Paid to Produce Absolutely Nothing? A Nash-Cournot Analysis of a Proposed Power Purchase Agreement

Benjamin Chaiken[a], Joseph E. Duggan, Jr.[b,c], Ramteen Sioshansi[a,*]

[a] *Department of Integrated Systems Engineering, The Ohio State University, 1971 Neil Avenue, Columbus, Ohio 43210, United States of America*

[b] *Department of Economics and Finance, University of Dayton, 300 College Park, Dayton, Ohio 45469, United States of America*

[c] *Hanley Sustainability Institute, University of Dayton, 300 College Park, Dayton, Ohio 45469, United States of America*

Abstract

We investigate the incentive, market-behavior, and welfare effects of a proposed profit guarantee and associated power purchase agreement (PPA), which was introduced to ensure that generating firms remain viable through periods of higher-than-normal costs. The PPA ensures a guaranteed profit level either by transferring excess revenues from the affected firms to consumers or levying a surcharge on consumers to fund a subsidy for the affected firms. We develop and analyze a stylized Nash-Cournot model of a wholesale electricity market to examine the incentive effects of the proposed PPA. We find that the proposed PPA has incentive impacts that are contrary to its stated aim. The PPA incentivizes uneconomic firms to remain in the market when otherwise they would exit and incentivizes the shutdown of otherwise economically viable firms to restrict output, increasing prices. We find that the effects are pronounced by the corporate-separation asset-ownership structure that is employed in many jurisdictions. The theoretical results of the Nash-Cournot analysis are illustrated with a numerical case study which shows the deleterious consumer- and social-welfare effects of this incentive scheme. We discuss practical implications for regulatory policy, namely, that the proposed mechanism is ill-conceived, inefficient, and creates perverse incentives.

Keywords: Power purchase agreement, Nash-Cournot equilibrium, incentives, energy subsidy, market design, regulation

1. Introduction

Electricity systems are undergoing major structural changes that are related to policy and fuel prices. Zhao et al. (2017) demonstrate the impact of low natural-gas prices, which are spurred by the proliferation of hydraulic fracturing, which are causing price reversals in the merit order between coal- and natural-gas-fired generators. Feldman and Margolis (2018); Sawin et al. (2014); Wiser and Bolinger (2018) note that, contemporaneously, policymakers are imposing indirect decarbonization policies, many of which take the form of subsidies or mandates on renewable-energy use. Other environmental policies (*e.g.*, United States Environmental Protection Agency's Mercury and Air Toxics Standards[1]) are increasing compliance costs of older generating units.

This combination of oversupply, that is caused by renewable-energy policy, and new cost realities that generators face is straining some generating firms financially. A number of works propose changes to wholesale electricity markets to accommodate these changes more efficiently. Aggarwal (2019) provides a survey of this literature and highlights some of the inherent challenges.

*Corresponding author

Email addresses: `chaiken.2@buckeyemail.osu.edu` (Benjamin Chaiken), `jduggan1@udayton.edu` (Joseph E. Duggan, Jr.), `sioshansi.1@osu.edu` (Ramteen Sioshansi)

[1] https://www.epa.gov/mats

Assuming full information and no transactions costs, wholesale electricity markets that set prices based on society's value of lost load during periods of scarcity and short-run marginal generation costs during other periods provide sufficient revenues for an optimal generation mix to recover all of its costs. Boiteux (1960); Joskow (2007); Stoft (2002) provide detailed expositions of this result. Thus, generating resources having difficulty recovering their costs in a wholesale market does not reflect necessarily any market failure. Rather, financial strains on some generating resources may be market signals indicating that the mix of generation capacity is not socially optimal. In such a case, generating technologies that are unable to recover costs should exit the market while technologies that would earn positive rents should enter.

This idealized functioning of wholesale electricity markets is challenged by the institutional designs of some markets, which can create incentives for cross-subsidization of electricity services. A number of jurisdictions, including the state of Ohio, employ a corporate-separation approach to unbundling the electricity supply chain. Dormady (2017) discusses the corporate-separation market structure in Ohio. He notes that three of the four investor-owned electricity utilities in Ohio retain ownership of generation resources, which are held by corporate affiliates. Conversely, the fourth investor-owned utility in Ohio retains no generation resources, which have been divested. Dormady et al. (2019a,b) show that transmission, distribution, and retail customers of the three utilities with corporate affiliates pay regulated rates that are above the level that can be explained by wholesale energy prices. Conversely, regulated rates that are levied by the utility that has no generation affiliates follow wholesale energy prices more closely. On the basis of these findings, Dormady et al. (2019a,b) surmise that the higher retail rates that are levied by the three utilities with corporate affiliates is due to cross-subsidization of generation resources that are strained financially in the wholesale market. If true, these cross subsidies can result in economically inefficient capacity remaining in the market, to the detriment of consumer and social welfare.

This cross-subsidization is becoming more explicit under a series of proposed financial contracts between regulated utilities and their generation affiliates. Under these proposals,[2] regulated utilities execute multi-year power-purchase agreements (PPAs) with their generation affiliates. Retail customers are responsible for the difference between the contracted cost of the PPAs and the revenues that are earned by the generation resources in the wholesale market. If this difference is positive, a nonbypassable surcharge[3] is levied on customers, which is transferred to the generation affiliate. If the difference is negative, customers receive a credit to their retail bills. As such, the proposed financial contract can be viewed as a subsidy which provides a guaranteed profit level to the generation affiliates of the utilities.

The ostensible rationale behind these proposals is that this generating capacity is socially beneficial in the long run, as the capacity will become economically competitive in the wholesale electricity market in the future. Without the PPAs, the generating capacity may exit the market, if it is unable to recover costs in the short run. Thus, the utilities and their generation affiliates claim that is it in the public interest for this capacity to remain in the system and the PPAs are intended to ensure that this happens.

An important question that underlies these proposals is how the PPAs would impact the wholesale electricity market. We address this question using a stylized Nash-Cournot model, with which we demonstrate that the proposed structure of the PPAs creates perverse incentives for the contracted capacity to be withdrawn from the market. Our theoretical analysis and an illustrative case study demonstrate that Ohio's corporate-separation market structure exacerbates these incentives. These incentives stem from the firms that are subject to the PPAs being indifferent, in the absence of corporate separation, between producing and not producing. In the presence of corporate separation, contracted capacity that is affiliated with generating capacity that is not subject to the profit guarantee has strong incentives for capacity withholding. Thus, regardless of the veracity of the claims regarding the benefits of the generating capacity that is involved in the proposed PPAs, we show that the proposals can be counterproductive relative to their stated aim and decrease consumer and social welfare to the benefit of generating firms.

The remainder of this paper proceeds as follows. Section 2 reviews relevant literature and contextualizes

[2] *cf.* Federal Energy Regulatory Commission docket numbers EL16-33-000 and EL16-34-000 for detailed histories and decisions of two illustrative cases.

[3] The proposed surcharge is nonbypassable in the sense that a retail customer cannot avoid it through switching its retail supplier away from the utility.

our work. Section 3 develops the Nash-Cournot model and provides our theoretical results, which show the incentive properties of the proposed affiliate PPAs. Section 4 presents a simple illustrative numerical case study of the market model that is developed in Section 3 and shows that the theoretical characteristics of the market are borne out. Sections 5 provides a discussion. Section 6 concludes with policy implications of our work.

2. Related Literature

We use a Nash-Cournot framework to model and study equilibria in a stylized wholesale spot market for energy with and without the proposed PPA. Nash-Cournot models are used widely in the study of industrial organization, economics, and operations research and Friedman (1976); Tirole (1988); Vives (2000) survey a variety of such applications. Nash-Cournot models are particularly useful for studying restructured electricity markets, especially in understanding how market designs and industry structures can impact market efficiency and anti-competitive behavior. Borenstein et al. (1999) argue that concentration measures, which are used often to assess market competitiveness, are inadequate in electricity systems, due to a number of structural properties. These properties include highly price-inelastic short-run demand, stringent capacity constraints with limited options for storing electricity, and complex physical laws that govern electricity systems. Our work makes use of the price-inelasticity of short-run electricity demand in deriving our results regarding the proposed PPA. Vasin and Kartunova (2016) survey Nash-Cournot models of electricity markets. In addition, they study a two-node market with binding and non-binding transmission-capacity constraints. Their work is concerned with deriving an optimal amount of transmission capacity to maximize social welfare. This can be contrasted with our work, which is concerned with examining the incentive, welfare, and anti-competitive effects of the proposed PPA.

There is a technical issue that arises in our analysis, which stems from the specific nature of the proposed PPAs. In particular, the proposed wealth-transfer mechanism that funds the PPA is essentially a tax on or credit to consumers that is dependent on the total quantity that is produced in the market. This dependence is due to the charge or credit being allocated to customers *pro rata* to their consumption. Levin (1985) studies a Cournot model that includes taxation. However, the tax that Levin (1985) studies is paid by each firm on a fixed per-unit basis and the payment is independent of aggregate production. The nature of the surcharge or credit in our model changes the theoretical analysis considerably.

The revenue-transfer mechanism that is coupled with the proposed PPA entails an endogenously determined surcharge or credit that varies with aggregate production. Endogenously determined surcharges and credits are a somewhat common feature of energy-market design and regulation. Renewable portfolio standards (RPS) result often in an endogenous subsidy to or tax on producers. Carley et al. (2018) evaluate empirically the design of RPS programs, exploring how changes in RPS policy impact market outcomes. Zhou and Solomon (2020) study whether RPS programs serve as a ceiling or floor on renewable deployment. Our analysis can be differentiated from these two studies in that different policy mechanisms are examined—PPAs in our case and RPS in theirs.

Our analysis raises the issue of the exercise of market power. Wolak (2000) models bidding behavior in an electricity market, accounting for uncertainty and the positions of generating firms in the market for financial-hedge contracts. He illustrates that such contracts may help mitigate the exercise of market power. We do not consider financial hedging in our stylized analysis. Thus, the results of Wolak (2000) suggest a further avenue for exploring market mechanisms to counteract the anti-competitive impacts that we find of the proposed PPA.

The endogenous nature of the surcharge or credit complicates our theoretical analysis, and there may be concerns about whether a Nash-Cournot equilibrium exists. We ignore these concerns and study the characteristics of equilibria should they exist. There is a vast literature that studies the existence of Nash-Cournot equilibria, and interested readers are referred to the following works that examine this question in detail. Roberts and Sonnenschein (1976) study the existence of Nash-Cournot equilibria when firms' marginal revenues may not be decreasing in output. Novshek (1985) examines the existence of equilibria in a setting in which a firm's marginal revenue is declining in the aggregate output of its rivals. Szidarovszky and Yakowitz (1977) restrict their analysis of the existence of Nash-Cournot equilibria to cases of concave demand. Kolstad and Mathiesen (1987) derive necessary and sufficient conditions for the existence of Nash-Cournot equilibria, and in doing so relax the assumption of concave demand that is used by Szidarovszky and Yakowitz (1977). However, the analysis of Kolstad and Mathiesen (1987) disallows degenerate equilibria, which can be problematic given many multistage games have such equilibria. Gaudet and Salant (1991) relax the requirement of no degenerate equilibria. Amir (1996) generalizes the work of Novshek (1985) using the theory of supermodular games. Van Long and Soubeyran (2000) use a contraction-mapping approach to study the existence of Nash-Cournot equilibria.

The works of Amir (1996); Gaudet and Salant (1991); Kolstad and Mathiesen (1987); Novshek (1985); Roberts and Sonnenschein (1976); Szidarovszky and Yakowitz (1977); Van Long and Soubeyran (2000) differ considerably from our analysis. The former focus on the existence and uniqueness of Nash-Cournot equilibria. Our work analyzes the market impacts of the proposed PPA using the stylized framework of a Cournot model and a novel demand function that captures the relevant features of the proposed wealth-transfer mechanism that funds the PPA. Thus, we abstract away questions of the existence and uniqueness of equilibria. An interesting theoretical question concerns the existence and uniqueness of Nash-Cournot equilibria with a demand function that endogenizes the surcharge or credit that funds the PPA. However, such an analysis is beyond the scope of our work.

3. Theoretical Analysis

3.1. Preliminaries

We consider a single-shot spot electricity market, with n competing suppliers. Each firm, $i \in 1, \ldots, n$, has a fixed cost, F_i, which is measured in dollars, and a constant marginal cost of producing energy, c_i, which is measured in \$/MWh. We assume this relatively simple setting to ease the exposition and focus our analysis on the incentive properties of the proposed PPA mechanism. One could extend the analysis to account for fluctuating fuel costs or other production constraints (*e.g.*, ramping limitations), which we defer to future work.

Each firm decides its production quantity. For all $i \in 1, \ldots, n$, we let q_i denote firm i's production, which is measured in MWh. Let:

$$Q = \sum_{i=1}^{n} q_i, \tag{1}$$

be total production. For any firm, j, define $Q_{-j} = Q - q_j$ to be the production of all firms excluding firm j. Market prices, which are measured in \$/MWh, are determined by the twice continuously differentiable inverse demand function, $P(Q)$.

Firm i's profit is given by $\pi_i(q_i, Q_{-i}) = [P(q_i + Q_{-i}) - c_i]q_i - F_i$. We study Nash-Cournot equilibria and assume hereafter that at least one equilibrium exists. We denote firm i's equilibrium output as q_i^* and its equilibrium profit as π_i^*.

Henceforth, we assume that the following two standard properties of $P(Q)$ hold. We introduce two additional assumptions in Section 3.3.

Assumption 1. *$P(Q)$ is non-increasing, i.e., $P'(Q) \leq 0, \forall Q \geq 0$.*

Assumption 2. *$P(Q)$ is concave, i.e., $P''(Q) \leq 0, \forall Q \geq 0$.*

One firm, which we denote as $s \in 1, \ldots, n$ and refer to as the subsidized firm, receives a guaranteed profit level, L (*e.g.*, through a proposed affiliate PPA). Thus, $\pi_s^* = L$ and the transfer payment to firm s to achieve this profit is $\sigma(q_s, Q_{-s}) = L - \{[P(q_s + Q_{-s}) - c_s]q_s - F_s\}$.

The net cost of this transfer payment is spread across the customer base as a per-unit surcharge or credit, which depends on the total amount that is consumed. That is, each customer pays a charge of $\sigma(q_s, Q_{-s})/Q$ per MWh that he or she consumes. The nonlinearity of this charge makes the problem difficult to analyze. Thus, we begin in Section 3.2 by examining a simplified case in which the cost of $\sigma(q_s, Q_{-s})$ is paid exogenously and does not impact customer demand. Section 3.3 tackles the more complex case in which the cost of $\sigma(q_s, Q_{-s})$ is endogenized.

3.2. Effect of Affiliate PPA on Equilibrium Behavior with Exogenous Transfer Payment

To begin, we assume that $\sigma(q_s, Q_{-s})$ is paid exogenously and ignore its effect on demand. This simplification allows for a straightforward analysis and suggests some potential directions for future work on the dynamics of Nash-Cournot equilibria generally. The incentives that are engendered by the proposed profit guarantee in this setting are a consequence of the following, more general result, about Nash-Cournot equilibria with inverse demand satisfying Assumptions 1 and 2.

Proposition 1. *Under Assumptions 1 and 2 every firm's equilibrium profit is decreasing as a function of its rivals' outputs. Namely, $\forall i, j \in 1, \ldots, n$, $j \neq i$ we have that:*

$$\frac{d}{dq_j}\pi_i^*(q_i^*, Q_{-i}^*) \leq 0. \tag{2}$$

Proof. See Appendix A. □

Proposition 1 implies that, *ceteris paribus*, every non-subsidized firm prefers that the subsidized firm produces less (or, *in extremis*, that it produces zero). The corporate-separation asset-ownership structure that Ohio and other jurisdictions allow may exacerbate the incentives for the subsidized firm to withhold production. This is because investor-owned utilities may own a mix of generation assets that do and do not receive a fixed profit guarantee under the PPA. Proposition 1 demonstrates that in such a case, such a utility always has an incentive to decrease the output of its generators that receive a fixed profit guarantee to benefit its generators that do not receive the subsidy. We address the specific incentives for such withholding in greater detail in Section 3.3.

We conclude by noting that Proposition 1 is a stronger result than we need. The property holds for any pair of firms (whether they are subsidized or not), and the profit guarantee is not needed to prove the result. The profit guarantee appears only in the justification for why, in its presence, subsidized generators may produce nothing.

3.3. Effect of Affiliate PPA on Equilibrium Behavior with Endogenous Transfer Payment

In reality, $\sigma(q_s, Q_{-s})$ is paid by customers as a surcharge on or credit to their retail electricity bills. This introduces an added complication, arising from the interaction between $\sigma(q_s, Q_{-s})$ and the inverse demand function. Namely, customers' willingnesses-to-pay are affected by $\sigma(q_s, Q_{-s})$, causing a disconnect between the market price that is perceived by consumers and that which determines firms' revenues.

The surcharge is distributed per unit as a fraction of the total production level. Thus, consumers perceive the market price as $P(Q) + \sigma(q_s, Q_{-s})/Q$. This means that consumers' willingnesses to pay are shifted downward on the quantity axis. That is, any given amount, $\hat{Q}$, that firms expect consumers to purchase at the price, $P(\hat{Q})$, is shifted to the lower price, $P(\hat{Q}) - \sigma(\hat{q}_s, \hat{Q}_{-s})/\hat{Q}$. This observation motivates the definition of the adjusted inverse demand function:

$$\tilde{P}(Q) = P(Q) - \frac{L + F_s - [\tilde{P}(Q) - c_s]q_s}{Q}, \tag{3}$$

which captures the change in customers' willingnesses-to-pay that result from the transfer. The second term in the right-hand side of (3) is the per-MWh surcharge that is required to fund the difference between the subsidized firm's guaranteed profit level, L, and its operating profit, $[\tilde{P}(Q) - c_s]q_s - F_s$. The amount of the transfer payment that appears in (3) is not exactly $\sigma(q_s, Q_{-s})$. This is because firm s faces the same adjusted inverse demand function. Collecting terms in (3) gives the closed-form definition:

$$\tilde{P}(Q) = \frac{Q}{Q_{-s}}P(Q) - \frac{L + F_s + c_s q_s}{Q_{-s}}. \tag{4}$$

Using (4), firm i's profit is given by $\tilde{\pi}_i(q_i, Q_{-i}) = [\tilde{P}(q_i + Q_{-i}) - c_i]q_i - F_i$. As with Proposition 1, we are interested in how q_s impacts the equilibrium profit of other firms. The price function, and by extension the firms' profits, are coupled with the quantity in a more complicated way. In particular, even if $P(Q)$ satisfies Assumptions 1 and 2, $\tilde{P}(Q)$ may not satisfy them. Thus, we introduce the following two additional assumptions on $P(Q)$.

Assumption 3. *$P(Q)$ is relatively inelastic, with:*

$$P'(Q) \cdot \frac{Q}{P(Q)} \leq -1, \forall Q \geq 0. \tag{5}$$

Assumption 4. *Firm s accounts for at most half of total equilibrium production, i.e.:*

$$q_s^* \leq \frac{1}{2} Q^*. \tag{6}$$

Assumptions 3 and 4 are consistent with the short-run price elasticity of electricity demand that is estimated by Burke and Abayasekara (2018) and the energy-supply mix of many wholesale electricity markets, including that in Ohio.[4] Assumption 4 requires that market concentration be measured on a per-firm basis. That is to say, it is insufficient for a single subsidized generator to serve at most half of the market. Rather, if a single firm holds multiple subsidized generators, their collective supply must be at most half of the market. Assumptions 3 and 4 do not guarantee that $\tilde{P}(Q)$ satisfies Assumptions 1 and 2. Thus, Proposition 1 does not hold necessarily in this context. However, with all of Assumptions 1–4, we have the following result.

Proposition 2. *Under Assumptions 1–4 equilibrium profits with the adjusted inverse demand function, $\tilde{P}(Q)$, satisfy:*

$$\frac{d}{dq_s} \tilde{\pi}_i^*(q_i^*, Q_{-i}^*) \leq 0, \forall i \in 1, \ldots, n, i \neq s. \tag{7}$$

Proof. See Appendix A. □

In this case of endogenous transfer payments we do not have the stronger result of Proposition 1 that equilibrium profit is decreasing as a function of *any* rival firms' output. Under the given assumptions, we show only that the equilibrium profit of a non-subsidized firm decreases as a function of q_s. Proposition 2 demonstrates that when we take account of the demand effects of the transfer payment, the perverse incentive persists. The profits of subsidized generators are fixed. Thus, the profit of any affiliated generator that is not subject to the profit guarantee increases as the production of a subsidized generator decreases. Given that the corporate affiliates of the utilities in Ohio hold generating units that would and would not be subject to the PPA, there is an incentive for the generating units that are subject to the PPA to decrease production. We summarize the implications of this dynamic in the following corollary.

Corollary 1. *Irrespective of underlying market conditions, the profit guarantee creates incentives that may reduce social welfare.*

Proof. Proposition 2 does not depend on any specific assumptions about the fixed or marginal costs of firm s. This means that the profit guarantee engenders the same incentives to reduce q_s regardless of whether firm s earns positive or negative profit in its absence. If q_s goes to zero with the profit guarantee, as is incentivized, this changes the market outcome in one of two ways, depending on whether firm s could or could not operate profitably without the subsidy. We consider these two cases in turn.

Case 1: The subsidized firm can operate profitably without the profit guarantee.
In this case, $q_s = 0$ may increase the price and reduce social welfare. Furthermore, consumers cover the cost of $\sigma(q_s, Q_{-s}) = F_s$, despite the subsidized firm providing no output.

Case 2: The subsidized firm cannot operate profitably without the profit guarantee.
In this case, absent the profit guarantee, there is pressure for the subsidized firm to exit the market. The profit guarantee suppresses this pressure. Meanwhile, consumers must cover the cost of $\sigma(q_s, Q_{-s}) = F_s$, despite the subsidized firm providing no output.

□

[4] https://www.eia.gov/state/?sid=OH

4. Numerical Case Study

This section presents a numerical case study, through which we demonstrate our theoretical analysis, with a particular focus on Proposition 2 and Corollary 1. We compute equilibrium solutions under different cost settings for a market that consists of six generating firms, one of which is subsidized. Furthermore, we assume that the subsidized firm is part of a holding company that owns another affiliated unsubsidized generating firm. This assumption mimics the asset-ownership structure that underlies the proposed affiliate PPAs in Ohio, wherein the generation affiliates of the investor-owned utilities hold mixes of generators, only a subset of which are covered by the affiliate PPAs and given profit guarantees. Our case study can be extended to handle simulations with more complex market structures and dynamics.

We simulate the market with the subsidized firm having high and low marginal costs. These cost values are meant to replicate the conditions that are used to rationalize the PPAs. Under the proposal, firms that have high near-term operating costs are given customer-funded subsidies so they do not withdraw their capacity, which would be socially valuable in the future when their operating costs are purported to decrease. The marginal-cost values that we use in our case study are selected to test the validity of our theoretical results and are in-line with estimates of fossil-fuel generation costs.[5] However, our case study is not meant to represent any specific market conditions, other than those that are specified by the assumptions that underlie our theoretical analysis.

As predicted by Proposition 2, equilibrium production of the subsidized firm is zero with both high and low marginal costs. As such, we constrain explicitly the subsidized firm to produce a minimum amount to examine how profits and welfare are impacted by the subsidized firm's production. We impose capacity constraints on the firms as well. For all $i \in 1, \ldots, n$, we let $q_i^{\min}$ and $q_i^{\max}$ denote firm i's minimum and maximum production levels, respectively.

As predicted by our theoretical analysis, we see that total producer welfare, including the holding company's profit, decrease as $q_s^{\min}$ increases. In all but one specific instance, we see also that consumer welfare decreases compared to a case in which the subsidized firm exits the market. Consumer welfare may increase, very slightly, in the case that the subsidized firm's marginal cost is low and its production remains high with the subsidy. However, the structure of the holding company's profit function incentivizes the subsidized firm to produce nothing, which decreases consumer welfare, unless there are additional policy restrictions that force production. These results demonstrate clearly the potential welfare impacts that are set forth in Corollary 1.

4.1. Case-Study Data and Implementation

Table 1 summarizes the assumed costs and operating capacities of the six generators. The two affiliated generators are labeled as a and s, where a denotes the unsubsidized affiliate of firm s. Our base case assumes that firm s has a relatively high marginal cost of \$33/MWh. $c_1 = 29$ and $c_s = 33$ are meant to mimic market conditions when the affiliate PPAs were proposed, which are that coal is an expensive generating fuel relative to natural gas (*i.e.*, we assume that firms 1 and s use coal-fired generators). We consider a sensitivity case in which $c_s = 27$, which could reflect future conditions under which coal is more competitive with natural gas. Such future cost reductions, and the associated consumer-welfare gains, are a justification of the proposed affiliate PPAs. We assume that the guaranteed profit level of firm s is $\$(10000 + F_s)$, which represents a reasonable return on the pre-subsidy fuel costs of firm s. Because firms a and s are corporate affiliates under a holding company, we model them as determining their production levels to maximize their joint profits.

We assume a concave and decreasing inverse demand function of the form:

$$P(Q) = t_0 - t_1 Q^{2.5}. \tag{8}$$

The values of t_0 and t_1 are found using the reference values $P(9000) = 40$ and $P(20000) = 20$, which are similar to those that are used by Borenstein and Bushnell (1999). This demand function and the assumed characteristics of the supply side of the market satisfy Assumptions 1–4.

[5] https://www.eia.gov/outlooks/aeo/electricity_generation.php

Table 1: Generating-Firm Characteristics

Generating Firm	Marginal Cost (\$/MWh)	Fixed Cost (\$)	Capacity (MW)
Unaffiliated			
1	29	1 200	4 000
2	25	1 400	4 000
3	26	1 500	4 000
4	27	1 200	4 000
Affiliated			
a	27	1 500	4 000
s	33	1 800	4 000

We compute equilibria by adapting the grid-search method that Borenstein and Bushnell (1999) use in their work. Alternatively, one could use a software package that is designed explicitly to compute an equilibrium. For instance, Ferris and Munson (2000) develop PATH, which can solve for equilibria that are cast as solutions of complementarity problems. The grid-search method works by optimizing sequentially the output of each firm, holding the other output levels fixed, until no firm can improve its profit by changing its output. Algorithm 1 provides pseudocode for the grid-search method in our case of a single subsidized firm. The method can be generalized to include more subsidized firms. Line 1 takes algorithm inputs, with ϵ being the convergence tolerance. Line 2 initializes the iteration counter, k, and production levels.

Algorithm 1 Grid Search

1: **input:** $\epsilon > 0$, $q_a^{\min}, q_s^{\min}, q_1^{\min}, \dots, q_n^{\min}$, $q_a^{\max}, q_s^{\max}, q_1^{\max}, \dots, q_n^{\max}$
2: **initialize:** $k \leftarrow 0$, $q_a^0, q_s^0, q_1^0, \dots, q_n^0$
3: **repeat**
4: $\quad Q_{-(a,s)}^k \leftarrow \sum_{i=1}^n q_i^k$
5: $\quad (q_a^{k+1}, q_s^{k+1}) \leftarrow \arg\max_{q_a \in [q_a^{\min}, q_a^{\max}], q_s \in [q_s^{\min}, q_s^{\max}]} \tilde{\pi}_{a,s}^*(q_a + q_s, Q_{-(a,s)}^k)$
6: $\quad \Delta \leftarrow \max\{|q_a^{k+1} - q_a^k|, |q_s^{k+1} - q_s^k|\}$
7: $\quad$ **for** $i \leftarrow 1$ to n **do**
8: $\qquad Q_{-i}^k \leftarrow q_a^{k+1} + q_s^{k+1} + \sum_{j=1}^{i-1} q_i^{k+1} + \sum_{j=i+1}^n q_i^k$
9: $\qquad q_i^{k+1} \leftarrow \arg\max_{q_i \in [q_i^{\min}, q_i^{\max}]} \tilde{\pi}_i^*(q_i, Q_{-i}^k)$
10: $\qquad \Delta \leftarrow \max\{\Delta, |q_i^{k+1} - q_i^k|\}$
11: $\quad$ **end for**
12: $\quad k \leftarrow k + 1$
13: **until** $\Delta \le \epsilon$
14: **output:** $q_a^k, q_s^k, q_1^k, \dots, q_n^k$

Lines 3–13 constitute the main iterative loop. The loop begins in Line 4 by computing the output from the previous iteration of the holding company's rivals. Line 5 optimizes the holding company's outputs, holding the output of its rivals as fixed at $Q_{-(a,s)}^k$. Line 6 determines the maximum change in the outputs of the affiliated firms compared to the quantities from the previous iteration. Lines 7–11 constitute a loop that repeats Lines 4–6 for each of the holding company's rivals. Line 12 updates the iteration counter and Line 13 is the termination criterion for the main iterative loop.

When the algorithm terminates, Line 14 outputs the final production levels. These production levels constitute an ϵ-equilibrium, meaning that no firm has a profitable unilateral deviation that is larger than ϵ. An ϵ-equilibrium with $\epsilon = 0$ coincides with the standard definition of a Nash equilibrium (*cf.* Fudenberg and Tirole (1991) for further details). Algorithm 1 introduces path dependency, in that the solutions of the optimization problems that are solved in Lines 5 and 9 depend upon the order in which the firms are considered. This path dependency does not affect our analysis, however, because the final solution that is output is an ϵ Nash-Cournot equilibrium.

4.2. Case-Study Results

We begin by analyzing a case with $c_s = 33$, $q_a^{\min} = q_1^{\min} = \cdots = q_n^{\min} = 0$, and $q_s^{\min}$ equal to different values. Firm s produces $q_s^{\min}$ in every case, which impacts equilibrium production levels of the other firms. Figure 1 summarizes the breakdown of producer welfare for different values of $q_s^{\min}$. The figure demonstrates the result that is expected from Proposition 2. As the subsidized firm's production increases, total producer welfare drops by 18% from \$82 000 to \$67 000. Furthermore, each individual firm's profit decreases monotonically as the subsidized firm's output increases. In particular, holding-company profit decreases by about 12% from \$22 000 to \$19 500. This finding reinforces the perverse incentive that the PPA and profit guarantee provide. The holding company has control over the subsidized firm's output and clearly the company prefers zero subsidized-firm production.

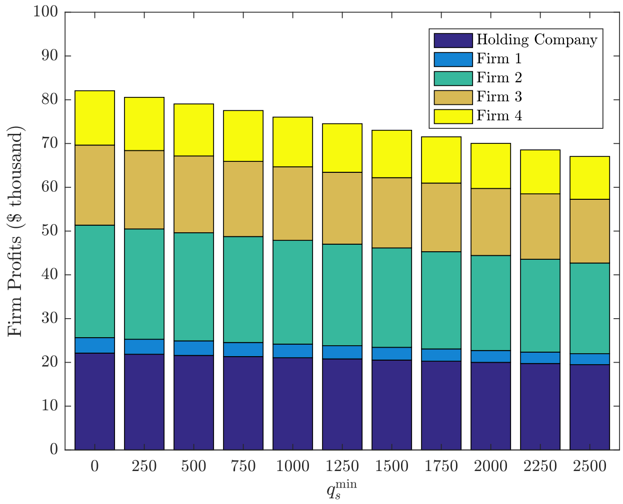

Figure 1: Firm Profits With Profit Guarantee, $c_s = 33$, and Different Values of $q_s^{\min}$

Figure 2 summarizes consumer and producer welfare under equilibria with different values of $q_s^{\min}$. Due to its price and quantity impact, consumer welfare is computed as:

$$\int_0^{Q^*} P(x)dx - \left\{ P(Q^*) + \frac{L + F_s - [P(Q^*) - c_s]q_s}{Q^*} \right\} Q^*, \tag{9}$$

in the presence of the profit guarantee. Absent the profit guarantee, consumer welfare is computed (as usual) as:

$$\int_0^{Q^*} P(x)dx - P(Q^*)Q^*. \tag{10}$$

Figure 2 shows that in the presence of the profit guarantee, consumer and producer welfare are decreasing in $q_s^{\min}$. We know from Figure 1 and Proposition 2 that producers benefit from firm s reducing its output. Consumers benefit from reduced firm-s production as well, because the wealth transfer that funds the profit guarantee requires them to pay the cost of uneconomic production. This wealth transfer imposes greater net costs on consumers if firm s produces more.

For purposes of comparison, without the profit guarantee, firm s shuts down and removes its capacity from the market. In the long run, this is done by retiring its capacity. In the short run, the operation of firm s depends upon the assumed behavior of the holding company. Algorithm 1 assumes that operations of firms a and s are co-optimized to maximize joint profits. In such a case, without the profit guarantee, $q_s^* = 0$ and the holding company shifts all production to firm a. If the generators are operated to maximize

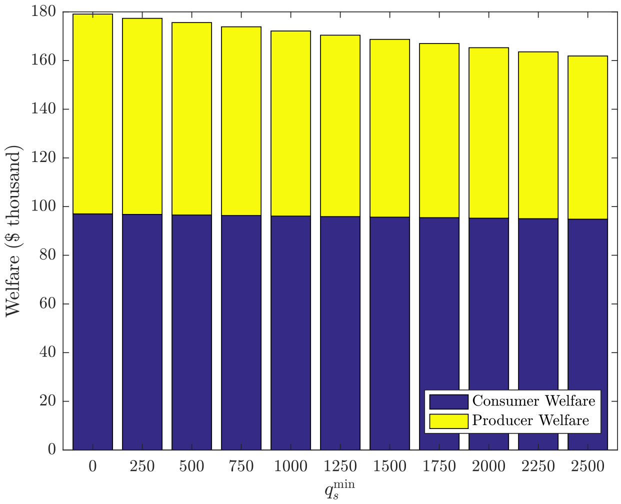

Figure 2: Consumer and Producer Welfare With Profit Guarantee, $c_s = 33$, and Different Values of $q_s^{\min}$

individual profits, $q_s^* > 0$, but firm s operates at a net loss (when taking account of F_s). Removing the capacity of firm s from the market yields consumer, producer, and social welfare of about \$115 158, \$77 000, and \$192 000, respectively. Conversely, social welfare ranges between \$161 879 and \$179 078 with the profit guarantee. Thus, the profit guarantee results in social welfare losses of between 7% and 16% (relative to the no-subsidy case), depending upon $q_s^{\min}$. The value of $q_s^{\min}$ impacts the extent of social-welfare losses through the amount of uneconomic production that is provided by the subsidized firm.

Figures 3 and 4 summarize, respectively, the breakdown of firms' profits and social welfare in an identical case to that shown in Figures 1 and 2, except that $c_s = 27$ in the case that is presented in Figures 3 and 4. The important distinction between this case and the previous one is that firm s is an economic source of energy with $c_s = 27$. Figure 3 displays clearly the market dynamics that are predicted by Proposition 2. Total producer welfare decreases by about 9.7% from \$82 000 to \$74 000 with $c_s = 27$ as the subsidized firm increases its output. Crucially the holding company's profit decreases by 4.5% from \$22 000 to \$21 000. Thus, again, the company with control over subsidized-firm output prefers that it produce nothing, reinforcing the incentive property that we discuss in Section 3.

Consumers are harmed by this reduction in firm-s output, because they are being provided with less energy from an economic source. Consumer welfare in the presence of the profit guarantee is lower than in its absence $\forall q_s^{\min} \leq 2000$. For the highest two production levels, consumer surplus rises slightly to \$115 170 and \$117 113, respectively, which represent modest gains of approximately \$10 and \$2 000. This increased consumer welfare is because the wealth transfer that is associated with the affiliate PPA results in a credit to consumers. This credit outweighs the welfare losses that are associated with firm s withholding its production from the market.

5. Discussion

The affiliate PPAs and associated profit guarantees that have been proposed in Ohio and in other jurisdictions (including New York and Illinois) create perverse incentives for firms participating in a wholesale electricity market. Proposition 2 and our numerical example in Section 4 demonstrate that generating firms, including any unsubsidized affiliates of the generating firms that receive a profit guarantee, benefit from the subsidized firm reducing its output. These findings mean that the profit guarantees may not deliver their purported benefit of keeping subsidized generators in the market. As Corollary 1 shows, consumers are made worse-off by this withholding of production from the subsidized generator. The mechanism of consumer harm depends upon market conditions. In the first case that we consider in Section 4, wherein

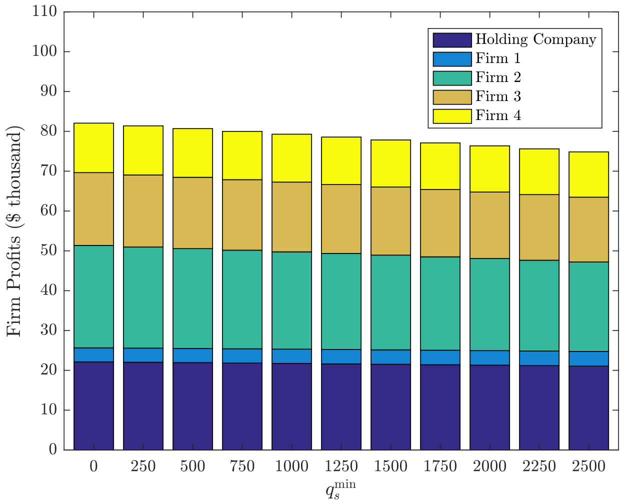

Figure 3: Firm Profits With Profit Guarantee, $c_s = 27$, and Different Values of $q_s^{\min}$

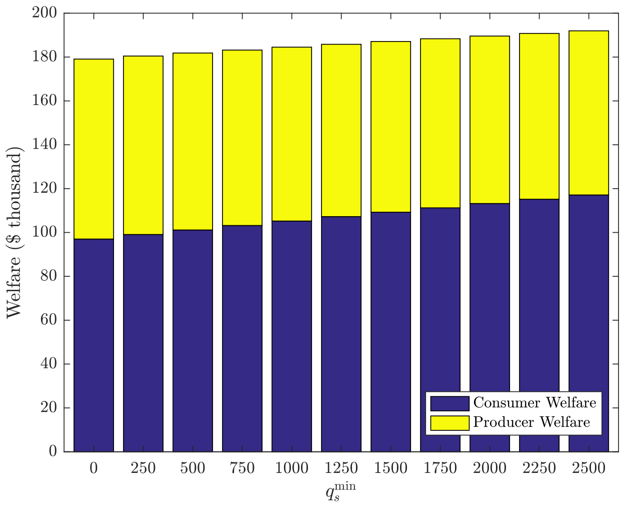

Figure 4: Consumer and Producer Welfare With Profit Guarantee, $c_s = 27$, and Different Values of $q_s^{\min}$

the subsidized generator is a relatively expensive energy source, consumers are made to subsidize the fixed cost of a generator that consumers would prefer to have retire. Conversely, in the second case, in which the subsidized generator is relatively inexpensive, consumers may see less production from this economic source of energy *and* are made to subsidize its costs.

One reason that we examine market equilibria with different values of $q_s^{\min}$ is due to regulatory risk or scrutiny. Proposition 2 proves and Figures 1 and 3 demonstrate that absent a lower-bound on q_s, the holding company's equilibrium strategy is to produce $q_s^* = 0$ in the presence of the profit guarantee. However, in practice, the holding company may be inclined to maintain some level of production from the subsidized firm, to avoid regulatory scrutiny (*e.g.*, policymakers adjusting or rescinding the terms of the profit guarantee). Our findings show that such regulatory risk or scrutiny can exacerbate the welfare losses that are engendered by the profit guarantee. For instance, Figure 2 shows that welfare losses can arise in cases in which the marginal cost of the subsidized firm is relatively high, because consumers are worse-off from the subsidized firm increasing its production.

The profit guarantees and affiliate PPAs that were proposed in Ohio were rationalized on claims that although the market (at the time) was in conditions that are akin to those with $c_s = 33$, the market would move in the long-run to conditions that are akin to $c_s = 27$. In essence, consumers would have been made to subsidize the plants with profit guarantees in the short-run, in exchange for credits in the long-run. Our numerical case study in Section 4 shows, however, that the incentives that are engendered by the proposed structure of the affiliate PPAs are highly distortionary and create substantial efficiency losses.

In our case study, the only situation that yields a positive credit to consumers is one in which the subsidized firm has a low marginal cost ($c_s = 27$) and its production is high. Indeed, the profit guarantee and affiliate PPA yield a consumer credit, which increases consumer welfare relative to a no-subsidy case, so long as two conditions are met. First, the subsidized firm must be economic. Second, the subsidized firm's production in the presence of the subsidy must be sufficiently high to earn a profit (without the subsidy) so that the wealth transfer to consumers outweighs any welfare loss that occurs if the subsidized firm reduces its output relative to the no-subsidy case. Without the subsidy, consumer welfare with $c_s = 27$ is approximately \$115 158. With the subsidy in place, the best-case outcome, in which the subsidized firm maximizes its production, engenders \$117 113 of consumer welfare. On the other hand, the best-case consumer welfare with $c_s = 33$ is \$97 013. These results indicate that the per-period cost to consumers when the subsidized firm's cost is high may far outweigh the potential per-period benefits when its cost is low. Furthermore, we see (both theoretically and in the case study), that *all* firms prefer that the subsidized firm produce nothing when $c_s = 27$. Thus, without additional policy constraining the subsidized firm to produce, we would expect its production to be low (if not zero). Ignoring the two highest production levels, consumer surplus ranges between \$97 013 and \$113 212 with $c_s = 27$. Thus, for this setting, consumer welfare decreases, regardless of changes in the subsidized firm's marginal cost. These findings serve to illustrate the possibilities that are indicated by Corollary 1. The specific welfare values vary considerably, as they depend upon market structure and equilibria.

6. Conclusion and Policy Implications

We develop a Nash-Cournot model for analyzing the incentives that are implied by profit guarantees and associated PPAs that have been proposed in a number of jurisdictions. At the time that these arrangements were proposed, some generators faced disproportionately high costs compared to other generating units, which threatened their short-run financial viability. This is represented by the case that we consider in Section 4 of the subsidized firm having a marginal cost of \$33/MWh. The profit guarantees were rationalized on claims that this situation would reverse itself, and that consumers would be worse-off in the long-run if these generators exit the market. Naïvely speaking, the structure of the PPAs and profit guarantees are intended to transfer this future benefit to the generators now, to keep them viable financially until those benefits are realized and consumers are able to recoup the cost of the wealth transfers.

Under realistic assumptions, we demonstrate that the profit guarantee creates incentives for subsidized generators to withhold production from the market, regardless of their costs. Such an outcome negates any purported benefit from the proposed profit guarantees, and creates unnecessary market inefficiencies. There are two market characteristics that are primarily responsible for these outcomes. The first is the price-inelasticity of demand for electricity, which implies that generators benefit from their rivals withholding production. One of our technical contributions is showing that this dynamic persists when the market price is distorted by the wealth transfer that funds the profit guarantee. The potential for perverse incentives is clear from the subsidized firms' indifference between *any* market outcome, because its profit is uncoupled from its production level. The second characteristic is the corporate-separation structure that is prevalent in many jurisdictions. This asset-ownership structure increases the likelihood that utilities act on these perverse incentives. Under complete separation or forced divestiture, the subsidized firm is entirely indifferent among all possible production levels, as its profit is guaranteed under the PPA irrespective of its output decisions. This is not true under *any* level of affiliation. For example, some firms may own both subsidized and unsubsidized generators, which gives them actionable short-run incentives to decrease the output of their subsidized generators, regardless of underlying cost structures. These incentives are illustrated clearly by Figures 1 and 3.

It is unsurprising to find that the subsidy distorts the market-allocation mechanism. On occasion, industrial policy argues for the use of subsidies to prop-up economically unviable firms or industries until such a time that they may become economically viable on their own. Robinson (2009) notes a variety of ways, including tariffs, trade policy, protectionism, tax relief, subsidies, export-processing zones, and state ownership of industry, in which this can be done. According to a comprehensive survey that is conducted by Pack and Saggi (2006), industrial policy is used by governments to support a range of industries, including agriculture, manufacturing, and research and development. Rodrik (2014) provides an extensive analysis of industrial policy in the context of green growth and the adoption of renewable energy. Rodrik (2014) finds that critics of industrial policy tend to argue that the government lacks the information that is necessary to discriminate *ex ante* between industries that ultimately will prove successful and those that will not. Another criticism of industrial policy is that once the government begins insulating certain industries from competition, this invites corruption and rent-seeking behavior. However, Rodrik (2014) contends that market failures that are endemic to green energy, particularly externalities that arise from research and development and the mispricing of greenhouse gases, result in a situation in which government support and promotion of green industries may be socially desirable.

Our analysis demonstrates clearly that the PPA distorts the price mechanism. The purported aim of this distortion is to guarantee the continued operation of certain generating firms, which serves the interests of consumers. Our analysis shows that the PPA performs poorly with respect to these goals. The results of our analysis go beyond this fact, however. Not only does the profit guarantee prop-up economically unviable firms, it goes further to create an incentive for otherwise economically viable firms to restrict output to increase price and overall industry profits. This effect is pronounced particularly under the corporate-separation asset-ownership structure that we examine. This finding is an important policy consideration in evaluating these types of PPAs—the PPA incentivizes outcomes (*i.e.*, restricted output and higher prices) that would be generated by collusive behavior. This result means that the PPA forces consumers to support anticompetitive practices that in a non-regulated industry may invite the scrutiny of antitrust and competition authorities. While regulated utilities are exempt often from traditional antitrust doctrine, such exemptions are not absolute. Wara (2017) explores a variety of issues surrounding antitrust law, anticompetitive practices, and rate regulation in the electricity sector.

The clear implication of this analysis is that PPAs and profit guarantees are likely to fail to accomplish their stated aims. The precise mechanism of failure yields possible ideas or implications for improving the policy intervention. One idea is more stringent corporate separation (or eliminating completely the corporate-separation asset-ownership structure). Such a policy intervention could mitigate the exacerbated incentives for withholding production. However, scrutiny or elimination of corporate separation would not alleviate the indifference of the subsidized firm to its own production level. While corporate separation is no worse than the subsidized and unsubsidized firms being integrated fully, it does create clear perverse incentives that are mitigated if the two firms are forced to separate or divest from one another entirely. A second possibility is to impose bounds on production from the subsidized firm. However, these bounds should depend on whether the subsidized firm would be profitable in the absence of the profit guarantee (*cf.* Figures 2 and 4 and the accompanying discussion). Otherwise, requiring minimum production levels from the subsidized firm may exacerbate consumer- and social-welfare losses. This observation regarding bounds on production from the subsidized firm could lead to a performance-based profit subsidy. Alternatively, Carley et al. (2018); Wolak (2000); Zhou and Solomon (2020) suggest other policy or market-design interventions that could mitigate the perverse incentives that are created by the PPAs and profit guarantees. For instance, a liquid market for financial-hedge contracts may alleviate some of the incentives to exercise market power through withholding the capacity of the subsidized firm(s). The incentive properties of these types of interventions would require close examination, however, and are beyond the scope of our work.

There are aspects of the proposed profit guarantees and PPAs that are beyond the scope of our analysis. For one, we do not examine the claims that the subsidized firms would become cost-competitive with other firms in the future. Rather, the focus of our work is to show that the proposed mechanism to maintain high-cost generators in the market is ill-conceived, inefficient, and creates poor incentives. This result is borne-out by our finding in our case study that the profit guarantee and PPA are guaranteed to decrease social welfare when the subsidized firm is relatively expensive and that it is likely to decrease social welfare when the subsidized firm is relatively inexpensive. Relatedly, we neglect the fact that the profit guarantees and PPAs transfer all cost risk away from generators to consumers. Indeed, if the cost of the subsidized firm does not decline in the future, the profit guarantees may result in consumers bearing costs with no offsetting credits.

Concerns surrounding climate change and other air, water, and health impacts of energy use are another factor that is driving the switch away from coal for electricity production. We do not model directly the impacts of such environmental externalities. We make this modeling choice because the focus of our analysis is on understanding the incentive properties of the proposed PPAs and associated profit guarantees. However, we can draw some conclusions regarding the impacts of such considerations. Specifically, an ostensible goal of the PPAs and profit guarantees is to retain high-cost capacity that is purported to become economic in the future. If one accounts for the environmental attributes of this (mainly coal-fired) capacity, claims that this capacity becomes economic in the future become more tenuous. As such, one may conclude that the PPAs and associated profit guarantees create perverse incentives and force consumers to subsidize capacity that *never* may become economically viable.

Another purported benefit of the profit guarantees and PPAs is that the subsidized generators can hedge against issues of supply reliability or resilience. While system reliability and resilience are important, the focus of our work is on understanding the economic efficiency of the proposed arrangements. Based on our analysis, the efficiency of profit guarantees to ensure system reliability and resilience is questionable.

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Appendix A. Proofs of Propositions

Proof of Proposition 1. Firm i's equilibrium profit is $\pi_i^*(q_i^*, Q_{-i}^*) = [P(q_i^* + Q_{-i}^*) - c_i]q_i^* - F_i$. Differentiating this profit expression with respect to q_j, where $j \neq i$, gives the total derivative:

$$\frac{d}{dq_j}\pi_i^*(q_i^*, Q_{-i}^*) = \frac{\partial}{\partial q_j}\pi_i^*(q_i^*, Q_{-i}^*) + \frac{\partial}{\partial q_i^*}\pi_i^*(q_i^*, Q_{-i}^*)\frac{d}{dq_j}q_i^*. \tag{A.1}$$

In an equilibrium we have, from the first-order necessary condition (FONC) of firm i's profit-maximization problem, that:

$$\frac{\partial}{\partial q_i^*}\pi_i^*(q_i^*, Q_{-i}^*) = 0. \tag{A.2}$$

Thus, (A.1) simplifies to:

$$\frac{d}{dq_j}\pi_i^*(q_i^*, Q_{-i}^*) = \frac{\partial}{\partial q_j}\pi_i^*(q_i^*, Q_{-i}^*). \tag{A.3}$$

We have also that:

$$\frac{\partial}{\partial q_j}\pi_i^*(q_i^*, Q_{-i}^*) = [P(q_i^* + Q_{-i}^*) - c_i]\frac{d}{dq_j}q_i^* + P'(q_i^* + Q_{-i}^*)q_i^*. \tag{A.4}$$

By Assumption 1 we have that $P'(q_i^* + Q_{-i}^*) \leq 0$, thus:

$$\frac{d}{dq_j}\pi_i^*(q_i^*, Q_{-i}^*), \tag{A.5}$$

is non-positive if:

$$\frac{d}{dq_j}q_i^*, \tag{A.6}$$

is. q_i^* is defined by FONC (A.2). Differentiating (A.2) implicitly gives:

$$\frac{d}{dq_j}q_i^* = -\frac{\partial^2}{\partial q_i^* \partial q_j}\pi_i^*(q_i^*, Q_{-i}^*) \Big/ \left[\frac{\partial^2}{\partial q_i^{*2}}\pi_i^*(q_i^*, Q_{-i}^*)\right]. \tag{A.7}$$

The second-order necessary condition (SONC) of firm i's problem gives:

$$\frac{\partial^2}{\partial q_i^{*2}}\pi_i^*(q_i^*, Q_{-i}^*) \leq 0. \tag{A.8}$$

Furthermore, we have that:

$$\frac{\partial^2}{\partial q_i^* \partial q_j}\pi_i^*(q_i^*, Q_{-i}^*) = q_i^* P''(q_i^*, Q_{-i}^*) + P'(q_i^*, Q_{-i}^*) \leq 0, \tag{A.9}$$

where non-positivity of (A.9) follows from Assumptions 1 and 2. Substituting (A.8) and (A.9) into (A.7) gives the desired result. □

Proof of Proposition 2. Equilibrium profit of firm i, where $i \neq s$, is $\tilde{\pi}_i(q_i^*, Q_{-i}^*) = [\tilde{P}(q_i^* + Q_{-i}^*) - c_i]q_i^* - F_i$. Differentiating this profit expression with respect to q_s gives the total derivative:

$$\frac{d}{dq_s}\tilde{\pi}_i(q_i^*, Q_{-i}^*) = \frac{\partial}{\partial q_s}\tilde{\pi}_i(q_i^*, Q_{-i}^*) + \frac{\partial}{\partial q_i^*}\tilde{\pi}_i(q_i^*, Q_{-i}^*)\frac{d}{dq_s}q_i^*, \tag{A.10}$$

which simplifies to:

$$\frac{d}{dq_s}\tilde{\pi}_i(q_i^*, Q_{-i}^*) = \frac{\partial}{\partial q_s}\tilde{\pi}_i(q_i^*, Q_{-i}^*), \tag{A.11}$$

due to the FONC of firm i's profit-maximization problem, which is:

$$\frac{\partial}{\partial q_i^*}\tilde{\pi}_i^*(q_i^*, Q_{-i}^*) = 0. \tag{A.12}$$

Moreover, we have that:

$$\frac{\partial}{\partial q_s}\tilde{\pi}_i(q_i^*, Q_{-i}^*) = [\tilde{P}(q_i^* + Q_{-i}^*) - c_i]\frac{d}{dq_s}q_i^* + \frac{\partial}{\partial q_s}\tilde{P}(q_i^* + Q_{-i}^*)q_i^*. \tag{A.13}$$

The proposition follows from the observation that both terms on the right-hand side of (A.13) are non-positive. To verify this, we consider first the second term. Using the definition of $\tilde{P}(\cdot)$, we want to show that:

$$q_i^*\frac{\partial}{\partial q_s}\tilde{P}(q_i^* + Q_{-i}^*) = \frac{P(q_i^* + Q_{-i}^*) + Q^* P'(q_i^* + Q_{-i}^*) - c_s}{Q_{-s}^*}q_i^* \leq 0. \tag{A.14}$$

Because $Q_{-s}^* \geq 0$ and $q_i^* \geq 0$, we can rearrange the terms in the left-hand side of (A.14) and divide by $P(q_i^* + Q_{-i}^*)$ to obtain the equivalent condition:

$$\frac{Q^* P'(q_i^* + Q_{-i}^*)}{P(q_i^* + Q_{-i}^*)} - \frac{c_s}{P(q_i^* + Q_{-i}^*)} \leq -1. \tag{A.15}$$

Because $c_s \geq 0$, Assumption 3 implies that:

$$q_i^*\frac{\partial}{\partial q_s}\tilde{P}(q_i^* + Q_{-i}^*) \leq 0. \tag{A.16}$$

As for the first term in the right-hand side of (A.13), we assume hereafter that $\tilde{P}(q_i^* + Q_{-i}^*) \geq c_i$ (otherwise, $q_i^* = 0$ and the result is true trivially). Thus, the sign of the first term in the right-hand side of (A.13) depends on the sign of:

$$\frac{d}{dq_s} q_i^*. \tag{A.17}$$

q_i^* is defined by (A.12), the implicit derivative of which is:

$$\frac{d}{dq_s} q_i^* = -\frac{\partial^2}{\partial q_i^* \partial q_s} \tilde{\pi}_i^*(q_i^*, Q_{-i}^*) \Big/ \left[\frac{\partial^2}{\partial {q_i^*}^2} \tilde{\pi}_i^*(q_i^*, Q_{-i}^*) \right]. \tag{A.18}$$

The SONC of firm i's problem requires that:

$$\frac{\partial^2}{\partial {q_i^*}^2} \tilde{\pi}_i^*(q_i^*, Q_{-i}^*) \leq 0. \tag{A.19}$$

Thus, the sign of (A.18) depends on the sign of:

$$\frac{\partial^2}{\partial q_i^* \partial q_s} \tilde{\pi}_i^*(q_i^*, Q_{-i}^*) = q_i^* \frac{\partial^2}{\partial q_i^* \partial q_s} \tilde{P}(q_i^* + Q_{-i}^*) + \frac{\partial}{\partial q_s} \tilde{P}(q_i^* + Q_{-i}^*). \tag{A.20}$$

We consider now two cases, which depend on how large c_s is relative to the equilibrium price.

Case 1: $c_s \geq P(q_i^* + Q_{-i}^*)$
Expanding (A.20) gives:

$$\begin{aligned} \frac{\partial^2}{\partial q_i^* \partial q_s} \tilde{\pi}_i^*(q_i^*, Q_{-i}^*) &= \frac{1}{Q_{-s}^*} \left[P(q_i^* + Q_{-i}^*) + Q^* P'(q_i^* + Q_{-i}^*) - c_s \right] \\ &\quad + \frac{q_i^*}{{Q_{-s}^*}^2} \left[Q_{-s}^* Q^* P''(q_i^* + Q_{-i}^*) + (Q_{-s}^* - q_s^*) P'(q_i^* + Q_{-i}^*) + c_s - P(q_i^* + Q_{-i}^*) \right], \end{aligned} \tag{A.21}$$

which is negative due to $c_s \geq P(q_i^* + Q_{-i}^*)$ and Assumptions 1 and 2.

Case 2: $c_s < P(q_i^* + Q_{-i}^*)$
We have that:

$$\begin{aligned} &\frac{\partial^2}{\partial q_i^* \partial q_s} \tilde{P}(q_i^* + Q_{-i}^*) \\ &\quad = \frac{1}{{Q_{-s}^*}^2} \left[Q_{-s}^* Q^* P''(q_i^* + Q_{-i}^*) + Q_{-s}^* P'(q_i^* + Q_{-i}^*) - q_s^* P'(q_i^* + Q_{-i}^*) + c_s - P(q_i^* + Q_{-i}^*) \right]. \end{aligned} \tag{A.22}$$

Because of Assumption 3, we have that:

$$\frac{Q^* P'(q_i^* + Q_{-i}^*)}{P(q_i^* + Q_{-i}^*)} - \frac{c_s}{P(q_i^* + Q_{-i}^*)} \leq -1. \tag{A.23}$$

Thus, (A.20) and (A.22) are negative if $(Q_{-s}^* - q_s^*) P'(q_i^* + Q_{-i}^*) + c_s - P(q_i^* + Q_{-i}^*) \leq 0$, which is true because $c_s < P(q_i^* + Q_{-i}^*)$ and Assumptions 1, 2, and 4.

Taking these two cases together gives the desired result. □