m \\[2ex] k^u_{I_j} & \text{if } b^u_{I_k} < b_m \\[2ex] R(\widehat{\theta}, p^*; \boldsymbol{\beta}) & \text{if } b^u_{I_j} = b_m. \end{cases} \tag{5}$$

[17] In practice, all bids are subject to bid mitigation through bid caps and/or bid floors. However, the focus on the current article is to investigate the outcome of capacity auctions in the face of subsidized entry if there are no regulatory restrictions on new capacity investments. This provides insight into the potential policy implications of bid mitigation measures such as PJM's MOPR.

[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. In such settings, an incumbent's bid for such an installed unit may set or exceed the stop-out price. The results in this article are robust to the setting where an incumbent can set the stop-out price as shown in the Appendix.

[19] 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).

[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.

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}, ψ^{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). 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. 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.[21] 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.

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.

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, $c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$.[22] 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.

[21] Because the incumbents' bids are constrained by bid offer-caps, 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] 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}.

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 $c_{E_s} - \bar{\pi}_{E_s}(\psi) - \tau$.[23] 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.[24]

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.[25] For now, assume that the buyer provides a subsidy $\tau > \widetilde{\tau}$.[26]

In practice, capacity subsidies have been given to base-load generation technologies. The subsidized unit(s) displace generation unit(s) that would have been dispatched in the absence of the subsidy. In particular, these base-load units often displace generation investments such as natural gas units[27] In addition, there are often geographical differences between the subsidized and displaced unit(s). OOM payments have been given to assist with new capacity investments in regions with constrained generation and/or transmission capacity. Bringing these two effects together, if E_s's unit is dispatched in the capacity auction, the construction of this unit is likely to put downward pressure on subsequent energy prices because the base-load unit has lower electricity production costs than the displaced unit(s) and the generation and transmission scarcity is eased in the constrained region.[28] This is referred to as the energy portfolio effect. Hence, 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 subsequent energy markets 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 $j \in \{\mathbf{I}, \mathbf{E}\}$.

[23]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.

[24]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.

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

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

[27]Base-load units have high capacity investment costs and low electricity production costs, whereas natural gas units have lower capacity investment costs and higher electricity production costs.

[28]This is reflected by a weak downward shift in the marginal cost function of electricity production in future energy markets (see Section 7).

[29]It will be shown later that without this energy portfolio effect, the effect of subsidized entry is strictly welfare-reducing (see Corollary 2).

Proposition 2 characterizes the PSNE of the capacity auction when E_s is receiving a capacity subsidy.

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 $\psi^S = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l-1}}, U_{E_s}\}$. Analogous 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 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 auction price and induces allocative inefficiencies.

Now, I briefly investigate the buyer's incentive to provide a subsidy $\tau > \widetilde{\tau}$. Conditional on the buyer wanting to provide a subsidy, the buyer wants to provide just enough to ensure that the subsidized entrant can profitably procure its capacity in the market. Any subsidy higher than this amount would reflect a transfer from the buyer to the subsidized entrant with no benefit to the buyer. Therefore, the buyer provides one of two potential levels of τ: (1) $\tau = 0$ or (2) $\tau = \widetilde{\tau} + \epsilon$ for some $\epsilon > 0$.[30] Lemma 2 summarizes this statement.

Lemma 2. A buyer provides one of two potential subsidy levels of τ: (1) $\tau = 0$ or (2) $\tau = \widetilde{\tau} + \epsilon$.

Using Propositions 1 and 2, Lemma 3 identifies the effects of subsidized entry on industry profit.

Lemma 3. The change in total industry profit $\Delta\Pi = \Pi|_{\tau=0} - \Pi|_{\tau>\widetilde{\tau}} \gtreqless 0$ as:

$$\sum_{j=1}^{2} \Delta\Pi_{I_j} + \sum_{i=1}^{l-1} \Delta\Pi_{E_i} + \Pi_{E_l}\big|_{\tau=0} - \Pi_{E_s}\big|_{\tau>\widetilde{\tau}} \gtreqless \tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^S). \tag{11}$$

The first term on the left-hand side of inequality (11) 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

[30] 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 $\epsilon > 0$.

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 (11) 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 (11) reveals that subsidized entry reduces the total industry profit unless the subsidy is sufficiently large to 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 4. Suppose Assumption 3 holds. Then subsidized entry strictly reduces the level of aggregate industry profit (i.e., $\Delta\Pi > 0$).

From Lemma 3, subsidized entry reduces aggregate industry profit unless τ is sufficiently large. Proposition 4 reveals that the highest potential subsidy value chosen by the buyer will never increase industry profits.

The impact on the capacity auction varies with the efficiency of the generation technology that is subsidized. Corollary 1 follows directly from Propositions 3 and 4.

Corollary 1. The degree of allocative inefficiency and the reduction in industry profit from subsidized entry 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. (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 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).[31]

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:

$$V(\psi, \boldsymbol{\beta}) = \sum_{t=1}^{T} \int_{P_t}^{P_t^{max}} \phi(t, \mu) dP \tag{12}$$

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;[32] and $\phi(t, \mu)$ is the price-inelastic energy demand function.[33] 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.[34] 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 portfolio ψ, the expected short-run welfare function is:

$$E[W(\boldsymbol{\beta}, \psi)] = \sum_{v \in \{\mathbf{I}, \mathbf{E}\}} \Pi_v + E\left[\sum_{t=1}^{T} \int_{P_t}^{P_t^{max}} \phi(t, \mu) dP \middle| \psi \right] - (1 + \lambda)\tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}). \tag{13}$$

Using the equilibrium outcomes in Propositions 1 and 2, Lemma 4 characterizes the change in expected short-run welfare by comparing the welfare levels with ($\tau > \widetilde{\tau}$) and without ($\tau = 0$) subsidized entry.

Lemma 4. The change in expected welfare $E[\Delta W] = E[W(\boldsymbol{\beta}^{NS}, \psi^{NS})|_{\tau=0}] - E[W(\boldsymbol{\beta}^{S}, \psi^{S})|_{\tau>\widetilde{\tau}}]$ equals:

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

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

[33] The qualitative conclusions carry forth if electricity demand is price-elastic.

[34] 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.

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

The first term in (14) 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 4, the change in total industry profit term is positive. The social cost of subsidizing the entrant is also positive. Since the 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 $\Big($i.e., $\sum_{t=1}^{T}E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right]>\sum_{t=1}^{T}E\left[P_t^E\phi(t,\mu)\middle|\psi^{S}\right]\Big)$.[35]

Using Lemma 4, Proposition 5 evaluates the effect of subsidized entry on expected short-run welfare.

Proposition 5. The change in expected welfare $E[\Delta W]=E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}]-E[W(\boldsymbol{\beta}^{S},\psi^{S})|_{\tau>\widetilde{\tau}}]\gtreqless 0$ as:

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

The components in both the right-hand and left-hand sides of inequality (15) are non-negative. Therefore, Proposition 5 reveals that subsidized entry is welfare-enhancing (i.e., $E[\Delta W]<0$) if and only 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. Alternatively, if the capacity payment effect and E_s's energy portfolio effect is limited, then subsidized entry reduces expected short-run welfare because the negative aspects of allowing OOM payments detailed in Propositions 3 and 4 outweigh the benefits to consumers from suppressed capacity and energy procurement prices.

Corollary 2. Suppose Assumption 3 holds. If E_s's expected energy portfolio effect is zero, then $E[\Delta W]>0$.

Corollary 2 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 arises because any benefits to consumers due to the lower

[35]That is, because E_s's unit is constructed in a region with scarce generation and transmission capacity (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}.

capacity auction price are more than offset by the social cost associated with paying the subsidy. This implies that subsidized entry enhances short-run expected welfare if and only if E_s's energy portfolio effect is sufficiently positive.

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 illustrative 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.[36]

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 $\phi(t)$.[37]

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.[38] 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:

$$P_t^E(\psi) = \min\{\gamma(\phi(t)|\psi), \bar{P}^E\} \quad \text{for each } t = L, H \tag{16}$$

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.

[36] The subsidized unit may also ease transmission capacity (congestion) constraints, putting further downward pressure on expected electricity prices. The illustrative example in this section does not account for these effects.

[37] 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.

[38] Modeling the bidding behavior in the energy auction is not the focus of the current analysis. For a detailed treatment see Crawford et al. (2007) and Fabra et al. (2006). Introducing strategic bidding does not alter the intuition gained from this illustrative example.

Lemma 5. 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 5 reveals that subsidized entry weakly reduces the market-clearing electricity procurement price for any level of energy demand. Figure 2 illustrates how altering the generation portfolio can shift the aggregate marginal cost function and its potential price reducing effects for both demand states.

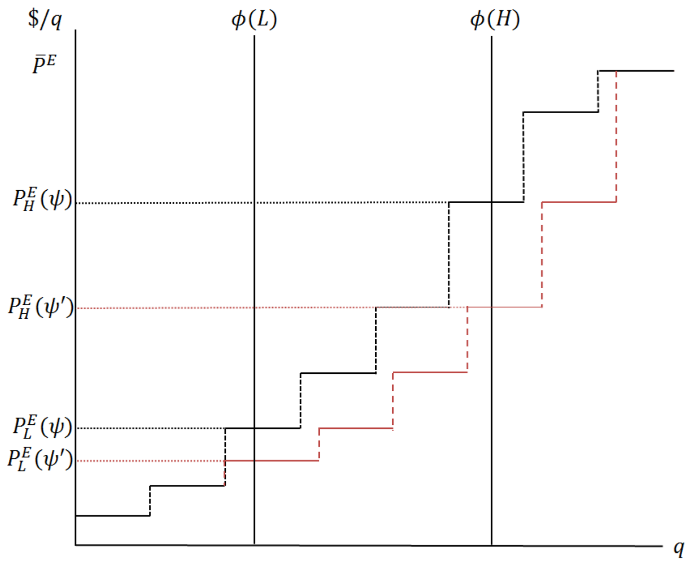


Figure 2: The Marginal Cost Functions $\gamma(q|\psi^{NS})$ and $\gamma(q|\psi^{S})$ with $\gamma(q|\psi^{NS}) \geq \gamma(q|\psi^{S}) \; \forall \; q \geq 0$.

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 5, 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 6 substitutes the realization of the energy portfolio effect into the expected short-run welfare analysis detailed in Proposition 5 to demonstrate when subsidized entry is welfare-enhancing or -reducing.

Proposition 6. 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:

$$P_L^E(\psi^{NS})\phi(L)+P_H^E(\psi^{NS})\phi(H)-\left(P_L^E(\psi^{S})\phi(L) + P_H^E(\psi^{S})\phi(H)\right) > \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v+(1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)-(p^{NS}-p^S)\widehat{\theta}. \tag{17}$$

Proposition 6 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.

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 is more (less) pronounced. For example, in New Jersey and Maryland, generation and transmission capacity is scarce during high-demand periods, leading to high electricity prices, congestion of their transmission lines due to import constraints, and concerns over potential outages. Alternatively, almost all other states in the Northeastern United States have sufficient generation capacity to ensure few periods of capacity scarcity. Short-run expected welfare is less likely to increase in the presence of subsidized entry if the subsidized unit enters into a region with a low degree of generation and/or transmission capacity scarcity.[39]

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.[40] If E_i chooses to invest, then it is making its new capacity 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.[41] 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 submit 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 6 summarizes the outcome of the capacity auction for each $a \in A$ and $\tau \in \{0, \widetilde{\tau} + \epsilon\}$.

[39] The energy portfolio effect is magnified (dampened) if the unit displaced by E_s would have been constructed in a region with a low (high) degree of generation and/or transmission capacity scarcity.

[40] 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.

[41] 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 6. 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 6 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 6 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 7 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 7. 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:

$$[p_{a_1} + \bar{\pi}_{E_i}(\psi_{a_1})] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) \geq c_{E_i} X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) + \zeta. \tag{18}$$

Lemma 7 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 (18) holds. This analysis illustrates the implications that the magnitude of the capacity price and expected earnings in energy markets can have on a firm's investment decisions. Proposition 7 investigates the impact of subsidized entry on E_i's investment decision.

Proposition 7. Suppose Assumption 3 holds. Subsidized entry strictly reduces E_i's incentive to undertake a new capacity investment.

As illustrated in Lemma 6, 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 capacity auction and subsequent delivery-year energy markets. Therefore, E_i has reduced incentives to invest in new capacity in the presence of subsidized entry.[42]

[42]More broadly, capacity subsidies reduce capacity investment if Assumption 3 does not hold as long as the expected earnings in subsequent

Reduced participation in capacity auctions has the potential to have substantial long-term impacts on resource adequacy and 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 markets because during periods of high-demand costly generation units are called upon to meet electricity demanded.[43] 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:

$$E[W_{LR}] = E[\Pi_{LR}] + E\left[\sum_{t=1}^{T_{LR}} \left(\int_{\widetilde{p}_t}^{p_t^{max}} \phi(t,\mu_{LR})dp\right)(1-\rho_o(\tau)) + \left(\int_{\widetilde{p}_t}^{p_t^{max}} \phi(t,\mu_{LR})dp\right)(1-\omega)\rho_o(\tau)\right] \quad (19)$$

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 (19) 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.[44] 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. 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 8. The change in long-run expected welfare $E[\Delta W_{LR}] = E[W_{LR}|_{\tau=0}] - E[W_{LR}|_{\tau>\widetilde{\tau}}] \gtreqless 0$ as $E[\Delta\Pi_{LR}^C] + E[\Delta\Pi_{LR}^E] + E[\Delta CS_{LR}] \gtreqless 0$ where:

energy markets are not substantially higher under the generation portfolio with the subsidized unit compared to the portfolio with the displaced unit.

[43] 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.

[44] 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 $[\underline{\sigma}, \bar{\sigma}] \subset \mathbb{R}\ \forall\ \psi \in \Psi$.

$$E[\Delta CS_{LR}] = E\Big[\sum_{t=1}^{T_{LR}} \phi(t,\mu_{LR})\big\{[p_t^{max} - \widetilde{p}_t^{NS}]\,(1-\rho_o(\tau=0)+\rho_o(\tau=0)(1-\omega)) - [p_t^{max} - \widetilde{p}_t^{S}]\,(1-\rho_o(\tau>\widetilde{\tau})+\rho_o(\tau>\widetilde{\tau})(1-\omega))\big\}\Big]. \tag{20}$$

Proposition 8 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, 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 sufficiently 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. $\rho_o(\tau > \widetilde{\tau}) > \rho_o(\tau = 0)$). Therefore, 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. 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 reduction in consumer surplus to all other consumers from system-wide expected electricity price increases, the social cost of the subsidy, and the increased probability of blackouts. In both of these settings, if long-run expected welfare increases in the presence of OOM payments, it increases because of a substantial rent transfer from consumers to producers.

Proposition 8 reveals that capacity scarcity has major implications on the level of expected long-run consumer surplus.[45] 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, expected

[45]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.

long-run consumer surplus decreases due to reduced participation and hence, it is more 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 8. 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 capacity investments. Reduced participation is more likely to raise capacity scarcity and resource adequacy concerns in regions with higher amounts 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, if the sun (wind) is unexpectedly blocked (stops), then electricity markets rely on quick-response generators 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 will limit the degree of capacity scarcity associated with lower investment incentives due to subsidized entry.

Two important caveats to the discussion above must be made. First, reduced capacity investment incentives may be temporary because the higher expected long-run capacity and electricity prices induced by reduced participation will partially (or fully) restore firms' investment incentives. This implies that capacity subsidies may induce short-term welfare-reducing boom and bust investment cycles leading to periods of over and under investment. Alternatively, capacity subsidies can be self-reinforcing. A capacity subsidy in the current period reduces investment incentives and hence, creates the need for further subsidies in subsequent capacity auctions to ensure resource adequacy. This is detrimental to one of the central objectives of competitive electricity markets, to use market-based forces to induce long-run efficiency with limited political and regulatory intervention.

9 Conclusion

Ensuring that sufficient generation resources are available is a central concern of regulators and policy-makers. I have constructed a model that evaluates the effect of subsidized entry on capacity market outcomes, accounting for the impacts on subsequent market interactions. I have shown that subsidized entry reduces the capacity price and induces 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. However, capacity subsidies may increase short-run consumer surplus because of its affect on the generation portfolio. This implies that the effect of subsidized entry on the overall level of expected short-run welfare is ambiguous. However, subsidized entry increases short-run welfare only if the increase in consumer surplus via the energy portfolio and capacity price suppressing effects more than offset the reduction in total industry profits and the social cost of raising the subsidy.

In addition, subsidized entry reduces the incentives of non-subsidized firms 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 future prices of electricity and capacity and an increased probability of local and system-wide blackouts. Reduced participation will likely undo the subsidized unit's potential short-run price-reducing effects and increase expected system-wide electricity prices. If there is no further subsidized entry, reduced investment has the potential to increase expected long-run industry profits as expected capacity and electricity prices rise. Consequently, the overall effect on long-run welfare is also ambiguous. However, if expected long-run welfare increases, it reflects a substantial transfer of rents from consumers to producers.[46] In addition to the adverse impacts on participation, capacity subsidies may induce welfare-reducing boom and bust investment cycles and/or be self-reinforcing as they may exacerbate reliability concerns, motivating the need for further capacity subsidies.

The potentially substantial adverse long-run impacts of subsidized entry identified in the current analysis lead further credence to Briggs and Kleit's (2013) findings and regulatory polices such as PJM's MOPR that are used to eliminate capacity subsidies. The impact of each of the factors identified in this paper vary with the characteristics of the electricity market under consideration. For instance, the potential short-run expected electricity price suppressing effects will be less pronounced if the subsidized unit is constructed in a region with a low 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 renewable generation technologies (demand-response).

For illustrative purposes, the analysis has considered a simple setting. However, the key qualitative conclusions hold more generally.[47] In particular, allowing the incumbents' to undertake new capacity investments does not affect the short-run or long-run effects of subsidized entry.[48] 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, the subsi-

[46] In the analysis, the expected welfare function equally weights consumer and producer surplus. In the long-run, if consumer surplus is weighted more heavily than producer surplus, capacities subsidies are much more likely to be welfare-reducing.

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

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

dized unit (E_s) may have a heterogeneous capacity limit (i.e., $k_{E_s} > k_E$).[49] 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. Capacity-demand is an administratively set price-elastic demand function. However, the effects of subsidized entry identified in the current analysis are robust to an environment where capacity demand is price-elastic. Lastly, Assumption 2.4 states that the allocation externalities are sufficiently small such that the set of entrants (**E**) can be ordered in terms of their net marginal cost for any portfolio $\psi \in \Psi$. 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. This article provides a robust framework to assess such considerations. First, the potential indirect impacts that subsidized entry has on firms' retirement incentives for their installed generation units warrants attention. The lower capacity and expected electricity prices may induce a firm to retire an installed unit. Second, a more robust 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. Being able to identifying which buyers are more likely to provide capacity subsidies would lower the cost of oversight in these capacity auctions.[50] Third, a setting that incorporates the repeated nature of capacity auctions warrants formal analysis. By incorporating repeated interactions, the model would likely capture the potentially self-reinforcing impacts of capacity subsidies and/or the potential boom and bust investment cycles induced by capacity subsidies. However, the core results identified in the current analysis seem likely to persist.

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

[50] 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.

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APPENDIX A

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) $p^* < p' < b^{'}_{E_i}$. E_i goes from procuring capacity for a loss, to procuring capacity at net marginal cost (case (i)) or procuring no capacity at all (case (ii)). In either case, E_i is strictly better off because it now earns a payoff of zero.

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.[51] 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 $\epsilon \geq 0$.[52] Define this new bid profile as $\boldsymbol{\beta'}$ and the resulting stop-out price as $p' \in \{p^* - \epsilon, p^*\}$. Under the bid profile $\boldsymbol{\beta'}$ E_i is procuring capacity for a non-negative payoff. Hence, E_i's payoff weakly increases by unilaterally deviating.[53]

□

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 $K_I = \displaystyle\sum_{j=1}^{2} \sum_{u \in U_{I_j}} k^u_{I_j}$. 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 $\forall\ j > l$.

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:

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

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

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

[53] It is assumed that E_i prefers the potential to procure positive capacity for a payoff of zero, rather than procure no capacity with certainty.

$$\Leftrightarrow \quad \bar{b}_E \leq (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS})) + [c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM}) - (c_{E_k} - \bar{\pi}_{E_k}(\psi^{NS}))] \left(\frac{X_{E_k}(\widehat{\theta}; \boldsymbol{\beta}^{NS})}{k_E} \right). \quad (21)$$

If inequality (21) 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 (21)). 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) $b^{'}_{E_j} > p^{NS}$. In case (i), E_j's payoff is unchanged because there is no change in the stop-out price and E_j's output. In case (ii), E_j's payoff weakly falls because the stop-out price is unchanged, while its output weakly decreases because it is now rationed. In case (iii), E_j is strictly worse off 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) $b_{E_k} < b^{'}_{E_k}$. In case (i), conditional on the non price-setters' bids satisfying inequality (21), it is not profitable for entrant E_k to make such a deviation as shown above. In case (ii), E_k's payoff falls because its output remains unchanged, but the stop-out price falls (i.e., $p^{NS'} < p^{NS}$). In case (iii), E_k's payoff decreases (to zero) because its capacity investment is replaced by E_{l+1}'s unit.

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.[54] This PSNE is unique up to the identity of the price-setter and non price-setting firms.

□

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 Lemma 2: 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: $U^B(p, \tau, \alpha\widehat{\theta}, V_\alpha(p, \alpha\widehat{\theta}, \psi))$. 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.

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

[54]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 undercut its bid b_{E_k}.

characterized in Proposition 2. At $\widetilde{\tau}$ there is a shift in the equilibrium outcome resulting in a discontinuous change in the buyer's equilibrium utility.

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

□

Proof of Lemma 3: Using (4)-(10) and the PSNE characterized in Proposition 1, the total industry profit for the setting without OOM payments ($\tau = 0$) is:

$$\sum_{v \in \{\mathbf{I},\mathbf{E}\}} \Pi_v|_{\tau=0} = \sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{NS} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{NS}))\right] k^u_{I_j} + \sum_{i=1}^{l} \left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{NS}). \quad (22)$$

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:

$$\begin{aligned}\sum_{v \in \{\mathbf{I},\mathbf{E}\}} \Pi_v|_{\tau>\widetilde{\tau}} \quad &= \quad \sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{S} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{S}))\right] k^u_{I_j} + \sum_{i=1}^{l-1} \left[p^{S} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{S}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{S}) \\ &+ \quad \left[p^{S} - (c_{E_s} - \bar{\pi}_{E_s}(\psi^{S}) - \tau)\right] X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^{S}). \end{aligned} \quad (23)$$

Using (22) and (23):

$$\begin{aligned}&\sum_{v \in \{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v = \sum_{v \in \{\mathbf{I},\mathbf{E}\}} \Pi_v|_{\tau=0} - \sum_{v \in \{\mathbf{I},\mathbf{E}\}} \Pi_v|_{\tau>\widetilde{\tau}} \gtreqless 0 \\ \Leftrightarrow \quad &\sum_{j=1}^{2} \sum_{u \in U_{I_j}} \left[p^{NS} - p^{S} + \bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^{S})\right] k^u_{I_j} + \sum_{i=1}^{l-1} \left\{ \left[p^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \right. \\ - \quad &\left. \left[p^{S} - (c_{E_i} - \bar{\pi}_{E_i}(\psi^{S}))\right] X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}^{S}) \right\} + \left[p^{NS} - (c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS}))\right] X_{E_l}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \\ - \quad &[p^{S} - (c_{E_s} - \bar{\pi}_{E_s}(\psi^{S}))] X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^{S}) \gtreqless \tau X_{E_s}(\widehat{\theta}; \boldsymbol{\beta}^{S}). \end{aligned} \quad (24)$$

□

Proof of Proposition 4: As characterized in Lemma 2, 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 (11) holds with equality:

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

$$
\begin{aligned}
- & \quad \left[p^S - (c_{E_i} - \bar{\pi}_{E_i}(\psi^S))\right] X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S)\Big\} + \left[p^{NS} - (c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS}))\right] X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) \\
- & \quad [p^S - (c_{E_s} - \bar{\pi}_{E_s}(\psi^S))] X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \\
= & \quad p^{NS}\left(K_I + \sum_{i=1}^{l-1} X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) + X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})\right) - p^S\left(K_I + \sum_{i=1}^{l-1} X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) + X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)\right) \\
+ & \quad \sum_{j=1}^{2}\sum_{u\in U_{I_j}}[\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} + \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) + [c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \\
- & \quad \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}). \qquad (25)
\end{aligned}
$$

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, $\widehat{\theta} = K_I + \sum_{i=1}^{l-1} X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) + X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) = K_I + \sum_{i=1}^{l-1} X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) + X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)$. (25) simplifies to:

$$
\begin{aligned}
& (p^{NS} - p^S)\widehat{\theta} + \sum_{j=1}^{2}\sum_{u\in U_{I_j}}[\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} + \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) \\
+ & \ [c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}). \ (26)
\end{aligned}
$$

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 (26) and $\widetilde{\tau} = c_{E_s} - \bar{\pi}_{E_s}(\psi^S) - (c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS}))$:

$$
\begin{aligned}
& \quad (\widetilde{\tau} + \epsilon)X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) < \tau^* X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \\
\Leftrightarrow & \quad (\widetilde{\tau} + \epsilon)X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) < (p^{NS} - p^S)\widehat{\theta} + \sum_{j=1}^{2}\sum_{u\in U_{I_j}}[\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} + [c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \\
& + \sum_{i=1}^{l-1}\Big([c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) \\
\Leftrightarrow & \quad (p^{NS} - p^S)\widehat{\theta} + \sum_{i=1}^{l-1}\Big([c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) \\
- & \quad [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]\Big(X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) - X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)\Big) + \sum_{j=1}^{2}\sum_{u\in U_{I_j}}[\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^S)]k^u_{I_j} > 0. \qquad (27)
\end{aligned}
$$

$p^{NS} > p^S$, 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 (27) 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 (27) holds.

$\square$

Proof of Corollary 1: Follows directly from Propositions 3 and 4. $\square$

Proof of Lemma 4: Using Proposition 1, (12), (13), and (22), the expected short-run welfare with $\tau = 0$ is:

$$\begin{aligned} E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}] &= \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\left[p^{NS}-(c^u_{I_j}-\bar{\pi}^u_{I_j}(\psi^{NS}))\right]k^u_{I_j}+\sum_{i=1}^{l}\left[p^{NS}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{NS}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) \\ &+ E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}}\phi(t,\mu)dP\middle|\psi^{NS}\right] \end{aligned} \tag{28}$$

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 $P_t^{NS} = P_t^E + P_t^{C^{NS}}$.[55] $P_t^{C^{NS}} = f(p^{NS}, \widehat{\theta}, T, \phi(t,\mu))$ 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, (12), (13), and (23), the expected short-run welfare when $\tau > \widetilde{\tau}$ is:

$$\begin{aligned} E[W(\boldsymbol{\beta}^{S},\psi^{S})|_{\tau>\widetilde{\tau}}] &= \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\left[p^{S}-(c^u_{I_j}-\bar{\pi}^u_{I_j}(\psi^{S}))\right]k^u_{I_j}+\sum_{i=1}^{l-1}\left[p^{S}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{S}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{S}) \\ &+ \left[p^{S}-(c_{E_s}-\bar{\pi}_{E_s}(\psi^{S})-\tau)\right]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S}) + E\left[\sum_{t=1}^{T}\int_{P_t^{S}}^{P_t^{max}}\phi(t,\mu)dP\middle|\psi^{S}\right] \\ &- (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^{S}) \end{aligned} \tag{29}$$

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 (28) and (29):

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

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

$$
\begin{aligned}
- & \sum_{i=1}^{l-1}\left[p^S-(c_{E_i}-\bar{\pi}_{E_i}(\psi^S))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S)-\left[p^S-(c_{E_s}-\bar{\pi}_{E_s}(\psi^S))\right]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)\\
+ & E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}}\phi(t,\mu)dP\middle|\psi^{NS}\right]-E\left[\sum_{t=1}^{T}\int_{P_t^{S}}^{P_t^{max}}\phi(t,\mu)dP\middle|\psi^{S}\right]+(1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S). \qquad (30)
\end{aligned}
$$

The first four terms in (30) represent the change in 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 capacity investment ($(1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)$). The change in expected consumer surplus in (30) can be simplified further:

$$
\begin{aligned}
E[\Delta V] &= E\left[\sum_{t=1}^{T}\int_{P_t^{NS}}^{P_t^{max}}\phi(t,\mu)dP\middle|\psi^{NS}\right]-E\left[\sum_{t=1}^{T}\int_{P_t^{S}}^{P_t^{max}}\phi(t,\mu)dP\middle|\psi^{S}\right]\\
&= E\left[\sum_{t=1}^{T}(P_t^{max}-P_t^{NS})\phi(t,\mu)\middle|\psi^{NS}\right]-E\left[\sum_{t=1}^{T}(P_t^{max}-P_t^{S})\phi(t,\mu)\middle|\psi^{S}\right]. \qquad (31)
\end{aligned}
$$

The maximum consumers are willing-to-pay for electricity is unaffected by the portfolio allocation. That is, $E\left[\sum_{t=1}^{T}P_t^{max}\phi(t,\mu)\middle|\psi\right]=E\left[\sum_{t=1}^{T}P_t^{max}\phi(t,\mu)\right]$ 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. (31) simplifies to:

$$
\sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]-E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right]+E\left[P_t^{C^S}\phi(t,\mu)\middle|\psi^S\right]-E\left[P_t^{C^{NS}}\phi(t,\mu)\middle|\psi^{NS}\right]\right). \qquad (32)
$$

By assumption, the capacity payment schedule is such that the total capacity procurement costs are recovered over all t market interactions (e.g., $E\left[\sum_{t=1}^{T}P_t^C\phi(t,\mu)\middle|\psi^{NS}\right]=p^{NS}\widehat{\theta}$). (32) simplifies to:

$$
\sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]-E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right]\right)+p^S\widehat{\theta}-p^{NS}\widehat{\theta}. \qquad (33)
$$

Using (33), (30) can be rewritten as:

$$
\begin{aligned}
E[\Delta W] &= E[W(\boldsymbol{\beta}^{NS},\psi^{NS})|_{\tau=0}]-E[W(\boldsymbol{\beta}^{S},\psi^{S})|_{\tau>\tilde{\tau}}]\\
&= \sum_{j=1}^{2}\sum_{u\in U_{I_j}}\left(p^{NS}+\bar{\pi}_{I_j}^u(\psi^{NS})-\left[p^S+\bar{\pi}_{I_j}^u(\psi^S)\right]\right)k_{I_j}^u+\sum_{i=1}^{l}\left[p^{NS}-(c_{E_i}-\bar{\pi}_{E_i}(\psi^{NS}))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\\
&- \sum_{i=1}^{l-1}\left[p^S-(c_{E_i}-\bar{\pi}_{E_i}(\psi^S))\right]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S)-\left[p^S-(c_{E_s}-\bar{\pi}_{E_s}(\psi^S))\right]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S)\\
&+ \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]-E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right]\right)+(p^S-p^{NS})\widehat{\theta}+(1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S). \qquad (34)
\end{aligned}
$$

Recognizing that the first four components in (34) reflect the change in industry profit, (34) simplifies to:

$$E[\Delta W] = \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) + \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right]\right) + (p^S - p^{NS})\widehat{\theta}. \tag{35}$$

$\square$

Proof of Proposition 5: Using (35), $E[\Delta W] \gtreqless 0$ as:

$$\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\Pi_v + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) \gtreqless \sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]\right) + (p^{NS} - p^S)\widehat{\theta}. \tag{36}$$

$\square$

Proof of Corollary 2: Suppose Assumption 3 holds. Further, assume that the energy portfolio effect is zero (i.e., $\sum_{t=1}^{T} E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right] = \sum_{t=1}^{T} E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]$). Denote the change in 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 (35), $E[\Delta W] > 0$ as:

$$\begin{aligned}
&\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v - \tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) + (1+\lambda)\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \Delta p^C > \sum_{t=1}^{T} E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right] \\
\Leftrightarrow &\sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v + \lambda\tau X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \Delta p^C > 0 \quad \Leftarrow \quad \sum_{v\in\{\mathbf{I},\mathbf{E}\}} \Delta\widetilde{\Pi}_v > \Delta p^C.
\end{aligned} \tag{37}$$

Using $\sum_{v\in\{\mathbf{I},\mathbf{E}\}}\Delta\widetilde{\Pi}_v$ defined in (26) and $\Delta p^C = (p^{NS} - p^S)\widehat{\theta}$, (37) can be written as:

$$\begin{aligned}
&\Delta p^C + \sum_{j=1}^{2}\sum_{u\in U_{I_j}} [\bar{\pi}_{I_j}^u(\psi^{NS}) - \bar{\pi}_{I_j}^u(\psi^S)]k_{I_j}^u + \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) \\
+ \quad & [c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - \sum_{i=1}^{l-1}[c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS}) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS}) > \Delta p^C \\
\Leftrightarrow \quad & \sum_{j=1}^{2}\sum_{u\in U_{I_j}} [\bar{\pi}_{I_j}^u(\psi^{NS}) - \bar{\pi}_{I_j}^u(\psi^S)]k_{I_j}^u + \sum_{i=1}^{l-1}\Big([c_{E_i} - \bar{\pi}_{E_i}(\psi^S)]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_i} - \bar{\pi}_{E_i}(\psi^{NS})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) \\
+ \quad & \Big([c_{E_s} - \bar{\pi}_{E_s}(\psi^S)]X_{E_s}(\widehat{\theta};\boldsymbol{\beta}^S) - [c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS})]X_{E_l}(\widehat{\theta};\boldsymbol{\beta}^{NS})\Big) > 0.
\end{aligned} \tag{38}$$

From Assumption 3, the first term in (38) is non-negative and the second and third terms are positive because subsidized entry increases the aggregate net marginal cost of supplying capacity demand.[56]

$\square$

Proof of Lemma 5: 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 (16), this implies that $P_t^E(\psi^{NS}) = \min\{\gamma(\phi(t)|\psi^{NS}), \bar{P}^E\} \geq P_t^E(\psi^S) = \min\{\gamma(\phi(t)|\psi^S), \bar{P}^E\}$. $\square$

Proof of Proposition 6: Assume that $T = 2$ and firms bid non-strategically in the electricity auctions. Using (35) and substituting $\sum_{t=1}^{T}\left(E\left[P_t^E\phi(t,\mu)\middle|\psi^{NS}\right] - E\left[P_t^E\phi(t,\mu)\middle|\psi^S\right]\right) = P_L^E(\psi^{NS})\phi(L) + P_H^E(\psi^{NS})\phi(H) -$

[56]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.

$\left(P_L^E(\psi^S)\phi(L) + P_H^E(\psi^S)\phi(H)\right)$ 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:

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

$\square$

Proof of Lemma 6: 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 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 $U_{E_i} = \emptyset$.[57] 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 portfolio for each of these cases is provided in the Lemma.[58] $\square$

Proof of Lemma 7: For any value $\tau \in \{0, \widetilde{\tau} + \epsilon\}$, given its beliefs about the outcome of the subsequent capacity auction summarized in Lemma 6 $\forall\, a \in A$, entrant E_i will choose a_1 if and only if $\Pi_{E_i}(a_1)|_\tau \geq \Pi_{E_i}(a_2)|_\tau$.[59] 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 6 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 $a = a_1$.[60] Using (9) and (10) and Lemma 6, E_i will choose a_1 if and only if:

$$\begin{aligned} & \Pi_{E_i}(a_1)|_\tau \geq \Pi_{E_i}(a_2)|_\tau = 0 \\ \Leftrightarrow \quad & [p_{a_1} - (c_{E_i} - \bar{\pi}_{E_i}(\psi_{a_1}))]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}) - \zeta \geq 0 \\ \Leftrightarrow \quad & [p_{a_1} + \bar{\pi}_{E_i}(\psi_{a_1})]X_{E_i}(\widehat{\theta};\boldsymbol{\beta}) \geq c_{E_i}X_{E_i}(\widehat{\theta};\boldsymbol{\beta}) + \zeta. \end{aligned} \tag{39}$$

$\square$

Proof of Proposition 7: Using the Nash Equilibrium outcomes summarized in Lemma 6, (9), and (10), E_i has reduced incentive to invest in new capacity in the presence of subsidized entry if:

$$\begin{aligned} & \Pi_{E_i}(a_1)|_{\tau=0} > \Pi_{E_i}(a_1)|_{\tau=\widetilde{\tau}+\epsilon} \\ \Leftrightarrow \quad & [p_{a_1}^{NS} - (c_{E_i} - \bar{\pi}_{E_i}(\psi_{a_1}^{NS}))]X_{E_i}(\cdot) - \zeta > [p_{a_1}^{S} - (c_{E_i} - \bar{\pi}_{E_i}(\psi_{a_1}^{S}))]X_{E_i}(\cdot) - \zeta \\ \Leftrightarrow \quad & p_{a_1}^{NS} - p_{a_1}^{S} + \bar{\pi}_{E_i}(\psi_{a_1}^{NS}) - \bar{\pi}_{E_i}(\psi_{a_1}^{S}) > 0. \end{aligned} \tag{40}$$

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

[58] 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 (EM) 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 portfolio in the setting in which EM undercuts the marginal bidder.

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

[60] As defined in Lemma 6, for each value of τ the notation (superscripts) on the price and generation portfolio varies. However, the result in inequality (39) applies for each value of $\tau \in \{0, \widetilde{\tau} + \epsilon\}$.

From Lemma 6, $p_{a_1}^{NS} > p_{a_1}^{S}$ and from Assumption 3 $\bar{\pi}_{E_i}(\psi_{a_1}^{NS}) \geq \bar{\pi}_{E_i}(\psi_{a_1}^{S})$ such that inequality (40) holds. $\square$

Proof of Proposition 8: $E[W_{LR}] = E[\Pi_{LR}^{E}] + E[\Pi_{LR}^{C}] + E[CS_{LR}]$. Using (19), for any $\tau \in \{0, \widetilde{\tau} + \epsilon\}$:

$$
\begin{aligned}
E[CS_{LR}] &= E\left[\sum_{t=1}^{T_{LR}} \left(\int_{\widetilde{p}_t}^{p_t^{max}} \phi(t, \mu_{LR})dp\right)(1 - \rho_o(\tau)) + \left(\int_{\widetilde{p}_t}^{p_t^{max}} \phi(t, \mu_{LR})dp\right)(1 - \omega)\rho_o(\tau)\right] \\
&= E\left[\sum_{t=1}^{T_{LR}} \phi(t, \mu_{LR})\left\{[p_t^{max} - \widetilde{p}_t](1 - \rho_o(\tau)) + [p_t^{max} - \widetilde{p}_t](1 - \omega)\rho_o(\tau)\right\}\right]. \qquad (41)
\end{aligned}
$$

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 (41), $E[\Delta CS_{LR}]$ is detailed in (20). $\square$

APPENDIX B

Incumbents' New Capacity Investments

The analysis to this point has assumed that the incumbents only have installed generation units. In practice, incumbents often can undertake a new capacity investment in addition to their installed generation units. This section characterizes the incumbents' bidding behavior for these potential new capacity investments with and without subsidized entry.

Assume that both incumbents have a single new potential capacity investment. Unlike the incumbents' installed generation units, these new capacity investments are not constrained by bid offer-caps. Denote incumbent I_j's set of generation units by $U_{I_j} = \{U_{I_j}^0, U_{I_j}^n\}$ where $U_{I_j}^0$ is the set of installed units and $U_{I_j}^n$ is the unit set of the new potential capacity investment for each $j = 1, 2$. Assume that I_j submits a single bid for its new capacity investment, $b_{I_j}^n$, for its entire capacity up to its capacity limit $k_{I_j}^n$. Assume that $k_{I_j}^n = k_E \ \forall \ j = 1, 2$. There are two important settings to consider: (i) $c_{I_j}^n - \bar{\pi}_{I_j}^n(\psi) < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi) \ \forall \ \psi \in \Psi$ and $\forall \ j = 1, 2$ and (ii) $c_{I_j}^n - \bar{\pi}_{I_j}^n(\psi) > c_{E_l} - \bar{\pi}_{E_l}(\psi)$ $\forall \ \psi \in \Psi$ for some $j = 1, 2$. In case (i), both of the incumbent's new capacity investments are among the l least-cost new investments in terms of net marginal cost. Alternatively, in case (ii) new capacity investment of one or both incumbents is not among the l least-cost new investments. The following Assumption plays a key role in the subsequent analysis.

Assumption 4. Define ψ and ψ' to be the generation portfolios with $U_{I_j}^n \in \psi$ and $\psi' = \{\psi \backslash U_{I_j}^n, U_{E_i}\}$ for some $i = 1, 2, ..., M$. Assume that $\sum_{u \in U_{I_j}^0} \bar{\pi}_{I_j}^u(\psi) - \bar{\pi}_{I_j}^u(\psi') \geq 0$.

Assumption 4 states that incumbent I_j's aggregate expected payoff in subsequent energy market interactions for its installed generation units weakly decreases when its new capacity investment is displaced by an entrant E_i's new capacity investment for all $j = 1, 2$. This implies that each incumbent prefers to procure its own new capacity investment over allowing the entry of an entrant's new capacity investment.[1]

Lemma 8. Suppose Assumption 4 holds. If $p^* > c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi)$, then $b^n_{I_j} \leq p^* \; \forall \; j = 1, 2$.

Lemma 8 reveals that no incumbent will forgo procuring its new capacity investment for a profit under plausible conditions. This bidding behavior is driven by two forces. First, if $b^n_{I_j} > p^*$, then I_j is forgoing a positive payoff on its n^{th} unit. Second, if I_j's n^{th} unit is not dispatched, then an additional entrant's new capacity investment is procured, weakly reducing I_j's expected payoff in subsequent energy markets on all of it's inframarginal installed units per Assumption 4. Alternatively, Lemma 9 considers case (ii) where an incumbent's new capacity investment is not among the l least-cost new capacity investments.

Lemma 9. Suppose Assumption 4 holds. Define ψ and ψ' to be the generation portfolios resulting in the stop-out prices p^* and p', respectively, with $U^n_{I_j} \notin \psi$ and $\psi' = \{\psi \backslash U_{E_k}, U^n_{I_j}\}$ for some $k = 1, 2, ..., M$. $b^n_{I_j} > p^*$ if and only if $p^* \leq p^C_{I_j} = [c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi')]X^n_{I_j}(\cdot) - \sum_{u \in U^0_{I_j}} [\bar{\pi}^u_{I_j}(\psi') - \bar{\pi}^u_{I_j}(\psi)]k^u_{I_j}$.

Lemma 9 reveals that there are conditions under which an incumbent may procure its new capacity investment for a loss to avoid the (weak) reduction in expected payoffs on its installed generation units caused by the entry of an entrant's new capacity investment per Assumption 4. Assume that $b^n_{I_j} > p^*$. I_j will unilaterally deviate and undercut the marginal bidder E_k resulting in the price $p' = p^* - \epsilon$ for some $\epsilon > 0$ and generation portfolio ψ' if and only if, as $\epsilon \to 0$:

$$\sum_{u \in U^0_{I_j}} [\bar{\pi}^u_{I_j}(\psi') - \bar{\pi}^u_{I_j}(\psi)]k^u_{I_j} > [c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi') - p^*]X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta'}). \tag{B.1}$$

(B.1) shows that an incumbent I_j may procure its new capacity for a loss ($p^* < c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi')$) if the benefits from deterring entry of E_k's generation unit through (weakly) higher expected earnings from subsequent energy markets for I_j's inframarginal installed units (recall Assumption 4) exceeds the cost of supplying its new capacity unit for a loss. There is a critical stop-out price where this holds with equality:

$$p^C_{I_j} = [c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi)]X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}) - \sum_{u \in U^0_{I_j}} [\bar{\pi}^u_{I_j}(\psi) - \bar{\pi}^u_{I_j}(\psi')]k^u_{I_j}. \tag{B.2}$$

If $p^* \leq p^C_{I_j}$, then it is not profitable for I_j to unilaterally undercut E_k's bid because the cost of procuring its new capacity for a loss exceeds the entry-deterring benefits. If $p^* > p^C_{I_j}$, then inequality (B.1) holds and I_j will unilaterally deviate. Therefore, if the reduction in expected profits induced by the procurement of E_k's unit over I_j's new capacity

[1] This is likely to be the case in these highly concentrated markets where incumbents benefit from the lack of competition.

investment and $p^* = b_{E_k}$ is sufficiently large, then I_j will procure its new capacity for a loss to deter entry of E_k's unit and hence, (weakly) increase its payoff on its installed generation units. Further, as this allocation externality increases, it is more likely that the benefits of entry-deterrence exceeds the costs. The incumbents may prefer to deter multiple entrants' generation units. However, their ability to deter entry is limited by their capacity constraints.

Proposition 9 summarizes the incumbents' bidding behavior for their new capacity investments in the PSNE of the capacity auction without subsidized entry.

Proposition 9. Suppose Assumption 4 holds and $\tau = 0$. The PSNE of the capacity auction entails:[2]

1. If $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi) < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi)\ \forall\ \psi \in \Psi$ and $\forall\ j = 1, 2$, then the marginal bidder $v \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ sets the stop-out price $b^u_v = p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$, while all other firms $r \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ with $r \neq v$ bid sufficiently low resulting in the portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_1}, U^0_{I_2}, U^n_{I_2}, U_{E_1}, U_{E_2}, ..., U_{E_{l-2}}\}$.

2. If $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi) < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi)$ and $c^n_{I_k} - \bar{\pi}^n_{I_k}(\psi) > c_{E_l} - \bar{\pi}_{E_l}(\psi)\ \forall\ \psi \in \Psi$ where $j, k = 1, 2$ with $j \neq k$ there are two potential outcomes:

   I. If $p^C_{I_k} \geq c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$, then the marginal bidder $v \in \{I_j, E_1, ..., E_{l-1}\}$ sets the stop-out price $b^u_v = p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$, while all other firms $r \in \{I_j, E_1, ..., E_{l-1}\}$ with $r \neq v$ bid sufficiently low resulting in the portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_j}, U^0_{I_2}, U_{E_1}, U_{E_2}, ..., U_{E_{l-1}}\}$.

   II. If $p^C_{I_k} < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$, then the marginal bidder $v \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ sets the stop-out price $b^u_v = p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM}) - \epsilon$ for some $\epsilon \geq 0$, while all other firms $r \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ with $r \neq v$ bid sufficiently low resulting in the portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_1}, U^0_{I_2}, U^n_{I_2}, U_{E_1}, ..., U_{E_{l-2}}\}$.

3. If $\min\{c^n_{I_1} - \bar{\pi}^n_{I_1}(\psi), c^n_{I_2} - \bar{\pi}^n_{I_2}(\psi)\} > c_{E_l} - \bar{\pi}_{E_l}(\psi)\ \forall\ \psi \in \Psi$, there are three potential outcomes:

   I. If $\max\{p^C_{I_1}, p^C_{I_2}\} < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$, then the marginal bidder E_i with $i < l - 1$ sets the stop-out price $b_{E_i} = p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$, while all other firms $r \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ with $r \neq E_i$ bid sufficiently low resulting in the portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_1}, U^0_{I_2}, U^n_{I_2}, U_{E_1}, U_{E_2}, ..., U_{E_{l-2}}\}$.

   II. If $p^C_{I_j} < c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) \leq p^C_{I_k}$, then the marginal bidder $v \in \{I_j, E_1, ..., E_{l-1}\}$ sets the stop-out price $b^u_v = p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) - \epsilon$ for some $\epsilon \geq 0$, while all other firms $r \in \{I_j, E_1, ..., E_{l-1}\}$ with $r \neq v$ bid sufficiently low resulting in the portfolio $\psi^{NS} = \{U^0_{I_1}, U^0_{I_2}, U^n_{I_j}, U_{E_1}, U_{E_2}, ..., U_{E_{l-1}}\}$ where $j, k = 1, 2$ with $j \neq k$.

[2] In a few special cases it is necessary to use the ϵ-Nash Equilibrium solution mechanism. An ϵ-Nash Equilibrium is an approximation to a Nash Equilibrium (Radner, 1980). A bid profile $\boldsymbol{\beta}$ is a Pure Strategy ϵ-Nash Equilibrium if no player can improve its payoff by more than ϵ by unilaterally deviating for some $\epsilon > 0$.

III. If $\min\{p_{I_1}^C, p_{I_2}^C\} \geq c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$, then the marginal bidder E_i for some $i \leq l$ sets the stop-out price $b_{E_i} = p^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$, while all other firms $E_r \in \{E_1, ..., E_l\}$ with $r \neq i$ bid sufficiently low resulting in the portfolio $\psi^{NS} = \{U_{I_1}^0, U_{I_2}^0, U_{E_1}, U_{E_2}, ..., U_{E_l}\}$.

Proposition 9 shows that an incumbent's new capacity investment is only procured if: (i) it is among the l least-cost new capacity investments (outcome (1)) or (ii) the benefits from entry-deterrence are sufficiently large, i.e., $p_{I_j}^C$ in (B.2) is sufficiently low (outcomes (2) and (3)). This reveals that there are conditions under which the incumbents procure their new capacity investments for a loss to deter entry of E_{l-1}'s and E_l's new potential capacity investments in equilibrium.

Proposition 10 describes the effect of subsidized entry on the incumbents' bidding incentives for their new capacity investments.

Proposition 10. Suppose Assumption 3 holds and $c_{I_j}^n$ is drawn prior to the auction from a monotonically increasing cumulative distribution function $H_{I_j}^n(c)$ on the support $[0, \infty)$ $\forall$ $j = 1, 2$. Subsidized entry weakly reduces the incumbents' incentives to procure their new capacity investments.

From Proposition 2, subsidized entry suppresses the capacity price and alters the generation portfolio. Proposition 10 reveals that subsidized entry weakly reduces the propensity for the incumbents to procure their new capacity investments in the capacity auction. This is driven by two forces. First, the lower stop-out price induced by subsidized entry makes it less likely that the incumbents' new capacity investments can be procured for a profit. Second, a lower stop-out price implies that in order for an incumbent to deter the marginal entrant's generation unit, it must procure its new capacity investment for a lower capacity price compared to the setting without subsidized entry. Assuming that the realization of the incumbents' costs are drawn from some distribution $H_{I_j}^n(c)$ $\forall$ $j = 1, 2$, from Lemmas 8 and 9, it is less likely that the realization of $c_{I_j}^n$ will be sufficiently low such that either $p^* \geq c_{I_j}^n - \bar{\pi}_{I_j}^n(\cdot)$ or $p^* > p_{I_j}^C$ holds.

Proof of Lemma 8: Suppose there is a bid profile $\boldsymbol{\beta'}$ which results in the stop-out price p' and generation portfolio $\psi' \in \Psi$. $U_{I_j}^0 \subset \psi'$ because I_j's installed capacities are constrained by bid offer-caps and hence, are always dispatched. Assume that $b_{I_j}^{n'} > p' > c_{I_j}^n - \bar{\pi}_{I_j}^n(\psi)$ such that $U_{I_j}^n \notin \psi'$ where $\psi = \{\psi' \backslash U_{E_k}, U_{I_j}^n\}$ is the generation portfolio in which I_j's n^{th} unit is dispatched and displaces the marginal bidder's unit U_{E_k} for some $i = 1, 2, ..., M$ (i.e., $b_{E_k} = p'$). Assume that I_j unilaterally deviates and bids $b_{I_j}^n = b_{E_k} - \epsilon = p' - \epsilon$ for some $\epsilon > 0$ such that I_j's n^{th} unit is now the marginal unit setting the new stop-out price $p^* = p' - \epsilon$. Define $\boldsymbol{\beta}$ to be the new bid profile. Using (1), (3), and (4) -(8), as $\epsilon \to 0$:

$$\begin{aligned}
\Delta\Pi_{I_j} &= \Pi_{I_j}\Big|_{b^n_{I_j}} - \Pi_{I_j}\Big|_{b^{n'}_{I_j}} > 0 \\
&\Leftrightarrow \sum_{u\in U^0_{I_j}} [p^* - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi))]k^u_{I_j} + [p^* - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi))]X^n_{I_j}(\widehat{\theta};\boldsymbol{\beta}) - \sum_{u\in U^0_{I_j}} [p' - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi'))]k^u_{I_j} > 0 \\
&\Leftrightarrow \sum_{u\in U^0_{I_j}} [\bar{\pi}^u_{I_j}(\psi)) - \bar{\pi}^u_{I_j}(\psi'))]k^u_{I_j} + [p' - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi))]X^n_{I_j}(\widehat{\theta};\boldsymbol{\beta}) > 0. \qquad \text{(B.3)}
\end{aligned}$$

From Assumption 4, the first term in (B.3) is non-negative. $p' > c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi)$ and $X^n_{I_j}(\widehat{\theta};\boldsymbol{\beta}) > 0$ implies that the second-term is positive. Hence, inequality (B.3) holds.

□

Proof of Lemma 9: Assume there is a bid profile $\boldsymbol{\beta}$ resulting in the generation portfolio ψ and stop-out price p^* with $b^n_{I_j} > p^*$ such that $U^n_{I_j} \notin \psi$. $U^0_{I_j} \subset \psi$ because the incumbents' installed bids are constrained by bid offer-caps. Assume that I_j unilaterally deviates by bidding $b^{n'}_{I_j} = p^* - \epsilon$ for some $\epsilon > 0$, setting a new stop-out price $p' = b^{n'}_{I_j}$, and generation portfolio $\psi' = \{\psi \backslash U_{E_k}, U^n_{I_j}\}$ where E_k was the marginal bidder under the bid profile $\boldsymbol{\beta}$ for some $k = 1, 2, ..., M$. Denote this new bid profile by $\boldsymbol{\beta'}$. Using (1), (3), and (4) -(8), as $\epsilon \to 0$:

$$\begin{aligned}
\Delta\Pi_{I_j} &= \Pi_{I_j}\Big|_{b^{n'}_{I_j}} - \Pi_{I_j}\Big|_{b^n_{I_j}} > 0 \\
&\Leftrightarrow \sum_{u\in U^0_{I_j}} [p' - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi'))]k^u_{I_j} + [p' - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi'))]X^n_{I_j}(\widehat{\theta};\boldsymbol{\beta'}) - \sum_{u\in U^0_{I_j}} [p^* - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi))]k^u_{I_j} > 0 \\
&\Leftrightarrow \sum_{u\in U^0_{I_j}} [\bar{\pi}^u_{I_j}(\psi') - \bar{\pi}^u_{I_j}(\psi)]k^u_{I_j} > [c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi') - p^*]X^n_{I_j}(\widehat{\theta};\boldsymbol{\beta'}). \qquad \text{(B.4)}
\end{aligned}$$

Suppose Assumption 4 holds, if $p^* > c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi')$, then inequality (B.4) strictly holds. Alternatively, if $p^* \leq c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi')$, then (B.4) may not hold. There is a critical stop-out price where (B.4) holds with equality:

$$p^C_{I_j} = [c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi')]X^n_{I_j}(\widehat{\theta};\boldsymbol{\beta'}) - \sum_{u\in U^0_{I_j}} [\bar{\pi}^u_{I_j}(\psi') - \bar{\pi}^u_{I_j}(\psi)]k^u_{I_j}. \qquad \text{(B.5)}$$

If $p^* \leq p^C_{I_j} \leq c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi')$, then $\Delta\Pi_{I_j} \leq 0$ such that deviating to $b^{n'}_{I_j}$ does not strictly increase I_j's payoff. If $p^* > p^C_{I_j}$, then $\Delta\Pi_{I_j} > 0$ and it is profitable to unilaterally deviate to $b^{n'}_{I_j}$. □

Proof of Proposition 9: By assumption, the incumbents' installed generation units are always dispatched due to the constraining bid offer-caps. Therefore, the incumbents and entrants compete over residual demand $\widehat{\theta} - \sum_{j=1}^{2}\sum_{u\in U^0_{I_j}} k^u_{I_j}$ with their bids for new capacity investment. There are multiple cases to consider: (1) $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi) < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi)$ $\forall\ \psi \in \Psi$ and $\forall\ j = 1, 2$; (2) $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi) < c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi)$ and $c^n_{I_k} - \bar{\pi}^n_{I_k}(\psi) > c_{E_l} - \bar{\pi}_{E_l}(\psi)$ $\forall\ \psi \in \Psi$ where $j, k = 1, 2$ with $j \neq k$; and (3) $\min\{c^n_{I_1} - \bar{\pi}^n_{I_1}(\psi), c^n_{I_2} - \bar{\pi}^n_{I_2}(\psi)\} > c_{E_l} - \bar{\pi}_{E_l}(\psi)$ $\forall\ \psi \in \Psi$. In each of these cases, the entrant's bidding incentives are analogous to those identified in Proposition 1. Therefore, I focus on the incumbents incentives to deviate from $b^n_{I_j} \in \boldsymbol{\beta}^{NS} \; \forall \; j = 1, 2$.

Case (1).[3] Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ where a firm $v \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ bids $b^u_v = p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM}) = b_{E_{l-1}}$ with $u \in U_v$ resulting in the generation portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_1}, U^0_{I_2}, U^n_{I_2}, U_{E_1}, U_{E_2}, ..., U_{E_{l-2}}\}$, while all other bidders with units in the set ψ^{NS} (non price-setters) bid sufficiently low (defined below).[4] I derive conditions under which the bid profile $\boldsymbol{\beta}^{NS}$ is a PSNE that is unique up to the identity of the price-setting and non price-setting firms.

There are two settings to consider: (a) $v = E_i$ for some $i < l-1$ (i.e., $p^{NS} = b_{E_i}$) or (b) $v = I_j$ for some $j = 1, 2$ (i.e., $p^{NS} = b^n_{I_j}$). First, focus on setting (a) such that the incumbents are non price-setters and hence, are bidding sufficiently low, $b^n_{I_j} \leq \bar{b}_E \; \forall j = 1, 2$, as defined in (21) such that the marginal entrant has no incentive to unilaterally deviate. Investigate the incumbents' incentives to unilaterally deviate from $b^n_{I_j} \leq \bar{b}_E$ to $b^{n'}_{I_j} > \bar{b}_E \; \forall \; j = 1, 2$. There are two potential outcomes: (i) $\bar{b}_E < b^{n'}_{I_j} \leq p^{NS}$ and (ii) $b^{n'}_{I_j} > p^{NS}$. In outcome (i), I_j weakly reduces its payoff because deviating weakly reduces the output of it's n^{th} unit procured in the auction, while the stop-out price is unchanged. From Assumption 4 and Lemma 8, it is known that no incumbent will forgo procuring its new capacity for a profit and hence, I_j's payoff is strictly reduced in outcome (ii).

Next, consider case setting (b) where $p^{NS} = b^n_{I_j}$ for some $j = 1, 2$. First, I characterize what it means for the inframarginal bidders to be bidding sufficiently low. Define $\bar{b}_{I_j} = \max\{b^u_h \; \forall \; u \in \psi^{NS}$ with $u \in U_h$ and $b^u_h \neq b^n_{I_j}\}$ to be the highest inframarginal bid. Assume that I_j unilaterally deviates to $b^{n'}_{I_j} = \bar{b}_{I_j} - \epsilon$ for some $\epsilon > 0$ resulting in a new stop-out price $p^{NS'} = \bar{b}_{I_j}$. Denote $\boldsymbol{\beta}^{NS'}$ to be the new bid profile. Using (1), (3), and (4) -(8), $\bar{b}_{I_j}$ is sufficiently low if:

$$
\begin{aligned}
&\Delta\Pi_{I_j} = \Pi_{I_j}\Big|_{b^n_{I_j}} - \Pi_{I_j}\Big|_{b^{n'}_{I_j}} \geq 0 \\
\Leftrightarrow &\sum_{u \in U^0_{I_j}} [p^{NS} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{NS}))]k^u_{I_j} + [p^{NS} - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}))]X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \\
- &\sum_{u \in U^0_{I_j}} [p^{NS'} - (c^u_{I_j} - \bar{\pi}^u_{I_j}(\psi^{NS}))]k^u_{I_j} - [p^{NS'} - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}))]X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS'}) \geq 0 \\
\Leftrightarrow &\sum_{u \in U^0_{I_j}} [p^{NS} - \bar{b}_{I_j}]k^u_{I_j} + [p^{NS} - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}))]X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) - [\bar{b}_{I_j} - (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}))]X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS'}) \geq 0
\end{aligned}
$$

$$
\bar{b}_{I_j} \leq \frac{1}{\sum\limits_{u \in U^0_{I_j}} k^u_{I_j} + X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS'})} \left(p^{NS} \left[\sum_{u \in U^0_{I_j}} k^u_{I_j} + X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS}) \right] + (c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}))\Delta X^n_{I_j} \right) \tag{B.6}
$$

[3] In this setting, both incumbents are procuring their new generation capacities for a profit.

[4] $\psi^{EM} = \{\psi^{NS} \backslash u, U_{E_{l-1}}\}$ represents the set at which the first extramarginal entrant unilaterally deviates and undercuts the marginal bidder's unit $u \in U_v$. By pricing at the first extramarginal unit's net marginal cost with this generation portfolio, firm v ensures that E_{l-1} can not profitably deviate.

where $p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$ and $\Delta X^n_{I_j} = X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS'}) - X^n_{I_j}(\widehat{\theta}; \boldsymbol{\beta}^{NS})$. Assuming $\bar{b}_{I_j}$ satisfies that condition in inequality (B.6), I_j has no incentive to deviate to $b^{n'}_{I_j} < b^n_{I_j}$. There are two types of inframarginal bids for new capacity investment: entrants and incumbent I_k.[5] From Proposition 1, no entrant wants to unilaterally deviate from bidding sufficiently low. If I_k unilaterally deviates from bidding sufficiently low (i.e., $b^n_{I_k} \leq \bar{b}_{I_j}$) to $b^{n'}_{I_k} > \bar{b}_{I_j}$, then either: (i) I_k's output weakly decreases, the stop-out price remains unchanged, and I_k's payoff weakly decreases (if $\bar{b}_{I_j} < b^{n'}_{I_k} \leq p^{NS}$) or (ii) I_k's new capacity investment is no longer dispatched (if $b^{n'}_{I_k} > p^{NS}$) and from Assumption 4 and Lemma 8, I_k is worse-off because it forgoes procuring it's n^{th} unit for a profit. Lastly, from Assumption 4 and Lemma 8, it is known that no incumbent will forgo procuring its new capacity for a profit and hence, I_j has no incentive to deviate to $b^{n'}_{I_j} > b^n_{I_j}$.

Case (2).

Part I. It is without loss of generality to assume that $j = 1$ and $k = 2$.[6] Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ where a firm $v \in \{I_1, E_1, ..., E_{l-1}\}$ bids $b^u_v = p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) = b_{E_l}$ with $u \in U_v$ resulting in the generation portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_1}, U^0_{I_2}, U_{E_1}, U_{E_2}, ..., U_{E_{l-1}}\}$, while all other bidders with units in the set ψ^{NS} (non price-setters) bid sufficiently low (defined below).[7] Further, assume that $b^n_{I_2} > p^{NS}$ with $b^n_{I_2} \in \boldsymbol{\beta}^{NS}$. I derive conditions under which the bid profile $\boldsymbol{\beta}^{NS}$ is a PSNE that is unique up to the identity of the price-setting and non price-setting firms.

There are two settings to consider: (a) $v = E_i$ for some $i < l$ (i.e., $p^{NS} = b_{E_i}$) or (b) $v = I_1$ (i.e., $p^{NS} = b^n_{I_1}$). First, focus on setting (a). As detailed in Case (1) above, I_1 is procuring its new capacity investment for a profit and hence, has no incentive to deviate in this setting from bidding sufficiently low as defined by $\bar{b}_E$ in (21). However, $c^n_{I_2} - \bar{\pi}^n_{I_2}(\psi) > c_{E_l} - \bar{\pi}_{E_l}(\psi)\ \forall\ \psi \in \Psi$ and $b^n_{I_2} > p^{NS}$ such that I_2's new capacity investment is extramarginal and can not be procured for a profit. From Lemma 9, I_2 wants to unilaterally deviate to $b^{n'}_{I_2} = p^{NS} - \epsilon$ for some $\epsilon > 0$ if and only if $p^{NS} > p^C_{I_2} = c^n_{I_2} - \bar{\pi}^n_{I_2}(\psi^{NS'}) - \sum_{u \in U^0_{I_2}} \left(\bar{\pi}^u_{I_2}(\psi^{NS'}) - \bar{\pi}^u_{I_2}(\psi^{NS})\right) \frac{k^u_{I_2}}{X^n_{I_2}(\widehat{\theta}; \boldsymbol{\beta}^{NS'})}$ where $\psi^{NS'} = \{\psi^{NS} \backslash U_{E_i}, U^n_{I_2}\}$. Therefore, I_2 has no incentive to unilaterally deviate if $p^C_{I_2} \geq p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$.[8]

Next, consider setting (b) where $p^{NS} = b^n_{I_1}$. As in Case (1), the inframarginal bidders are bidding sufficiently low if $\bar{b}_{I_1} = \max\{b^u_h\ \forall\ h \in \psi^{NS}$ with $u \in U_h$ and $h \neq I_1\}$ satisfies the condition in inequality (B.6). From Proposition 1, no entrant E_i with $i < l$ wants to unilaterally deviate from bidding sufficiently low. From Assumption 4 and Lemma 8, it is known that no incumbent will forgo procuring its new capacity for a profit and hence, I_1 has no incentive to deviate to $b^{n'}_{I_1} > b^n_{I_1}$. Therefore, I_1 has no incentive to deviate from being the marginal bidder.

[5]The incumbents' bids for their installed capacity units are inframarginal. However, they are constrained to always be dispatched by the bid offer-caps less than the threshold defined in (B.6).

[6]In this setting, I_1 is the only incumbent procuring its new generation capacity investment.

[7]$\psi^{EM} = \{\psi^{NS} \backslash u, U_{E_{l-1}}\}$ represents the set at which the first extramarginal entrant unilaterally deviates and undercuts the marginal bidder's unit $u \in U_v$.

[8]Define $\boldsymbol{\beta}^{NS'}$ to be the new bid profile resulting from I_2's unilateral deviation. If deterring entry of E_i's new capacity investment does not sufficiently reduce I_2's expected earnings in subsequent energy markets for its installed units, then I_2 has no incentive to deviate.

From Lemma 9, I_2 will unilaterally deviate to $b_{I_2}^{n'} = p^{NS} - \epsilon$ for some $\epsilon > 0$ if and only if $p^{NS} > p_{I_2}^C = c_{I_2}^n - \bar{\pi}_{I_2}^n(\psi^{NS'}) - \sum_{u \in U_{I_2}^0} \left(\bar{\pi}_{I_2}^u(\psi^{NS'}) - \bar{\pi}_{I_2}^u(\psi^{NS}) \right) \frac{k_{I_2}^u}{X_{I_2}^n(\hat{\theta};\boldsymbol{\beta}^{NS'})}$ where $\psi^{NS'} = \{\psi^{NS} \backslash U_{I_1}^n, U_{I_2}^n\}$. Therefore, I_2 has no incentive to unilaterally deviate if $p_{I_2}^C \geq p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$.[9]

Part II. It is without loss of generality to assume that $j = 1$ and $k = 2$.[10] Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ where a firm $v \in \{I_1, I_2, E_1, ..., E_{l-2}\}$ bids $b_v^u = p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM}) - \epsilon \leq b_{E_{l-1}}$ for some $\epsilon \geq 0$ with $u \in U_v$ resulting in the generation portfolio $\psi^{NS} = \{U_{I_1}^0, U_{I_1}^n, U_{I_2}^0, U_{I_2}^n, U_{E_1}, U_{E_2}, ..., U_{E_{l-2}}\}$, while all other bidders with units in the set ψ^{NS} (non price-setters) bid sufficiently low (defined below).[11] I derive conditions under which the bid profile $\boldsymbol{\beta}^{NS}$ is a PSNE (or ϵ-Nash Equilibrium) that is unique up to the identity of the price-setting and non price-setting firms.

There are three settings to consider: (a) $v = E_i$ for some $i < l - 1$ (i.e., $p^{NS} = b_{E_i}$); (b) $v = I_1$ (i.e., $p^{NS} = b_{I_1}^n$); and (c) $v = I_2$ (i.e., $p^{NS} = b_{I_2}^n$).[12] First, focus on setting (a). As detailed in Case (1) above, I_1 is procuring its new capacity investment for a profit and hence, has no incentive to deviate in this setting from bidding sufficiently low as defined by $\bar{b}_E$ in (21). However, $c_{I_2}^n - \bar{\pi}_{I_2}^n(\psi^{NS}) > c_{E_l} - \bar{\pi}_{E_l}(\psi^{NS}) > p^{NS}$ such that I_2's new capacity investment is being procured for a loss. Assume that I_2 unilaterally deviates from bidding sufficiently low (i.e., $b_{I_2}^n \leq \bar{b}_E$ defined in (21)) to $b_{I_2}^{n'} \geq p^{NS}$.[13] From Lemma 9, I_2's payoff weakly decreases by unilaterally deviating if and only if $p_{I_2}^C = c_{I_2}^n - \bar{\pi}_{I_2}^n(\psi^{NS}) - \sum_{u \in U_{I_2}^0} \left(\bar{\pi}_{I_2}^u(\psi^{NS}) - \bar{\pi}_{I_2}^u(\psi^{NS'}) \right) \frac{k_{I_2}^u}{X_{I_2}^n(\hat{\theta};\boldsymbol{\beta}^{NS})} < p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$ where $\psi^{NS'} = \{\psi^{NS} \backslash U_{I_2}^n, U_{E_{l-1}}\}$.[14]

Next, consider setting (b). From Lemma 8, I_1 has no incentive to unilaterally deviate to any $b_{I_1}^{n'} > p^{NS}$. Assuming that all inframarginal non price-setters are bidding sufficiently low as defined in (B.6), I_1 has no incentive to deviate unilaterally to any $b_{I_1}^{n'} < p^{NS}$. Because I_2 is inframarginal, I_2's new capacity investment is being procured for a loss. I_2's incentive to unilaterally deviate to $b_{I_2}^{n'} \geq p^{NS}$ are analogous to those identified in setting (a).

Lastly, consider setting (c). I_1 is procuring its new capacity investment for a profit and hence, has no incentive to deviate in this setting from bidding sufficiently low as defined by $\bar{b}_{I_2}$ in (B.6). I_2's incentive to unilaterally deviate to $b_{I_2}^{n'} \geq p^{NS}$ are analogous to those identified in setting (a).

Case (3).

[9]Define $\boldsymbol{\beta}^{NS'}$ to be the new bid profile resulting from I_2's unilateral deviation. If deterring entry of I_1's new capacity investment does not sufficiently reduce I_2's expected earnings in subsequent energy markets for its installed units, then I_2 has no incentive to deviate.

[10]In this setting, I_1 and I_2 are both procuring their new generation capacities. However, I_1 is procuring its new capacity for a profit, whereas I_2 is procuring its unit for a loss.

[11]$\psi^{EM} = \{\psi^{NS} \backslash u, U_{E_{l-1}}\}$ represents the set at which the first extramarginal entrant unilaterally deviates and undercuts the marginal bidder's unit $u \in U_v$.

[12]In settings (a) and (b), $\epsilon = 0$. However, in setting (c) $\epsilon > 0$ because I_2 is undercutting E_{l-1}'s bid. Otherwise, due to the presumed efficient rationing, if $\epsilon = 0$ E_{l-1}'s new capacity would be rationed over I_2's new capacity. Therefore, settings (a) and (b) characterize a PSNE, whereas setting (c) is an ϵ-Nash Equilibrium.

[13]If I_2 unilaterally deviates to $b_{I_2}^{n'} \in (\bar{b}_E, p^{NS})$, I_2's payoff remains unchanged as the capacity auction outcome remains unchanged.

[14]That is, if the subsequent entry of E_{l-1}'s new capacity investment reduces I_2's payoff such that I_2 is weakly worse off by unilaterally deviating to $b_{I_2}^{n'}$, then I_2 prefers to procure its new capacity for a loss.

Part I.[15] Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ where an entrant E_i with $i < l-1$ bids $b_{E_i} = p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM}) = b_{E_{l-1}}$ resulting in the generation portfolio $\psi^{NS} = \{U^0_{I_1}, U^n_{I_1}, U^0_{I_2}, U^n_{I_2}, U_{E_1}, ..., U_{E_{l-2}}\}$, while all other bidders with units in the set ψ^{NS} (non price-setters) bid sufficiently low (defined below).[16] I derive conditions under which the bid profile $\boldsymbol{\beta}^{NS}$ is a PSNE that is unique up to the identity of the price-setting and non price-setting firms.

Both incumbents are procuring their new capacities for a loss in this setting by bidding sufficiently low (i.e., $\max\{b^n_{I_1}, b^n_{I_2}\} \leq \bar{b}_E$ defined in (21)). Assume that I_1 unilaterally deviates from bidding sufficiently low (i.e., $b^n_{I_1} \leq \bar{b}_E$) to $b^{n'}_{I_1} \geq p^{NS}$.[17] From Lemma 9, I_1's payoff weakly decreases by unilaterally deviating if and only if $p^C_{I_1} = c^n_{I_1} - \bar{\pi}^n_{I_1}(\psi^{NS}) - \sum_{u \in U^0_{I_1}} \left(\bar{\pi}^u_{I_1}(\psi^{NS}) - \bar{\pi}^u_{I_1}(\psi^{NS'})\right) \frac{k^u_{I_1}}{X^n_{I_1}(\hat{\theta};\boldsymbol{\beta}^{NS})} < p^{NS} = c_{E_{l-1}} - \bar{\pi}_{E_{l-1}}(\psi^{EM})$ where $\psi^{NS'} = \{\psi^{NS} \backslash U^n_{I_1}, U_{E_{l-1}}\}$.[18] I_2's incentives are analogous.

Part II.[19] Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ where a firm $v \in \{I_j, E_1, ..., E_{l-1}\}$ bids $b^u_v = p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) - \epsilon \leq b_{E_l}$ for some $\epsilon \geq 0$ with $u \in U_v$ resulting in the generation portfolio $\psi^{NS} = \{U^0_{I_1}, U^0_{I_2}, U^n_{I_j}, U_{E_1}, U_{E_2}, ..., U_{E_{l-1}}\}$, while all other bidders with units in the set ψ^{NS} (non price-setters) bid sufficiently low (defined below).[20] I derive conditions under which the bid profile $\boldsymbol{\beta}^{NS}$ is a PSNE (or ϵ-Nash Equilibrium) that is unique up to the identity of the price-setting and non price-setting firms.

There is two settings to consider: (a) $v = E_i$ for some $i < l$ (i.e., $p^{NS} = b_{E_i}$); (b) $v = I_j$ for some $j = 1, 2$ (i.e., $p^{NS} = b^n_{I_j}$).[21] First, focus on setting (a). I_j is procuring its new capacity for a loss in this setting by bidding sufficiently low (i.e., $b^n_{I_j} \leq \bar{b}_E$ defined in (21)). Assume that I_j unilaterally deviates from bidding sufficiently low to $b^{n'}_{I_j} \geq p^{NS}$.[22] From Lemma 9, I_j's payoff weakly decreases by unilaterally deviating if and only if $p^C_{I_j} = c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}) - \sum_{u \in U^0_{I_j}} \left(\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^{NS'})\right) \frac{k^u_{I_j}}{X^n_{I_j}(\hat{\theta};\boldsymbol{\beta}^{NS})} < p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$ where $\psi^{NS'} = \{\psi^{NS} \backslash U^n_{I_j}, U_{E_l}\}$.[23]

I_k is bidding $b^n_{I_k} > p^{NS}$ such that it's new capacity is not procured. Assume that I_k unilaterally deviates to $b^{n'}_{I_k} = p^{NS} - \epsilon$ for some $\epsilon > 0$. Define this new bid profile as $\boldsymbol{\beta}^{NS'}$. From Lemma 9, I_k's payoff falls if $p^C_{I_k} = c^n_{I_k} - \bar{\pi}^n_{I_k}(\psi^{NS'}) - \sum_{u \in U^0_{I_k}} \left(\bar{\pi}^u_{I_k}(\psi^{NS'}) - \bar{\pi}^u_{I_k}(\psi^{NS})\right) \frac{k^u_{I_k}}{X^n_{I_k}(\hat{\theta};\boldsymbol{\beta}^{NS'})} \geq p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM})$ where $\psi^{NS'} =$

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[15] In this setting, both I_1 and I_2 are procuring their new generation capacities for a loss.

[16] $\psi^{EM} = \{\psi^{NS} \backslash U_{E_i}, U_{E_{l-1}}\}$ represents the set at which the first extramarginal entrant unilaterally deviates and undercuts the marginal bidder's unit.

[17] If I_1 unilaterally deviates to $b^{n'}_{I_1} \in (\bar{b}_E, p^{NS})$, I_1's payoff remains unchanged as the capacity auction outcome remains unchanged.

[18] That is, if the subsequent entry of E_{l-1}'s new capacity investment reduces I_1's payoff such that I_1 is weakly worse off by unilaterally deviating to $b^{n'}_{I_1}$ because E_{l-1}'s new capacity is procured, then I_1 prefers to procure its new capacity for a loss.

[19] In this setting, I_j is procuring its new capacity investment for a loss.

[20] $\psi^{EM} = \{\psi^{NS} \backslash u, U_{E_l}\}$ represents the set at which the first extramarginal entrant unilaterally deviates and undercuts the marginal bidder's unit $u \in U_v$.

[21] In this setting (a), $\epsilon = 0$. However, in setting (b) $\epsilon > 0$ because I_j is undercutting E_l's bid. Otherwise, due to the presumed efficient rationing, if $\epsilon = 0$ E_l's new capacity would be rationed over I_j's new capacity.

[22] If I_j unilaterally deviates to $b^{n'}_{I_1} \in (\bar{b}_E, p^{NS})$, I_j's payoff remains unchanged as the capacity auction outcome remains unchanged.

[23] That is, if the subsequent entry of E_l's new capacity investment reduces I_j's payoff such that I_j is weakly worse off by unilaterally deviating to $b^{n'}_{I_j}$ because E_{l-1}'s new capacity is procured, then I_j prefers to procure its new capacity for a loss.

$\{\psi^{NS} \backslash U_{E_i}, U^n_{I_k}\}$.[24]

Next, consider setting (b) where $p^{NS} = b^n_{I_j} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) - \epsilon$ for some $\epsilon > 0$. By definition, I_j has no incentive to unilaterally deviate to $b^{n'}_{I_j} < p^{NS}$ because all inframarginal bidders are bidding sufficiently low as defined in (B.6). As shown for setting (a), I_j has no incentive to unilaterally deviate and become extramarginal if $p^C_{I_j} = c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS}) - \sum_{u \in U^0_{I_j}} \left(\bar{\pi}^u_{I_j}(\psi^{NS}) - \bar{\pi}^u_{I_j}(\psi^{NS'})\right) \frac{k^u_{I_j}}{X^n_{I_j}(\hat{\theta};\boldsymbol{\beta}^{NS})} < p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) - \epsilon$ where $\psi^{NS'} = \{\psi^{NS} \backslash U^n_{I_j}, U_{E_l}\}$.

Lastly, I_k has no incentive to unilaterally deviate from $b^n_{I_k} > p^{NS}$ to $b^{n'}_{I_k} = p^{NS} - \epsilon'$ for some $\epsilon' > 0$ with $b^{n'}_{I_k} \in \boldsymbol{\beta}^{NS'}$ and deter entry of I_1's new capacity investment if, using Lemma 9, $p^C_{I_k} = c^n_{I_k} - \bar{\pi}^n_{I_k}(\psi^{NS'}) - \sum_{u \in U^0_{I_k}} \left(\bar{\pi}^u_{I_k}(\psi^{NS'}) - \bar{\pi}^u_{I_k}(\psi^{NS})\right) \frac{k^u_{I_k}}{X^n_{I_k}(\hat{\theta};\boldsymbol{\beta}^{NS'})} \geq p^{NS} = c_{E_l} - \bar{\pi}_{E_l}(\psi^{EM}) - \epsilon$ where $\psi^{NS'} = \{\psi^{NS} \backslash U^n_{I_j}, U^n_{I_k}\}$.

Part III.[25] Assume there is a bid profile $\boldsymbol{\beta}^{NS}$ where a firm E_i for some $i < l+1$ bids $b_{E_i} = p^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM}) = b_{E_{l+1}}$ resulting in the generation portfolio $\psi^{NS} = \{U^0_{I_1}, U^0_{I_2}, U_{E_1}, U_{E_2}, ..., U_{E_l}\}$, while all other bidders with units in the set ψ^{NS} (non price-setters) bid sufficiently low (defined below).[26] I derive conditions under which the bid profile $\boldsymbol{\beta}^{NS}$ is a PSNE that is unique up to the identity of the price-setting and non price-setting firms.

Both incumbents' new capacity investments are extramarginal. Assume that I_j unilaterally deviates from $b^n_{I_j} > p^{NS}$ to $b^{n'}_{I_j} = p^{NS} - \epsilon$ for some $\epsilon > 0$ and $j = 1, 2$. Define this new bid profile as $\boldsymbol{\beta}^{NS'}$. Using Lemma 9, I_j's payoff falls if $p^C_{I_j} = c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi^{NS'}) - \sum_{u \in U^0_{I_j}} \left(\bar{\pi}^u_{I_j}(\psi^{NS'}) - \bar{\pi}^u_{I_j}(\psi^{NS})\right) \frac{k^u_{I_j}}{X^n_{I_j}(\hat{\theta};\boldsymbol{\beta}^{NS'})} \geq p^{NS} = c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM})$ where $\psi^{NS'} = \{\psi^{NS} \backslash U_{E_i}, U^n_{I_j}\}$.[27]

$\square$

Proof of Proposition 10: Suppose Assumption 3 holds. There are four outcomes to consider. (1) $\tau = 0$ and I_j's n^{th} unit is not procured; (2) $\tau = 0$ and I_j's n^{th} unit is procured; (3) $\tau > 0$ and I_j's n^{th} unit is not procured; and (4) $\tau > 0$ and I_j's n^{th} unit is procured. Define p_i and ψ_i to be the equilibrium stop-out price and generation portfolio given outcome i where $i = 1, 2, 3, 4$ represents each of these outcomes.

Proposition 9 reveals that I_j will procure its new capacity investment if and only if: (i) $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_i) \leq p_i$ where $i = 2, 4$ or (ii) $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_i) \leq p^C_{I_j} = p_i + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_i) - \bar{\pi}^n_{I_j}(\psi_h)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right)$ where if $i = 2$, then $h = 1$ and if $i = 4$, then $h = 3$. This implies that in either setting $c^n_{I_j}$ must be sufficiently small.

Assume that each firm's cost of capacity (installed or new) is drawn from a probability distribution. Assume that $c^n_{I_j}$ is randomly drawn in the interval $[0, \infty)$ according to the continuous cumulative distribution function $H^n_{I_j}(c)$. $H^n_{I_j}(c)$ is monotonically increasing on its support $[0, \infty)$.

[24] That is, if the benefit from deterring the marginal bidder's unit, U_{E_i}, is not sufficiently large, then I_k has no incentive to unilaterally deviate and procure its new capacity for a loss.

[25] In this setting, neither incumbent is procuring its new capacity investment.

[26] $\psi^{EM} = \{\psi^{NS} \backslash U_{E_i}, U_{E_{l+1}}\}$ represents the set at which the first extramarginal entrant unilaterally deviates and undercuts the marginal bidder's unit.

[27] That is, if the benefit from deterring the marginal bidder's unit, U_{E_i}, is not sufficiently large, then I_j has no incentive to unilaterally deviate and procure its new capacity for a loss.

I will show that for cases (i) and (ii), subsidized entry weakly reduces the likelihood that I_j procures its n^{th} unit in the auction. First consider case (i). I_j's n^{th} unit is procured if $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_i) \leq p_i$ where $i = 2, 4$. Subsidized entry reduces the likelihood that this inequality holds if:

$$\begin{aligned} P(c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_2) \leq p_2) &\geq P(c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_4) \leq p_4) \\ &\Leftrightarrow H^n_{I_j}(p_2 + \bar{\pi}^n_{I_j}(\psi_2)) \geq H^n_{I_j}(p_4 + \bar{\pi}^n_{I_j}(\psi_4)). \end{aligned} \tag{B.7}$$

Because $H^n_{I_j}(\cdot)$ is monotonically increasing, (B.7) holds if:

$$\begin{aligned} p_2 + \bar{\pi}^n_{I_j}(\psi_2) &\geq p_4 + \bar{\pi}^n_{I_j}(\psi_4) \\ &\Leftrightarrow p_2 - p_4 + \bar{\pi}^n_{I_j}(\psi_2) - \bar{\pi}^n_{I_j}(\psi_4) \geq 0. \end{aligned} \tag{B.8}$$

From Proposition 3, $p_2 > p_4$ because subsidized entry reduces the stop-out price. Assumption 3 implies that $\bar{\pi}^n_{I_j}(\psi_2) \geq \bar{\pi}^n_{I_j}(\psi_4)$. Hence, inequality (B.8) holds.

Next, consider case (ii). I_j's n^{th} unit is procured if $c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_i) \leq p^C_{I_j} = p_i + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_i) - \bar{\pi}^n_{I_j}(\psi_h)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right)$ where if $i = 2$, then $h = 1$ and if $i = 4$, then $h = 3$. Subsidized entry reduces the likelihood that this inequality holds if:

$$\begin{aligned} &P\left(c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_2) \leq p_2 + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_2) - \bar{\pi}^n_{I_1}(\psi_1)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right)\right) \\ \geq\ &P\left(c^n_{I_j} - \bar{\pi}^n_{I_j}(\psi_4) \leq p_4 + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_4) - \bar{\pi}^n_{I_1}(\psi_3)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right)\right) \\ \Leftrightarrow\ &H^n_{I_j}\left(p_2 + \bar{\pi}^n_{I_j}(\psi_2) + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_2) - \bar{\pi}^n_{I_1}(\psi_1)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right)\right) \\ \geq\ &H^n_{I_j}\left(p_4 + \bar{\pi}^n_{I_j}(\psi_4) + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_4) - \bar{\pi}^n_{I_1}(\psi_3)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right)\right). \end{aligned} \tag{B.9}$$

Because $H^n_{I_j}(\cdot)$ is monotonically increasing, (B.9) holds if:

$$\begin{aligned} &p_2 + \bar{\pi}^n_{I_j}(\psi_2) + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_2) - \bar{\pi}^n_{I_1}(\psi_1)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right) \geq p_4 + \bar{\pi}^n_{I_j}(\psi_4) + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_4) - \bar{\pi}^n_{I_1}(\psi_3)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right) \\ \Leftrightarrow\ &p_2 - p_4 + \bar{\pi}^n_{I_j}(\psi_2) - \bar{\pi}^n_{I_j}(\psi_4) + \sum_{u \in U^0_{I_j}} \left[\bar{\pi}^n_{I_j}(\psi_2) - \bar{\pi}^n_{I_1}(\psi_4) + \bar{\pi}^n_{I_j}(\psi_3) - \bar{\pi}^n_{I_1}(\psi_1)\right] \left(\frac{k^u_{I_j}}{X^n_{I_j}(\cdot)}\right) \geq 0. \end{aligned} \tag{B.10}$$

From Proposition 3, $p_2 > p_4$ because subsidized entry reduces the stop-out price. Assumption 3 implies that $\bar{\pi}^n_{I_j}(\psi_2) \geq \bar{\pi}^n_{I_j}(\psi_4)$ and $\bar{\pi}^n_{I_j}(\psi_3) \geq \bar{\pi}^n_{I_1}(\psi_1)\ \forall\ u \in U^0_{I_j}$. Hence, inequality (B.10) holds.

□

Heterogeneous Capacity Limit, $k_{E_s} > k_E$

Now suppose that the subsidized entrant's capacity limit $k_{E_s} > k_E = k_{E_i}$ $\forall$ $i = 1, 2, ..., M$ with $i \neq s$. This implies that if E_s's new capacity investment receives an OOM payment and is dispatched in the capacity auction, at least one more efficient new capacity investment will be displaced. Define $h \in \mathbb{Z}$ with $h \geq 1$ to be the number of new capacity investments displaced if E_s's unit is dispatched.[28] It is assumed that $l - h \geq 1$ such that E_s's unit is not sufficiently large to solely serve residual capacity demand (i.e., $k_{E_s} < \widehat{\theta} - K_I$). Lastly, it is assumed that if E_s receives a subsidy $\tau > \widetilde{\tau}$, then E_s bids sufficiently low to ensure that its subsidized capacity is full dispatched.[29]

If there is no capacity subsidy ($\tau = 0$), then the outcome is identical to the benchmark setting characterized in Proposition 1. Proposition 11 characterizes the PSNE in the capacity auction when E_s is receiving a subsidy $\tau > \widetilde{\tau}$ and $k_{E_s} > k_E$.

Proposition 11. Suppose $\tau = \widetilde{\tau} + \epsilon$ for some $\epsilon > 0$. Let E_k denote the marginal bidder who sets the stop-out price p^{NS} for some $k \leq l - h$. E_k sets the stop-out price p^{NS} with its bid $b_{E_k} = c_{E_{l-h+1}} - \bar{\pi}_{E_{l-h+1}}(\psi^{EM})$, while all other entrants E_i bid sufficiently low to make undercutting unprofitable $\forall$ $i = 1, 2, ..., l - h, s$ with $i \neq k$.

Comparing the results in Proposition 11 to those in Proposition 2, the firms' bidding behavior is unchanged. However, in this setting the subsidization and subsequent procurement of E_s's new capacity in the auction results in the displacement of $h \geq 1$ units of more efficient new capacity investments. If $h \geq 2$, this implies that E_s displaces at least two additional more efficient new capacity investments.[30] Further, in this setting the first extramarginal firm's net marginal cost is lower compared to the setting in which $h = 1$ and hence, the market-clearing capacity price is lower compared to the setting in Proposition 2. These results imply that the allocative inefficiencies and capacity price suppression induced by subsidized entry are strictly (weakly) larger in the setting where $k_{E_s} > k_E$ and $h \geq 2$ ($h = 1$) compared to when $k_{E_s} = k_E$ as in Proposition 2. Corollary 3 reveals that a larger capacity limit results in a PSNE with more allocative inefficiencies and a lower capacity price compared to a setting with a lower capacity limit.

Corollary 3. Suppose $h, h' \in \mathbb{Z}$ with $h' > h$, then the level of allocative inefficiency is larger and the capacity price is lower under the setting with h' compared to h.

Proof of Proposition 11: Is analogous to the proof of Proposition 1. $\square$

Proof of Corollary 3: Assume that there are two capacity limits k_{E_s} and k'_{E_s} where $h = \lceil n \rceil = \min\{n \in \mathbb{Z} : k_{E_s} \leq nk_E\}$ and $h' = \lceil n' \rceil = \min\{n' \in \mathbb{Z} : k'_{E_s} \leq n'k_E\}$ reflect the number of new capacity investments displaced by E_s's

[28]More formally, using a ceiling function $h = \lceil n \rceil = \min\{n \in \mathbb{Z} : k_{E_s} \leq nk_E\}$ where $\mathbb{Z}$ is the set of integers.

[29]Recall, this assumes that E_s and buyer's objective functions are aligned such that E_s always bids sufficiently low to be a non price-setter to maximize the level of capacity price suppression. If this assumption is relaxed, then E_s may maximize its payoff by being a price-setter and partially procuring its new capacity investment resulting in less than the maximum level of capacity price suppression. This behavior reflects the classic principal-agent problem where the entrant (agent) does not act in the best interests of the buyer (principal).

[30]If $h = 1$ and $k_{E_s} > k_E$, then E_s's unit only displaces E_l's new capacity investment as in Proposition 2. However, the residual demand rationed to the marginal bidder, E_k, is smaller compared to the setting in which $k_{E_s} = k_E$.

new capacity if it is dispatched under each setting. Further, assume that $h' > h$ and $l - h' \geq 1$. From Proposition 11, the PSNE when E_s's capacity limit is k_{E_s} and k'_{E_s} entails the stop-out prices $b_{E_k} = p^{NS} = c_{E_{l-h+1}} - \bar{\pi}_{E_{l-h+1}}(\psi^{EM1})$ and $b_{E_v} = p^{NS'} = c_{E_{l-h'+1}} - \bar{\pi}_{E_{l-h'+1}}(\psi^{EM2})$ and generation portfolios $\psi^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l-h}}, U_{E_s}\}$ and $\psi^{NS'} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l-h'}}, U_{E_s}\}$ for some $k = 1, ..., l - h$ and $v = 1, ..., l - h'$, respectively.[31]

From Assumption 2.4 and given $h' > h$: (i) $c_{E_{l-h+1}} - \bar{\pi}_{E_{l-h+1}}(\psi) > c_{E_{l-h'+1}} - \bar{\pi}_{E_{l-h'+1}}(\psi) \; \forall \; \psi \in \Psi$ and (ii) $c_{E_s} - \bar{\pi}_{E_s}(\psi) > c_{E_l} - \bar{\pi}_{E_l}(\psi) > c_{E_i} - \bar{\pi}_{E_i}(\psi) \; \forall \; \psi \in \Psi$ and for all $i < l$ with $U_{E_i} \in \widehat{U} = \{U_{E_{l-h}}, ..., U_{E_{l-h'+1}}\}$. Condition (i) implies that $p^{NS} > p^{NS'}$. Condition (ii) implies that the level of allocative inefficiencies increase in Nash Equilibrium resulting from the setting in which E_s's capacity limit is k'_{E_s} compared to the setting in which E_s's capacity limit is k_{E_s} because additional more efficient entrants in the set $\widehat{U}$ are displaced by E_s's less efficient new capacity investment.

$\square$

Large Portfolio Effects

Throughout the analysis it was assumed that the allocation externalities are sufficiently small such that Assumption 2.4 holds. Assumption 2.4 implies that the set of entrants **E** can be ordered in terms of the entrants' net marginal cost of new capacity investment. This section characterizes the necessary and sufficient conditions for a PSNE when Assumption 2.4 no longer holds. Further, I provide an example under which there always exists at least one PSNE in this setting.[32]

Consider the following example. There are three potential entrants (i.e., $M = 3$) and, in addition to the incumbents' installed capacities, two entrants' new capacity investments are needed to serve capacity demand (i.e., $l = 2$). Therefore, there are three potential generation portfolios defined by $\Psi = \{(U_{I_1}, U_{I_1}, U_{E_1}, U_{E_2}); (U_{I_1}, U_{I_1}, U_{E_1}, U_{E_3}); (U_{I_1}, U_{I_1}, U_{E_2}, U_{E_3})\} = \{\psi_{12}; \psi_{13}; \psi_{23}\}$.[33] By relaxing Assumption 2.4, the set of entrants are no longer ordered by the rank of their net marginal costs. A potential net marginal cost ranking is: $c_{E_1} - \bar{\pi}_{E_1}(\psi_{12}) < c_{E_1} - \bar{\pi}_{E_1}(\psi_{13}) < c_{E_2} - \bar{\pi}_{E_2}(\psi_{12}) < c_{E_3} - \bar{\pi}_{E_3}(\psi_{13}) < c_{E_2} - \bar{\pi}_{E_2}(\psi_{23}) < c_{E_3} - \bar{\pi}_{E_3}(\psi_{23})$. In this setting, E_1 has the most efficient new capacity investment. Alternatively, the ranking of E_2 and E_3 in terms of their net marginal cost of new capacity varies by the generation portfolio.

Relaxing Assumption 2.4 complicates the characterization of the Nash Equilibrium substantially because there is no *ex ante* set of the l least-cost new capacity investments. Rather, the l least-cost new capacity investments can vary depending on the potential generation portfolio. Proposition 12 provides necessary and sufficient conditions for a Pure

[31] $\psi^{EM1} = \{\psi^{NS} \backslash U_{E_k}, U_{E_{l-h+1}}\}$ and $\psi^{EM2} = \{\psi^{NS'} \backslash U_{E_v}, U_{E_{l-h'+1}}\}$ ensure that the first extramarginal bidder has no incentive to unilaterally deviate and undercut the marginal bidder E_k and E_v under either Nash Equilibrium.

[32] Jehiel and Moldovanu (2001) characterize the efficient mechanism in a multi-unit auction with allocation externalities. They identify conditions under which efficient incentive compatible mechanisms exist. This section characterizes conditions under which there exists at least one PSNE in the current multi-unit auction with allocation externalities. More general existence conditions remain to be identified.

[33] In general there are $\frac{M!}{l!(M-l)!}$ potential generation portfolios $\left(\text{i.e., } |\Psi| = \frac{M!}{l!(M-l)!}\right)$.

Strategy Nash Equilibrium in this setting.

Proposition 12. Define $\boldsymbol{\beta}$ to be a bid profile in which there is a subset of entrants $\widetilde{\mathbf{E}} \subset \mathbf{E}$ where an entrant $E_k \in \widetilde{\mathbf{E}}$ sets the stop-out price $p^* = b_{E_k} = \min\{c_{E_j} - \bar{\pi}_{E_j}(\psi^{EM}) \; \forall \; E_j \in \mathbf{E}' = \mathbf{E} \backslash \widetilde{\mathbf{E}}\}$, while all other entrants in $\widetilde{\mathbf{E}}$ bid sufficiently low resulting in the portfolio ψ. $\boldsymbol{\beta}$ is a PSNE if and only if $c_{E_i} - \bar{\pi}_{E_i}(\psi) \leq p^* \; \forall \; E_i \in \widetilde{\mathbf{E}}$.

Similar to Propositions 1 and 2, Proposition 12 reveals that in any potential PSNE a single entrant sets the stop-out price at the first extramarginal firm's net marginal cost, while all other entrants that procure positive capacity bid sufficiently low.[34] If all of the entrants procuring positive capacity (i.e., all $E_i \in \widetilde{\mathbf{E}}$) earn non-negative payoff at the stop-out price p^*, then this bidding profile is a PSNE.[35] Otherwise, an entrant has an incentive to deviate unilaterally to $b'_{E_i} > p^*$ to forgo procuring capacity for a loss.

In Propositions 1 and 2, the set $\widetilde{\mathbf{E}} = \{E_1, ..., E_l\}$ if $\tau = 0$ and $\widetilde{\mathbf{E}} = \{E_1, ..., E_{l-1}, E_s\}$ if $\tau = \widetilde{\tau} + \epsilon$. However, in the current setting, $\widetilde{\mathbf{E}}$ can be any subset of $\mathbf{E}$ and hence, there are $\frac{M!}{(l-1)!(M-l)!}$ potential equilibrium outcomes.[36,37] The conditions characterized in Proposition 12 depend upon the ranking of the net marginal cost of each firm for all potential generation portfolios. Therefore, the combinations of parameters that need to be considered grows exponentially as M and l increase. Proposition 13 provides an example of a setting in which there exists at least one PSNE.[38]

Proposition 13. Suppose $l = 2$, $c_{E_1} - \bar{\pi}_{E_1}(\psi) \leq \min\{c_{E_2} - \bar{\pi}_{E_2}(\psi), c_{E_3} - \bar{\pi}_{E_3}(\psi)\}$, and $\max\{c_{E_2} - \bar{\pi}_{E_2}(\psi), c_{E_3} - \bar{\pi}_{E_3}(\psi)\} \leq \min\{c_{E_h} - \bar{\pi}_{E_h}(\psi) \; \forall \; h > 3\} \; \forall \; \psi \in \Psi$. Then, a PSNE exists.

Proof of Proposition 12: By assumption, due to bid offer-caps the incumbents' installed capacities are fully procured and the entrants compete over residual demand $\widehat{\theta} - K_I$. Assume there is a bid profile $\boldsymbol{\beta}$ in which there is a subset of entrants $\widetilde{\mathbf{E}} \subset \mathbf{E}$ where an entrant $E_k \in \widetilde{\mathbf{E}}$ sets the stop-out price $p^* = b_{E_k} = \min\{c_{E_j} - \bar{\pi}_{E_j}(\psi^{EM}) \; \forall \; j \in \mathbf{E}' = \mathbf{E} \backslash \widetilde{\mathbf{E}}\}$, while all other entrants in $\widetilde{\mathbf{E}}$ bid sufficiently low resulting in the portfolio $\psi = \{U_{I_1}, U_{I_2}, U_{\widetilde{E}}\}$ with $\sum_{E_i \in \widetilde{\mathbf{E}}} X_{E_i}(\widehat{\theta}; \boldsymbol{\beta}) = \widehat{\theta} - K_I$. $\psi^{EM} = \{\psi \backslash U_{E_k}, U_{E_j}\}$ is the portfolio in which entrant E_j displaces the marginal bidder's new capacity investment, U_{E_k}. Further, assume that $c_{E_i} - \bar{\pi}_{E_i}(\psi) \leq p^* \; \forall \; E_i \in \widetilde{\mathbf{E}}$. I show that $\boldsymbol{\beta}$ characterizes a PSNE.

From Proposition 1, any entrant $E_h \in \widetilde{\mathbf{E}}$ with $h \neq k$ has no incentive to unilaterally deviate from bidding sufficiently low as defined by $\bar{b}_E$ in (21). By assumption $c_{E_i} - \bar{\pi}_{E_i}(\psi) \leq p^* \; \forall \; E_i \in \widetilde{\mathbf{E}}$ such that from Lemma 1 no entrant

[34]As in Propositions 1 and 2, $\psi^{EM} = \{\psi \backslash U_{E_k}, U_{E_h}\}$ where E_h is the first extramarginal bidder. This is to ensure that E_h has no incentive to deviate to $b'_{E_h} = p^* - \epsilon$ for some $\epsilon > 0$.

[35]The necessary and sufficient conditions characterized in Proposition 12 are the same with and without subsidized entry. If entry is subsidized, then $E_s \in \widetilde{\mathbf{E}}$ in any potential PSNE.

[36]There are $\frac{M!}{l!(M-l)!}$ potential generation portfolios. For each of these portfolios, there are l potential PSNE dependent on the identity of the price-setter and non price-setters.

[37]This section does not explicitly discuss the effect of subsidized entry. However, if there is a capacity subsidy that is sufficiently large such that E_S can profitably procure its new capacity investment, then $E_S \in \widetilde{\mathbf{E}}$ in any potential equilibrium.

[38]This example provides an approach for proving existence of a PSNE in multi-unit auctions with allocation externalities. More general conditions on existence in this framework is left for future research.

in the set $\widetilde{\mathbf{E}}$ has an incentive to deviate to $b'_{E_i} > p^*$. Lastly, because $p^* = \min\{c_{E_j} - \bar{\pi}_{E_j}(\psi^{EM}) \; \forall \; j \in \mathbf{E}' = \mathbf{E} \backslash \widetilde{\mathbf{E}}\}$ no extramarginal entrant can unilaterally deviate and profitably procure its capacity.

Alternatively, from Lemma 1, if $c_{E_i} - \bar{\pi}_{E_i}(\psi) > p^*$ for some $E_i \in \widetilde{\mathbf{E}}$, then $\boldsymbol{\beta}$ is not a Nash Equilibrium because E_i can unilaterally deviate to $b'_{E_i} > p^*$ and strictly increase its payoff (to zero). □

Proof of Proposition 13: Suppose $l = 2$, $c_{E_1} - \bar{\pi}_{E_1}(\psi) \leq \min\{c_{E_2} - \bar{\pi}_{E_2}(\psi), c_{E_3} - \bar{\pi}_{E_3}(\psi)\}$, and $\max\{c_{E_2} - \bar{\pi}_{E_2}(\psi), c_{E_3} - \bar{\pi}_{E_3}(\psi)\} \leq \min\{c_{E_h} - \bar{\pi}_{E_h}(\psi) \; \forall \; h > 3\} \; \forall \; \psi \in \Psi$. By assumption in any potential equilibrium, the incumbents' installed capacities are dispatched such that the entrants compete over $\widehat{\theta} - K_I$.

From Lemma 1, given $l = 2$, $c_{E_1} - \bar{\pi}_{E_1}(\psi) \leq \min\{c_{E_2} - \bar{\pi}_{E_2}(\psi), c_{E_3} - \bar{\pi}_{E_3}(\psi)\}$, and $\max\{c_{E_2} - \bar{\pi}_{E_2}(\psi), c_{E_3} - \bar{\pi}_{E_3}(\psi)\} \leq \min\{c_{E_h} - \bar{\pi}_{E_h}(\psi) \; \forall \; h > 3\} \; \forall \; \psi \in \Psi$, any PSNE will entail two entrants in the set $\{E_1, E_2, E_3\}$ procuring their units in the capacity auction.[39] Hence, there are three potential portfolios such that $\Psi = \{(U_{I_1}, U_{I_2}, U_{E_1}, U_{E_2}), (U_{I_1}, U_{I_2}, U_{E_1},$ $\{\psi_{12}, \psi_{13}, \psi_{23}\}$.

This implies that there are six net marginal costs to consider (i.e., two for each E_i for all $i = 1, 2, 3$). $\widetilde{nc} = \{nc_{E_1}(\psi_{12}), nc_{E_1}(\psi_{13}), nc_{E_2}(\psi_{12}), nc_{E_2}(\psi_{23}), nc_{E_3}(\psi_{13}), nc_{E_3}(\psi_{23})\}$ denotes the 6-tuple of net marginal cost where $nc_{E_i}(\psi_{ij}) = c_{E_i} - \bar{\pi}_{E_i}(\psi_{ij})$ for each $i, j = 1, 2, 3$ with $i \neq j$. Define $\Omega = \{\widetilde{nc} \mid nc_{E_i}(\psi) \in [0, \infty) \; \forall \; i = 1, 2, 3$ and $\forall \; \psi \in \Psi\}$ to be the set of all of potential realizations of $\widetilde{nc}$. Proposition 12 provides necessary and sufficient conditions on these parameter ranges for a bid profile to be a PSNE. Using the potential equilibrium outcomes characterized in Proposition 12, the following sets detail the conditions on $\widetilde{nc}$ in which there exists a PSNE.[40]

$$
\begin{aligned}
\mathbb{C}_1 &= \{\widetilde{nc} \in \Omega \mid nc_{E_1}(\psi_{12}) \leq nc_{E_3}(\psi_{13}) \text{ and } nc_{E_2}(\psi_{12}) \leq nc_{E_3}(\psi_{13})\} \\
\mathbb{C}_2 &= \{\widetilde{nc} \in \Omega \mid nc_{E_1}(\psi_{12}) \leq nc_{E_3}(\psi_{23}) \text{ and } nc_{E_2}(\psi_{12}) \leq nc_{E_3}(\psi_{23})\} \\
\mathbb{C}_3 &= \{\widetilde{nc} \in \Omega \mid nc_{E_1}(\psi_{13}) \leq nc_{E_2}(\psi_{12}) \text{ and } nc_{E_3}(\psi_{13}) \leq nc_{E_2}(\psi_{12})\} \\
\mathbb{C}_4 &= \{\widetilde{nc} \in \Omega \mid nc_{E_1}(\psi_{13}) \leq nc_{E_2}(\psi_{23}) \text{ and } nc_{E_3}(\psi_{13}) \leq nc_{E_2}(\psi_{23})\} \\
\mathbb{C}_5 &= \{\widetilde{nc} \in \Omega \mid nc_{E_2}(\psi_{23}) \leq nc_{E_1}(\psi_{12}) \text{ and } nc_{E_3}(\psi_{23}) \leq nc_{E_1}(\psi_{12})\} \\
\mathbb{C}_6 &= \{\widetilde{nc} \in \Omega \mid nc_{E_2}(\psi_{23}) \leq nc_{E_1}(\psi_{13}) \text{ and } nc_{E_3}(\psi_{23}) \leq nc_{E_1}(\psi_{13})\}
\end{aligned}
$$

If $\widetilde{nc} \in \mathbb{C}_i$ for some $i = 1, 2, ..., 6$, then there exists at least one PSNE.[41] By assumption $nc_{E_1}(\psi) \leq \min\{nc_{E_2}(\psi), nc_{E_3}(\psi)\}$ $\forall \; \psi \in \Psi$. Therefore, $\widetilde{nc} \notin \mathbb{C}_5 \cup \mathbb{C}_6$. Further, the first inequality in the sets $\mathbb{C}_i \; \forall \; i = 1, 2, 3, 4$ always hold.

[39] Assumption 2.4 fails to hold in this setting because the rank of E_2 and E_3's net marginal cost is allowed to vary by the generation portfolio. That is, $c_{E_2} - \bar{\pi}_{E_2}(\psi) > c_{E_3} - \bar{\pi}_{E_3}(\psi)$ and $c_{E_2} - \bar{\pi}_{E_2}(\psi') \leq c_{E_3} - \bar{\pi}_{E_3}(\psi')$ for some $\psi, \psi' \in \Psi$.

[40] These conditions characterize the necessary and sufficient conditions on $\widetilde{nc}$ in which there is a PSNE. There are six potential equilibrium outcomes, two for each generation portfolio depending on the identity of the price-setting entrant. Each of these sets form a convex polytopes. If $\widetilde{nc}$ is a point in one of these 6-dimensional geometric objects, then there exists a PSNE.

[41] Using Proposition 12, $\mathbb{C}_1$ characterizes the necessary and sufficient conditions on $\widetilde{nc}$ in the setting in which there is a bid profile $\boldsymbol{\beta}$ where $\max\{b^u_{I_j} \; \forall \; u \in U_{I_j}$ and $\forall \; i = 1, 2\} < b_{E_1} < p^* = b_{E_2} = b_{E_3} = nc_{E_3}(\psi_{13})$, for example.

To prove that there must exist at least one PSNE in the current setting assume that $\widetilde{nc} \notin \mathbb{C}_i$ for some $i = 1, 2, ..., 4$. From $\mathbb{C}_1$, $\mathbb{C}_2$, $\mathbb{C}_3$, and $\mathbb{C}_4$ this implies that: (i) $nc_{E_2}(\psi_{12}) > nc_{E_3}(\psi_{13})$; (ii) $nc_{E_2}(\psi_{12}) > nc_{E_3}(\psi_{23})$; (iii) $nc_{E_3}(\psi_{13}) > nc_{E_2}(\psi_{12})$; and (iv) $nc_{E_3}(\psi_{13}) > nc_{E_2}(\psi_{23})$. However, this leads to a contradiction because (i) and (iii) can not simultaneously hold. This implies that for any $\widetilde{nc} \in \Omega$, $\widetilde{nc} \notin \mathbb{C}_1$ and $\widetilde{nc} \notin \mathbb{C}_3$ can not simultaneously hold. Therefore, there must be at least one PSNE because $\widetilde{nc} \in \mathbb{C}_1 \cup \mathbb{C}_3$.

□

Elastic Capacity Demand

For illustrative purposes, the analysis has focused on an environment where capacity demand $\widehat{\theta}$ is price-inelastic. In practice, capacity demand is price-elastic.[42] This section reveals that the conclusions in the basic model are robust to the introduction of a price-elastic demand function.

Define $D(p, \theta)$ to be the capacity demand where θ is a random variable with a known probability distribution $f(\theta)$ on the support $[\underline{\theta}, \overline{\theta}] \subset \mathbb{R}_+$ and $\widehat{\theta}$ denotes the realization of θ. It is assumed that $D(\cdot)$ is continuous and bounded, there is a value $\bar{p}(\widehat{\theta})$ such that $D(\bar{p}(\widehat{\theta}), \widehat{\theta}) = 0 \; \forall \; p \geq \bar{p}(\widehat{\theta})$, and $pD(\cdot)$ is strictly quasi-concave in $p \; \forall \; p \in [0, \bar{p}(\widehat{\theta})]$. Further, assume that $D(0, \widehat{\theta}) > K_I$ such that new capacity investments from the entrants are necessary to clear capacity demand at any price-level. The incumbents' bids for their installed capacities are constrained and below the most efficient entrant's net marginal cost of capacity investment (see Section 9). Therefore, the entrants compete over residual aggregate capacity demand $D(p, \widehat{\theta}) - K_I$, while the incumbents' installed capacities are always dispatched. The entrants' profit functions are defined in (9) and (10). However, using (6), $R(\widehat{\theta}, p^*; \boldsymbol{\beta}) = D(p^*, \widehat{\theta}) - X_-(\widehat{\theta}, p^*; \boldsymbol{\beta})$.

Two environments are considered: (i) no capacity subsidies are given and (ii) a capacity subsidy τ is provided to entrant E_s that is sufficiently large such that E_s is able to procure its new capacity investment in the capacity auction.[43] If the subsidy was not given to entrant E_s, then E_s would not have dispatched its capacity in the capacity auction.

Define p^{*j} to be the market-clearing (stop-out) price in the no subsidy ($j = NS$) or subsidy ($j = S$) environment (i.e., $\forall \; j \in \{S, NS\}$). For any stop-out price p^{*j}, there are l new capacity investments that are undertaken to meet capacity demand. Recall, from Assumption 2.4 the entrants are ordered in terms of their net marginal cost of capacity. Proposition 14 summarizes the PSNE with and without subsidized entry when capacity demand is price-elastic.

Proposition 14. Define $\widetilde{E}^j \subset \boldsymbol{E}$. Let $E_k \in \widetilde{E}^j$ be the marginal bidder who sets the stop-out price p^{*j}, while all other entrants in the set $\widetilde{E}^j$ bid sufficiently low to make undercutting unprofitable $\forall \; j \in \{S, NS\}$ where[44]

[42] In practice, capacity demand is an administratively set function. The design of this demand function is highly debated. For the current analysis, the design of this demand function is taken as given. A detailed treatment of the capacity demand function is out of the scope of the current analysis.

[43] Recall, it was assumed that the entrant E_s's incentives are aligned with the buyer providing the subsidy such that it bids as a non-price setter to ensure that its entire capacity is dispatched in the capacity auction. The results of this article are robust to this assumption.

[44] $|\widetilde{E}^j|$ is the cardinality of the set $\widetilde{E}^j$.

i. $\widetilde{E}^j$ is defined such that $(|\widetilde{E}^j| - 1)k_E < D(p^{*j}, \widehat{\theta}) - K_I \leq |\widetilde{E}^j|k_E$;

ii. If $j = NS$, then $\psi^{NS} = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_l}\}$ and $\widetilde{E}^{NS} = \{E_1, E_2, ..., E_l\}$;

iii. If $j = S$, then $\psi^S = \{U_{I_1}, U_{I_2}, U_{E_1}, ..., U_{E_{l-1}}, U_{E_s}\}$ and $\widetilde{E}^S = \{E_1, E_2, ..., E_{l-1}, E_s\}$;

iv. If $j = NS$, then $p^{*NS} = \min\{c_{E_{l+1}} - \bar{\pi}_{E_{l+1}}(\psi^{EM}), argmax_p\{[p - (c_{E_k} - \bar{\pi}_{E_k}(\psi))](D(p, \widehat{\theta}) - K_I - [|\widetilde{E}^{NS}| - 1]k_E)\}\}$ where $\psi^{EM} = \{\psi^{NS} \backslash U_{E_k}, U_{E_{l+1}}\}$; and

v. If $j = S$, then $p^{*S} = \min\{c_{E_l} - \bar{\pi}_{E_{l+1}}(\psi^{EM}), argmax_p\{[p - (c_{E_k} - \bar{\pi}_{E_k}(\psi))](D(p, \widehat{\theta}) - K_I - [|\widetilde{E}^S| - 1]k_E)\}\}$ where $\psi^{EM} = \{\psi^S \backslash U_{E_k}, U_{E_l}\}$.

Proposition 14 reveals that the bidding behavior is analogous to that in Propositions 1 and 2 where the price-setter maximizes its expected payoff facing residual demand, while the inframarginal entrants bid sufficiently low such that there is no incentive for the marginal bidder to deviate unilaterally to become inframarginal. However, unlike the environment with price-inelastic demand, the marginal bidder, E_k, faces a downward sloping residual demand curve in addition to the extramarginal entrant's bid at its net marginal cost. As shown in Fabra et al. (2006), the addition of price-elastic demand reduces the marginal bidder's monopoly power facing residual demand.[45]

From Lemma 1, if there is no subsidized entry, the least-cost (most efficient) entrants' generation units will be procured in the capacity auction. This results in the portfolio ψ^{NS} defined in Proposition 14. Alternatively, if a buyer provides a subsidy τ that is sufficiently large such that an entrant, E_s, who would not have been procured in the capacity auction if the subsidy was not provided, is able to profitably dispatch its capacity in the auction. Then, the set of least-cost entrants (adjusted by the subsidy) now includes E_s's generation unit resulting in the portfolio ψ^S. Similar to the basic model, it is straightforward to show that the addition of the subsidized unit (E_s) results in an allocative inefficiency and suppresses the capacity auction price.

The discussion has focused on how price-elastic demand affects the bidding behavior in the auction. However, now I describe why the addition of price-elastic demand has no impact on the subsequent results of the analysis presented in the basic model. It is assumed (and empirically supported) that the capacity costs are fully passed down to consumers through volumized rates. This implies that the capacity charge for each time period t, P_t^C, in the welfare analysis is constructed such that $E[\sum_{t=1}^{T} P_t^C \phi(t, \mu)] = p^{*j} D(p^{*j}, \widehat{\theta}) \ \forall\ j \in \{S, NS\}$ (see footnote 34). Further, the intuition behind Assumption 3 carries over to the environment with price-elastic capacity demand. Therefore, the analysis and intuition in the subsequent short-run and long-run welfare analyses in the basic model carry over analogously. To summarize, the addition of price-elastic demand only impacts the nature of the bidding behavior by reducing the

[45] For more details on the bidding behavior in a multi-unit, uniform priced, sealed bid auction with discrete bid functions where demand is price-elastic, see Fabra et al. (2006).

marginal bidder's market power execution facing the residual demand function. This arises because in the presence of a subsidy that induces a less efficient entrant to procure capacity in the capacity auction and enter the market, the subsequent welfare analysis is unaffected by the addition of price-elastic capacity demand.

Proof of Proposition 14: Is analogous to the proof of Proposition 1. The critical difference between these two environments is that the marginal bidder maximizes its expected payoff facing a downward sloping residual demand function in addition to the extramarginal entrant's bid at its net marginal cost of undercutting the marginal bidder. $\square$

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