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Capacity Payment Mechanisms and Investment Incentives in Restructured Electricity Markets

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Abstract

I analyze the ability of capacity payment mechanisms to alleviate underinvestment in electricity generation capacity. I derive the optimal capacity payment parameters under two capacity payment mechanisms, when capacity demand is price-elastic and when it is price-inelastic. Price-elastic capacity demand reduces the firms' abilities to exercise market power, alleviates the bimodal capacity market pricing structure, and reduces the degree of market concentration. Further, at the optimal capacity demand parameters, expected welfare, consumer surplus, and aggregate capacity is higher under the price-elastic demand setting. However, a certain degree of underinvestment in generation capacity persists. These findings support the movement of regulatory policy towards a price-elastic capacity demand regime with market monitoring.

Keywords: electricity, capacity markets, reliability, market power, regulation

JEL Classifications: D44, L13, L50, L94, Q40

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1 Introduction

Regulators around the world work incessantly to ensure that there is sufficient electricity generation capacity to meet electricity demand. However, several unique characteristics of electricity markets has lead to concerns that generation units do not earn sufficient revenues in electricity markets to promote the appropriate level of generation capacity investment.[1] Regulators have adopted capacity payment mechanisms (CPMs) to encourage firms to invest in generation capacity. These CPMs have become a centerpiece of electricity markets worldwide (Pfeifenberger et al., 2009). However, the design of CPMs is often the subject of contentious debate.[2] This paper aims to contribute to this debate and provide guidance to policymakers.

"Energy-only" markets rely solely on competitive electricity markets to provide sufficient revenues to cover generators' fixed costs of investment. However, the inability of these markets to provide the appropriate revenues to promote the welfare-maximizing level of capacity investment has led to the adoption of CPMs to provide supplementary revenues. In particular, CPMs that rely on a capacity procurement auction that occurs prior to the subsequent electricity markets has gained significant traction worldwide (Pfeifenberger et al., 2009).[3] In these capacity auctions, the regulator sets a targeted amount of production capacity by establishing a certain level of generation capacity that must be installed. Then, firms submit bids in the capacity auction that reflect the price at which they are willing to make their capacity available in subsequent electricity markets.

Proponents of these capacity auctions contend that this CPM promotes investment, provides a transparent signal for investment (the capacity auction price), and revenue certainty (e.g., Pfeifenberger et al. (2009); Bowring (2013)). However, critics argue that the capacity markets may be prone to issues associated with the administratively-set demand parameters, volatile capacity market prices, and market power execution because of the concentrated market structure (e.g., Bidwell (2005); Kleit and Michaels (2013)). In particular, early capacity market designs involved a per-

[1] In practice, during periods of scarce production capacity, electricity prices are suppressed due to regulatory restrictions. For example, price-caps are used to limit firms' abilities to execute market power and the magnitude of politically disastrous price-spikes. Further, generation capacity is often viewed as providing a public good, market reliability. These forces have been observed to induce underinvestment in generation capacity (Joskow, 2008).

[2] See Bidwell (2005), Cramton and Stoft (2006, 2008), Joskow (2008), and Kleit and Michaels (2013), for example.

[3] Capacity auctions occur in several regions in the United States (US): New York, New England, Midwestern US, Pennsylvania, and New Jersey, for example.

fectly price-inelastic capacity demand curve with a price-cap $\overline{P}^C$. In practice, this created a volatile bimodal pricing structure in the capacity auctions. When there was scarce generation capacity, the capacity price often equaled the price-cap in the capacity market. Otherwise, the capacity price was near zero (Bidwell, 2005). This led regulators to adjust the nature of the capacity market demand curve from one that is perfectly price-inelastic to allowing for price-responsiveness.[4] The impact and determination of the administrative parameters used to characterize this price-elastic capacity demand curve is highly debated (Bidwell, 2005; Pfeifenberger et al., 2009; Kleit and Michaels, 2013). In this paper, I aim to establish a framework that begins to address these issues.

There has been a wide-array of policy discussions on how to design these CPMs (e.g., Bidwell (2005); Joskow (2008); Batlle and Perez-Arriaga (2008); Cramton and Stoft (2006, 2008); Bowring (2013)). However, few scholars have developed rigorous models to inform regulators on the relative performance of alternative CPMs or to determine the impact of capacity payments on investment incentives, market structure, and the nature of competition in the subsequent electricity auctions.

Fabra et al. (2011) and Zöttl (2011) provide important contributions that examine how market design affects firms' investment incentives and market performance in restructured electricity markets. These studies consider an environment where firms make capacity investment decisions anticipating their revenues from a subsequent electricity market with a price cap ($\overline{P}^E$) and stochastic electricity demand.[5] The authors find that electricity auction price-caps restrict firms' investment incentives and lead to underinvestment in generation capacity. Further, they consider adjusting the price-cap $\overline{P}^E$ to reduce the degree of underinvestment. Alternatively, I take the electricity auction price-cap as exogenous and inefficiently low as it seems to be in practice (Joskow, 2008). Then, I employ Fabra et al.'s (2011) results to characterize equilibria, given the presence of capacity payments.[6] In particular, I focus on the optimal design of critical capacity demand parameters. To the

[4] In addition, to increase the elasticity of supply, several markets moved from a capacity market that occurred weeks before the subsequent electricity markets, to a forward market that occurred three to five years prior (Pfeifenberger et al., 2009). The focus of the current analysis is on the short-run capacity markets. However, incorporating the additional characteristics of these forward markets warrants future research, as discussed in detail in the conclusion.

[5] More generally, this relates to a growing literature that analyzes settings in which firms make their capacity investment decisions prior to a competition stage with stochastic demand (e.g., Reynolds and Wilson (2000); Murphy and Smeers (2005); de Frutos and Fabra (2011); Grimm and Gregor (2013)).

[6] Further, because the electricity and capacity auctions are multi-unit uniform-priced auctions, to model firms' bidding behavior I rely on the discrete multi-unit auction literature established by von der Fehr and Harbord (1993) and extended by Fabra et al. (2006); Crawford et al. (2007); among others.

best of my knowledge, this is the first study that incorporates the existence of capacity payments in such an environment.

The purpose of this paper is to begin to fill the void in the literature on the impact of CPMs by characterizing the optimal capacity demand parameters in a setting where the regulator chooses the nature of the capacity demand curve in two CPM designs: with a price-inelastic and price-elastic capacity demand curve. Under both CPMs, the regulator chooses the capacity auction price-cap ($\overline{P}^C$) and reserve margin (r) above forecasted (peak) electricity demand. When capacity demand is elastic, the regulator also adjusts a slope parameter (b) that impacts the slope of the capacity demand curve. The regulator chooses the capacity demand parameters to maximize welfare, facing uncertainty in electricity and capacity demand. The generation firms choose their capacity investment decisions without observing capacity or electricity demand with certainty. Then, there are sequential multi-unit, uniform-priced, capacity and electricity procurement auctions. The capacity auction under consideration takes place weeks to months prior to the electricity auction.[7]

The addition of price-elastic capacity demand has substantial impacts on capacity market bidding behavior. When a firm is capacity constrained, there is a pivotal bidder that is required to serve capacity or electricity demand. Therefore, the bidder setting the market-clearing price behaves as a monopolist facing residual demand and hence, is able to exercise market power. As observed in practice, with a perfectly price-inelastic capacity demand curve there is bimodal pricing where the equilibrium capacity auction price $p^{c*} \in \{0, \overline{P}^C\}$. The addition of price-elastic demand eliminates this bimodal pricing structure and alleviates the firms' abilities to exercise market power in the capacity auction. This difference arises because when capacity demand is price-elastic (inelastic) the bidder setting the market-clearing price faces a price-elastic (perfectly inelastic) residual demand function. This lowers the expected capacity auction price and capacity payments without lowering capacity investment. Also, the addition of price-elastic capacity demand reduces the asymmetry of capacity investment (market concerntration) under plausible conditions. This reduces the firms' market power capabilities in the subsequent electricity market.

[7]The forward period of capacity auctions can vary from weeks to years depending on the CPM design (Pfeifenberger et al., 2009). As noted in the conclusion, capacity auctions that occur years in advance warrants further research.

When there is no CPM, there is underinvestment in generation capacity because the electricity market price-cap ($\overline{P}^E$) is inefficiently low. I show that the addition of the CPMs alleviates the degree of underinvestment in the market. However, some degree of underinvestment in aggregate capacity compared to the first-best K^* persists under both CPMs even at the optimal capacity payments. This arises because socially costly market power execution in the capacity auction limits the regulator's ability to increase the capacity demand parameters to a level that is sufficiently high to induce K^*. However, the price-elastic setting results in less underinvestment because the addition of price-elastic capacity demand alleviates the degree of market power execution and hence, the regulator can set higher levels on $\overline{P}^C$ and r to induce further investment.

Bringing these factors together, the addition of price-elastic capacity demand increases expected welfare and consumer surplus because it limits socially costly market power execution in both the electricity and capacity auctions and alleviates underinvestment. These findings support the movement of recent regulatory policies to implement CPMs with price-elastic demand and market monitoring to limit market power execution (Pfeifenberger et al., 2009).

The analysis proceeds as follows. Section 2 describes the formal model. Section 3 characterizes firms' investment incentives, bidding behavior, and the optimal capacity demand parameters under both CPMs. Section 4 compares the performance of both capacity payment mechanisms. Section 5 concludes. The Appendix contains proofs of all formal conclusions.[8]

2 The Model

Two firms compete in a multi-stage game where firms choose their production capacities $k_i > 0$ anticipating revenues from an electricity auction and capacity payment mechanism (CPM) for each $i = 1, 2$. Prior to the electricity auction, firms compete in a CPM that takes the form of a capacity auction. Further, the level of electricity and capacity demand is unobserved when firms make their capacity investment decisions.[9]

After the firms choose their capacities simultaneously and independently, the firms compete

[8]In addition, the Technical Appendix provides several extensions of the basic model.

[9]This reflects the fact that firms make their investment decisions far in advance of the capacity and electricity markets.

to supply a fraction of the capacity and electricity demand in sequential capacity and electricity auctions, respectively. The levels of capacity and electricity demand are (partially) determined by random variables θ^C and θ^E with a joint cumulative density function $G^J(\theta^E, \theta^C)$ on the support $\Omega = \{(\theta^E, \theta^C) : (\theta^E, \theta^C) \in (0, 1]^2\}$. The level of capacity demand (θ^C) is a forecast of the capacity need to meet the maximum expected (peak) electricity demand over the subsequent energy markets.[10]

Two CPM designs are considered. Under each CPM, the nature of the capacity demand function is administratively determined and serves as a central regulatory tool. Under the price-inelastic CPM (CPM-PI), the capacity demand function is assumed to be price-inelastic with a price cap ($\overline{P}^C$) and a reserve margin (r) above the realization of θ^C. Under the price-elastic CPM (CPM-PE), the capacity demand function is assumed to be price-elastic with a price cap ($\overline{P}^C$), slope parameter (b), and a reserve margin (r) above the realization of θ^C. In both settings, the reserve margin r reflects the amount of capacity above θ^C that the regulator aims to secure.[11] The price-inelastic (PI) and price-elastic (PE) capacity demand functions are represented as follows:

$$D^{PI}(\cdot) = \begin{cases} \theta^C + r & \text{if } p^c \le \overline{P}^C \\ 0 & \text{if } p^c > \overline{P}^C \end{cases} \quad \text{and} \quad D^{PE}(\cdot) = \begin{cases} \widetilde{D}(p^c, \theta^C; r, b, \overline{P}^C) & \text{if } p^c < \overline{P}^C \\ \theta^C + r & \text{if } p^c = \overline{P}^C \\ 0 & \text{if } p^c > \overline{P}^C \end{cases} \tag{1}$$

where p^c is the market clearing price in the capacity auction and $\widetilde{D}(p^c, \theta^C; r, b, \overline{P}^C)$ is a price-elastic demand function. Assume that $\widetilde{D}(\cdot)$ is increasing in θ^C, $\overline{P}^C$, and r and decreasing in b and p^c $\forall$ $p^c < \overline{P}^C$. Assumption 1 provides a linear specification of the price-elastic demand function.[12]

Assumption 1. For any $p^C \le \overline{P}^C$, $\widetilde{D}(p^c, \theta^C; r, b, \overline{P}^C) = \frac{\overline{P}^C - p^c}{b} + \theta^C + r$.

In the current setting, under CPM-PI and CPM-PE, the regulator chooses the critical capacity demand parameters $\mathbb{P}^{PI} = \{\overline{P}^C, r\}$ and $\mathbb{P}^{PE} = \{\overline{P}^C, b, r\}$ to maximize expected welfare, facing uncertain capacity and electricity demand parameters (θ^E, θ^C).

[10] In the model, it is assumed that there is a single subsequent electricity market. However, if there are multiple (N) energy markets, then the capacity demand realization reflects a forecast of the maximum electricity demand over these N markets. While this alters the notation, the findings of the current analysis persist.

[11] Recall, θ^C reflects a forecast of capacity necessary to serve peak electricity demand. In practice, the reserve margin is often set to be 7 to 15 percent above θ^C (Pfeifenberger et al., 2009).

[12] This is closely related to the capacity demand functions used in practice (Pfeifenberger et al., 2009).

In the electricity auction, electricity demand is assumed to be perfectly price-inelastic. Electricity demand equals θ^E if $p^E \leq \overline{P}^E$, and zero otherwise, where p^E is the market-clearing price of electricity and $\overline{P}^E$ is the energy auction price-cap.

Under either CPM, the timing of the game is as follows. First, without observing electricity or capacity demand (θ^E, θ^C), the regulator chooses the capacity demand parameters $\mathbb{P}^{PI} = \{\overline{P}^C, r\}$ or $\mathbb{P}^{PE} = \{\overline{P}^C, b, r\}$ to maximize expected social welfare under CPM-PI or CPM-PE, respectively. Second, firms simultaneously choose their capacities (k_1, k_2) at unit cost $c > 0$ without observing electricity or capacity demand (θ^E, θ^C).[13] Third and fourth, the firms sequentially choose to withhold (mothball) a fraction of their capacity with the firm with the smaller capacity limit moving first.[14] Fifth, capacity demand θ^C is realized and both firms compete in a capacity procurement auction. Sixth, electricity demand θ^E is realized and the firms compete in an electricity procurement auction.

The regulator chooses the parameter set $\mathbb{P}^j$ to maximize weighted expected welfare:

$$E[W^j] = \alpha\, E[CS^j] + (1-\alpha)\, E[\pi^j] \tag{2}$$

where $\alpha > \frac{1}{2}$ and $E[CS^j]$ and $E[\pi^j]$ reflects consumers surplus and industry profit for all $j \in \{PI, PE\}$, respectively.[15]

In the energy (E) and capacity (C) auctions, having observed the demand parameters θ^j, each firm simultaneously and independently submits a bid $b_i^j \leq \overline{P}^j$ to the auctioneer $\forall\, i = 1, 2$ and $j \in \{E, C\}$. $\mathbf{b}^j = (b_1^j, b_2^j)$ denotes the bid profile for auction $j \in \{E, C\}$. In the energy auction, b_i^E reflects the price at which firm i is willing to supply q_i^E units of electricity. Each unit of electricity costs the firm $\gamma > 0$ to produce up its capacity limit $k_i\ \forall\ i = 1, 2$. In the capacity auction, b_i^C reflects the price at which firm i is willing to make its all of its capacity available in the subsequent electricity auction. Capacity constraints ensure that $0 \leq q_i^j \leq k_i\ \forall\, i = 1, 2$ and $j \in \{E, C\}$.

For a given bid profile $\mathbf{b}^j$, the auctioneer procures (dispatches) the lowest bid first and the highest bid serves any residual demand $\forall\, j \in \{E, C\}$. If bids are equal, the auctioneer dispatches

[13] The firms are symmetric, prior to their investment decisions. This setting can be thought of as analyzing investment and bidding decisions of a natural gas technology. An asymmetric environment warrants future research.

[14] In practice, firms often strategically reduce (mothball) proportions of their capacities from subsequent electricity and capacity auctions after their capacity decisions have been made (Kwoka and Sabodash, 2011). For a detailed discussion on capacity withholding in the current framework, see Fabra et al. (2011).

[15] The results of the setting where $\alpha = \frac{1}{2}$ will be summarized throughout the analysis.

them with equal probability. For the energy auction, the output allocated to firm i is:

$$q_i^E(\theta^E;\mathbf{b}^E) = \begin{cases} \min\{\theta^E, k_i\} & \text{if } b_i^E < b_h^E \\ \frac{1}{2}\min\{\theta^E, k_i\} + \frac{1}{2}\min\{\max\{0, \theta^E - k_h\}, k_i\} & \text{if } b_i^E = b_h^E \\ \min\{\max\{0, \theta^E - k_h\}, k_i\} & \text{if } b_i^E > b_h^E \end{cases} \tag{3}$$

where $i, h = 1, 2$ and $i \neq h$. For the capacity auction, the output allocated to firm i is:

$$q_i^C(\theta^C;\mathbf{b}^C) = \begin{cases} \min\{D^l(\cdot), k_i\} & \text{if } b_i^C < b_h^C \\ \frac{1}{2}\min\{D^l(\cdot), k_i\} + \frac{1}{2}\min\{\max\{0, D^l(\cdot) - k_h\}, k_i\} & \text{if } b_i^C = b_h^C \\ \min\{\max\{0, D^l(\cdot) - k_h\}, k_i\} & \text{if } b_i^C > b_h^C \end{cases} \tag{4}$$

where $i, h = 1, 2$ and $i \neq h$ and $l \in \{PI, PE\}$. The auctions are uniform-price auctions. Therefore, the equilibrium price p^j equals the highest accepted bid. Because the auction is uniform-priced, p^j is paid to all firms that are called upon (dispatched) to supply output in auction j. Define the firm whose bid sets the market-clearing price as the marginal bidder and its bid the marginal bid.

Define $v > \overline{P}^E$ to be the consumers' per-unit value of electricity consumption.[16] It is assumed that $v > c + \gamma$, so the value of electricity to consumers exceeds the cost of bringing it forth. It is assumed that electricity and capacity payments are fully passed down to consumers, so the retail price paid by consumers contain the costs of capacity payments and electricity procurement.[17]

Firms are risk neutral and maximize expected profits. Firms' energy and capacity costs and capacity limits are common knowledge. Let $k^- = \min\{k_1, k_2\}$ and $k^+ = \max\{k_1, k_2\}$ denote the capacity limits of the firm with the smallest and largest capacities, respectively.

3 Main Findings

This section begins by summarizing several key findings established by Fabra et al. (2006) and Fabra et al. (2011) that will be used throughout the analysis. Then, I extend Fabra et al.'s (2011) analysis by accounting for the CPMs used in practice. I derive the optimal capacity demand parameters

[16] This is often referred to as the Value of Lost Load (VOLL) (London Economics, 2013). In practice, the $\overline{P}^E$ is set inefficiently low (i.e., $\overline{P}^E < v$), motivating the need for CPMs (Joskow, 2008).

[17] This reflects how capacity and wholesale payments are passed down to consumers in practice, regardless of the CPM (Pfeifenberger et al., 2009).

for both CPMs, determine how capacity payments impact investment decisions, and investigate differences in the equilibrium outcomes across the CPM designs.

3.1 Investment Incentives and Bidding Behavior

Fabra et al. (2011) consider a setting where firms make their initial capacity investment decisions without observing electricity demand. Then, the firms are able to withhold (mothball) a portion of capacity with the small firm moving first. After this multi-stage investment game, electricity demand is realized and the firms compete in a uniform-priced multi-unit electricity procurment auction. The bidding behavior in the electricity procurement auction is derived in Fabra et al. (2006).[18] Proposition 1 summarizes the firms' investment incentives and electricity market bidding behavior in any potential equilibrium.

Proposition 1. In any Nash Equilibrium:

1. (Fabra et al., 2006) Equilibrium bidding behavior in the electricity auction is as follows:
   (a) (Base-Load) If $\theta^E \leq k^-$, then the unique PSNE entails both firms bidding at marginal cost γ and earning a payoff of zero.
   (b) (Mid-Load) If $k^- < \theta^E \leq k^+$, then the unique PSNE entails the large firm bidding at $\overline{P}^E$ and serving residual demand $\theta^E - k^-$, while the small firm procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable.
   (c) (Peak-Load) If $k^+ < \theta^E \leq K$, then there are two PSNE where a firm i bids at $\overline{P}^E$ and serves residual demand $\theta^E - k_h$, while firm h procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable with $i, h = 1, 2$ and $i \neq h$.
   (d) (Capacity Scarcity) If $\theta^E > K$, then there are two PSNE where a firm i bids at $\overline{P}^E$, firm h bids sufficiently low such that undercutting is unprofitable, and both firms procure their entire capacities with $i, h = 1, 2$ and $i \neq h$.

2. (Fabra et al., 2011) The equilibrium capacity levels (k^-, k^+) always exists and satisfy the following three properties: (i) firm's capacity limits are asymmetric; (ii) the large firm chooses

[18] More generally, this discrete multi-unit auction literature was established by von der Fehr and Harbord (1993) and extended by Fabra et al. (2006, 2011) and Crawford et al. (2007), among others.

k^+ to maximize its expected profits; and (iii) the small firm chooses k^- such that the large firm and the small firm have the same level of expected revenues.

First, I will describe the equilibrium bidding behavior in the last-stage electricity auction. In the base-load demand region when one firm can supply all of the electricity demanded ($\theta^E \leq k^-$), the equilibrium outcome entails intense price competition resulting in both firms bidding at the marginal cost of electricity γ. For the mid-load, peak-load, and capacity scarcity regions, at least one firm is capacity constrained, so both firms are required to meet demand. Therefore, the marginal bidder maximizes its payoff in the electricity auction facing residual demand by setting its bid equal to the price-cap $\overline{P}^E$, while the other supplier bids low enough to ensure that the marginal bidder has no incentive to unilaterally deviate and undercut its bid. Unless stated otherwise, in the peak-load demand region I focus on the equilibrium where the large firm is the marginal bidder.[19]

The firms undergo a multi-stage investment game, forming expectations about their earnings from the subsequent electricity procurement auction. As Fabra et al. (2011) show, an equilibrium capacity pair (k^-, k^+) exists and satisfies the following properties. The small firm chooses its capacity limit k^- such that both firms have the same level of expected revenues. The large firm chooses its capacity limit k^+ to maximize its expected profit.[20] Even though the firms are symmetric ex-ante, in equilibrium they choose asymmetric capacity limits.

3.2 Price-Inelastic Capacity Demand

Now suppose there is a capacity payment mechanism that occurs after the firms' investment decisions and before the electricity auction. In this section, I investigate the bidding behavior, investment decisions, and optimal capacity parameters $\mathbb{P}^{PI} = \{\overline{P}^C, r\}$ under CPM-PI.

The bidding behavior in the last-stage electricity auction is analogous to that specified in Propo-

[19] As Fabra et al. (2011) show, this is the only equilibrium robust to the introduction of slight electricity demand uncertainty. In the Technical Appendix I relax this assumption by considering all continuation equilibria.

[20] Because the small firm procures its entire capacity in the electricity auction for the mid-load and peak-load regions, while the large firm serves residual demand, it is often the case that the large firm prefers to alter its capacity (unilaterally deviate) to become the small firm. However, taking into account that the firms mothball (withhold) portions of capacity after their initial capacity investment decisions in practice, the small firm sets its capacity at a level such that the large firm no longer has an incentive to unilaterally deviate and undercut the small firm's capacity limit. For a complete discussion of these results see Fabra et al. (2011).

sition 1.[21] Continuing to work backwards, Proposition 2 specifies the firms' bidding behavior in the second to last-stage capacity procurement auction, taking the capacity limits (k^-, k^+), capacity price-cap $\overline{P}^C$, reserve margin r, and capacity demand θ^C as given.

Proposition 2. Equilibrium bidding behavior in the capacity auction is as follows:

1. (Low-Demand) If $\theta^C \leq k^- - r$, then the unique PSNE entails both firms bidding at zero for each unit of capacity and earning a payoff of zero.
2. (Mid-Demand) If $k^- - r < \theta^C \leq k^+ - r$, then the unique PSNE entails the large firm bidding at $\overline{P}^C$ and serving residual demand $\theta^C - k^-$, while the small firm procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable.
3. (Peak-Demand) If $k^+ - r < \theta^C \leq K - r$, then there are two PSNE where a firm i bids at $\overline{P}^C$ and serves residual demand $\theta^C - k_h$, while firm h procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable with $i, h = 1, 2$ and $i \neq h$.
4. (Capacity Scarcity) If $\theta^C > K - r$, then there are two PSNE where a firm i bids at $\overline{P}^C$, firm h bids sufficiently low such that undercutting is unprofitable, and both firms procure their entire capacities with $i, h = 1, 2$ and $i \neq h$.

For the low-demand region, intense competition drives the firms' bids down to zero resulting in a payoff of zero for both firms.[22] This arises because one firm can supply all of the capacity demanded, creating the incentive for firms to bid slightly below their opponent to serve capacity demand driving the price to zero. For the mid-demand to capacity scarcity demand regions, at least one firm is capacity constrained. Therefore, the marginal bidder maximizes its payoff facing residual demand by bidding at the price-cap $\overline{P}^C$, while the other bidder bids sufficiently low to make undercutting unprofitable. The bidder not setting the market-clearing price has an incentive to bid sufficiently low to ensure that its entire unit's capacity is dispatched at the high price $\overline{P}^C$. Unless

[21] If a firm procures capacity in the capacity auction, the firm must make the capacity available in the subsequent electricity auction. However, procuring capacity in the capacity auction does not put any restrictions on the firm's bidding behavior in the subsequent electricity auction.

[22] Recall, the CPMs under consideration occur months or weeks prior to the subsequent electricity auction(s). Therefore, the capacity auction occurs after firms' capacity choices are sunk such that the marginal cost of procuring capacity in the capacity auction is zero. The conclusion section discusses an important extension of the current analysis that would consider CPMs that occur several years prior to the subsequent electricity markets.

specified otherwise, in the high-demand region I focus on the equilibrium where the large bidder sets the market-clearing price $\overline{P}^C$.[23] In any PSNE, the capacity auction price $p^{c*} \in \{0, \overline{P}^C\}$. This reflects the bimodal pricing structure observed in practice when capacity demand is perfectly price-inelastic (Bidwell, 2005). When a single firm can supply all of the capacity demanded, competition drives price to zero. However, when capacity supply is tight, because capacity demand is inelastic the marginal bidder bids up to the price-cap.

Lemma 1. Define $g^E(\theta^E) = \int_0^1 g^J(\theta^E, \theta^C)d\theta^C$ and $g^C(\theta^C) = \int_0^1 g^J(\theta^E, \theta^C)d\theta^E$ to be the marginal density functions for energy and capacity demand. Firm i's expected profit under CPM-PI is:

$$\pi_i^{PI}(k_i, k_h) = \begin{cases} \pi_i^{-PI} & \text{if } k_i = k^- < k_h = k^+, \\ \pi_i^{=PI} & \text{if } k_i = k_h = k, \text{ and} \\ \pi_i^{+PI} & \text{if } k_i = k^+ > k_h = k^- \end{cases} \tag{5}$$

where

$$\begin{aligned}
\pi_i^{-PI} &= \int_{k^-}^1 (\overline{P}^E - \gamma)k^- \, dG^E(\theta^E) + \int_{k^- - r}^1 \overline{P}^C k^- \, dG^C(\theta^C) - ck^-, \\
\pi_i^{=PI} &= \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma)k \, dG^E(\theta^E) \\
&+ \int_{k-r}^{K-r} \overline{P}^C \frac{1}{2}(\theta^C + r) \, dG^C(\theta^C) + \int_{K-r}^1 \overline{P}^C k \, dG^C(\theta^C) - ck, \text{ and} \\
\pi_i^{+PI} &= \int_{k^-}^K (\overline{P}^E - \gamma)[\theta^E - k^-] \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma)k^+ \, dG^E(\theta^E) \\
&+ \int_{k^- - r}^{K-r} \overline{P}^C [\theta^C + r - k^-] \, dG^C(\theta^C) + \int_{K-r}^1 \overline{P}^C k^+ \, dG^C(\theta^C) - ck^+.
\end{aligned}$$

Lemma 1 specifies a firm's profit functions after forming expectations about its earnings in the subsequent electricity and capacity auctions.[24,25] The introduction of the capacity auction does not change the strategic nature of the multi-stage investment game facing the firms. Therefore, in equilibrium the capacity pair (k^-, k^+) retains the characteristics identified in Fabra et al.'s (2011) analysis detailed in Proposition 1.

[23] This is the only equilibrium that is robust to the introduction of slight capacity demand uncertainty (Fabra et al., 2011). This assumption is relaxed in the Technical Appendix by considering all continuation equilibria.

[24] The stochastic electricity and capacity demand parameters are not observed at the capacity investment stage. Rather, they are realized before each of their respective procurement auctions.

[25] Procuring capacity in the capacity auction does not restrict bidding behavior in the electricity auction. This independence reduces the bivariate distribution of (θ^E, θ^C) to the marginal density functions used in Lemma 1.

Lemma 2. The equilibrium capacity levels (k^-, k^+) always exists and satisfy:

$$(\overline{P}^E - \gamma)[1 - G^E(k^- + k^+)] + \overline{P}^C[1 - G^C(k^- + k^+ - r)] = c, \text{ and} \tag{6}$$

$$(\overline{P}^E - \gamma)k^-[1 - G^E(k^-)] + \overline{P}^C k^-[1 - G^C(k^- - r)] = \int_{k^-}^{K} (\overline{P}^E - \gamma)[\theta^E - k^-]\, dG^E(\theta^E)$$
$$+ \int_{k^- - r}^{K-r} \overline{P}^C[\theta^C + r - k^-]\, dG^C(\theta^C) + (\overline{P}^E - \gamma)k^+[1 - G^E(K)] + \overline{P}^C k^+[1 - G^C(K - r)]. \tag{7}$$

Condition (6) indicates the large firm expands its capacity to the point where the marginal benefit of relaxing its capacity constraint (increasing output) in the capacity scarcity demand regions of the electricity and capacity auctions equals the marginal costs of capacity. (7) indicates that the small firm chooses its capacity level such that the large firm and small firm have the same level of expected revenues.

Proposition 3 reveals that the aggregate capacity level increases as the price-cap in either the energy or capacity auction increases ($\overline{P}^E$, $\overline{P}^C$) or as the reserve margin (r) increases. In addition, the aggregate capacity level decreases as the cost of capacity (c) or electricity provision (γ) increases. This arises because an increase in $\overline{P}^E$, $\overline{P}^C$, or r (c or γ) strictly increases (decreases) the firms' expected payments from the capacity and electricity auctions in the regions with capacity scarcity. From condition (6), we can see this increases (decreases) aggregate capacity.

Proposition 3. Aggregate capacity K increases as: (i) $\overline{P}^E$, $\overline{P}^C$, or r increases or (ii) γ or c decreases.

Under CPM-PI, for any realization of θ^C, the regulator chooses the capacity demand parameters $(\overline{P}^C, r)$ to maximize expected welfare anticipating the firms' subsequent capacity investment decisions and bidding behavior in the energy and capacity auctions. Proposition 4 characterizes the welfare-maximizing parameters under CPM-PI.

Proposition 4. The expected welfare maximizing parameters $(\overline{P}^C, r)$ satisfy:

$$\overline{P}^C: \quad \alpha\left[(v - \overline{P}^E)[1 - G^E(K)] - \overline{P}^C[1 - G^C(K - r)]\right]\frac{dK}{d\overline{P}^C} + (2\alpha - 1)\Big[(\overline{P}^E - \gamma)k^- g^E(k^-)\frac{dk^-}{d\overline{P}^C}$$
$$+\overline{P}^C g^C(k^- - r)k^-\frac{dk^-}{d\overline{P}^C}\Big] - (2\alpha - 1)\left[\int_{k^- - r}^{K-r} \theta^C + r\, dG^C(\theta^C) + [1 - G^C(K - r)]K\right] = 0; \text{ and} \tag{8}$$

$$r: \quad \alpha\left[(v-\overline{P}^E)[1-G^E(K)]-\overline{P}^C[1-G^C(K-r)]\right]\frac{dK}{dr}+(2\alpha-1)\Bigg[(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{dr}$$
$$+\overline{P}^C g^C(k^- - r)k^-\left(\frac{dk^-}{dr}-1\right)\Bigg]-(2\alpha-1)\left[\overline{P}^C[G^C(K-r)-G^C(k^- - r)]\right]=0. \qquad (9)$$

The first term in (8) and (9) reflects the social value of the increased amount of electricity demand served in the capacity scarcity demand region net of the increase in capacity payments as aggregate capacity increases due to an increase in the parameters $\overline{P}^C$ and r, respectively. The second term in (8) and (9) represent the impact of an increase in the capacity demand parameters on k^- which affects the degree of capacity asymmetry in equilibrium. For example, an increase in k^- (weakly) increases social welfare because it raises the incidence of capacity and electricity demand realizations where no firm is capacity constrained in either auction.[26] The third term in (8) and (9) reflects the social loss associated with increasing capacity payments to firms, holding aggregate capacity constant. This effect represents a rent transfer from consumers to producers and arises because the marginal bidder is able to exercise market power as a firm is capacity constrained in the capacity auction in these demand regions. More specifically, the marginal bidder behaves as a monopolist facing residual demand $\theta^C - k^-$ and sets the capacity auction price at $\overline{P}^C$. Because the aggregate capacity level is driven by payments accrued in the capacity scarcity region (condition (6)), this has no impact on aggregate capacity and only represents a socially costly rent transfer.

3.3 Price-Elastic Capacity Demand

In this section, I consider the environment where capacity demand is price-elastic. In particular, I analyze how elastic demand alters bidding behavior, investment decisions, and the optimal capacity demand parameters, focusing on the optimal degree of price-elasticity (b) chosen by the regulator. When capacity demand is sufficiently high, the marginal bidder behaves as a monopolist facing residual demand in the capacity auction and exercises market power by raising (shading) its bid upwards towards the price-cap $\overline{P}^C$. It is shown that the addition of price-elastic capacity demand moderates the marginal bidder's ability to exercise market power in the capacity auction because residual capacity demand is now price-elastic.

[26] This impact is strictly positive if $\alpha > \frac{1}{2}$.

The bidding behavior in the last-stage electricity auction is analogous to that specified in Proposition 1. Proposition 5 specifies the bidding behavior in the capacity auction with elastic demand, taking the firms' capacity limits (k^-, k^+), capacity demand parameters $(\overline{P}^C, b, r)$, and the realization of θ^C as given.

Proposition 5. Equilibrium bidding behavior in the capacity auction with price-elastic demand:[27]

1. (Low-Demand) If $\theta^C \leq \widehat{\theta}_1^C$, then the unique PSNE entails both firms bidding at zero and earning a payoff of zero.
2. (Mid-Demand) If $\widehat{\theta}_1^C < \theta^C \leq \widehat{\theta}_2^C$, then the PSNE entails the large firm bidding at $p_+^{c\,*}$ and serving residual demand $D(p_+^{c\,*}, \theta^C; \cdot) - k^-$, while the small firm procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable.
3. (Peak-Demand) If $\widehat{\theta}_2^C < \theta^C \leq \widehat{\theta}_3^C$, then the PSNE entails the large firm bidding at $\overline{P}^C$ and serving residual demand $D(\overline{P}^C, \theta^C; \cdot) - k^-$, while the small firm procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable.
4. (Capacity Scarcity) If $\theta^C > \widehat{\theta}_3^C$, then there are two PSNE where a firm i bids at $\overline{P}^C$, firm h bids sufficiently low such that undercutting is unprofitable, and both firms procure their entire capacities with $i, h = 1, 2$ and $i \neq h$.

where $p_+^{c\,*} = \max_{p^c} p^c[\widetilde{D}(p^c, \theta^C; \cdot) - k^-]$; $\widehat{\theta}_1^C : \widetilde{D}(p^c = 0, \widehat{\theta}_1^C; \cdot) = 0$; $\widehat{\theta}_2^C : p_+^{c\,*}(\widehat{\theta}_2^C) = \overline{P}^C$; and $\widehat{\theta}_3^C : \widetilde{D}(p^c = \overline{P}^C, \widehat{\theta}_3^C; \cdot) = K$.

For the low-demand region $(\theta^C \leq \widehat{\theta}_1^C)$, intense competition drives the firms' bids to zero because a single firm can supply all of the capacity demanded. For the mid-demand to capacity scarcity demand regions $(\theta^C > \widehat{\theta}_1^C)$, at least one firm is capacity constrained. Therefore, the marginal bidder chooses its bid to maximizes its payoff facing residual demand, while the other bidder bids sufficiently low to make undercutting from its rival unprofitable. Focusing on the setting where the large firm is the marginal bidder, if $\theta^C > \widehat{\theta}_1^C$ the large firm behaves as a monopolist facing residual demand and chooses its bid (sets the market-clearing price) to maximize its payoff. That

[27] There are multiple PSNE in the mid-demand to peak-demand regions. I focus on the PSNE where the large firm is the marginal bidder. This is the only PSNE that is robust to the introduction of slight demand uncertainty (Fabra et al., 2011). In the Technical Appendix, I show that the results are robust to this assumption.

is, $b^{+} = p^{c*} = \min\{\overline{P}^{C}, p_{+}^{c\,*}\}$ where $p_{+}^{c\,*} = \max_{p^c} p^c[\widetilde{D}(p^c, \theta^C; \cdot) - k^{-}]$. If $\theta^C \geq \widehat{\theta}_2^C$, then $p_{+}^{c\,*} \geq \overline{P}^{C}$, so the price-cap is reached (i.e., $p^{c*} = \overline{P}^{C}$).

The addition of price-elastic capacity demand eliminates the bimodal pricing observed in the perfectly price-inelastic PSNE detailed in Proposition 2. Under CPM-PI, when a firm is constrained the marginal bidder behaves as a monopolist facing a perfectly price-inelastic residual demand function and bids at the price-cap $\overline{P}^{C}$. When capacity demand is price-elastic and a firm is constrained, the marginal bidder faces an elastic residual demand function. This alleviates the marginal bidder's ability to exercise market power by bidding up to the price-cap $\overline{P}^{C}$.

Focusing on the setting with linear demand, Proposition 6 analyzes how changes in the capacity demand parameters impact the outcome of the capacity auction for any pair of capacity limits.

Proposition 6. Suppose Assumption 1 holds. $p_{+}^{c\,*}$ increases as: (i) $\overline{P}^{C}$ or r increases or (ii) b increases if $\theta^C + r > k^{-}$. $\widehat{\theta}_1^C$ decreases as: (i) $\overline{P}^{C}$ or r increases or (ii) b decreases. $\widehat{\theta}_2^C$ increases as: (i) $\overline{P}^{C}$ increases or (ii) r or b decreases.

An increase in the price-cap $\overline{P}^{C}$ shifts the entire capacity demand curve upwards (and outwards). Using the capacity demand specification in Assumption 1, increasing $\overline{P}^{C}$ increases the maximum willingness to pay and output demanded at each price level up to the price-cap. For the mid-demand to capacity scarcity demand regions ($\theta^C > \widehat{\theta}_1^C$), this strictly increases the capacity auction price p^{c*}. In this demand region, a firm is constrained and the marginal bidder behaves as a monopolist facing residual demand. An increase in $\overline{P}^{C}$ increases the marginal bidder's residual demand, and so increases its payoff-maximizing marginal bid that sets p^{c*}. Further, this increases the incidence of demand realizations where a firm is capacity constrained (i.e., $\widehat{\theta}_1^C$ decreases). By analogous intuition, an increase in the reserve margin r shifts the capacity demand curve outward and hence, increases p^{c*} in the mid-demand to capacity scarcity demand regions and decreases $\widehat{\theta}_1^C$.

An increase in the slope parameter b renders the capacity demand curve less price-elastic. An increase in b reduces the incidence of capacity demand realizations where a firm is capacity constrained making it more likely that the low-demand region will arise (i.e., $\widehat{\theta}_1^C$ increases). In addition, an increase in b has two countervailing impacts on the capacity auction price. First, as demand becomes less elastic, the reduction in price-responsiveness of demand puts upward pressure on the marginal bidder's bid and hence, p^{c*} for the mid-demand to capacity scarcity regions (*price effect*). Second, increasing b shifts the capacity demand curve inward, reducing the marginal bidder's residual demand putting downward pressure on p^{c*} (*quantity effect*). For low values of θ^C ($\theta^C < k^- - r$), the *quantity effect* dominates, so an increase in b decreases p^{c*}. For $\theta^C \geq k^- - r$, the *price effect* dominates, so an increase in b increases p^{c*}.

Lemma 3. Firm i's expected profit under CPM-PE:

$$\pi_i^{PE}(k_i, k_h) = \begin{cases} \pi_i^{-PE} & \text{if } k_i = k^- < k_h = k^+, \\ \pi_i^{=PE} & \text{if } k_i = k_h = k, \text{ and} \\ \pi_i^{+PE} & \text{if } k_i = k^+ > k_h = k^- \end{cases} \tag{10}$$

where

$$\begin{aligned}
\pi_i^{-PE} &= \int_{k^-}^{1} (\overline{P}^E - \gamma) k^- \, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} k^- \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C k^- \, dG^C(\theta^C) - ck^-, \\
\pi_i^{=PE} &= (\overline{P}^E - \gamma) \left(\int_k^K \frac{\theta^E}{2} \, dG^E(\theta^E) + \int_K^1 k \, dG^E(\theta^E) \right) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} \frac{1}{2} \widetilde{D}(\cdot) \, dG^C(\theta^C) \\
&+ \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \frac{1}{2} (\theta^C + r) \, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} k \, dG^C(\theta^C) \right) - ck, \text{ and} \\
\pi_i^{+PE} &= (\overline{P}^E - \gamma) \left(\int_{k^-}^{K} [\theta^E - k^-] \, dG^E(\theta^E) + \int_K^1 k^+ \, dG^E(\theta^E) \right) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} [\widetilde{D}(\cdot) - k^-] \, dG^C(\theta^C) \\
&+ \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} [\theta^C + r - k^-] \, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} k^+ \, dG^C(\theta^C) \right) - ck^+.
\end{aligned}$$

Lemma 3 specifies a firm's profit functions. Similar to the CPM-PI environment, the introduction of the capacity auction does not change the strategic nature of the multi-stage investment game facing the firms. Therefore, in equilibrium the capacity pair (k^-, k^+) retains the characteristics identified in Fabra et al.'s (2011) analysis detailed in Proposition 1.

Lemma 4. The equilibrium capacity levels (k^-, k^+) always exists and satisfy:

$$(\overline{P}^E - \gamma)[1 - G^E(k^- + k^+)] + \overline{P}^C [1 - G^C(K - r)] = c, \text{ and} \tag{11}$$

$$\int_{k^-}^{1} (\overline{P}^E - \gamma) k^- \, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} k^- \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C k^- \, dG^C(\theta^C)$$

$$= \quad (\overline{P}^E - \gamma)\left(\int_{k^-}^{K}[\theta^E - k^-]\, dG^E(\theta^E) + \int_K^1 k^+\, dG^E(\theta^E)\right) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*}[\widetilde{D}(\cdot) - k^-]\, dG^C(\theta^C)$$

$$+ \quad \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C}[\theta^C + r - k^-]\, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} k^+\, dG^C(\theta^C)\right). \qquad (12)$$

Condition (11) indicates the large firm expands its capacity to the point where the marginal benefit of relaxing its capacity constraint (increasing output) in the capacity scarcity demand regions of the electricity and capacity auctions equals the marginal costs of capacity. (12) indicates that the small firm chooses its capacity level such that the large firm and small firm have the same level of expected revenues.

Proposition 7. Aggregate capacity K increases as: (i) $\overline{P}^E$, $\overline{P}^C$, or r increase or (ii) γ or c decrease. Furthermore, K does not change as b changes.

Proposition 7 reveals that the aggregate capacity (K) increases as: (i) the price-cap in either the energy or capacity auction increases; (ii) as the reserve margin increases; and (iii) decreases as the cost of capacity or electricity provision increases. In addition, K does not change as the slope of capacity demand varies. This arises because the equilibrium choice of K is based upon the revenues earned in the scarcity regions of the energy and capacity auctions when firms are constrained.[28] In this demand region, adjusting b has no impact on the expected revenues because the market-clearing bids are equal to the price-caps in both auctions. The slope parameter only impacts equilibrium bidding behavior in the capacity auction for interior prices (i.e., $p^{c*} < \overline{P}^C$).

Under CPM-PE, the regulator chooses the capacity demand parameters $(\overline{P}^C, r, b)$ to maximize expected welfare anticipating how the firms will respond in their subsequent capacity investment decisions and the bidding behavior in the energy and capacity auctions. Proposition 8 characterizes the optimal parameters under CPM-PE.

Proposition 8. The expected welfare maximizing parameters $(\overline{P}^C, r, b)$ satisfy:

$$\overline{P}^C:\ \alpha\left[(v - \overline{P}^E)[1 - G^E(K)] - \overline{P}^C[1 - G^C(K - r)]\right]\frac{dK}{d\overline{P}^C} + (2\alpha - 1)\left[(\overline{P}^E - \gamma)k^- g^E(k^-)\frac{dk^-}{d\overline{P}^C}\right]$$

$$-(2\alpha - 1)\left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{d\overline{P}^C}\, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C}\theta^C + r\, dG^C(\theta^C) + [1 - G^C(\widehat{\theta}_3^C)]K\right] = 0; \qquad (13)$$

[28]Recall from (11), K is implicitly determined by the additional marginal revenues the large firm expects to earn in the capacity scarcity regions of the electricity and capacity auctions by relaxing its capacity constraint.

$$r: \quad \alpha\left[(v-\overline{P}^E)[1-G^E(K)]-\overline{P}^C[1-G^C(K-r)]\right]\frac{dK}{dr}+(2\alpha-1)\left[(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{dr}\right]$$

$$-(2\alpha-1)\left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{dr}\,dG^C(\theta^C)+\overline{P}^C[G^C(\widehat{\theta}_3^C)-G^C(\widehat{\theta}_2^C)]\right]=0;\text{ and} \tag{14}$$

$$b: \quad (2\alpha-1)\left[(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{dr}-\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{db}\,dG^C(\theta^C)\right]=0. \tag{15}$$

The intuition behind the optimal choice of $\overline{P}^C$ and r in (13) and (14) is analogous to (8) and (9) detailed in Proposition 4. Therefore, attention is focused on the choice of the slope parameter b. The first term in (15) reflects the social impact of an increase in b on the small firm's capacity limit (k^-). As k^- increases due to a rise in b there are fewer demand realizations where a firm is capacity constrained resulting in a high market-clearing price. The second term in (15) represents the social impact of reducing the price-responsiveness of the capacity demand curve. There is a trade-off associated with an increase in b. First, increasing b shifts the capacity demand curve inwards reducing the level of capacity payments to firms as the quantity of capacity demand falls (*quantity effect*). Second, increasing b reduces the price-responsiveness of capacity demand and from Proposition 6, this puts upward pressure on the market-clearing capacity auction price increasing the level of socially costly capacity payments (*price effect*). The optimal level of b depends on the magnitude of these two countervailing effects.

Proposition 9 details properties of the optimal slope parameter. In particular, under plausible conditions, the optimal slope parameter leads to an environment with price-elastic capacity demand.

Proposition 9. Suppose Assumption 1 holds. If $P(\,\widehat{\theta}_1^C \leq \theta^C \leq k^- - r\,) < P(\,k^- - r < \theta^C \leq \widehat{\theta}_2^C\,)$, then b^* is interior. Otherwise, $b^* = \infty$.

Proposition 9 reveals that there is a (interior) optimal value on $b^* < \infty$ under plausible conditions.[29] In particular, if the probability that the capacity demand falls within the low-demand region is sufficiently small (i.e., $P(\,\widehat{\theta}_1^C \leq \theta^C \leq k^- - r\,) < P(\,k^- - r < \theta^C \leq \widehat{\theta}_2^C\,)$), then $b^* < \infty$. If $\theta^C > k^- - r$, then no single firm can serve all of the capacity demanded. This setting is often referred to as having a pivotal-bidder.[30] Recall, from Proposition 6, increasing the degree of price-

[29]Notice, if $b = \infty$, then we revert back to the perfectly price-inelastic setting (CPM-PI).

[30]In practice, it has systematically been the case that there are pivotal bidders in the capacity auctions (Bowring, 2013). Therefore, the assumption that $P(\theta^C < k^- - r)$ is sufficiently small is supported empirically.

responsiveness (reducing b) has two countervailing effects. It reduces the marginal bidder's market power capabilities, lowering the capacity auction price (*price effect*). Alternatively, it increases the quantity of capacity demanded at any given price level, increasing the level of capacity payments (*quantity effect*). If the incidence of capacity demand periods with low-demand is sufficiently small, then the social gain associated with the *price effect* dominates the social losses due to the *quantity effect*. Therefore, in this setting the regulator sets $b^* < \infty$ to increase social welfare by reducing the marginal bidder's abilities to exercise market power.[31]

4 Comparison Across Capacity Payment Mechanisms

This section compares the performance of the CPMs. In particular, I investigate how the addition of price-elastic capacity demand affects the execution of market power, expected welfare and its distribution across consumer and producer surplus, total expected capacity payments, and the level of aggregate capacity in equilibrium.

Proposition 10 details how the addition of price-elastic demand affects the bidding behavior in the capacity auction.

Proposition 10. Define ${p_I^c}^*$ and ${p_E^c}^*$ to be the equilibrium capacity auction prices under CPM-PI and CPM-PE environments, respectively. For any pair $(\overline{P}^C, r)$: (i) if $\theta^C \in [\widehat{\theta}_1^C, k^- - r]$, then ${p_E^c}^* > {p_I^c}^*$; (ii) if $\theta^C \in (k^- - r, \widehat{\theta}_2^C]$, then ${p_E^c}^* < {p_I^c}^*$;or (iii) if $\theta^C \in (\widehat{\theta}_2^C, 1]$, then ${p_E^c}^* = {p_I^c}^*$.

Comparing Propositions 2 and 5, the addition of price-elastic demand eliminates the bimodal pricing structure often criticized in the perfectly price-elastic capacity demand environment. For any pair $(\overline{P}^C, r)$, the addition of price-elastic capacity demand increases the quantity of capacity demanded for all $p^c < \overline{P}^C$. If $\theta^C \in [\widehat{\theta}_1^C, k^- - r]$ then the *quantity effect* dominates the *price effect* identified above, causing the capacity auction price to be higher under CPM-PE compared to CPM-PI. Alternatively, if $\theta^C \in (k^- - r, \widehat{\theta}_2^C]$, the addition of price-elastic demand reduces the capacity auction price. This occurs because the *price effect* reduces the marginal bidder's market power capabilities and this impact dominates the *quantity effect* in this region.

[31] If $\alpha = \frac{1}{2}$, then $b^* \in (0, \infty]$. Altering b adjusts the transfer of payments from consumers to producers. Therefore, if $\alpha = \frac{1}{2}$, any value on $b^* \in (0, \infty]$ is optimal because the regulator is indifferent to the distribution of surplus.

Corollary 1. Suppose Assumption 1 holds. Then, if the $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r)$ is sufficiently low, the expected market-clearing capacity auction price is lower under the price-elastic setting.

Corollary 1 reveals that if the probability of the low-demand region arising is sufficiently low (i.e., the likelihood that there is a pivotal-bidder is sufficiently high), then the expected capacity auction price is lower under the CPM-PE setting compared to the CPM-PI environment. This arises because from Proposition 10 when capacity demand is elastic the marginal bidder's market power capabilities in the mid-demand to peak-demand regions is reduced. This price reduction dominates any price-effects associated with the *quantity effect* when $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r)$ is sufficiently low.

Proposition 11 compares the aggregate capacity level across CPMs in equilibrium.

Proposition 11. For any pair $(\overline{P}^C, r)$, aggregate capacity is the same under both CPMs.

While the expected capacity auction price is lower under CPM-PE under plausible conditions (Corollary 1), Proposition 11 reveals that for any pair $(\overline{P}^C, r)$ the aggregate capacity level is the same across CPMs. The addition of elastic demand reduces the marginal bidder's market power in the mid-demand to peak-demand regions, reducing the capacity auction price. However, when there is capacity scarcity, under CPM-PE the addition of elastic demand does not limit the capacity price. Recall from Lemmas 2 and 4, the level of aggregate capacity is driven by revenues in the capacity scarcity demand regions under both CPMs. Therefore, compared with CPM-PI, the addition of elastic demand limits the marginal bidder's market power capabilities without eliminating the compensation to induce investment.

Proposition 12 compares the level and distribution of expected welfare and capacity payments under both CPMs.

Proposition 12. Suppose Assumption 1 holds and $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r) < P(k^- - r < \theta^C \leq \widehat{\theta}_2^C)$. Then, at the optimal capacity demand parameters expected welfare is higher under CPM-PE than CPM-PI. Further, suppose $P(\theta^E \leq k^-)$ is sufficiently small, then expected capacity payments are lower and expected consumer surplus is higher under CPM-PE compared to CPM-PI.

Proposition 12 reveals that expected welfare is higher under the price-elastic demand setting at the optimal capacity payments under plausible conditions.[32,33] Further, if the probability that no firm is capacity constrained in the energy auction is sufficiently low, then the level of expected capacity payments is lower and consumer surplus is higher in the price-elastic setting.[34] These results arise because of the social gain associated with the lower expected capacity auction price as the marginal bidder's market power capabilities are limited in the mid-demand to peak-demand region under CPM-PE. Recall, the marginal bidder's market power execution in this demand region does not impact the aggregate capacity investment level, it just results in a rent transfer from consumers to producers. Therefore, the socially costly market power is limited without eliminating the firms' investment incentives in the CPM-PE setting compared to the CPM-PI environment.

Corollary 2 details addition findings across the capacity market designs in the same setting.

Corollary 2. Suppose Assumption 1 holds and $P(\,\widehat{\theta}_1^C \leq \theta^C \leq k^- - r\,) < P(\,k^- - r < \theta^C \leq \widehat{\theta}_2^C\,)$. For any pair $(\overline{P}^C, r)$, at the optimal slope parameter b^*:

(i) the same level of aggregate capacity is obtained with less capacity payments under CPM-PE;

(ii) market concentration is lower under CPM-PE; and

(iii) expected electricity prices are higher under CPM-PI.

In particular, Corollary 2 reveals that there is less capacity asymmetry (market concentration) under plausible conditions. The reduced asymmetry decreases expected electricity prices by reducing the incidence of demand realizations where a firm is capacity constrained which would allow the marginal bidder to execute market power, without adversely impacting the level of aggregate capacity (Proposition 11). Next, the equilibrium aggregate capacity level at the optimal capacity payments is compared to the first-best level of aggregate capacity.

Proposition 13. Define K^* to be the first-best aggregate capacity level. Then, if there is no CPM, then there is underinvestment in generation capacity. Furthermore, at the optimal capacity payments there is underinvestment in generation capacity under both CPMs. However, less underinvestment arises than in the environment with no CPM.

[32] If equal weight is given to consumer and producer surplus ($\alpha = \frac{1}{2}$), then from Proposition 9 the capacity market design only impacts the distribution of welfare across consumers and producers, not the overall level of welfare.

[33] If the probability that a single firm can serve all of the capacity demand (i.e., no firm is constrained) is sufficiently low, then the market power reducing benefits of the addition of elastic demand (*price effect*) dominate the higher capacity payments caused by the *quantity effect*. As noted above, this condition has held empirically (Bowring, 2013).

[34] Because θ^E reflects the peak energy demand period in the current setting, it is very plausible that $P(\theta^E \leq k^-)$ is sufficiently low (i.e., there are pivotal bidders). In practice, during the peak electricity demand periods, there are concerns over the market power of firms in the energy auction because of constrained bidders (Bowring, 2013).

Proposition 13 provides several key findings. If there is no CPM so we are in the setting with an energy-only market, there is underinvestment in electricity generation capacity. This result is driven by the fact that the price-cap $\overline{P}^E$ is inefficiently low (i.e., $\overline{P}^E < v$).[35] At the optimal capacity demand parameters, there is underinvestment in generation capacity compared to the first-best under both CPMs at the optimal capacity parameters. However, the underinvestment is less than what would have occurred without a CPM. The intuition behind this result is as follows. Under both CPMs, firms are able to exercise some degree of market power. This induces socially costly rent transfers from consumers to producers. Increasing the parameters $(\overline{P}^C, r)$ increases this rent transfer in the mid-demand to peak-demand regions in the capacity auction because the residual demand faced by the marginal bidder is higher as either $\overline{P}^C$ or r expand (e.g., see Proposition 6). To limit this socially costly distortion, the optimal pair $(\overline{P}^C, r)$ is set below levels that would induce the first-best aggregate capacity in both CPMs. However, because the CPM-PE setting alleviates the degree of these distortions under plausible conditions (Corollary 1), the CPM-PE leads to a higher aggregate capacity investment level (closer to K^*) as the regulator is able to increase $(\overline{P}^C, r)$ further in this environment.[36]

5 Conclusion

Capacity markets used to promote generation capacity investment have become an integral component of restructured electricity markets. In this paper, I characterize the optimal capacity payments for two widely used CPMs: capacity auctions with and without price-elastic capacity demand. This allows me to evaluate both the short-term and long-term effects of capacity market design on the performance of electricity markets. Without capacity payments there is underinvestment in generation capacity. At the optimal capacity payment parameters, the underinvestment persists because the regulator restricts payments to an inefficiently low level to limit the firms' abilities to exercise market power. However, the degree of underinvestment is lower in the presence of capacity pay-

[35] This result is analogous to the underinvestment found in Fabra et al. (2011) and Zöttl (2011).

[36] If consumer and producer surplus is equally weighted ($\alpha = \frac{1}{2}$), then K^* is restored under both CPMs. The regulator increases the capacity demand parameters to induce the first-best capacity investment because the regulator has no preference over the distribution of welfare across consumers and producers.

ments. Further, the degree of underinvestment is lowest in the price-elastic capacity demand setting at the optimal capacity payments under plausible conditions. This arises because the regulator is able to raise the capacity payment parameters in the price-elastic setting due to its ability to limit socially costly market power execution.

The addition of the price-elastic capacity demand affects the short-run conduct of firm behavior. Price-elastic capacity demand eliminates the bimodal pricing behavior, reduces firms' abilities to exercise market power, and results in a lower expected capacity auction prices compared to the price-inelastic setting. Further, because there is less market concentration (capacity asymmetry) in the price-elastic setting, the electricity market is more competitive resulting in lower expected electricity prices. These results imply that the addition of price-elastic capacity demand increases expected welfare and consumer surplus under plausible conditions.

Capacity auctions with perfectly price-inelastic capacity demand can enhance expected welfare by promoting capacity investment. However, the addition of price-elastic capacity demand can be instituted to enhance welfare even further. In practice, regulators have transitioned from the price-inelastic setting to one with price-elastic demand. In addition, market monitors are employed to limit the degree of socially costly market power execution in these concentrated capacity auctions (Pfeifenberger et al., 2009). While the details of implementation are controversial in these capacity markets (Bidwell, 2005; Kleit and Michaels, 2013), the current analysis suggests that the underlying fundamentals of these market mechanisms relies on sound economic principles.

For illustrative purposes, I have analyzed a simple setting. More general results can be derived.[37] For instance, throughout the analysis I assumed that the large firm is the marginal bidder in the high-demand region (i.e., $\theta^j \in (k^-, K] \; \forall \, j \in \{L, C\}$). This assumption can be relaxed by considering all continuation equilibria in this demand region. I find that the results of the basic model carry over to this environment. Further, I consider a duopoly setting. However, von der Fehr and Harbord (1998) demonstrate that the essential characteristics of the current environment carry over to the oligopoly setting. The number of firms only affects the distribution of capacity across firms, not the absolute level of capacity. In addition, in practice there is a set of existing generation units

[37] For a detailed treatment of several of these extensions, see the Technical Appendix.

in addition to new potential entrants. The basic results of the model hold in this environment. In particular, in this setting the benefits of alleviating market power are heightened because rent transfers from consumers to producers have the potential to be substantially larger as the installed generation units also receive capacity payments from the capacity auctions in practice.

Future research should account for asymmetries in firms' costs of electricity generation and capacity investment.[38] In addition, future research should consider the performance of additional capacity market designs. For instance, another widely used market design holds the capacity auction three to five years prior to the electricity procurement auctions.[39] Therefore, when firms make their capacity auction bidding decisions, capacity limits are no longer taken as given.[40] Alternative mechanisms rely on a call-option capacity payment approach (e.g., Bidwell (2005); Oren (2005); Cramton and Stoft (2006, 2008)). The optimal design of these policies warrants formal investigation.

[38]In practice, the motivation for the underinvestment problem is due to the fact that natural gas generators do not receive sufficient revenues from electricity markets due to price-caps $\overline{P}^E < v$. Therefore, the current symmetric environment can be thought of as an analysis of the investment and bidding decisions of natural gas generation units.

[39]This addition increases the elasticity of supply, provides a longer time horizon for investments, and reduces risk. I conjecture that the main findings of the current analysis will carry over to this environment. However, the longer-time horizon will likely alleviate some of the dynamic inefficiencies not captured in the current analysis.

[40]In this setting, firms submit a price-quantity pair into the capacity auction. This reflects both the amount of capacity the firm wishes to install and the price at which the firm is willing to make this capacity available in the subsequent electricity procurement auctions.

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APPENDIX

Proof of Propositions 1 and 2: Follow directly from (1) – (4) and Proposition 1 in (Fabra et al., 2006) and Propositions 4 and 6 in (Fabra et al., 2011). □

Proof of Lemma 1: Firm i's profit function under CPM-PI follows directly from using (1) – (4) and Propositions 1 and 2.[41]
□

Proof of Lemma 2: From Proposition 1, the equilibrium capacity levels (k^-, k^+) satisfy: $\frac{dE[\pi^{+PI}]}{dk^+} = 0$ and $\pi^{+PI} + ck^+ = \pi^{-PI} + ck^-$. (6) and (7) follow directly from these conditions. □

Proof of Proposition 3: Implicitly differentiating (6):

$$-(\overline{P}^E - \gamma)g^E(K)\frac{dK}{d\overline{P}^C} - \overline{P}^C g^C(K-r)\frac{dK}{d\overline{P}^C} + 1 - G^C(K-r) = 0$$

$$\Rightarrow \frac{dK}{d\overline{P}^C} = \frac{1 - G^C(K-r)}{(\overline{P}^E - \gamma)g^E(K) + \overline{P}^C g^C(K-r)} > 0;$$

$$-(\overline{P}^E - \gamma)g^E(K)\frac{dK}{d\overline{P}^E} - \overline{P}^C g^C(K-r)\frac{dK}{d\overline{P}^E} + 1 - G^E(K) = 0$$

$$\Rightarrow \frac{dK}{d\overline{P}^E} = \frac{1 - G^E(K)}{(\overline{P}^E - \gamma)g^E(K) + \overline{P}^C g^C(K-r)} > 0;$$

$$-(\overline{P}^E - \gamma)g^E(K)\frac{dK}{d\gamma} - \overline{P}^C g^C(K-r)\frac{dK}{d\gamma} - [1 - G^E(K)] = 0$$

$$\Rightarrow \frac{dK}{d\gamma} = -\frac{1 - G^E(K)}{(\overline{P}^E - \gamma)g^E(K) + \overline{P}^C g^C(K-r)} < 0;$$

$$-(\overline{P}^E - \gamma)g^E(K)\frac{dK}{dc} - \overline{P}^C g^C(K-r)\frac{dK}{dc} = 1$$

$$\Rightarrow \frac{dK}{dc} = -\frac{1}{(\overline{P}^E - \gamma)g^E(K) + \overline{P}^C g^C(K-r)} < 0; \text{ and}$$

$$-(\overline{P}^E - \gamma)g^E(K)\frac{dK}{dr} - \overline{P}^C g^C(K-r)\left(\frac{dK}{dr} - 1\right) = 0$$

$$\Rightarrow \frac{dK}{dr} = \frac{\overline{P}^C g^C(K-r)}{(\overline{P}^E - \gamma)g^E(K) + \overline{P}^C g^C(K-r)} > 0.$$

□

Proof of Proposition 4: Using (1) - (4), Propositions 1 and 2, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is:[42]

[41] For a detailed derivation of the firm i's profit function under CPM-PI, see the Technical Appendix.
[42] For a detailed derivation of Consumer Surplus under CPM-PI, see the Technical Appendix.

$$E[CS^{PI}] = \int_0^{k^-}(v-\gamma)\theta^E\,dG^E(\theta^E) + \int_{k^-}^{K}(v-\overline{P}^E)\theta^E\,dG^E(\theta^E) + \int_K^1(v-\overline{P}^E)K\,dG^E(\theta^E)$$
$$- \int_{k^- -r}^{K-r}\overline{P}^C(\theta^C+r)\,dG^C(\theta^C) - \int_{K-r}^{1}\overline{P}^C K\,dG^C(\theta^C). \quad (16)$$

Using (2), (5), and (16)

$$E[W^{PI}] = \alpha\left[\int_0^{k^-}(v-\gamma)\theta^E\,dG^E(\theta^E) + \int_{k^-}^{K}(v-\overline{P}^E)\theta^E\,dG^E(\theta^E) + \int_K^1(v-\overline{P}^E)K\,dG^E(\theta^E)\right]$$
$$+(1-\alpha)\left[\int_{k^-}^{K}(\overline{P}^E-\gamma)\theta^E\,dG^E(\theta)^E + \int_K^1(\overline{P}^E-\gamma)K\,dG^E(\theta^E) - cK\right]$$
$$-(2\alpha-1)\left[\int_{k^- -r}^{K-r}\overline{P}^C(\theta^C+r)\,dG^C(\theta^C) + \int_{K-r}^{1}\overline{P}^C K\,dG^C(\theta)^C)\right]. \quad (17)$$

Using (6) and (17):

$$\frac{dE[W^{PI}]}{d\overline{P}^C} = \alpha\left[\frac{dk^-}{d\overline{P}^C}(\overline{P}^E-\gamma)k^-g^E(k^-) + (v-\overline{P}^E)[1-G^E(K)]\frac{dK}{d\overline{P}^C}\right]$$
$$+(1-\alpha)\left[-\frac{dk^-}{d\overline{P}^C}(\overline{P}^E-\gamma)k^-g^E(k^-) + \left((\overline{P}^E-\gamma)[1-G^E(K)]-c\right)\frac{dK}{d\overline{P}^C}\right]$$
$$-(2\alpha-1)\left[-\frac{dk^-}{d\overline{P}^C}\overline{P}^C k^- g^C(k^- - r) + \int_{k^- -r}^{K-r}(\theta^C+r)\,dG^C(\theta^C) + \int_{K-r}^{1}\overline{P}^C\frac{dK}{d\overline{P}^C} + K\,dG^C(\theta^C)\right] = 0$$
$$\Rightarrow\ \alpha\left[(v-\overline{P}^E)[1-G^E(K)] - \overline{P}^C[1-G^C(K-r)]\right]\frac{dK}{d\overline{P}^C} - (2\alpha-1)\Bigg[-(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{d\overline{P}^C}$$
$$-\overline{P}^C g^C(k^- - r)k^-\frac{dk^-}{d\overline{P}^C} + \int_{k^- -r}^{K-r}\theta^C + r\,dG^C(\theta^C) + [1-G^C(K-r)]K\Bigg] = 0;\ \text{and}$$
$$\frac{dE[W^{PI}]}{dr} = \alpha\left[\frac{dk^-}{dr}(\overline{P}^E-\gamma)k^-g^E(k^-) + (v-\overline{P}^E)[1-G^E(K)]\frac{dK}{dr}\right]$$
$$+(1-\alpha)\left[-\frac{dk^-}{dr}(\overline{P}^E-\gamma)k^-g^E(k^-) + \left((\overline{P}^E-\gamma)[1-G^E(K)]-c\right)\frac{dK}{dr}\right]$$
$$-(2\alpha-1)\left[\left(\frac{dk^-}{dr}-1\right)\overline{P}^C k^- g^C(k^- - r) + \int_{k^- -r}^{K-r}\overline{P}^C\,dG^C(\theta^C) + \int_{K-r}^{1}\overline{P}^C\frac{dK}{dr}\,dG^C(\theta^C)\right] = 0$$
$$\Rightarrow\ \alpha\left[(v-\overline{P}^E)[1-G^E(K)] - \overline{P}^C[1-G^C(K-r)]\right]\frac{dK}{dr} - (2\alpha-1)\Bigg[-(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{dr}$$
$$-\overline{P}^C g^C(k^- - r)k^-\left(\frac{dk^-}{dr}-1\right) + \overline{P}^C[G^C(K-r) - G^C(k^- - r)]\Bigg] = 0.$$

□

Proof of Proposition 5: If $\theta^C \in [0, \widehat{\theta}_1^C]$ or $\theta^C \in (\widehat{\theta}_3^C, 1]$, the bidding behavior follows directly from Proposition 1 in Fabra et al. (2006). If $\theta^C \in (\widehat{\theta}_1^C, \widehat{\theta}_3^C]$, the marginal bidder behaves as a monopolist facing residual demand by bidding $b^{+C} = \min\{p^{c}_{+}{}^{*}, \overline{P}^{C}\}$. The marginal bidder has no incentive to unilaterally deviate if the small firm is bidding sufficiently low. Suppose the large firm unilaterally alters its bid to $\widetilde{b}^{+C} = b^{-C} - \epsilon$ for some $\epsilon > 0$ resulting in a new capacity auction price $\widetilde{p}^{C} = b^{-C}$ This unilateral deviation is unprofitable if the payoff in the capacity auction is reduced:

$$\Delta\pi^{+C} = \min\{p^{c}_{+}{}^{*}, \overline{P}^{C}\}[\widetilde{D}(\cdot) - k^{-}] - b^{-C}k^{+} \geq 0$$

$$\Leftrightarrow\; b^{-C} \leq \frac{1}{k^{+}}\left(\min\{p^{c}_{+}{}^{*}, \overline{P}^{C}\}[\widetilde{D}(\cdot) - k^{-}]\right). \tag{18}$$

The large firm has no incentive to unilaterally alter its bid to become inframarginal if inequality (18) holds for any $\theta^{C} \in (\widehat{\theta}^{C}_{1}, \widehat{\theta}^{C}_{3}]$. Suppose b^{-C} is such that (18) holds. I will show that the small firm has no incentive to unilaterally deviate to become the marginal bidder. Suppose the small firm unilaterally deviates to $\widetilde{b}^{-C} = \min\{\overline{P}^{C}, \max\{p^{c}_{-}{}^{*}, p^{c}_{+}{}^{*} + \epsilon\}\}$ for some $\epsilon > 0$ where $p^{c}_{-}{}^{*} = \max_{p^{c}} p^{c}[\widetilde{D}(\cdot) - k^{+}]$. Because $k^{+} > k^{-}$, it is straightforward to show that $p^{c}_{+}{}^{*} > p^{c}_{-}{}^{*}$ such that $\widetilde{b}^{-C} = \min\{\overline{P}^{C}, p^{c}_{+}{}^{*} + \epsilon\}$. Thus, the change in the small firm's payment in the capacity auction is non-positive as $\epsilon \to 0$ because $\widetilde{D}(\min\{\overline{P}^{C}, p^{c}_{+}{}^{*} + \epsilon\}, \theta^{C}; \cdot) - k^{+}] \leq k^{-}$ for any $\theta^{C} \in (\widehat{\theta}^{C}_{1}, \widehat{\theta}^{C}_{3}]$:

$$\Delta\pi^{-C} = \min\{\overline{P}^{C}, p^{c}_{+}{}^{*} + \epsilon\}[\widetilde{D}(\min\{\overline{P}^{C}, p^{c}_{+}{}^{*} + \epsilon\}, \theta^{C}; \cdot) - k^{+}] - \min\{\overline{P}^{C}, p^{c}_{+}{}^{*}\}k^{-} \leq 0. \tag{19}$$

Inequality (19) implies that if the large firm is marginal, the small firm never has an incentive to unilaterally deviate from bidding sufficiently low (inequality (18)) to become the marginal bidder. There exists a subregion of $\theta^{C} \in (\widehat{\theta}^{C}_{1}, \widehat{\theta}^{C}_{3}]$ where the small firm can be the marginal bidder. See the Technical Appendix for a Proof that the main findings persist with multiple equilibria.

□

Proof of Proposition 6: Suppose Assumption 1 holds. Using (1), Assumption 1, and Proposition 5:

$$p^{C*}_{+} :\; \widetilde{D}(p^{C*}_{+}, \theta^{C}; \cdot) - k^{-} + p^{C*}_{+}\frac{d\widetilde{d}(\cdot)}{dp^{c}} = 0 \;\Rightarrow\; p^{C*}_{+} = \frac{b}{2}\left[\frac{\overline{P}^{C}}{b} + \theta^{C} + r - k^{-}\right]; \tag{20}$$

$$\widehat{\theta}^{C}_{1} :\; \widetilde{D}(p^{c} = 0, \widehat{\theta}^{C}_{1}; \cdot) = k^{-} \;\Rightarrow\; \widehat{\theta}^{C}_{1} = k^{-} - r - \frac{\overline{P}^{C}}{b}; \tag{21}$$

$$\widehat{\theta}^{C}_{2} :\; p^{c}_{+}{}^{*}(\widehat{\theta}^{C}_{2}) = \overline{P}^{C} \;\Rightarrow\; \widehat{\theta}^{C}_{2} = k^{-} - r + \frac{\overline{P}^{C}}{b}; \tag{22}$$

$$\widehat{\theta}^{C}_{3} :\; \widetilde{D}(p^{c} = \overline{P}^{C}, \widehat{\theta}^{C}_{3}; \cdot) = K \;\Rightarrow\; \widehat{\theta}^{C}_{3} = K - r; \tag{23}$$

For any given pair of capacity limits (k^{-}, k^{+}), the conclusions in the Proposition follow directly from (20) – (23).

□

Proof of Lemma 3: Firm i's expected profit function follows directly from (1) - (4) and Propositions 1 and 5. [43]

□

[43] For a detailed derivation of firm i's profit function under CPM-PE, see the Technical Appendix.

Proof of Lemma 4: From Proposition 1, the equilibrium capacity levels (k^-, k^+) satisfy: $\frac{dE[\pi^{+PE}]}{dk^+} = 0$ and $\pi^{+PE} + ck^+ = \pi^{-PE} + ck^-$. (11) and (12) follow directly from these conditions. $\square$

Proof of Proposition 7: Using (11) and that $\widehat{\theta}_3^C$ is increasing in K because $\frac{d\widetilde{D}(\cdot)}{d\theta^C} > 0$, the conclusions in the Proposition follow analogously from the Proof of Proposition 3. $\square$

Proof of Proposition 8: Using (1) - (4), Propositions 1 and 5, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is:[44]

$$\begin{aligned} E[CS^{PE}] &= \int_0^{k^-} (v-\gamma)\theta^E \, dG^E(\theta^E) + \int_{k^-}^{K} (v-\overline{P}^E)\theta^E \, dG^E(\theta^E) + \int_K^1 (v-\overline{P}^E)K \, dG^E(\theta^E) \\ &- \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*}\widetilde{D}(\cdot)\, dG^C(\theta^C) - \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C(\theta^C + r)\, dG^C(\theta^C) - \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C K \, dG^C(\theta^C). \qquad (24) \end{aligned}$$

Using (2), (10), and (24)

$$\begin{aligned} E[W^{PE}] = \alpha & \left[\int_0^{k^-} (v-\gamma)\theta^E \, dG^E(\theta^E) + \int_{k^-}^{K} (v-\overline{P}^E)\theta^E \, dG^E(\theta^E) + \int_K^1 (v-\overline{P}^E)K \, dG^E(\theta^E) \right] \\ &+ (1-\alpha)\left[\int_{k^-}^{K} (\overline{P}^E-\gamma)\theta^E \, dG^E(\theta)^E + \int_K^1 (\overline{P}^E-\gamma)K\, dG^E(\theta^E) - cK \right] - (2\alpha-1)\times \\ & \left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*}\widetilde{D}(\cdot)\, dG^C(\theta^C) + \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} (\theta^C + r)\, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} K\, dG^C(\theta^C) \right) \right]. \qquad (25) \end{aligned}$$

Using (11), (25), and from Proposition 7, K does not vary with b in equilibrium:

$$\begin{aligned} \frac{dE[W^{PE}]}{d\overline{P}^C} &= \alpha \left[\frac{dk^-}{d\overline{P}^C}(\overline{P}^E-\gamma)k^- g^E(k^-) + (v-\overline{P}^E)[1-G^E(K)]\frac{dK}{d\overline{P}^C} \right] \\ &+ (1-\alpha)\left[-\frac{dk^-}{d\overline{P}^C}(\overline{P}^E-\gamma)k^- g^E(k^-) + \left((\overline{P}^E-\gamma)[1-G^E(K)] - c \right)\frac{dK}{d\overline{P}^C} \right] \\ -(2\alpha-1) & \left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{dp_+^{C*}\widetilde{D}(\cdot)}{d\overline{P}^C}\, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \theta^C + r\, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C\frac{dK}{d\overline{P}^C} + K\, dG^C(\theta^C) \right] = 0 \end{aligned}$$

$$\begin{aligned} \Rightarrow \alpha & \left[(v-\overline{P}^E)[1-G^E(K)] - \overline{P}^C[1-G^C(K-r)] \right] \frac{dK}{d\overline{P}^C} - (2\alpha-1)\Bigg[-(\overline{P}^E-\gamma)k^- g^E(k^-)\frac{dk^-}{d\overline{P}^C} \\ &+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{dp_+^{C*}\widetilde{D}(\cdot)}{d\overline{P}^C}\, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \theta^C + r\, dG^C(\theta^C) + [1-G^C(\widehat{\theta}_3^C)]K \Bigg] = 0; \end{aligned}$$

$$\begin{aligned} \frac{dE[W^{PE}]}{dr} &= \alpha \left[\frac{dk^-}{dr}(\overline{P}^E-\gamma)k^- g^E(k^-) + (v-\overline{P}^E)[1-G^E(K)]\frac{dK}{dr} \right] \\ &+ (1-\alpha)\left[-\frac{dk^-}{dr}(\overline{P}^E-\gamma)k^- g^E(k^-) + \left((\overline{P}^E-\gamma)[1-G^E(K)] - c \right)\frac{dK}{dr} \right] \end{aligned}$$

[44] For a detailed derivation of Consumer Surplus under CPM-PE, see the Technical Appendix.

$$-(2\alpha-1)\left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{dr}\,dG^C(\theta^C)+\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C}\overline{P}^C\,dG^C(\theta^C)+\int_{\widehat{\theta}_3^C}^{1}\overline{P}^C\frac{dK}{dr}\,dG^C(\theta^C)\right]=0$$

$$\Rightarrow\quad \alpha\Big[(v-\overline{P}^E)[1-G^E(K)]-\overline{P}^C[1-G^C(K-r)]\Big]\frac{dK}{dr}-(2\alpha-1)\Big[-(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{dr}$$
$$+\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{dr}\,dG^C(\theta^C)+\overline{P}^C[G^C(\widehat{\theta}_3^C)-G^C(\widehat{\theta}_2^C)]\Big]=0;$$

$$\frac{dE[W^{PE}]}{db}=\alpha\left[\frac{dk^-}{db}(\overline{P}^E-\gamma)k^-g^E(k^-)\right]+(1-\alpha)\left[-\frac{dk^-}{db}(\overline{P}^E-\gamma)k^-g^E(k^-)\right]$$
$$-(2\alpha-1)\left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{db}\,dG^C(\theta^C)\right]=0$$

$$\Rightarrow\quad(2\alpha-1)\left[\frac{dk^-}{db}(\overline{P}^E-\gamma)k^-g^E(k^-)-\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{db}\,dG^C(\theta^C)\right]=0.$$

□

Proof of Proposition 9: Suppose Assumption 1 holds. If $\alpha=\frac{1}{2}$, then (15) holds for any $b^*\in(0,\infty]$. Suppose $\alpha>\frac{1}{2}$. It will be shown that there is an interior solution if $P(\,\widehat{\theta}_1^C\le\theta^C\le k^--r\,)<P(\,k^--r<\theta^C\le\widehat{\theta}_2^C\,)$. Otherwise, expected welfare is monotonically increasing in b and hence, $b^*=\infty$. It will be shown that if $P(\,\widehat{\theta}_1^C\le\theta^C\le k^--r\,)<P(\,k^--r<\theta^C\le\widehat{\theta}_2^C\,)$, then $\lim_{b\to0}\frac{dE[W^{PE}]}{db}>0$ and $\lim_{b\to\widetilde{b}}\frac{dE[W^{PE}]}{db}<0$ for some $\widetilde{b}<\infty$ such that $b^*<\infty$.

Suppose $\alpha>\frac{1}{2}$, using (15):

$$\frac{dE[W^{PE}]}{db}\stackrel{s}{=}(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{db}-\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{db}\,dG^C(\theta^C).\tag{26}$$

From Proposition 5, it is known that at ${p_+^c}^*:\widetilde{D}(\cdot)+{p_+^c}^*\frac{d\widetilde{D}(\cdot)}{db}=k^-$ such that:

$$\frac{d{p_+^c}^*\widetilde{D}(\cdot)}{db}=\left(\frac{d{p_+^c}^*}{db}+\frac{d{p_+^c}^*}{dk^-}\frac{dk^-}{db}\right)\widetilde{D}(\cdot)+{p_+^c}^*\left(\frac{d\widetilde{D}(\cdot)}{dp^c}\frac{d{p_+^c}^*}{db}+\frac{d\widetilde{D}(\cdot)}{dp^c}\frac{d{p_+^c}^*}{dk^-}\frac{dk^-}{db}+\frac{d\widetilde{D}(\cdot)}{db}\right)$$
$$=\left(\frac{d{p_+^c}^*}{db}+\frac{d{p_+^c}^*}{dk^-}\frac{dk^-}{db}\right)\left[\widetilde{D}(\cdot)+{p_+^c}^*\frac{d\widetilde{D}(\cdot)}{db}\right]+{p_+^c}^*\frac{d\widetilde{D}(\cdot)}{db}=\left(\frac{d{p_+^c}^*}{db}+\frac{d{p_+^c}^*}{dk^-}\frac{dk^-}{db}\right)k^-+{p_+^c}^*\frac{d\widetilde{D}(\cdot)}{db}.\tag{27}$$

Using Assumption 1 and (20), (27) simplifies such that:

$$\frac{d{p_+^c}^*\widetilde{D}(\cdot)}{db}=\left[\frac{1}{2}(\theta^C+r-k^-)-\frac{b}{2}\frac{dk^-}{db}\right]k^--\left(\frac{\overline{P}^C-{p_+^c}^*}{b^2}\right){p_+^c}^*.\tag{28}$$

Using (20) and (28), (26) simplifies:

$$\frac{dE[W^{PE}]}{db}\stackrel{s}{=}(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{db}-\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{1}{2}(\theta^C+r-k^-)k^--\frac{bk^-}{2}\frac{dk^-}{db}-\left(\frac{\overline{P}^C-{p_+^c}^*}{b^2}\right){p_+^c}^*\,dG^C(\theta^C).$$

$$= (\overline{P}^E - \gamma)k^- g^E(k^-)\frac{dk^-}{db} - \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{1}{2}(\theta^C + r - k^-)k^- - \frac{bk^-}{2}\frac{dk^-}{db} - \frac{1}{4}\left(\frac{\overline{P}^C}{b}\right)^2 + \frac{1}{4}\left(\theta^C + r - k^-\right)^2 dG^C(\theta^C).$$

$$= \frac{dk^-}{db}k^- \left[(\overline{P}^E - \gamma)g^E(k^-) + \frac{b}{2}[G^C(\widehat{\theta}_2^C) - G^C(\widehat{\theta}_1^C)]\right]$$

$$+ \frac{1}{4}\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \left(\frac{\overline{P}^C}{b}\right)^2 - 2(\theta^C + r - k^-)k^- - \left(\theta^C + r - k^-\right)^2 dG^C(\theta^C). \tag{29}$$

To analyze (29), $\frac{dk^-}{db}$ needs to be identified. Using (11) and Proposition 7, $\frac{dK}{db} = 0$ such that $\frac{dk^-}{db} = -\frac{dk^+}{db}$. Using (20) - (23) and that $p_+^{c\,*}(\widehat{\theta}_1^C) = 0$, implicitly differentiating (12) yields:

$$-(\overline{P}^E - \gamma)k^- g^E(k^-)\frac{dk^-}{db} + (\overline{P}^E - \gamma)[1 - G^E(k^-)]\frac{dk^-}{db} + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{dp_+^{c\,*}k^-}{db}\, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C \frac{dk^-}{db}\, dG^C(\theta^C)$$

$$= -\int_{k^-}^{K} (\overline{P}^E - \gamma)\frac{dk^-}{db}\, dG^E(\theta^E) + \int_{k}^{1} (\overline{P}^E - \gamma)\frac{dk^+}{db}\, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{dp_+^{c\,*}[\widetilde{D}(\cdot) - k^-]}{db}\, dG^C(\theta^C)$$

$$- \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C \frac{dk^-}{db}\, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C \frac{dk^+}{db}\, dG^C(\theta^C) \tag{30}$$

From Proposition 5, it is known that at $p_+^{c\,*} : \widetilde{D}(\cdot) + p_+^{c\,*}\frac{d\widetilde{D}(\cdot)}{db} = k^-$:

$$\frac{dp_+^{c\,*}k^-}{db} = \left(\frac{dp_+^{c\,*}}{db} + \frac{dp_+^{c\,*}}{dk^-}\frac{dk^-}{db}\right)k^- + p_+^{c\,*}\frac{dk^-}{db} \tag{31}$$

$$\frac{dp_+^{c\,*}[\widetilde{D}(\cdot) - k^-]}{db} = \left(\frac{dp_+^{c\,*}}{db} + \frac{dp_+^{c\,*}}{dk^-}\frac{dk^-}{db}\right)[\widetilde{D}(\cdot) - k^-] + p_+^{c\,*}\Bigg(\frac{d\widetilde{D}(\cdot)}{dp^c}\frac{dp_+^{c\,*}}{db} + \frac{d\widetilde{D}(\cdot)}{dp^c}\frac{dp_+^{c\,*}}{dk^-}\frac{dk^-}{db}$$

$$+ \frac{d\widetilde{D}(\cdot)}{db} - \frac{dk^-}{db}\Bigg) = \left(\frac{dp_+^{c\,*}}{db} + \frac{dp_+^{c\,*}}{dk^-}\frac{dk^-}{db}\right)\left[p_+^{c\,*}\frac{d\widetilde{D}(\cdot)}{db} + \widetilde{D}(\cdot) - k^-\right] + p_+^{c\,*}\left(\frac{d\widetilde{D}(\cdot)}{db} - \frac{dk^-}{db}\right)$$

$$= p_+^{c\,*}\left(\frac{d\widetilde{D}(\cdot)}{db} - \frac{dk^-}{db}\right). \tag{32}$$

Using Assumption 1, (20), (31), (32), and that $\frac{dk^-}{db} = -\frac{dk^+}{db}$, (30) simplifies to:

$$\frac{dk^-}{db}\Bigg[(\overline{P}^E - \gamma)[2(1 - G^E(K)) + G^E(K) - G^E(K^-) - k^- g^E(k^-)] + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \overline{P}^C + b(\theta^C + r - \frac{3}{2}k^-)\, dG^C(\theta^C)$$

$$+ \int_{\widehat{\theta}_2^C}^{1} 2\overline{P}^C\, dG^C(\theta^C)\Bigg] + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{1}{2}(\theta^C + r - k^-)k^- + \left(\frac{\overline{P}^C - p_+^{c\,*}}{b}\right)\frac{p_+^{c\,*}}{b}\, dG^C(\theta^C) = 0$$

$$\Rightarrow \frac{dk^-}{db} = -A\left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{1}{2}(\theta^C + r - k^-)k^- + \left(\frac{\overline{P}^C - p_+^{c\,*}}{b}\right)\frac{p_+^{c\,*}}{b}\, dG^C(\theta^C)\right] \tag{33}$$

where $A = (\overline{P}^E - \gamma)[2(1 - G^E(K)) + G^E(K) - G^E(K^-) - k^- g^E(k^-)] + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \overline{P}^C + b(\theta^C + r - \frac{3}{2}k^-)\, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} 2\overline{P}^C\, dG^C(\theta^C)$.

Using (20), (33), and L'Hopital's rule, it can be shown that $\lim_{b\to 0} \frac{dk^-}{db}$ is finite:

$$\lim_{b\to 0} \left(\frac{\overline{P}^C - {p_+^c}^*}{b}\right) \frac{{p_+^c}^*}{b} = \lim_{b\to 0} -\frac{1}{4}(\theta^C + r - k^-) = -\frac{1}{4}(\theta^C + r - k^-). \tag{34}$$

Using (21) and (22), $\lim_{b\to 0} \widehat{\theta}_1^C = -\infty$ and $\lim_{b\to 0} \widehat{\theta}_2^C = \infty$. Consequently, using (33) and (34), $\lim_{b\to 0} \frac{dk^-}{db}$ is finite because $G^j(\theta^j) \in (0,1]\ \forall\ j \in \{E, C\}$.

Notice, $\theta^C + r - k^- \lesseqgtr 0$ as $\theta^C \lesseqgtr k^- - r$. Further, using (21) and (22), $\widehat{\theta}^2 - (k^- - r) = k^- - r - \widehat{\theta}_1^C = \frac{\overline{P}^C}{b}$ such that $\widehat{\theta_1^C}$ and $\widehat{\theta}_2^C$ are equidistant from $k^- - r$. This implies that if $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r) < P(k^- - r < \theta^C \leq \widehat{\theta}_2^C)$, then $\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \theta^C + r - k^-\, dG^C(\theta^C) > 0$. Further, this implies that $\frac{dk^-}{db} < 0$.

Using (29):

$$\begin{aligned}
\lim_{b\to 0} \frac{dE[W^{PE}]}{db} &= \lim_{b\to 0} \frac{dk^-}{db} k^-(\overline{P}^E - \gamma) g^E(k^-) - \frac{1}{4}\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} 2(\theta^C + r - k^-)k^- + \left(\theta^C + r - k^-\right)^2 dG^C(\theta^C) \\
&+ \lim_{b\to 0} \frac{1}{4}\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \left(\frac{\overline{P}^C}{b}\right)^2 dG^C(\theta^C) \\
&= B + \lim_{b\to 0} \frac{1}{4}\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \left(\frac{\overline{P}^C}{b}\right)^2 dG^C(\theta^C) = B + \infty > 0
\end{aligned} \tag{35}$$

where $B = \lim_{b\to 0} \frac{dk^-}{db} k^-(\overline{P}^E - \gamma) g^E(k^-) - \frac{1}{4}\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} 2(\theta^C + r - k^-)k^- + \left(\theta^C + r - k^-\right)^2 dG^C(\theta^C)$ is finite.

From (29), if $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r) < P(k^- - r < \theta^C \leq \widehat{\theta}_2^C)$, then $\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \theta^C + r - k^-\, dG^C(\theta^C) > 0$ and $\frac{dk^-}{db} < 0$ such that the sole positive term in (29) is $\left(\frac{\overline{P}^C}{b}\right)^2 [G^C(\widehat{\theta}_2^C) - G^C(\widehat{\theta}_1^C)]$. Thus, for a large (finite) value of b ($\widetilde{b}$) this term is sufficiently small such that $\lim_{b\to\widetilde{b}} \dfrac{dE[W^{PE}]}{db} < 0$.

If $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r)$ is sufficiently larger than $P(k^- - r < \theta^C \leq \widehat{\theta}_2^C)$, then $\frac{dE[W^{PE}]}{db} > 0\ \forall\ b$ such that $b^* = \infty$.

□

Proof of Proposition 10: Follows directly from Propositions 2 and 5. □

Proof of Corollary 1: Using the bidding behavior detailed in Propositions 2 and 5:

$$E[{p_I^c}^*] = \int_{k^- - r}^{1} \overline{P}^C d\, G^C(\theta^C) \text{ and} \tag{36}$$

$$E[{p_E^c}^*] = \int_{\widehat{\theta}_1^C}^{k^- - r} {p_+^c}^* d\, G^C(\theta^C) + \int_{k^- - r}^{\widehat{\theta}_2^C} {p_+^c}^* d\, G^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C\, d\, G^C(\theta^C). \tag{37}$$

Using (36) and (37):

$$E[p_I^{c*}] - E[p_E^{c*}] = \int_{k^- - r}^{\widehat{\theta}_2^C} \left(\overline{P}^C - p_+^{c*}\right) dG^C(\theta^C) - \int_{\widehat{\theta}_1^C}^{k^- - r} p_+^{c*} dG^C(\theta^C) > 0. \tag{38}$$

Suppose Assumption 1 holds. Using (20), $\overline{P}^C - p_+^{c*} > 0 \;\forall\; \theta^C < \widetilde{\theta}_2^C$. This implies that if the $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r)$ is sufficiently low, then inequality (38) holds.

□

Proof of Proposition 11: Follows directly from (6) and (11) given $\widehat{\theta}_3^C = K - r$. □

Proof of Proposition 12: Suppose Assumption 1 holds, $\alpha > \frac{1}{2}$, and $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r) < P(k^- - r < \theta^C \leq \widehat{\theta}_2^C)$. From Proposition 9, b^* is interior (i.e., $b^* \in (0, \infty)$). Notice, if $b^* = \infty$ the market design CPM-PE reverts to the CPM-PI market design. Because $b^* < \infty$, the expected welfare under CPM-PE exceeds the expected welfare under CPM-PI. That is, because $b^* = \infty$ was available and was not choose (i.e., it is not the expected welfare maximum), $E[W^{PE}] > E[W^{PI}]$.

Define k^{-j} to be the small firm's capacity in equilibrium $\forall\; j \in \{PE, PI\}$. From Proposition 11 aggregate capacity is the same across CPMs. Therefore, using (17) and (25), $E[W^{PE}] > E[W^{PI}]$ implies:

$$\int_a^b (\overline{P}^E - \gamma)\theta^E \, dG^E(\theta^E) - \Bigg[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} \widetilde{D}(\cdot) \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C)$$
$$+ \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C K \, dG^C(\theta^C) - \int_{k^- - r}^{K - r} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) - \int_{K - r}^{1} \overline{P}^C K \, dG^C(\theta)^C) \Bigg] > 0 \tag{39}$$

where if $k^{-PE} < k^{-PI}$, then $a = k^{-PE}$ and $b = k^{-PI}$ or if $k^{-PE} \geq k^{-PI}$, then $a = k^{-PI}$ and $b = k^{-PE}$. If $P(\theta^E \leq k^{-j})$ is sufficiently low for each $j \in \{PI, PE\}$, then inequality (39) implies that the expected capacity payments under CPM-PI exceed those under CPM-PE. If inequality (39) holds (i.e., $P(\theta^E \leq k^{-j})$ is sufficiently low for each $j \in \{PI, PE\}$), then using (16) and (24) it is straightforward to show that expected consumer surplus is higher under CPM-PE. □

Proof of Corollary 2: Suppose Assumption 1 holds, $\alpha > \frac{1}{2}$, and $P(\widehat{\theta}_1^C \leq \theta^C \leq k^- - r) < P(k^- - r < \theta^C \leq \widehat{\theta}_2^C)$. From Proposition 11, for any pair $(\overline{P}^C, r)$, aggregate capacity is the same across CPMs. From Proposition 12, for any pair $(\overline{P}^C, r)$ at b^*, expected capacity payments are lower under CPM-PE than CPM-PI. Therefore, conclusion (i) in the Corollary follows directly.

Define k^{-j} to be the small firm's capacity in equilibrium $\forall\; j \in \{PE, PI\}$. From Proposition 9, $b^* \in (0, \infty)$ and $\frac{dk^-}{db} < 0$ in the current setting. From Proposition 11, for any pair $(\overline{P}^C, r)$, aggregate capacity is the same across CPMs. This implies that $k^{-PE} > k^{-PI}$ such that there is less market concentration (conclusion (ii)). Define p_j^{E*} to the market-clearing pricing in the energy auction $\forall\; j \in \{PI, PE\}$. Using the bidding behavior from Proposition 1, it is straightforward to show that $E[p_{PI}^{E*}] > E[p_{PE}^{E*}]$ given $k^{-PE} > k^{-PI}$ (conclusion (iii)).

□

Proof of Proposition 13: The proof proceeds in several steps.

Step 1: First, the first-best aggregate capacity level is derived. Suppose that $\overline{P}^E = v$ and there is no CPM. The regulator chooses the capacity limits of both firms. I will show that if $\alpha > \frac{1}{2}$, then the regulator chooses symmetric capacities across firms. Further, if $\alpha = \frac{1}{2}$ asymmetric capacity can exist, but the aggregate capacity investment incentives across both environments remain the same.

Using (17) and (25), if $\overline{P}^E = v$ and there is no CPM, then for both $j \in \{PI, PE\}$:

$$E[W^j] = \alpha \int_0^{k^-} (v-\gamma)\theta^E dG^E(\theta^E) + (1-\alpha)\left[\int_{k^-}^{K} (v-\gamma)\theta^E dG^E(\theta^E) + \int_K^1 (v-\gamma)K dG^E(\theta^E) - cK\right] \tag{40}$$

The regulator faces the following maximization problem:

$$\underset{k^-, k^+}{Maximize} \;\; E\left[W^j\right] \;\; \text{subject to:} \;\; k^- \leq k^+$$

where $\lambda \geq 0$ is the Lagrangian multiplier on the inequality constraint. The necessary conditions for a solution to the regulator's problem include:

$$k^- : \quad (2\alpha - 1)\left[(v-\gamma)k^- g^E(k^-)\right] + (1-\alpha)\left[\int_K^1 (v-\gamma)\, dG^E(\theta^E) - c\right] - \lambda = 0, \text{ and} \tag{41}$$

$$k^+ : \quad (1-\alpha)\left[\int_K^1 (v-\gamma)\, dG^E(\theta^E) - c\right] + \lambda = 0. \tag{42}$$

Suppose $\lambda = 0$ such that the constraint that $k^- \leq k^+$ is not binding. Using (42), (41) becomes:

$$k^- : \quad (2\alpha - 1)\left[(v-\gamma)k^- g^E(k^-)\right] = 0. \tag{43}$$

If $\alpha > \frac{1}{2}$, (43) fails to hold given $v > \gamma$. This implies that if $\alpha > \frac{1}{2}$ the regulator chooses symmetric capacity limits. Alternatively, if $\alpha = \frac{1}{2}$, then from (41) and (42) the first-best aggregate capacity satisfies:[45]

$$(v-\gamma)[1 - G^E(K^*)] - c = 0. \tag{44}$$

Suppose $\alpha > \frac{1}{2}$, using (5), (10), (17), and (25), if $\overline{P}^E = v$ and there is no CPM, then for both $j \in \{PI, PE\}$ the aggregate capacity function with symmetric capacities (k):

$$E[W^j] = \alpha \int_0^{k} (v-\gamma)\theta^E dG^E(\theta^E) + (1-\alpha)\left[\int_{k}^{K} (v-\gamma)\theta^E dG^E(\theta^E) + \int_K^1 (v-\gamma)K dG^E(\theta^E) - cK\right] \tag{45}$$

where $K = 2k$ such that $k = \frac{1}{2}K$. Using (45), then for both $j \in \{PI, PE\}$ K^* is defined by:

$$\frac{dE[W^j]}{dk} = (2\alpha - 1)(v-\gamma)\left[\frac{K^*}{2} g^E\left(\frac{K^*}{2}\right)\right] + (1-\alpha)[(v-\gamma)[1 - G^E(K^*)] - c] = 0. \tag{46}$$

<u>Step 2</u>: If there is no CPM, then there is underinvestment in aggregate capacity. Denote $\widetilde{K}$ to be the equilibrium aggregate capacity resulting from the setting with no CPM. Using (6) and (11), the firms' investment incentives imply that $[1 - G^E(\widetilde{K})] = \frac{c}{(\overline{P}^E - \gamma)}$ when $\overline{P}^C = 0$. Because $v > \overline{P}^E$ in this (non first-best) environment, using (44) and (46) reveals that $K^* > \widetilde{K}$ $\forall$ $\alpha \geq \frac{1}{2}$:

$$(v-\gamma)[1 - G^E(\widetilde{K})] - c = (v-\gamma)\frac{c}{(\overline{P}^E - \gamma)} - c = c\left[\frac{v - \overline{P}^E}{v - \gamma}\right] > 0, \text{ and}$$

[45]In this setting $\lambda = 0$. If $\lambda > 0$ is assumed, a contradiction results from (41) and (42).

$$(2\alpha-1)(v-\gamma)\left[\frac{\widetilde{K}}{2}g^E\left(\frac{\widetilde{K}}{2}\right)\right]+(1-\alpha)[(v-\gamma)[1-G^E(\widetilde{K})]-c]=D+(1-\alpha)c\left[\frac{v-\overline{P}^E}{v-\gamma}\right]>0$$

where $D=(2\alpha-1)(v-\gamma)\left[\frac{\widetilde{K}}{2}g^E\left(\frac{\widetilde{K}}{2}\right)\right]>0$.

Step 3: If $\alpha=\frac{1}{2}$, the first-best aggregate capacity level is restored at the optimal capacity payments. Using (8) and (13), at the optimal capacity demand parameters when $\alpha=\frac{1}{2}$:

$$(v-\overline{P}^E)[1-G^E(K)]-\overline{P}^C[1-G^C(K-r)]=0 \tag{47}$$

Using (6) and (11), in any equilibrium $\overline{P}^C[1-G^C(K-r)]=c-(\overline{P}^E-\gamma)[1-G^E(K)]$. Thus, (47) simplifies to:

$$(v-\gamma)[1-G^E(K)]-c=0 \tag{48}$$

(48) is analogous to (44) such that K^* is restored by the CPMs.

Step 4: If $\alpha=\frac{1}{2}$, there is underinvestment at the optimal capacity demand parameters. Using (46), there exists a $K'<K^*$ where:

$$(v-\gamma)[1-G^E(K')]=c \tag{49}$$

Denote $\widetilde{K}$ to be the equilibrium aggregate capacity level choosen by the firms for any given level of the capacity demand parameters. Using (6) and (11), in order for $\widetilde{K}=K'$ $\overline{P}^C$ be sufficiently high such that:

$$(\overline{P}^E-\gamma)[1-G^E(K')]+\overline{P}^C[1-G^C(K'-r)]=c. \tag{50}$$

Using (49), (50) becomes:

$$(v-\overline{P}^E)[1-G^E(K')]-\overline{P}^C[1-G^C(K'-r)]=0. \tag{51}$$

Using (8) and (51), for any given value on r, under CPM-PI $\overline{P}^C$ is not sufficiently high enough to induce $\widetilde{K}=K'$:

$$\begin{aligned}\overline{P}^C:\quad &-(2\alpha-1)\Bigg[-(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{d\overline{P}^C}-\overline{P}^Cg^C(k^--r)k^-\frac{dk^-}{d\overline{P}^C}\\ &+\int_{k^--r}^{K'-r}\theta^C+r\,dG^C(\theta^C)+[1-G^C(K'-r)]K'\Bigg]<0\end{aligned} \tag{52}$$

From Proposition 3, K is increasing in $\overline{P}^C$. Thus, (52) implies that $\widetilde{K}<K'<K^*$ under CPM-PI.

Using (13) and (51), for any given value on r, at b^* under CPM-PE $\overline{P}^C$ is not sufficiently high enough to induce $\widetilde{K}=K'$:

$$\begin{aligned}&-(2\alpha-1)\Bigg[-(\overline{P}^E-\gamma)k^-g^E(k^-)\frac{dk^-}{d\overline{P}^C}\\ &+\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C}\frac{dp_+^{C*}\widetilde{D}(\cdot)}{d\overline{P}^C}\,dG^C(\theta^C)+\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C}\theta^C+r\,dG^C(\theta^C)+[1-G^C(\widehat{\theta}_3^C)]K\Bigg]\leq 0\end{aligned} \tag{53}$$

where using Assumption 1 and (20):

$$\frac{dp_+^{C*}\widetilde{D}(\cdot)}{d\overline{P}^C}=\frac{1}{2}\left[\theta^C+r-k^-+\frac{\overline{P}^C}{b}\right]+\frac{1}{2}\left[1-b\frac{dk^-}{d\overline{P}^C}\right]k^->0\ \ \forall\ \ \theta^C\geq\widehat{\theta}_1^C.$$

From Proposition 7, K is increasing in $\overline{P}^C$. Thus, (53) implies that $\widetilde{K} \leq K' < K^*$ under CPM-PE.

Step 5: The CPMs result in less underinvestment compared to the setting with no CPM.

Denote $\underline{K}$ to be the equilibrium aggregate capacity resulting from the setting with no CPM. Using (6) and (11), the firms' investment incentives imply that $(\overline{P}^E - \gamma)[1 - G^E(\underline{K})] = c$ when $\overline{P}^C = 0$. Using (6) and (11) and Propositions 3 and 7:

$$\frac{d\pi^{+j}}{dk^+}\Big|_{\underline{K}} = \overline{P}^C[1 - G^C(\underline{K} - r)] > 0$$

given $\overline{P}^C > 0$ and $\underline{K} < 1$.[46] Therefore, $K > \underline{K}$ for both $j \in \{PI, PE\}$. □

[46]Using (6) and (11), it is straightforward to show that $K < 1$ holds in any equilibrium given $G^h(1) = 1$ $\forall$ $h \in \{E, C\}$.

Technical Appendix to Accompany "Capacity Payment Mechanisms and Investment Incentives in Restructured Electricity Markets"

First, more detailed derivations of several proofs are provided. Then, extensions of the basic model are considered.

Proof of Lemma 1: Using (1) – (4) and Propositions 1 and 2, firm i's expected profit function:

$$\begin{aligned}
E[\pi^{-PI}] &= \int_0^{k^- - r}\int_0^{k^-} -ck^-\, g^J(\cdot)d\theta^E d\theta^C + \int_0^{k^- - r}\int_{k^-}^1 (\overline{P}^E - \gamma)k^- - ck^-\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k^- - r}^1\int_0^{k^-} \overline{P}^C k^- - ck^-\, g^J(\cdot)d\theta^E d\theta^C + \int_{k^- - r}^1\int_{k^-}^1 (\overline{P}^E - \gamma)k^- + \overline{P}^C k^- - ck^-\, g^J(\cdot)d\theta^E d\theta^C \\
&= \int_0^1\int_{k^-}^1 (\overline{P}^E - \gamma)k^-\, g^J(\cdot)d\theta^E d\theta^C + \int_{k-}^1\int_0^1 \overline{P}^C k^-\, g^J(\cdot)d\theta^E d\theta^C - \int_0^1\int_0^1 ck^-\, g^J(\cdot)d\theta^E d\theta^C \\
&= \int_{k^-}^1 (\overline{P}^E - \gamma)k^-\, dG^E(\theta^E) + \int_{k^- - r}^1 \overline{P}^C k^-\, dG^C(\theta^C) - ck^-;
\end{aligned}$$

$$\begin{aligned}
E[\pi^{=PI}] &= \int_0^{k-r}\int_0^k -ck\, g^J(\cdot)d\theta^E d\theta^C + \int_0^{k-r}\int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} - ck\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_0^{k-r}\int_K^1 (\overline{P}^E - \gamma)k - ck\, g^J(\cdot)d\theta^E d\theta^C + \int_{k-r}^{K-r}\int_0^k \overline{P}^C \frac{1}{2}(\theta^C + r) - ck\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k-r}^{K-r}\int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} + \overline{P}^C \frac{1}{2}(\theta^C + r) - ck\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k-r}^{K-r}\int_K^1 (\overline{P}^E - \gamma)k + \overline{P}^C \frac{1}{2}(\theta^C + r) - ck\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^1\int_0^k \overline{P}^C k - ck\, g^J(\cdot)d\theta^E d\theta^C + \int_{K-r}^1\int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} + \overline{P}^C k - ck\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^1\int_K^1 (\overline{P}^E - \gamma)k + \overline{P}^C k - ck\, g^J(\cdot)d\theta^E d\theta^C \\
&= \int_0^1\int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2}\, g^J(\cdot)d\theta^E d\theta^C + \int_0^1\int_K^1 (\overline{P}^E - \gamma)k\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^1\int_0^1 \overline{P}^C k\, g^J(\cdot)d\theta^E d\theta^C + \int_{k-r}^{K-r}\int_0^1 \overline{P}^C \frac{1}{2}(\theta^C + r)\, g^J(\cdot)d\theta^E d\theta^C - ck \\
&= \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2}\, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma)k\, dG^E(\theta^E) \\
&+ \int_{k-r}^{K-r} \overline{P}^C \frac{1}{2}(\theta^C + r)\, dG^C(\theta^C) + \int_{K-r}^1 \overline{P}^C k\, dG^C(\theta^C) - ck; \text{ and}
\end{aligned}$$

$$E[\pi^{+PI}] = \int_0^{k^- - r}\int_0^{k^-} -ck^+\, g^J(\cdot)d\theta^E d\theta^C + \int_0^{k^- - r}\int_{k^-}^K (\overline{P}^E - \gamma)[\theta^E - k^-] - ck^+\, g^J(\cdot)d\theta^E d\theta^C$$

$$
\begin{aligned}
&+ \int_0^{k^- - r}\int_K^1 (\overline{P}^E-\gamma)k^+ - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k^- - r}^{K-r}\int_0^{k^-} \overline{P}^C[\theta^C + r - k^-] - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k^- - r}^{K-r}\int_{k^-}^{K} (\overline{P}^E-\gamma)[\theta^E - k^-] + \overline{P}^C[\theta^C + r - k^-] - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k^- - r}^{K-r}\int_K^1 (\overline{P}^E-\gamma)k^+ + \overline{P}^C[\theta^C + r - k^-] - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^{1}\int_0^{k^-} \overline{P}^C k^+ - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^{1}\int_{k^-}^{K} (\overline{P}^E-\gamma)[\theta^E - k^-] + \overline{P}^C k^+ - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^{1}\int_K^1 (\overline{P}^E-\gamma)k^+ + \overline{P}^C k^+ - ck^+\, g^J(\cdot)d\theta^E d\theta^C \\
&= \int_0^1\int_{k^-}^{K} (\overline{P}^E-\gamma)[\theta^E - k^-]\, g^J(\cdot)d\theta^E d\theta^C + \int_0^1\int_K^1 (\overline{P}^E-\gamma)k^+\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^{1}\int_0^1 \overline{P}^C k^+\, g^J(\cdot)d\theta^E d\theta^C + \int_{k^- - r}^{K-r}\int_0^1 \overline{P}^C[\theta^C + r - k^-]\, g^J(\cdot)d\theta^E d\theta^C - ck^+ \\
&= \int_{k^-}^{K} (\overline{P}^E-\gamma)[\theta^E - k^-]\, dG^E(\theta^E) + \int_K^1 (\overline{P}^E-\gamma)k^+\, dG^E(\theta^E) \\
&+ \int_{k^- - r}^{K-r} \overline{P}^C[\theta^C + r - k^-]\, dG^C(\theta^C) + \int_{K-r}^{1} \overline{P}^C k^+\, dG^C(\theta^C) - ck^+.
\end{aligned}
$$

□

Proof of Proposition 4: Using (1) - (4), Propositions 1 and 2, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is:

$$
\begin{aligned}
E[CS^{PI}] &= \int_0^{k^- - r}\int_0^{k^-} (v-\gamma)\theta^E\, g^J(\cdot)d\theta^E d\theta^C + \int_0^{k^- - r}\int_{k^-}^{K} (v-\overline{P}^E)\theta^E\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_0^{k^- - r}\int_K^1 (v-\overline{P}^E)K\, g^J(\cdot)d\theta^E d\theta^C + \int_{k^- - r}^{K-r}\int_0^{k^-} (v-\gamma)\theta^E - \overline{P}^C(\theta^C + r)\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k^- - r}^{K-r}\int_{k^-}^{K} (v-\overline{P}^E)\theta^E - \overline{P}^C(\theta^C + r)\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{k^- - r}^{K-r}\int_K^1 (v-\overline{P}^E)K - \overline{P}^C(\theta^C + r)\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^{1}\int_0^{k^-} (v-\gamma)\theta^E - \overline{P}^C K\, g^J(\cdot)d\theta^E d\theta^C + \int_{K-r}^{1}\int_{k^-}^{K} (v-\overline{P}^E)\theta^E - \overline{P}^C K\, g^J(\cdot)d\theta^E d\theta^C \\
&+ \int_{K-r}^{1}\int_K^1 (v-\overline{P}^E)K - \overline{P}^C K\, g^J(\cdot)d\theta^E d\theta^C
\end{aligned}
$$

$$
\begin{aligned}
&= \int_0^1 \int_0^{k^-} (v-\gamma)\theta^E\, g^J(\cdot) d\theta^E d\theta^C + \int_0^1 \int_{k^-}^{K} (v-\overline{P}^E)\theta^E\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_0^1 \int_K^1 (v-\overline{P}^E) K\, g^J(\cdot) d\theta^E d\theta^C - \int_{k^- - r}^{K-r} \int_0^1 \overline{P}^C(\theta^C + r)\, g^J(\cdot) d\theta^E d\theta^C \\
&- \int_{K-r}^1 \int_0^1 \overline{P}^C K\, g^J(\cdot) d\theta^E d\theta^C \\
&= \int_0^{k^-} (v-\gamma)\theta^E\, dG^E(\theta^E) + \int_{k^-}^{K} (v-\overline{P}^E)\theta^E\, dG^E(\theta^E) + \int_K^1 (v-\overline{P}^E) K\, dG^E(\theta^E) \\
&- \int_{k^- - r}^{K-r} \overline{P}^C(\theta^C + r)\, dG^C(\theta^C) - \int_{K-r}^1 \overline{P}^C K\, dG^C(\theta^C). \qquad (54)
\end{aligned}
$$

□

Proof of Lemma 3: Using (1) - (4) and Propositions 1 and 5, firm i's expected profit function is:

$$
\begin{aligned}
E[\pi^{-PE}] &= \int_0^{\widehat{\theta}_1^C} \int_0^{k^-} -ck^-\, g^J(\cdot) d\theta^E d\theta^C + \int_0^{\widehat{\theta}_1^C} \int_{k^-}^1 (\overline{P}^E - \gamma)k^- - ck^-\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^{k^-} p_+^{c\,*} k^- - ck^-\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_2^C}^1 \int_0^{k^-} \overline{P}^C k^- - ck^-\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_{k^-}^1 (\overline{P}^E - \gamma)k^- + p_+^{c\,*} k^- - ck^-\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^1 \int_{k^-}^1 (\overline{P}^E - \gamma)k^- + \overline{P}^C k^- - ck^-\, g^J(\cdot) d\theta^E d\theta^C \\
&= \int_0^1 \int_{k^-}^1 (\overline{P}^E - \gamma)k^-\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^1 p_+^{c\,*} k^-\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^1 \int_0^1 \overline{P}^C k^-\, g^J(\cdot) d\theta^E d\theta^C - ck^- \\
&= \int_{k^-}^1 (\overline{P}^E - \gamma)k^-\, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} k^-\, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^1 \overline{P}^C k^-\, dG^C(\theta^C) - ck^-;
\end{aligned}
$$

$$
\begin{aligned}
E[\pi^{=PE}] &= \int_0^{\widehat{\theta}_1^C} \int_0^{k} -ck\, g^J(\cdot) d\theta^E d\theta^C + \int_0^{\widehat{\theta}_1^C} \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_0^{\widehat{\theta}_1^C} \int_K^1 (\overline{P}^E - \gamma)k - ck\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^k p_+^{c\,*}\frac{1}{2}\widetilde{D}(\cdot) - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} + p_+^{c\,*}\frac{1}{2}\widetilde{D}(\cdot) - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_K^1 (\overline{P}^E - \gamma)k + p_+^{c\,*}\frac{1}{2}\widetilde{D}(\cdot) - ck\, g^J(\cdot) d\theta^E d\theta^C
\end{aligned}
$$

$$
\begin{aligned}
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_0^k \overline{P}^C \frac{1}{2}(\theta^C + r) - ck\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} + \overline{P}^C \frac{1}{2}(\theta^C + r) \\
&- ck\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} + \overline{P}^C \frac{1}{2}(\theta^C + r) - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_K^1 (\overline{P}^E - \gamma)k + \overline{P}^C \frac{1}{2}(\theta^C + r) - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_3^C}^1 \int_0^k \overline{P}^C k - ck\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_3^C}^1 \int_k^K (\overline{P}^E - \gamma)\frac{\theta^E}{2} + \overline{P}^C k - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_3^C}^1 \int_K^1 (\overline{P}^E - \gamma)k + \overline{P}^C k - ck\, g^J(\cdot) d\theta^E d\theta^C \\
&= (\overline{P}^E - \gamma)\left(\int_0^1 \int_k^K \frac{\theta^E}{2}\, g^J(\cdot) d\theta^E d\theta^C + \int_0^1 \int_K^1 k\, g^J(\cdot) d\theta^E d\theta^C\right) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^1 p_+^{c\,*} \times \\
&\quad \frac{\widetilde{D}(\cdot)}{2}\, g^J(\cdot) d\theta^E d\theta^C + \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_0^1 \frac{1}{2}(\theta^C + r)\, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_3^C}^1 \int_0^1 k\, g^J(\cdot) d\theta^E d\theta^C\right) - ck \\
&= (\overline{P}^E - \gamma)\left(\int_k^K \frac{\theta^E}{2}\, dG^E(\theta^E) + \int_K^1 k\, dG^E(\theta^E)\right) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} \frac{1}{2} \widetilde{D}(\cdot)\, dG^C(\theta^C) \\
&+ \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \frac{1}{2}(\theta^C + r)\, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^1 k\, dG^C(\theta^C)\right) - ck; \text{ and}
\end{aligned}
$$

$$
\begin{aligned}
E[\pi^{+PE}] &= \int_0^{\widehat{\theta}_1^C} \int_0^{k^-} -ck^+\, g^J(\cdot) d\theta^E d\theta^C + \int_0^{\widehat{\theta}_1^C} \int_{k^-}^K (\overline{P}^E - \gamma)[\theta^E - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_0^{\widehat{\theta}_1^C} \int_K^1 (\overline{P}^E - \gamma)k^+ - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^{k^-} p_+^{C*}[\widetilde{D}(\cdot) - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_{k^-}^K (\overline{P}^E - \gamma)[\theta^E - k^-] + p_+^{C*}[\widetilde{D}(\cdot) - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_K^1 (\overline{P}^E - \gamma)k^+ + p_+^{C*}[\widetilde{D}(\cdot) - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_0^{k^-} \overline{P}^C[\theta^C + r - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_{k^-}^K (\overline{P}^E - \gamma)[\theta^E - k^-] + \overline{P}^C[\theta^C + r - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_K^1 (\overline{P}^E - \gamma)k^+ + \overline{P}^C[\theta^C + r - k^-] - ck^+\, g^J(\cdot) d\theta^E d\theta^C
\end{aligned}
$$

$$
\begin{aligned}
&+ \int_{\widehat{\theta}_3^C}^1 \int_0^{k^-} (\overline{P}^C - c)k^+ \, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_3^C}^1 \int_{k^-}^K (\overline{P}^E - \gamma)[\theta^E - k^-] + (\overline{P}^C - c)k^+ \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_3^C}^1 \int_K^1 (\overline{P}^E - \gamma)k^+ + \overline{P}^C k^+ - ck^+ \, g^J(\cdot) d\theta^E d\theta^C \\
&= (\overline{P}^E - \gamma) \left(\int_0^1 \int_{k^-}^K [\theta^E - k^-] \, g^J(\cdot) d\theta^E d\theta^C + \int_0^1 \int_K^1 k^+ \, g^J(\cdot) d\theta^E d\theta^C \right) \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^1 p_+^{c\,*} [\widetilde{D}(\cdot) - k^-] \, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_0^1 \overline{P}^C [\theta^C + r - k^-] \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_3^C}^1 \int_0^1 \overline{P}^C k^+ \, g^J(\cdot) d\theta^E d\theta^C - ck^+ \\
&= (\overline{P}^E - \gamma) \left(\int_{k^-}^K [\theta^E - k^-] \, dG^E(\theta^E) + \int_K^1 k^+ \, dG^E(\theta^E) \right) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} [\widetilde{D}(\cdot) - k^-] \, dG^C(\theta^C) \\
&+ \overline{P}^C \left(\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} [\theta^C + r - k^-] \, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^1 k^+ \, dG^C(\theta^C) \right) - ck^+.
\end{aligned}
$$

□

Proof of Proposition 8: Using (1) - (4), Propositions 1 and 5, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is:

$$
\begin{aligned}
E[CS^{PE}] &= \int_0^{\widehat{\theta}_1^C} \int_0^{k^-} (v - \gamma)\theta^E \, g^J(\cdot) d\theta^E d\theta^C + \int_0^{\widehat{\theta}_1^C} \int_{k^-}^K (v - \overline{P}^E)\theta^E \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_0^{\widehat{\theta}_1^C} \int_K^1 (v - \overline{P}^E) K \, g^J(\cdot) d\theta^E d\theta^C + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^{k^-} (v - \gamma)\theta^E - p_+^{c\,*} \widetilde{D}(\cdot) \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_{k^-}^K (v - \overline{P}^E)\theta^E - p_+^{c\,*} \widetilde{D}(\cdot) \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_K^1 (v - \overline{P}^E) K - p_+^{c\,*} \widetilde{D}(\cdot) \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_0^{k^-} (v - \gamma)\theta^E - \overline{P}^C (\theta^C + r) \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_{k^-}^K (v - \overline{P}^E)\theta^E - \overline{P}^C (\theta^C + r) \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_K^1 (v - \overline{P}^E) K - \overline{P}^C (\theta^C + r) \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widetilde{\theta}_3^C}^1 \int_0^{k^-} (v - \gamma)\theta^E - \overline{P}^C K \, g^J(\cdot) d\theta^E d\theta^C + \int_{\widetilde{\theta}_3^C}^1 \int_{k^-}^K (v - \overline{P}^E)\theta^E - \overline{P}^C K \, g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_{\widetilde{\theta}_3^C}^1 \int_K^1 (v - \overline{P}^E) K - \overline{P}^C K \, g^J(\cdot) d\theta^E d\theta^C
\end{aligned}
$$

$$
\begin{aligned}
&= \int_0^1 \int_0^{k^-} (v-\gamma)\theta^E g^J(\cdot) d\theta^E d\theta^C + \int_0^1 \int_{k^-}^{K} (v-\overline{P}^E)\theta^E g^J(\cdot) d\theta^E d\theta^C \\
&+ \int_0^1 \int_K^1 (v-\overline{P}^E) K g^J(\cdot) d\theta^E d\theta^C - \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \int_0^1 p_+^{C*} \widetilde{D}(\cdot) g^J(\cdot) d\theta^E d\theta^C \\
&- \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \int_0^1 \overline{P}^C (\theta^C + r) g^J(\cdot) d\theta^E d\theta^C - \int_{\widehat{\theta}_3^C}^{1} \int_0^1 \overline{P}^C K g^J(\cdot) d\theta^E d\theta^C \\
&= \int_0^{k^-} (v-\gamma)\theta^E dG^E(\theta^E) + \int_{k^-}^{K} (v-\overline{P}^E)\theta^E dG^E(\theta^E) + \int_K^1 (v-\overline{P}^E) K \, dG^E(\theta^E) \\
&- \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} \widetilde{D}(\cdot) \, dG^C(\theta^C) - \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) - \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C K \, dG^C(\theta^C). \qquad (55)
\end{aligned}
$$

□

Continuation Equilibria Extension

If $\theta^E \in (k^+, K]$ or $\theta^C > k^- - r$ there exists the potential for multiple equilibria to arise where firm i is the marginal bidder, while firm j bids sufficiently low to ensure that undercutting is unprofitable $\forall \ i, j = 1, 2$ with $i \neq j$. In the basic model under both CPMs, it was assumed that the large firm is the marginal bidder. In this section, I relax this assumption by considering all continuation equilibria.

CPM with Price-Inelastic Demand

The bidding behavior in the energy and capacity auctions are analogous to that specified in Propositions 1 and 2. For the demand regions $\theta^E \in (k^+, K]$ and $\theta^C \in (k^+ - r, K - r]$ firm i is the marginal bidder with probability ρ_i^j in auction $\forall \ i = 1, 2$ where $\rho_1^j + \rho_2^j = 1 \ \forall j \in \{E, C\}$.

Conclusion 1. Firm i's expected profit under CPM-PI:

$$
\pi_i^{PI}(k_i, k_h) = \begin{cases} \pi_i^{-PI} & \text{if } k_i = k^- \leq k_h = k^+, \text{ and} \\ \pi_i^{+PI} & \text{if } k_i = k^+ > k_h = k^- \end{cases} \qquad (56)
$$

where

$$
\begin{aligned}
\pi_i^{-PI} &= \int_{k^-}^{k^+} (\overline{P}^E - \gamma) k^- \, dG^E(\theta^E) + \int_{k^+}^{K} (\overline{P}^E - \gamma) \left[\rho_i^E(\theta^E - k^+) + (1-\rho_i^E) k^-\right] dG^E(\theta^E) \\
&+ \int_K^1 (\overline{P}^E - \gamma) k^- \, dG^E(\theta^E) + \int_{k^- - r}^{K-r} \overline{P}^C \left[\rho_i^C(\theta^C + r - k^+) + (1-\rho_i^C) k^-\right] dG^C(\theta^C) \\
&+ \int_{K-r}^{1} \overline{P}^C k^- \, dG^C(\theta^C) - c k^-, \text{ and} \\
\pi_i^{+PI} &= \int_{k^-}^{k^+} (\overline{P}^E - \gamma) [\theta^E - k^-] \, dG^E(\theta^E) + \int_{k^+}^{K} (\overline{P}^E - \gamma) \left[\rho_i^E(\theta^E - k^-) + (1-\rho_i^E) k^+\right] dG^E(\theta^E) \\
&+ \int_K^1 (\overline{P}^E - \gamma) k^+ \, dG^E(\theta^E) + \int_{k^- - r}^{k^+ - r} \overline{P}^C (\theta^C + r - k^-) \, dG^C(\theta^C)
\end{aligned}
$$

$$+\int_{k^+-r}^{K-r} \overline{P}^C \left[\rho_i^C(\theta^C + r - k^-) + (1-\rho_i^C)k^+\right] dG^C(\theta^C) + \int_{K-r}^{1} \overline{P}^C k^+ \, dG^C(\theta^C) - ck^+.$$

Proof. Using (1) – (4) and Propositions 1 and 2, a full derivation of firm i's expected profit function is analogous to that in the Proof of Lemma 1. □

Conclusion 2 details the firms' investment incentives in the current setting.

Conclusion 2. The equilibrium capacity levels (k^-, k^+) exists and satisfy:

$$\begin{aligned}&(\overline{P}^E - \gamma)[1 - G^E(K)] + (1-\rho_i^E)(\overline{P}^E - \gamma)[G^E(K) - G^E(k^+) - k^- g^E(k^+)] \\ &+\overline{P}^C[1 - G^C(K)] + (1-\rho_i^C)\overline{P}^C[G^C(K) - G^C(k^+) - k^- g^C(k^+)] = c, \text{ and}\end{aligned} \tag{57}$$

$$\begin{aligned}&(\overline{P}^E - \gamma)[1 - G^E(K) + G^E(k^+) - G^E(k^-) - k^- g^E(k^-)] \\ +\;& (1-\rho_i^E)(\overline{P}^E - \gamma)[G^E(K) - G^E(k^+)] + \overline{P}^C[1 - G^C(K) + g^C(k^+) \\ -\;& G^C(k^-) - k^- g^C(k^-)]_+ (1-\rho_i^C)\overline{P}^C[G^C(K) - G^C(k^+)] = c.\end{aligned} \tag{58}$$

Proof. Using Theorem 1 in Fabra et al. (2011), an asymmetric PSNE in capacity choices (and no symmetric NE) exist and entail the solution to the firms' first-order conditions if (i) the game is submodular; (ii) $\lim_{k^+ \downarrow k} \frac{d\pi_i^{+PI}}{dk^+} > \lim_{k^- \uparrow k} \frac{d\pi_i^{-PI}}{dk^-}$; and (iii) $\frac{d\pi_i^{+PI}(0,0)}{dk^+} > 0$ and $\frac{d\pi_i^{-PI}(1,1)}{dk^-} < 0$.

Using (56), it is straightforward to show that $\lim_{k^+ \downarrow k} \pi_i^{+PI} = \lim_{k^- \uparrow k} \pi_i^{-PI}$ such that the profit function is continuous in the capacity choice. Further, using (56), because $\overline{P}^E > \gamma$:

$$\lim_{k^+ \downarrow k} \frac{d\pi_i^{+PI}}{dk^+} - \lim_{k^- \uparrow k} \frac{d\pi_i^{-PI}}{dk^-} = \rho_i^E(\overline{P}^E - \gamma)kg^E(k) + \rho_i^C \overline{P}^C K g^C(K) > 0. \tag{59}$$

(59) implies that there is a kink in the profit function at the symmetric capacity limit. This implies that the best-reply functions do not cross the diagonal, i.e., there is a discontinuous jump in the best-reply functions. Thus, no symmetric equilibrium in pure strategies exists. In addition, using (56), it is straightforward to show that $\frac{d\pi_i^{+PI}(0,0)}{dk^+} = \overline{P}^E - \gamma + \overline{P}^C - c > 0$ and $\frac{d\pi_i^{-PI}(1,1)}{dk^-} = -(1-\rho_i^E)(\overline{P}^E - \gamma)g^E(1) - (1-\rho_i^C)\overline{P}^C g^C(1) - c < 0$. Lastly, if $\theta^j g^j(\theta^j) \; \forall \; j \in \{E, C\}$ is increasing, then the game is submodular (for more details see the proof of Propositon 3 in Fabra et al. (2011) and Proposition 4 in de Frutos and Fabra (2011)). This implies that the asymmetric equilibrium exists and satisfied the firms' first-order conditions. □

Condition (57) and (58) reflect the both the large and small firms' profit maximizing capacity decision, respectively.

Conclusion 3 details the expected aggregate welfare in the current environment.

Conclusion 3. Aggregate expected welfare:

$$E[W^{PI}] \;=\; \alpha \left[\int_0^{k^-} (v-\gamma)\theta^E \, dG^E(\theta^E) + \int_{k^-}^{K} (v - \overline{P}^E)\theta^E \, dG^E(\theta^E) + \int_K^1 (v - \overline{P}^E)K \, dG^E(\theta^E)\right]$$

$$+ (1-\alpha)\left[\int_{k^-}^{K} (\overline{P}^E - \gamma)\theta^E \, dG^E(\theta)^E + \int_{K}^{1} (\overline{P}^E - \gamma) K \, dG^E(\theta^E) - cK\right]$$
$$- (2\alpha - 1)\left[\int_{k^- - r}^{K-r} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) + \int_{K-r}^{1} \overline{P}^C K \, dG^C(\theta)^C)\right]. \tag{60}$$

Proof. Using (1) - (4), Propositions 1 and 2, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is analogous to that in (16). Using (2), (16), and (56), (60) follows directly. □

Under CPM-PI, the regulator chooses the capacity demand parameters $(\overline{P}^C, r)$ to maximize expected welfare anticipating how the firms will respond in their subsequent capacity investment decisions and the bidding behavior in the energy and capacity auctions. The optimal capacity payment parameters under CPM-PI follow analogously to those detailed in Proposition 4.

CPM with Price-Elastic Demand

Next, under CPM-PE I relax the assumption that the large firm is the marginal bidder if $\theta^E \in (k^+, K]$ or if $\theta^C > k^- - r$ with certainty. For a subset of the demand realizations, there exists multiple PSNE where either the small or large firm can be the marginal bidder. Consider the continuation equilibria where if there are multiple equilibria in a demand region, firm i is the marginal bidder with probability ρ_i^j $\forall\ i = 1, 2$ in auction $j \in \{E, C\}$.

The bidding behavior in the electricity procurement auction is analogous to that specified in Proposition 1. However, by allowing the small firm to be the marginal bidder, the capacity auction bidding behavior differs from that specified in Proposition 5. The following conclusions will play an important role in characterizing the bidding behavior in the capacity auction under CPM-PE.

Conclusion 4. Suppose Assumption 1 holds. Then, ${p_+^c}^* > {p_-^c}^*$ where
$$p_j^{c*} = \max_{p^c} p^c \left[\widetilde{D}(p^c, \theta^C; \cdot) - k^i\right] \quad \forall\ i, j \in \{-, +\} \text{ with } i \neq j. \tag{61}$$

Proof. Using Assumption 1 and (61):

$${p_+^c}^* = \frac{b}{2}\left[\frac{\overline{P}^C}{b} + \theta^C + r - k^-\right] > {p_-^c}^* = \frac{b}{2}\left[\frac{\overline{P}^C}{b} + \theta^C + r - k^+\right] \Leftrightarrow\ k^+ - k^- > 0. \ \square \tag{62}$$

Conclusion 5. Suppose Assumption 1 holds. Then, there exists a $\widehat{\theta}_2^C \in (0, 1)$ such that:

$${p_-^c}^* k^+ \gtreqless {p_+^c}^*[\widetilde{D}({p_+^c}^*, \theta^C; \cdot) - k^-] \quad \text{as} \quad \theta^C \gtreqless \widehat{\theta}_2^C. \tag{63}$$

Proof. Using Assumption 1 and Conclusion 4:

$$M(\theta^C) = {p_-^c}^* k^+ - {p_+^c}^*[\widetilde{D}({p_+^c}^*, \theta^C; \cdot) - k^-]$$

$$= \frac{b}{2}\left[\frac{\overline{P}^C}{b} + \theta^C + r - k^+\right]k^+ - \frac{1}{2}\left[\frac{\overline{P}^C}{b} + \theta^C + r - k^-\right]\left[\frac{\overline{P}^C}{b} - (\theta^C + r - k^-)\right] \tag{64}$$

Using (64), because $k^+ > k^-$:

$$M'(\theta^C) = k^+ + \frac{1}{2}\left[\frac{\overline{P}^C}{b} + \theta^C + r - k^- - \frac{\overline{P}^C}{b} + \theta^C + r - k^-\right] = k^+ - k^- + \theta^C + r > 0.$$

This implies that $M(\theta^C)$ is monotonically increasing in θ^C. Therefore, there exists a $\widehat{\theta}_2^C$ where $M(\widehat{\theta}_2^C) = 0$. This implies that $M(\theta^C) \gtreqless 0$ as $\theta^C \gtreqless \widehat{\theta}_2^C$. □

Conclusion 5 reveals that the large firm will only remain as the infra-marginal bidder ($b_+^C < b_-^C$) if $\theta^C \geq \widehat{\theta}_2^C$. Otherwise, it is profitable for the large firm to unilaterally deviate to set the market clearing price $b_+^{C\prime} = p_+^{c\,*} > p_-^{c\,*}$.

Conclusion 6. Suppose Assumption 1 holds. There exists $\widehat{\theta}_1^C < \widehat{\theta}_2^C < \widehat{\theta}_3^C < \widehat{\theta}_4^C$ where:

$$\widehat{\theta}_1^C \;:\; \widetilde{D}(p^c = 0, \widehat{\theta}_1^C; \cdot) = k^-; \tag{65}$$

$$\widehat{\theta}_2^C \;:\; p_-^{c\,*}(\widehat{\theta}_2^C)k^+ = p_+^{c\,*}(\widehat{\theta}_2^C)[\widetilde{D}(p_+^{c\,*}, \widehat{\theta}_2^C; \cdot) - k^-]; \tag{66}$$

$$\widehat{\theta}_3^C \;:\; p_+^{c\,*}(\widehat{\theta}_3^C) = \overline{P}^C; \text{ and} \tag{67}$$

$$\widehat{\theta}_4^C \;:\; p_+^{c\,*}(\widehat{\theta}_4^C) = \overline{P}^C. \tag{68}$$

Proof. Using Assumption 1, Conclusion 4, (1) and (21), $\widehat{\theta}_1^C = k^- - r - \frac{\overline{P}^C}{b}$. Using (64):

$$M(\widehat{\theta}_1^C) = \frac{b}{2}\left[k^- - k^+\right]k^+ - 0 = \frac{b}{2}\left[k^- - k^+\right]k^+ < 0.$$

From Conclusion 5, because $M'(\theta^C) > 0$, $M(\widehat{\theta}_1^C) < 0$, and $M(\widehat{\theta}_2^C) = 0$, then $\widehat{\theta}_1^C < \widehat{\theta}_2^C$.

Using Assumption 1, Conclusion 4, (1):

$$\widehat{\theta}_3^C = k^- - r + \frac{\overline{P}^C}{b} \tag{69}$$

$$\widehat{\theta}_4^C = k^+ - r + \frac{\overline{P}^C}{b} \tag{70}$$

Using (69) and (70), it is straightforward to show that $\widehat{\theta}_3^C < \widehat{\theta}_4^C$. □

Conclusion 7. Suppose Assumption 1 holds. If the large firm is the marginal bidder bidding $b_+^C = \min\{\overline{P}^C, p_+^{c\,*}\}$, the small firm has no incentive to unilaterally deviate from bidding sufficiently low to ensure that its entire capacity is procured.

Proof. Suppose Assumption 1 holds and there is a bid profile in the capacity auction where $b_+^C = \min\{\overline{P}^C, p_+^{c\,*}\} > b_-^C$. Suppose the small firm unilaterally deviates to $b_-^{C\prime} = \min\{\max\{p_-^{c\,*}, b_+^c + \epsilon\}\}, \overline{P}^C\}$ for some $\epsilon > 0$. From Conclusion 4, $p_+^{c\,*} > p_-^{c\,*}$ such that $b_-^{C\prime} = \min\{b_+^c + \epsilon, \overline{P}^C\}$. As $\epsilon \to 0$, the change in the small firm's payoff from the capacity auction is:

$$\Delta\pi^C_- = b^{C\prime}_-[\widetilde{D}(b^{C\prime}_-, \theta^C; \cdot) - k^+] - b^C_+ k^-. \tag{71}$$

Using Assumption 1 and (1), if $b^C_+ = \overline{P}^C$, then $b^{C\prime}_- = \overline{P}^C$ and $\widetilde{D}(b^{C\prime}_-, \theta^C; \cdot) = \theta^C + r$. Hence, for any $\theta^C \leq K - r$, $\Delta\pi^C_- \leq 0$. Similarly, if $b^C_+ = p^c_+{}^*$, then $b^{C\prime}_- = p^c_+{}^* - \epsilon$. As $\epsilon \to 0$, for any $\theta^C \leq K - r$ the reduction in output dominates the price benefit such that $\Delta\pi^C_- \leq 0$. □

The following conclusion characterizes the equilibrium bidding behavior in the capacity auction when the multiplicity of PSNE are taken into account.

Conclusion 8. Equilibrium bidding behavior in the capacity auction with price-elastic demand:

1. If $\theta^C \leq \widehat{\theta}^C_1$, then the unique PSNE entails both firms bidding at zero and earning a payoff of zero.
2. If $\widehat{\theta}^C_1 < \theta^C \leq \widehat{\theta}^C_2$, then the PSNE entails the large firm bidding at $p^c_+{}^*$ and serving residual demand $D(p^c_+{}^*, \theta^C; \cdot) - k^-$, while the small firm procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable.
3. If $\widehat{\theta}^C_2 < \theta^C \leq \widehat{\theta}^C_3$, then there are multiple PSNE where $b^C_i = p^{c*}_i$, while the firm j procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j \in \{-, +\}$ with $i \neq j$.
4. If $\widehat{\theta}^C_3 < \theta^C \leq \widehat{\theta}^C_4$, then there are multiple PSNE where $b^C_i = \min\{\overline{P}^C, p^{c*}_i\}$, while the firm j procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j \in \{-, +\}$ with $i \neq j$.
5. If $\widehat{\theta}^C_4 < \theta^C \leq K - r$, then there are multiple PSNE where $b^C_i = \overline{P}^C$, while the firm j procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j \in \{-, +\}$ with $i \neq j$.
6. If $\theta^C > K - r$, then there are two PSNE where a firm i bids at $\overline{P}^C$, firm h bids sufficiently low such that undercutting is unprofitable, and both firms procure their entire capacities with $i, h = 1, 2$ and $i \neq h$.

Proof. For $\theta^C \in [0, \widehat{\theta}^C_1]$ or $\theta^C \in [K - r, 1]$, the findings follow directly from Proposition 1 in Fabra et al. (2006). Suppose $\theta^C \in (\widehat{\theta}^C_1, \widehat{\theta}^C_2]$ and $b^C_+ = p^c_+{}^*$, while the small firm bids sufficiently low such that a unilateral deviation by the marginal bidder is unprofitable. From Conclusion 7, the inframarginal bidder has no incentive to unilaterally deviate to become the marginal bidder. Further, from Conclusion 5 the small firm will never be the marginal bidder in this demand region as the large firm always has an incentive to unilaterally deviate to set the equilibrium price.

Suppose $\theta^C \in [\widehat{\theta}^C_2, K - r]$ and $b^C_i = \min\{\overline{P}^C, p^{c*}_i\}$, while the firm j procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable. Thus, the marginal bidder has no incentive to unilaterally deviate to undercut the inframarginal bidder. From Conclusion 5, if $i = -$ and $j = +$, because $\theta^C > \widehat{\theta}^C_2$ the large firm has no incentive to unilaterally deviate to become the marginal bidder. From Conclusion 7, if $i = +$ and $j = -$, the small firm has no incentive to unilaterally deviate to become the marginal bidder. □

For the demand regions $\theta^E \in (k^+, K]$ and $\theta^C \in (\widehat{\theta}^C_2, K - r]$ firm i is the marginal bidder with probability ρ^j_i in auction j $\forall\ i = 1, 2$ where $\rho^j_1 + \rho^j_2 = 1\ \forall j \in \{E, C\}$.

Conclusion 9. Firm i's expected profit under CPM-PE:

$$\pi_i^{PE}(k_i, k_h) = \begin{cases} \pi_i^{-PE} & \text{if } k_i = k^- \leq k_h = k^+, \text{ and} \\ \pi_i^{+PE} & \text{if } k_i = k^+ > k_h = k^- \end{cases} \tag{72}$$

where

$$\begin{aligned}
\pi_i^{-PE} \;=\;& \int_{k^-}^{k^+} (\overline{P}^E - \gamma)k^- \, dG^E(\theta^E) + \int_{k^+}^{K} (\overline{P}^E - \gamma)\left[\rho_i^E(\theta^E - k^+) + (1-\rho_i^E)k^-\right] dG^E(\theta^E) \\
+\;& \int_{K}^{1} (\overline{P}^E - \gamma)k^- \, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} k^- \, dG^C(\theta^C) \\
+\;& \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} p_+^{c\,*}(1-\rho_i^C)k^- + p_-^{c\,*}\rho_i^C[\widetilde{D}(\cdot) - k^+] \, dG^C(\theta^C) \\
+\;& \int_{\widehat{\theta}_3^C}^{\widehat{\theta}_4^C} \overline{P}^C(1-\rho_i^C)k^- + p_-^{c\,*}\rho_i^C[\widetilde{D}(\cdot) - k^+] \, dG^C(\theta^C) \\
+\;& \int_{\widehat{\theta}_4^C}^{K-r} \overline{P}^C \left[\rho_i^C(\theta^C + r - k^+) + (1-\rho_i^C)k^-\right] dG^C(\theta^C) \\
+\;& \int_{K-r}^{1} \overline{P}^C k^- \, dG^C(\theta^C) - ck^-, \text{ and} \\
\pi_i^{+PE} \;=\;& \int_{k^-}^{k^+} (\overline{P}^E - \gamma)[\theta^E - k^-] \, dG^E(\theta^E) + \int_{k^+}^{K} (\overline{P}^E - \gamma)\left[\rho_i^E(\theta^E - k^-) + (1-\rho_i^E)k^+\right] dG^E(\theta^E) \\
+\;& \int_{K}^{1} (\overline{P}^E - \gamma)k^+ \, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*}[\widetilde{D}(\cdot) - k^-] \, dG^C(\theta^C) \\
+\;& \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} p_+^{c\,*}\rho_i^C[\widetilde{D}(\cdot) - k^-]p_-^{c\,*}(1-\rho_i^C)k^- \, dG^C(\theta^C) \\
+\;& \int_{\widehat{\theta}_3^C}^{\widehat{\theta}_4^C} \overline{P}^C\rho_i^C[\theta^C + r - k^-]p_-^{c\,*}(1-\rho_i^C)k^+ \, dG^C(\theta^C) \\
+\;& \int_{\widehat{\theta}_4^C}^{K-r} \overline{P}^C \left[\rho_i^C(\theta^C + r - k^-) + (1-\rho_i^C)k^+\right] dG^C(\theta^C) \\
+\;& \int_{K-r}^{1} \overline{P}^C k^+ \, dG^C(\theta^C) - ck^+.
\end{aligned}$$

Proof. Using (1) – (4) and Proposition 1 and Conclusion 8, a full derivation of firm i's expected profit function is analogous to that in the Proof of Lemma 3. □

Conclusion 10 details the firms' investment incentives in the current setting.

Conclusion 10. The equilibrium capacity levels (k^-, k^+) exists and satisfy:

$$(\overline{P}^E - \gamma)[1 - G^E(K)] + (1-\rho_i^E)(\overline{P}^E - \gamma)[G^E(K) - G^E(k^+) - k^- g^E(k^+)] + \overline{P}^C[1 - G^C(K)]$$

$$+ (1-\rho_i^C)\left[\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_4^C} p_-^{c\,*} + \frac{dp_-^{c\,*}}{dk^+}k^+\, dG^C(\theta^C) + \int_{\widehat{\theta}_4^C}^{K-r} \overline{P}^C\, dG^C(\theta^C)\right] = c, \text{ and} \tag{73}$$

$$\begin{aligned} &(\overline{P}^E - \gamma)[1 - G^E(K) + G^E(k^+) - G^E(k^-) - k^- g^E(k^-)] + (1-\rho_i^E)(\overline{P}^E - \gamma)[G^E(K) - G^E(k^+)] \\ + \; & \overline{P}^C[1 - G^C(K)] + (1-\rho_i^C)\overline{P}^C\left[G^C(K-r) - G^C(\widehat{\theta}_3^C)\right] + (1-\rho_i^C)\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} p_+^{c\,*} + \frac{dp_+^{c\,*}}{dk^-}k^-\, dG^C(\theta^C) \\ + \; & \frac{d\widehat{\theta}_2^C}{dk^-}\rho_i^C\left[p_+^{c\,*}(\widehat{\theta}_2^C)k^- - p_-^{c\,*}(\widehat{\theta}_2^C)[\widetilde{D}(p_-^{c\,*}, \widehat{\theta}_2^C; \cdot)]\right] = c. \end{aligned} \tag{74}$$

Proof. Using Theorem 1 in Fabra et al. (2011), an asymmetric PSNE in capacity choices (and no symmetric NE) exist and entail the solution to the firms' first-order conditions if (i) the game is submodular; (ii) $\lim_{k^+\downarrow k} \frac{d\pi_i^{+PI}}{dk^+} > \lim_{k^-\uparrow k} \frac{d\pi_i^{-PI}}{dk^-}$; and (iii) $\frac{d\pi_i^{+PI}(0,0)}{dk^+} > 0$ and $\frac{d\pi_i^{-PI}(1,1)}{dk^-} < 0$.

Using (61), (64) - (68), the following conditions follow directly:

$$\lim_{k^-\uparrow k} p_-^{c\,*} = \lim_{k^+\downarrow k} p_+^{c\,*} \tag{75}$$

$$\lim_{k^-\uparrow k}\lim_{k^+\downarrow k} \widehat{\theta}_2^C = \lim_{k^-\uparrow k} \widehat{\theta}_1^C \tag{76}$$

$$\lim_{k^-\uparrow k} \widehat{\theta}_3^C = \lim_{k^+\downarrow k} \widehat{\theta}_4^C \tag{77}$$

Using (72) and (75) – (77), it is straightforward to show that $\lim_{k^+\downarrow k} \pi_i^{+PE} = \lim_{k^-\uparrow k} \pi_i^{-PE}$ such that the profit function is continuous in the capacity choice. Further, using (61), (64) - (68), (75) – (77), that $p_+^{C*}(\widehat{\theta}_1^C) = 0$, $M(\widehat{\theta}_2^C) = 0$ defined in (64), and (72), because $\overline{P}^E > \gamma$:

$$\lim_{k^+\downarrow k}\lim_{k^-\uparrow k} \frac{d\pi_i^{+PI}}{dk^+} - \frac{d\pi_i^{-PI}}{dk^-} = \rho_i^E(\overline{P}^E - \gamma)kg^E(k) > 0. \tag{78}$$

(78) implies that there is a kink in the profit function at the symmetric capacity limit. This implies that the best-reply functions do not cross the diagonal, i.e., there is a discontinuous jump in the best-reply functions. Thus, no symmetric equilibrium in pure strategies exists. In addition, using (72) and that $p_+^{C*}(\widehat{\theta}_1^C) = 0$, it is straightforward to show that $\frac{d\pi_i^{+PI}(0,0)}{dk^+} = \overline{P}^E - \gamma + \overline{P}^C - c > 0$ and $\frac{d\pi_i^{-PI}(1,1)}{dk^-} = -(\overline{P}^E - \gamma)g^E(1) - c < 0$. Lastly, if $\theta^j g^j(\theta^j)\ \forall\ j \in \{E, C\}$ is increasing, then the game is submodular (for more details see the proof of Propositon 3 in Fabra et al. (2011) and Proposition 4 in de Frutos and Fabra (2011)). This implies that the asymmetric equilibrium exists and satisfied the firms' first-order conditions. □

Condition (73) and (74) reflect the both the large and small firms' profit maximizing capacity decision, respectively.

Assume firm 1 is the small firm. Define ρ_1^j to be the probability that firm 1 is the marginal bidder in auction $j \in \{E, C\}$. Conclusion 11 details the expected aggregate welfare in the current environment.

Conclusion 11. Aggregate expected welfare under CPM-PE:

$$E[W^{PE}] = \alpha \left[\int_0^{k^-} (v-\gamma)\theta^E \, dG^E(\theta^E) + \int_{k^-}^{K} (v-\overline{P}^E)\theta^E \, dG^E(\theta^E) + \int_K^1 (v-\overline{P}^E) K \, dG^E(\theta^E) \right]$$
$$+ (1-\alpha) \left[\int_{k^-}^{K} (\overline{P}^E - \gamma)\theta^E \, dG^E(\theta)^E + \int_K^1 (\overline{P}^E - \gamma) K \, dG^E(\theta^E) - cK \right]$$
$$- (2\alpha - 1) \Bigg[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} \widetilde{D}(p_+^{c\,*}, \theta^C; \cdot) \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} (1-\rho_1^C) p_+^{c\,*} \widetilde{D}(p_+^{c\,*}, \theta^C; \cdot)$$
$$+ \rho_1^C p_-^{c\,*} \widetilde{D}(p_-^{c\,*}, \theta^C; \cdot) \, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{\widehat{\theta}_4^C} \rho_1^C p_-^{c\,*} \widetilde{D}(p_-^{c\,*}, \theta^C; \cdot) + (1-\rho_1^C) \overline{P}^C (\theta^C + r) \, dG^C(\theta^C)$$
$$+ \int_{\widehat{\theta}_4^C}^{K-r} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) + \overline{P}^C K [1 - G^C(K-r)] \Bigg]. \tag{79}$$

Proof. Using (1) - (4), Proposition 1 and Conclusion 8, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus equals:[47]

$$E[CS^{PE}] = \int_0^{k^-} (v-\gamma)\theta^E \, dG^E(\theta^E) + \int_{k^-}^{K} (v-\overline{P}^E)\theta^E \, dG^E(\theta^E) + \int_K^1 (v-\overline{P}^E) K \, dG^E(\theta^E)$$
$$- \Bigg[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{c\,*} \widetilde{D}(p_+^{c\,*}, \theta^C; \cdot) \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} (1-\rho_1^C) p_+^{c\,*} \widetilde{D}(p_+^{c\,*}, \theta^C; \cdot)$$
$$+ \rho_1^C p_-^{c\,*} \widetilde{D}(p_-^{c\,*}, \theta^C; \cdot) \, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{\widehat{\theta}_4^C} \rho_1^C p_-^{c\,*} \widetilde{D}(p_-^{c\,*}, \theta^C; \cdot)$$
$$+ (1-\rho_1^C) \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) + \int_{\widehat{\theta}_4^C}^{K-r} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) + \overline{P}^C K [1 - G^C(K-r)] \Bigg]. \tag{80}$$

(79) follows directly from (72) and (80). □

Under CPM-PE, the regulator chooses the capacity demand parameters $(\overline{P}^C, r, b)$ to maximize expected welfare anticipating how the firms will respond in their subsequent capacity investment decisions and the bidding behavior in the energy and capacity auctions. Using (79), the characterization the optimal parameters $(\overline{P}^C, r)$ are analogous to those specified in Proposition 8. However, to show that the findings of the basic model are robust to an environment with multiple equilibria, it will be important to provide conditions under which $b^* \in (0, \infty)$.

Further characterization is difficult for general demand distributions. Therefore, attention is focused on a setting in which capacity and electricity demand is sufficiently high. Suppose $P(\theta^E \leq k^+) = 0$ and $P(\theta^C \leq \widehat{\theta}_2^C) = 0$. This condition ensures that we focus on demand realizations in which no single firm can supply electricity or capacity demand. Because electricity demand reflects the maximum peak demand (and capacity demand reflects a forecast of this maximum peak demand), this assumption is not restrictive in practice.

[47] A full characterization of the consumer surplus in this setting is analogous to (24).

Conclusion 12. Suppose Assumption 1 holds and $P(\theta^E \leq k^+) = P(\theta^C \leq \max\{\widehat{\theta}_2^C, k^- - r\}) = 0$. If $\alpha > \frac{1}{2}$, $P(k^- - r < \theta^C \leq \widehat{\theta}_4^C)$ is sufficiently large, and $P(\theta \leq K - r) = 1$, then $b^* \in (0, \infty)$.

Proof. Suppose Assumption 1 holds, $\alpha > \frac{1}{2}$ and $P(\theta^E \leq k^+) = P(\theta^C \leq \widehat{\theta}_2^C) = 0$. Using (79):

$$\frac{dE[W^{PE}]}{db} = \alpha\left[(v - \overline{P}^E)[1 - G^E(K)] - \overline{P}^C[1 - G^C(K - r)]\right]\frac{dK}{db}$$
$$+(1-\alpha)\left[(\overline{P}^E - \gamma)[1 - G^E(K)] + \overline{P}^C[1 - G^C(K - r)] - c\right]\frac{dK}{db}$$
$$-(2\alpha - 1)\Bigg[\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \rho_1^C\left(\frac{dp_-^{c\,*}\widetilde{D}(p_-^{c\,*}, \theta^C; \cdot)}{db}\right)$$
$$+(1-\rho_1^C)\left(\frac{dp_+^{c\,*}\widetilde{D}(p_+^{c\,*}, \theta^C; \cdot)}{db}\right) dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{\widehat{\theta}_4^C} \rho_1^C\left(\frac{dp_-^{c\,*}\widetilde{D}(p_-^{c\,*}, \theta^C; \cdot)}{db}\right) dG^C(\theta^C)\Bigg]. \tag{81}$$

where using (28), (82) simplifies to:

$$\frac{dE[W^{PE}]}{db} = \alpha\left[(v - \overline{P}^E)[1 - G^E(K)] - \overline{P}^C[1 - G^C(K - r)]\right]\frac{dK}{db}$$
$$+(1-\alpha)\left[(\overline{P}^E - \gamma)[1 - G^E(K)] + \overline{P}^C[1 - G^C(K - r)] - c\right]\frac{dK}{db}$$
$$-(2\alpha - 1)\Bigg[\rho_1^C\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_4^C} \frac{1}{2}(\theta^C + r - k^+)k^+ - \frac{b}{2}k^+\frac{dk^+}{db} - \frac{1}{4}\left(\frac{\overline{P}^C}{b}\right)^2 + \frac{1}{4}(\theta^C + r - k^+)^2\, dG^C(\theta^C)$$
$$+(1-\rho_1^C)\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \frac{1}{2}(\theta^C + r - k^-)k^- - \frac{b}{2}k^-\frac{dk^-}{db} - \frac{1}{4}\left(\frac{\overline{P}^C}{b}\right)^2 + \frac{1}{4}(\theta^C + r - k^-)^2\, dG^C(\theta^C)\Bigg]. \tag{82}$$

It will be necessary to determine the signs of $\frac{dk^-}{db}$ and $\frac{dk^+}{db}$. Using (73) and (74) and that $P(\theta^E \leq k^+) = P(\theta^C \leq \widehat{\theta}_2^C) = 0$ by assumption, comparative statics yields the following system:

$$\begin{bmatrix} A & B \\ D & E \end{bmatrix} \times \begin{bmatrix} \frac{dk^-}{db} \\ \frac{dk^+}{db} \end{bmatrix} = \begin{bmatrix} C \\ F \end{bmatrix} \tag{83}$$

where:

$$A = -\rho_1^E(\overline{P}^E - \gamma)g^E(K) - \rho_1^C\overline{P}^C g^C(K - r) - (1 - \rho_1^C)[G^C(\widehat{\theta}_3^C)b + k^- g^C(\widehat{\theta}_3^C)]; \tag{84}$$

$$B = -\rho_1^E(\overline{P}^E - \gamma)g^E(K) - \rho_1^C\overline{P}^C g^C(K - r); \tag{85}$$

$$C = -(1 - \rho_1^C)\left[\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \frac{1}{2}(\theta^C + r - k^-)k^- dG^C(\theta^C) + \frac{\overline{P}^C}{2b}k^- g^C(\widehat{\theta}_3^C)\right]; \tag{86}$$

$$D = -(1 - \rho_1^E)(\overline{P}^E - \gamma)g^E(K) - (1 - \rho_1^C)\overline{P}^C g^C(K - r); \tag{87}$$

$$E = -(1-\rho_1^E)(\overline{P}^E - \gamma)g^E(K) - (1-\rho_1^C)\overline{P}^C g^C(K-r) - \rho_1^C[bG^C(\widehat{\theta}_4^C) + g^C(\widehat{\theta}_4^C) + bG^C(\widehat{\theta}_4^C)]; \quad (88)$$

$$F = -\rho_1^C \left[\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_4^C} \frac{1}{2}(\theta^C + r - k^+)k^+ dG^C(\theta^C) + \frac{\overline{P}^C}{2b} g^C(\widehat{\theta}_4^C)k^+ \right]. \quad (89)$$

Under the maintained assumptions, A, B, C, D, and E are negative. Using Cramer's Rule:

$$\frac{dk^+}{db} = \frac{AF - CD}{AE - BD} \qquad \frac{dk^-}{db} = \frac{CE - BF}{AE - BD} \quad (90)$$

where using (84) - (87):

$$AE - BD = \left[\rho_1^E(\overline{P}^E - \gamma)g^E(K) + \rho_1^C \overline{P}^C g^C(K-r)\right]\left[2b\rho_1^C G^C(\widehat{\theta}_4^C) + \rho_1^C g^C(\widehat{\theta}_4^C) + \right]$$
$$+(1-\rho_1^C)\left[G^C(\widehat{\theta}_3^C)b + g^C(\widehat{\theta}_3^C)k^-\right]\left[(1-\rho_1^E)(\overline{P}^E - \gamma)g^E(K)\right.$$
$$\left. +(1-\rho_1^C)\overline{P}^C g^C(K-r) + 2b\rho_1^C G^C(\widehat{\theta}_4^C) + \rho_1^C g^C(\widehat{\theta}_4^C)\right] > 0. \quad (91)$$

(90) and (91) implies:

$$\frac{dk^+}{db} \stackrel{s}{=} AF - CD \qquad \frac{dk^-}{db} \stackrel{s}{=} CE - BF. \quad (92)$$

Recall, A, B, C, D, and E are negative. If F is sufficiently positive, then $\frac{dk^-}{db} < 0$ and $\frac{dk^-}{db}?0$. F is sufficiently negative when $P(\widehat{\theta}_2^C \le \theta^C \le \widehat{\theta}_4^C)$ is sufficiently large such that the (negative) integral term in (89) is sufficiently large such that $F > 0$.[48] Further, using (84) – (89), (91) when F is sufficiently positive:

$$\frac{dK}{db} = \frac{dk^+}{db} + \frac{dk^-}{db} = \frac{AF - CD + CE - BF}{AE - BD} \stackrel{s}{=} (A-B)F - C(D-E)$$
$$= -(1-\rho_1^C)F[G^C(\widehat{\theta}_3^C)k^-] - \rho_1^C C[2bG^C(\widehat{\theta}_4^C) + g^C(\widehat{\theta}_4^C)] < 0. \quad (93)$$

It will now be shown that $\lim_{b\to 0} \frac{dE[W^{PE}]}{db} > 0$ and $\lim_{b\to\infty} \frac{dE[W^{PE}]}{db} < 0$ such that $b^* \in (0,\infty)$. Using (61), (64) - (68), and (75) – (77), as $b \to 0$ it is straightforward to show that $\widehat{\theta}_1^C, p_-^{c\,*}$, and $p_+^{c\,*} \to 0$ and $\widehat{\theta}_2^C, \widehat{\theta}_3^C$, and $\widehat{\theta}_4^C \to \infty$. Therefore, suppose $P(\theta^C \le K - r) = 1$ and $P(\widehat{\theta}_2^C \le \theta^C \le \widehat{\theta}_4^C)$ is sufficiently large, using (82) because $\frac{dK}{db} < 0$:

$$\lim_{b\to 0} \frac{dE[W^{PE}]}{db} = -(1-\alpha)c\frac{dK}{db} > 0. \quad (94)$$

Using (61), (64) - (68), and (75) – (77), as $b \to \infty$ it is straightforward to show that $\widehat{\theta}_1^C = k^- - r, p_-^{c\,*} = p_+^{c\,*} = \overline{P}^C, \widehat{\theta}_3^C = k^- - r$, and $\widehat{\theta}_4^C = k^+ - r$. Therefore, suppose $P(\theta^E \le k^+) = P(\theta^C \le k^- - r) = 0$ and $P(\widehat{\theta}_2^C \le \theta^C \le \widehat{\theta}_4^C)$ is sufficiently large, using (82), because $\frac{dk^+}{db} < 0$ and $\frac{dK}{db} < 0$:

[48] This condition reflects demand realizations that result in a market clearing price on the sloped portion of the demand curve.

$$\lim_{b\to\infty} \frac{dE[W^{PE}]}{db} = -(1-\alpha)c\frac{dK}{db} - \frac{(2\alpha-1)}{4}\int_{k^- - r}^{\widehat{\theta}_4^C} 2(\theta^C + r - k^+)k^+$$

$$+ (\theta^C + r - k^+)^2 - \frac{dk^+}{db}\infty\, dG^C(\theta^C) = -\infty < 0. \tag{95}$$

(94) and (95) implies that $b^* \in (0, \infty)$. $\square$

Conclusion 12 provides plausible conditions where the optimal slope parameter is interior. Capacity demand must be distributed such that the probability that the equilibrium capacity auction price is on the sloped portion of the demand curve is sufficiently high.[49]

Proposition 12 follows directly from this result. Therefore, the core results of the model are robust to the consideration of multiple equilibria in the capacity and electricity auction. The CPM-PE outperforms the CPM-PI in terms of expected welfare.

Installed Generation Capacity Extension

The basic model focused on a setting in which there are two entrants choosing their capacity limits. In practice, in addition to the potential entrants, there is often a set of heterogeneous installed generation units. In this section, I consider an environment where the new entrants are peak-load generation technologies, while there is a set of installed generation units.

Assume there are two incumbents with installed generation units $\{1, 2\}$ with installed capacities k_1 and k_2, respectively. Further, there are two potential entrants $\{3, 4\}$ who will choose their capacity limits $k_i\ \forall\ i = 3, 4$ at a cost $c > 0$ per-unit of capacity. It is without loss of generality to assume that the two incumbents have a constant marginal electricity generation costs $\gamma_1 < \gamma_2$ up to their capacity limits. Further, the entrants' have constant marginal electricity generation costs $\gamma_E > \gamma_2$ up to their capacity limits.

Define $k(j) = \sum_{i=1}^{j} k_i$ to be the capacity of the first j generation units $\forall\ j = 1, 2, 3, 4$. Define $K = \sum_{i=1}^{4} k_i$ to be the aggregate capacity level. Define $k^- = \min\{k_3, k_4\}$ and $k^+ = \max\{k_3, k_4\}$ to be the minimum and maximum entrant's capacity, respectively. The timing and structure of the game is analogous to that in the basic model where the incumbents' capacities are taken as fixed. Analogous to the entrants' bids in the basic model, the incumbents submit a bid into both the energy and capacity auctions.

Conclusion 13. Equilibrium bidding behavior in the electricity auction:

1. If $\theta^E \leq k(1)$, then the unique PSNE entails firm 1 supplying all electricity demand at marginal cost γ_2.
2. If $k(1) < \theta^E \leq k(2)$, then there are multiple PSNE where firm i bids at γ_E and supplies residual demand $\theta^E - k_j$, while firm j procures its entire capacity by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j = 1, 2$ with $i \neq j$.

[49] This assumption is supported empirically. In practice, the capacity auction price has always been on the sloped portion of the demand curve.

3. If $k(2) < \theta^E \leq k(2) + k^-$, then there is a unique PSNE where the entrants bid at γ_E, while the incumbents procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable.
4. If $k(2) + k^- < \theta^E \leq k(2) + k^+$, then there is a unique PSNE where the large entrant bids at $\overline{P}^E$ and supplies residual demand $\theta^E - k(2) - k^-$, while the all other firms procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable.
5. If $k(2) + k^+ < \theta^E \leq K$, then there are multiple PSNE where a bidder i bids at $\overline{P}^E$ and supplies residual demand, while the all other firms j procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j = 1, 2, 3, 4$ with $i \neq j$.
6. If $\theta^E > K$, then there are multiple PSNE where a bidder i bids at $\overline{P}^E$ and supplies its entire capacity, while the all other firms j procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j = 1, 2, 3, 4$ with $i \neq j$.

Proof: Follows directly from Proposition 1 in Fabra et al. (2006). □

If $k(1) < \theta^E \leq k(2)$ or $k(2) + k^+ < \theta^E \leq 1$, there are multiple PSNE. I focus on the environment where: (i) if $k(1) < \theta^E \leq k(2)$, the least efficient incumbent is the marginal bidder and (ii) if $k(2) + k^+ < \theta^E \leq 1$, the large entrant is the marginal bidder. The Continuation Equilibrium Extension reveals that the core findings of the analysis are robust to considering continuation equilibrium in which the small firm can set the market clearing price. Further, the findings are robust to the environment where the most efficient incumbent sets the market clearing price in the region $k(1) < \theta^E \leq k(2)$.

CPM with Price-Inelastic Demand

Next I consider the bidding behavior in the capacity auction with price-inelastic demand. Recall, at the capacity auction stage, capacity investment decisions are taken as given such that the cost of capacity investments are sunk.

Conclusion 14. The equilibrium bidding behavior in the capacity auction:

1. If $\theta^C \leq k(2) + k^- - r$, then the unique PSNE where all bidders bid at zero.
2. If $k(2) + k^- - r < \theta^C \leq k(2) + k^+ - r$, then there is a unique PSNE where the large entrant bids at $\overline{P}^C$ and supplies residual demand $\theta^C + r - k(2) - k^-$, while the all other firms procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable .
3. If $k(2) + k^+ - r < \theta^C \leq K - r$, then there are multiple PSNE where a bidder i bids at $\overline{P}^C$ and supplies residual demand, while the all other firms j procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j = 1, 2, 3, 4$ with $i \neq j$.
4. If $\theta^C > K - r$, then there are multiple PSNE where a bidder i bids at $\overline{P}^E$ and supplies its entire capacity, while the all other firms j procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j = 1, 2, 3, 4$ with $i \neq j$.

Proof: Follows directly from Proposition 1 in Fabra et al. (2006). □

If $\theta^C > k(2) + k^+ - r$, there are multiple equilibria. I focus on the environment where the large firm sets the market clearing price. The Continuation Equilibrium Extension reveals that the core findings of the analysis are robust to considering continuation equilibrium in which the small firm can set the market clearing price.

Conclusion 15. The firm's profit functions are defined as follows:[50]

$$E[\pi_1^{PI}] = \int_0^{k(1)} (\gamma_2-\gamma_1)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)+k^-} (\gamma_E-\gamma_1)k_1 \, dG^E(\theta^E) + \int_{k(2)+k^-}^{1} (\overline{P}^E-\gamma_1)k_1 \, dG^E(\theta^E)$$
$$+ \int_{k(2)+k^- - r}^{1} \overline{P}^C k_1 \, dG^C(\theta^C); \tag{96}$$

$$E[\pi_2^{PI}] = \int_{k(1)}^{k(2)} (\gamma_E-\gamma_2)[\theta^E - k(1)] \, dG^E(\theta^E) + \int_{k(2)}^{k(2)+k^-} (\gamma_E-\gamma_2)k_2 \, dG^E(\theta^E) + \int_{k(2)+k^-}^{1} (\overline{P}^E-\gamma_2)k_2 \, dG^E(\theta^E)$$
$$+ \int_{k(2)+k^- - r}^{1} \overline{P}^C k_2 \, dG^C(\theta^C); \tag{97}$$

$$\pi_i^{PI}(k_i, k_h) = \begin{cases} \pi_i^{-PI} & \text{if } k_i = k^- < k_h = k^+, \\ \pi_i^{=PI} & \text{if } k_i = k_h = k, \text{ and} \\ \pi_i^{+PI} & \text{if } k_i = k^+ > k_h = k^- \end{cases} \tag{98}$$

where

$$\begin{aligned}
\pi_i^{-PI} &= \int_{k(2)+k^-}^{1} (\overline{P}^E - \gamma_E)k^- \, dG^E(\theta^E) + \int_{k(2)+k^- - r}^{1} \overline{P}^C k^- \, dG^C(\theta^C) - ck^-, \\
\pi_i^{=PI} &= \int_{k(2)+k}^{K} (\overline{P}^E - \gamma_E)\frac{1}{2}(\theta^E - k(2)) \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma_E)k \, dG^E(\theta^E) \\
&+ \int_{k(2)+k-r}^{K-r} \overline{P}^C \frac{1}{2}(\theta^C + r - k(2)) \, dG^C(\theta^C) + \int_{K-r}^{1} \overline{P}^C k \, dG^C(\theta^C) - ck, \text{ and} \\
\pi_i^{+PI} &= \int_{k(2)+k^-}^{K} (\overline{P}^E - \gamma_E)[\theta^E - k^- - k(2)] \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma_E)k^+ \, dG^E(\theta^E) \\
&+ \int_{k(2)+k^- - r}^{K-r} \overline{P}^C [\theta^C + r - k^- - k(2)] \, dG^C(\theta^C) + \int_{K-r}^{1} \overline{P}^C k^+ \, dG^C(\theta^C) - ck^+.
\end{aligned}$$

$\forall\ i, h = 3, 4$ with $i \neq h$.

Proof: Using the bidding behavior in Conclusions 13 and 14, the characterizations of the firms' profit functions follow analogously to those in Lemmas 1 and 3. □

The introduction of the installed generation units does not change the strategic nature of the entrants' capacity investment decision. That is, there is a discontinuity at symmetric capacities eliminating the potential for a symmetric equilibrium. Conclusion 16 details the firms' investment incentives in any equilibrium.

Conclusion 16. The equilibrium capacity levels (k^-, k^+) always exists and satisfy::

$$(\overline{P}^E - \gamma)[1 - G^E(K)] + \overline{P}^C[1 - G^C(K - r)] = c, \text{ and} \tag{99}$$

[50] It is assumed that if the entrants have symmetric capacities, they are the marginal bidder with probability $\frac{1}{2}$.

$$\int_{k(2)+k^-}^{1} (\overline{P}^E - \gamma_E) k^- \, dG^E(\theta^E) + \int_{k(2)+k^- - r}^{1} \overline{P}^C k^- \, dG^C(\theta^C)$$

$$= \int_{k(2)+k^-}^{K} (\overline{P}^E - \gamma_E)[\theta^E - k^- - k(2)] \, dG^E(\theta^E) + \int_{K}^{1} (\overline{P}^E - \gamma_E) k^+ \, dG^E(\theta^E)$$

$$+ \int_{k(2)+k^- - r}^{K-r} \overline{P}^C [\theta^C + r - k^- - k(2)] \, dG^C(\theta^C) + \int_{K-r}^{1} \overline{P}^C k^+ \, dG^C(\theta^C). \quad (100)$$

<u>Proof</u>: From Proposition 1, the equilibrium capacity levels (k^-, k^+) satisfy: $\frac{dE[\pi^{+PI}]}{dk^+} = 0$ and $\pi^{+PI} + ck^+ = \pi^{-PI} + ck^-$. Using (98), (99) and (100) follow directly from these conditions. □

Conclusion 17 reveals how aggregate capacity varies as critical parameters change.

Conclusion 17. Aggregate capacity K increases as: (i) $\overline{P}^E$, $\overline{P}^C$, or r increase or (ii) γ or c decrease.

<u>Proof</u>: Follows analogously from the Proof of Proposition 3. □

Next, in order to understand the regulator's incentives to choose $\overline{P}^C$ and r, we need to characterize the aggregate welfare function.

Conclusion 18. Aggregate expected welfare under CPM-PI:

$$E[W^{PI}] = \alpha \Big[\int_0^{k(1)} (v - \gamma_2)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)+k^-} (v - \gamma_E)\theta^E) \, dG^E(\theta^E) + \int_{k(2)+k^-}^{K} (v - \overline{P}^E)\theta^E \, dG^E(\theta^E)$$

$$+ \int_K^1 (v - \overline{P}^E) K \, dG^E(\theta^E) \Big] + (1-\alpha) \Big[\int_0^{k(1)} (\gamma_2 - \gamma_1)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)} \gamma_E \theta^E - \gamma_1 k_1 - \gamma_2 [\theta^E - k(1)] dG^E(\theta^E)$$

$$+ \int_{k(2)}^{k(2)+k^-} (\gamma_E - \gamma_1) k_1 + (\gamma_E - \gamma_2) k_2 \, dG^E(\theta^E) + \int_{k(2)+k^-}^{K} \overline{P}^E \theta^E - \gamma_1 k_1 - \gamma_2 k_2 - \gamma_E [\theta^E - K(2)] \, dG^E(\theta^E)$$

$$+ \int_K^1 \overline{P}^E K - \gamma_1 k_1 - \gamma_2 k_2 - \gamma_E (k^- + k^+) \, dG^E(\theta^E) - c(k^- + k^+) \Big] + (1 - 2\alpha) \Big[\int_{k(2)+k^- - r}^{K-r} \overline{P}^C \theta^C dG^C(\theta^C)$$

$$+ \int_{K-r}^1 \overline{P}^C K dG^C(\theta^C) \Big]. \quad (101)$$

<u>Proof</u>: Using (1) - (4), (96) – (98), Conclusions 13 and 14, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is:

$$E[CS^{PI}] = \int_0^{K(1)} (v - \gamma_2)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)+k^-} (v - \gamma_E)\theta^E \, dG^E(\theta^E) + \int_{k(2)+k^-}^{K} (v - \overline{P}^E)\theta^E \, dG^E(\theta^E)$$

$$+ \int_k^1 (v - \overline{P}^E) K \, dG^E(\theta^E) - \left[\int_{k(2)+k^- - r}^{K-r} \overline{P}^C (\theta^C + r) \, dG^C(\theta^C) + \int_{K-r}^1 \overline{P}^C K \, dG^C(\theta^C) \right]. \quad (102)$$

(101) follows directly from (2), (96) – (98) and (102). □

Using (101), the characterization of the optimal capacity demand parameters ($\overline{P}^C$, r) under CPM-PI are analogous to those specified in Proposition 4.

CPM with Price-Elastic Demand

Next I consider the bidding behavior in the capacity auction with price-elastic demand. The electricity auction bidding behavior with installed generation capacity is analogous to that specified in Conclusion 13. Recall, at the capacity auction stage, capacity investment decisions are taken as given such that the cost of capacity investments are sunk. Throughout the analysis, suppose Assumption 1 holds.

Conclusion 19. The equilibrium bidding behavior in the capacity auction:[51]

1. If $\theta^C \leq \widehat{\theta}_1^C$, then the unique PSNE where all bidders bid at zero.
2. If $\widehat{\theta}_1^C < \theta^C \leq \widehat{\theta}_2^C$, then there is a unique PSNE where the large entrant bids at $p_+^{c\,*}$ and supplies residual demand $\widetilde{D}(p_+^{C*}, \cdot) - k(2) - k^-$, while the all other firms procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable.
3. If $\widehat{\theta}_2^C < \theta^C \leq \widehat{\theta}_3^C$, then a PSNE entails the large entrant bidding at $\overline{P}^C$ and supplying residual demand $\theta^C + r - k(2) - k^-$, while the all other firms procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable.
4. If $\theta^C > \widehat{\theta}_3^C$, then there are multiple PSNE where a bidder i bids at $\overline{P}^E$ and supplies its entire capacity, while the all other firms j procure their entire capacities by bidding sufficiently low such that undercutting is unprofitable $\forall\ i, j = 1, 2, 3, 4$ with $i \neq j$.

where

$$p_+^{C*} :\ \widetilde{D}(p_+^{C*}, \theta^C; \cdot) - k^- - k(2) + p_+^{C*} \frac{d\widetilde{d}(\cdot)}{dp^c} = 0 \ \Rightarrow\ p_+^{C*} = \frac{b}{2}\left[\frac{\overline{P}^C}{b} + \theta^C + r - k^- - k(2)\right]; \tag{103}$$

$$\widehat{\theta}_1^C :\ \widetilde{D}(p^c = 0, \widehat{\theta}_1^C; \cdot) = k^- + k(2) \ \Rightarrow\ \widehat{\theta}_1^C = k(2) + k^- - r - \frac{\overline{P}^C}{b}; \tag{104}$$

$$\widehat{\theta}_2^C :\ p_+^{c\,*}(\widehat{\theta}_2^C) = \overline{P}^C \ \Rightarrow\ \widehat{\theta}_2^C = k(2) + k^- - r + \frac{\overline{P}^C}{b}; \tag{105}$$

$$\widehat{\theta}_3^C :\ \widetilde{D}(p^c = \overline{P}^C, \widehat{\theta}_3^C; \cdot) = K \ \Rightarrow\ \widehat{\theta}_3^C = K - r; \tag{106}$$

<u>Proof</u>: Follows directly from Proposition 1 in Fabra et al. (2006). □

Using the electricity and capacity auction bidding behavior, Conclusion 20 characterizes the firms' profit functions.

[51] As show in the Continuation Equilibria extension, there exists multiple equilibria for a subset of the region $(\widehat{\theta}_1^C, \widehat{\theta}_3^C]$. However, I focus on the environment where the large firm is the marginal bidder in this section. An analysis analogous to that in the Continuation Equilibria section could be carried out for the current setting to reveal that the results are robust to this assumption.

Conclusion 20. The firm's profit functions are defined as follows:[52]

$$E[\pi_1^{PE}] = \int_0^{k(1)} (\gamma_2 - \gamma_1)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)+k^-} (\gamma_E - \gamma_1) k_1 \, dG^E(\theta^E) + \int_{k(2)+k^-}^{1} (\overline{P}^E - \gamma_1) k_1 \, dG^E(\theta^E)$$
$$+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} k_1 \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C k_1 \, dG^C(\theta^C); \quad (107)$$

$$E[\pi_2^{PE}] = \int_{k(1)}^{k(2)} (\gamma_E - \gamma_2)[\theta^E - k(1)] \, dG^E(\theta^E) + \int_{k(2)}^{k(2)+k^-} (\gamma_E - \gamma_2) k_2 \, dG^E(\theta^E) + \int_{k(2)+k^-}^{1} (\overline{P}^E - \gamma_2) k_2 \, dG^E(\theta^E)$$
$$+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} k_2 \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C k_2 \, dG^C(\theta^C); \quad (108)$$

$$\pi_i^{PE}(k_i, k_h) = \begin{cases} \pi_i^{-PE} & \text{if } k_i = k^- < k_h = k^+, \\ \pi_i^{=PE} & \text{if } k_i = k_h = k, \text{ and} \\ \pi_i^{+PE} & \text{if } k_i = k^+ > k_h = k^- \end{cases} \quad (109)$$

where

$$\begin{aligned}
\pi_i^{-PE} &= \int_{k(2)+k^-}^{1} (\overline{P}^E - \gamma_E) k^- \, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} k^- \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C k^- \, dG^C(\theta^C) - ck^-, \\
\pi_i^{=PE} &= \int_{k(2)+k}^{K} (\overline{P}^E - \gamma_E) \frac{1}{2} (\theta^E - k(2)) \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma_E) k \, dG^E(\theta^E) \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} \frac{1}{2} \left[\widetilde{D}(\cdot) - k(2)\right] dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C \frac{1}{2} (\theta^C + r - k(2)) \, dG^C(\theta^C) \\
&+ \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C k \, dG^C(\theta^C) - ck, \text{ and} \\
\pi_i^{+PE} &= \int_{k(2)+k^-}^{K} (\overline{P}^E - \gamma_E)[\theta^E - k^- - k(2)] \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma_E) k^+ \, dG^E(\theta^E) \\
&+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} \left[\widetilde{D}(\cdot) - -k^- k(2)\right] dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C (\theta^C + r - k^- - k(2)) \, dG^C(\theta^C) \\
&+ \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C k \, dG^C(\theta^C) - ck^+.
\end{aligned}$$

$\forall \; i, h = 3, 4$ with $i \neq h$.

Proof: Using the bidding behavior in Conclusions 13 and 19, the characterizations of the firms' profit functions follow analogously to those in Lemmas 1 and 3. □

The introduction of the installed generation units does not change the strategic nature of the entrants' capacity investment decision. That is, there is a discontinuity at symmetric capacities

[52]It is assumed that if the entrants have symmetric capacities, they are the marginal bidder with probability $\frac{1}{2}$.

eliminating the potential for a symmetric equilibrium. Conclusion 21 details the firms' investment incentives in any equilibrium.

Conclusion 21. The equilibrium capacity levels (k^-, k^+) always exists and satisfy::

$$(\overline{P}^E - \gamma)[1 - G^E(K)] + \overline{P}^C[1 - G^C(K - r)] = c, \text{ and} \tag{110}$$

$$\begin{aligned}
&\int_{k(2)+k^-}^{1} (\overline{P}^E - \gamma_E)k^- \, dG^E(\theta^E) + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} k^- \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} \overline{P}^C k^- \, dG^C(\theta^C) \\
= \; & \int_{k(2)+k^-}^{K} (\overline{P}^E - \gamma_E)[\theta^E - k^- - k(2)] \, dG^E(\theta^E) + \int_K^1 (\overline{P}^E - \gamma_E)k^+ \, dG^E(\theta^E) \\
+ \; & \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} \left[\widetilde{D}(\cdot) - -k^- k(2)\right] dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C(\theta^C + r - k^- - k(2)) \, dG^C(\theta^C) \\
+ \; & \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C k \, dG^C(\theta^C).
\end{aligned} \tag{111}$$

Proof: From Proposition 1, the equilibrium capacity levels (k^-, k^+) satisfy: $\frac{dE[\pi^{+PE}]}{dk^+} = 0$ and $\pi^{+PE} + ck^+ = \pi^{-PE} + ck^-$. Using (109), (110) and (111) follow directly from these conditions. □

Conclusion 22 reveals how aggregate capacity varies as critical parameters change.

Conclusion 22. Aggregate capacity K increases as: (i) $\overline{P}^E$, $\overline{P}^C$, or r increase or (ii) γ or c decrease. Further, K does not change as b varies.

Proof: Follows analogously from the Proof of Proposition 7. □

Next, in order to understand the regulator's incentives to choose $\overline{P}^C$, b, and r, we need to characterize the aggregate welfare function.

Conclusion 23. Aggregate expected welfare under CPM-PE:

$$\begin{aligned}
E[W^{PE}] = \alpha\Bigg[&\int_0^{k(1)} (v - \gamma_2)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)+k^-} (v - \gamma_E)\theta^E \, dG^E(\theta^E) + \int_{k(2)+k^-}^{K} (v - \overline{P}^E)\theta^E \, dG^E(\theta^E) \\
+ &\int_K^1 (v - \overline{P}^E)K \, dG^E(\theta^E)\Bigg] + (1-\alpha)\Bigg[\int_0^{k(1)} (\gamma_2 - \gamma_1)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)} \gamma_E\theta^E - \gamma_1 k_1 - \gamma_2[\theta^E - k(1)] dG^E(\theta^E) \\
+ &\int_{k(2)}^{k(2)+k^-} (\gamma_E - \gamma_1)k_1 + (\gamma_E - \gamma_2)k_2 \, dG^E(\theta^E) + \int_{k(2)+k^-}^{K} \overline{P}^E\theta^E - \gamma_1 k_1 - \gamma_2 k_2 - \gamma_E[\theta^E - K(2)] \, dG^E(\theta^E) \\
+ &\int_K^1 \overline{P}^E K - \gamma_1 k_1 - \gamma_2 k_2 - \gamma_E(k^- + k^+) \, dG^E(\theta^E) - c(k^- + k^+)\Bigg] + (1-2\alpha)\Bigg[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*} \widetilde{D}(p_+^{C*}, \cdot) \, dG^C(\theta^C) \\
+ &\int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C(\theta^C + r) \, dG^C(\theta^C) + \int_{\widehat{\theta}_3^C}^{1} \overline{P}^C K \, dG^C(\theta^C)\Bigg].
\end{aligned} \tag{112}$$

Proof: Using (1) - (4), (107) – (109), Conclusions 13 and 19, and that all electricity and capacity auction costs are passed down to consumers, expected consumer surplus is:

$$E[CS^{PE}] = \int_0^{K(1)} (v-\gamma_2)\theta^E \, dG^E(\theta^E) + \int_{k(1)}^{k(2)+k^-} (v-\gamma_E)\theta^E \, dG^E(\theta^E) + \int_{k(2)+k^-}^{K} (v-\overline{P}^E)\theta^E \, dG^E(\theta^E)$$

$$+ \int_k^1 (v-\overline{P}^E)K \, dG^E(\theta^E) - \Bigg[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} p_+^{C*}\widetilde{D}(p_+^{C*},\cdot) \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{\widehat{\theta}_3^C} \overline{P}^C(\theta^C + r) \, dG^C(\theta^C)$$

$$+ \int_{\widehat{\theta}_3^C}^1 \overline{P}^C K \, dG^C(\theta^C) \Bigg]. \tag{113}$$

(112) follows directly from (2), (107) – (109) and (113). □

Using (112), the characterization of the optimal capacity demand parameters ($\overline{P}^C$, r) under CPM-PE are analogous to those specified in Proposition 8. However, to show that the findings of the basic model are robust to an environment with installed generation capacity, it will be important to provide conditions underwhich $b^* \in (0,\infty)$.

Conclusion 24. Suppose Assumption 1 holds. Then, if $\alpha = \frac{1}{2}, b^* \in (0,\infty]$. If $\alpha > \frac{1}{2}$ and $P(\,\widehat{\theta}_1^C \leq \theta^C \leq k(2)+k^- - r\,) < P(\,k(2)+k^- - r < \theta^C \leq \widehat{\theta}_2^C\,)$ b^* is interior. Otherwise, $b^* = \infty$.

Proof: Using (112):

$$\frac{dE[W^{PE}]}{db} = (2\alpha - 1)\left[\frac{dk^-}{db}(\overline{P}^E - \gamma)[k(2)+k^-]g^E(k(2)+k^-) - \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{dp_+^{C*}\widetilde{D}(\cdot)}{db} \, dG^C(\theta^C)\right] = 0. \tag{114}$$

Suppose Assumption 1 holds. If $\alpha = \frac{1}{2}$, then (114) holds for any $b^* \in (0,\infty]$. Suppose $\alpha > \frac{1}{2}$. It will be shown that there is an interior solution if $P(\,\widehat{\theta}_1^C \leq \theta^C \leq k(2)+k^- - r\,) < P(\,k(2)+k^- - r < \theta^C \leq \widehat{\theta}_2^C\,)$. Otherwise, expected welfare is monotonically increasing in b and hence, $b^* = \infty$. It will be shown that if $P(\,\widehat{\theta}_1^C \leq \theta^C \leq k(2)+k^- - r\,) < P(\,k(2)+k^- - r < \theta^C \leq \widehat{\theta}_2^C\,)$, then $\lim_{b\to 0}\frac{dE[W^{PE}]}{db} > 0$ and $\lim_{b\to\widetilde{b}}\frac{dE[W^{PE}]}{db} < 0$ for some $\widetilde{b} < \infty$ such that there does not exist a concern solution.

Suppose $\alpha > \frac{1}{2}$, using (114):

$$\frac{dE[W^{PE}]}{db} \stackrel{s}{=} (\overline{P}^E - \gamma)[k(2)+k^-]g^E(k(2)+k^-)\frac{dk^-}{db} - \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{dp_+^{C*}\widetilde{D}(\cdot)}{db} \, dG^C(\theta^C). \tag{115}$$

Using (27) – (29), in the current environment with installed generation capacity (115) simplifies:

$$\frac{dE[W^{PE}]}{db} \stackrel{s}{=} \frac{dk^-}{db}[k(2)+k^-]\left[(\overline{P}^E - \gamma)g^E(k(2)+k^-) + \frac{b}{2}[G^C(\widehat{\theta}_2^C) - G^C(\widehat{\theta}_1^C)]\right]$$

$$+ \frac{1}{4}\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \left(\frac{\overline{P}^C}{b}\right)^2 - 2(\theta^C + r - k(2) - k^-)[k(2)+k^-] - \left(\theta^C + r - -k(2) - k^-\right)^2 \, dG^C(\theta^C). \tag{116}$$

To analyze (116), $\frac{dk^-}{db}$ needs to be identified. Using (110) and Conclusion 22, $\frac{dK}{db} = 0$ such that $\frac{dk^-}{db} = -\frac{dk^+}{db}$. Using (103) - (106) and that $p_+^{c}{}^*(\widehat{\theta}_1^C) = 0$, implicitly differentiating (111) yields:[53]

$$\frac{dk^-}{db}\Bigg[(\overline{P}^E - \gamma)[2(1 - G^E(K)) + G^E(K) - G^E(k(2) + k^-) - k^- g^E(k(2) + k^-)] + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \overline{P}^C \, dG^C(\theta^C)$$

$$+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} b(\theta^C + r - \frac{3}{2}[k^- + k(2)]) \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} 2\overline{P}^C \, dG^C(\theta^C)\Bigg]$$

$$+ \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{1}{2}(\theta^C + r - k^- k(2))[k(2) + k^-] + \left(\frac{\overline{P}^C - p_+^{c\,*}}{b}\right) \frac{p_+^{c\,*}}{b} \, dG^C(\theta^C) = 0$$

$$\Rightarrow \; \frac{dk^-}{db} = -A\left[\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \frac{1}{2}(\theta^C + r - k^- - k(2))[k(2) + k^-] + \left(\frac{\overline{P}^C - p_+^{c\,*}}{b}\right) \frac{p_+^{c\,*}}{b} \, dG^C(\theta^C)\right] \tag{117}$$

where $A = (\overline{P}^E - \gamma)[2(1 - G^E(K)) + G^E(K) - G^E(k(2) + k^-) - k^- g^E(k(2) + k^-)] + \int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \overline{P}^C + b(\theta^C + r - \frac{3}{2}[k^- + k(2)]) \, dG^C(\theta^C) + \int_{\widehat{\theta}_2^C}^{1} 2\overline{P}^C \, dG^C(\theta^C)$.

Notice, $\theta^C + r - k(2) - k^- \lesseqgtr 0$ as $\theta^C \lesseqgtr k(2) + k^- - r$. Further, using (104) and (105), $\widehat{\theta}^2 - (k(2) + k^- - r) = k(2) + k^- - r - \widehat{\theta}_1^C = \frac{\overline{P}^C}{b}$ such that $\widehat{\theta_1^C}$ and $\widehat{\theta}_2^C$ are equidistant from $k(2) + k^- - r$. This implies that if $P(\widehat{\theta}_1^C \leq \theta^C \leq k(2) + k^- - r) < P(k(2) + k^- - r < \theta^C \leq \widehat{\theta}_2^C)$, then $\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \theta^C + r - -k(2) - k^- \, dG^C(\theta^C) > 0$. Further, this implies that $\frac{dk^-}{db} \leq 0$.

The result that $\lim_{b \to 0} \frac{dE[W^{PE}]}{db} > 0$ in the current setting follows analogously from (35). From (116), if $P(\widehat{\theta}_1^C \leq \theta^C \leq k(2 + k^- - r) < P(k(2) + k^- - r < \theta^C \leq \widehat{\theta}_2^C)$, then $\int_{\widehat{\theta}_1^C}^{\widehat{\theta}_2^C} \theta^C + r - k(2) - k^- \, dG^C(\theta^C) > 0$ and $\frac{dk^-}{db} \leq 0$ such that the sole positive term in (116) is $\left(\frac{\overline{P}^C}{b}\right)^2 [G^C(\widehat{\theta}_2^C) - G^C(\widehat{\theta}_1^C)]$. Thus, for a large (finite) value of b ($\widetilde{b}$) this term is sufficiently small such that $\lim_{b \to \widetilde{b}} \dfrac{dE[W^{PE}]}{db} < 0$. This implies that $b^* \in (0, \infty)$. □

Propositions 12 and 13 follow directly from this result. Therefore, the core results of the model are robust to the addition of installed generation capacity. The addition of elastic demand reduces the payments to both the installed and new entrants in the capacity auction during demand periods that solely reflect a rent transfer from producers to consumers. This strengthens the findings that CPM-PE outperforms CPM-PI under plausible conditions.

[53] A full derivation is analogous to that detailed in (30) - (33).

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