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by

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Abstract

Load-following forward contracts (LFFCs) are becoming increasingly popular in the electricity sector. A LFFC obligates an electricity supplier to deliver at a pre-specified unit price a fraction of the buyer's ultimate demand for electricity. We show that relative to more standard ("swap") forward contracts, LFFCs can increase the expected wholesale price of electricity and thereby reduce expected consumer surplus and welfare.

Keywords: load-following forward contracts; swap contracts; electricity sector

JEL Codes: L51, L94, Q28, Q40

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1 Introduction

Electricity is commonly purchased and sold in wholesale (spot) markets. The price of electricity can vary widely in such markets, depending on prevailing demand and supply conditions. Forward contracts can avoid the volatility of wholesale market prices by specifying in advance the unit price at which electricity will ultimately be supplied. Forward contracts are prevalent in the electricity sector and elsewhere. Holmberg and Willems (2015, p. 237) report that the total value of transactions governed by forward contracts exceeded 20% of the world's gross domestic product in 2008.[1]

In addition to reducing exposure to volatile wholesale prices, forward contracts can reduce the wholesale price of electricity. This is the case because a supplier's forward commitment reduces the amount of electricity it sells in the wholesale market. The supplier's corresponding reduced exposure to the wholesale price of electricity reduces its concern with any reduction in this price, thereby encouraging the supplier to expand its supply of electricity. The resulting increased supply promotes a lower wholesale price of electricity.

This well-known effect of forward contracts has been demonstrated formally in settings where buyers and sellers can sign swap forward contracts (SFCs). A SFC obligates a supplier to deliver a specified amount of the commodity in question in return for a fixed payment by the buyer (Allaz and Vila, 1993). Forward contracts assume other forms in practice. For example, a load-following forward contract (LFFC) obligates a seller to deliver a specified fraction of the buyer's ultimate demand for the product at a pre-determined unit price. To illustrate, under a LFFC, an electric distribution company (or retailer) that is committed to serve the demand of its retail customers might agree to pay an electricity supplier a pre-specified unit price for 10% of the customers' realized demand for electricity.[2] The

[1]Economic Consulting Associates (2015, Table 14) documents the extensive use of forward contracts in electricity sectors in the European Union. The ensuing analysis focuses on forward contracts for electricity. However, the analysis also applies to other commodities that are bought and sold in wholesale markets.

[2]The electricity supplier could be a particular generator. Alternatively, the supplier might be a third party that secures electricity from other sources and arranges for its delivery to the distribution company (NERA, 2017).

distribution company might purchase the remaining 90% of its customers' demand at the prevailing spot price.

Electric distribution companies in New Jersey and other parts of North America often employ LFFCs to serve customers that do not explicitly choose their preferred retail supplier of electricity (Loxley and Salant, 2004).[3] Retail suppliers of electricity in Australia employ LFFCs to help fulfil their mandate to secure via forward contract a specified fraction of the maximum demand for electricity they anticipate.[4] Some retail service contracts also take the form of LFFCs. In markets with retail competition where vertically-integrated producers (VIPs) compete against competitive retailers, the VIPs often agree to supply electricity to customers at a fixed price for a specified period of time. Such contracts effectively commit the VIP to supply the entire realized demand of its customers at the specified fixed price.

LFFCs differ from SFCs by automatically tailoring a seller's forward commitment to the realized demand for its product. In particular, an electricity generator that signs a LFFC commits itself to remove more output from exposure to the wholesale price as realized demand increases. The generator thereby commits itself to compete particularly aggressively in the wholesale market when demand is high and less aggressively when demand is less low. Such tailoring of competitive aggression to realized demand can be valuable for a generator because increased wholesale output can be particularly profitable when demand is pronounced. This is the case because high demand promotes a relatively high wholesale price, and thus a relatively large profit margin for the generator.

The ability of LFFCs to tailor a generator's competitive aggression to realized demand can promote their widespread adoption. We show that in a setting designed to reflect conditions that prevail in the wholesale electricity market in Alberta, Canada, generators

[3]Electric distribution companies that are not vertically integrated commonly sign LFFCs in many jurisdictions other than New Jersey. These jurisdications include Alberta in Canada and Connecticut, Delaware, Massachusetts, Maine, Maryland, New Hampshire, New Jersey, Ohio, Pennsylvania, Rhode Island, and Washington, DC in the U.S. (NERA, 2017; Littlechild, 2018).

[4]The Australian Energy Regulator (AER) imposes this mandate on retail suppliers of electricity in part to help generators secure long-term contracts for electricity supply rather than have to rely on sales in volatile wholesale markets. LFFCs are among the forward contracts explicitly authorized by the AER (AER, 2019).

adopt LFFCs exclusively when they have the option to sign LFFCs, SFCs, or both. The equilibrium adoption of LFFCs serves to increase expected consumer surplus and welfare above the levels that arise in the absence of forward contracting.[5] However, equilibrium expected consumer surplus and welfare fall below the levels that would arise if SFCs were the only feasible forward contracts. The reduced consumer surplus and welfare reflect the relatively limited competitive aggression that LFFCs foster when realized demand is low.

Our analysis builds upon many studies that examine the effects of forward contracting on wholesale market competition. These studies include Allaz and Vila (1993)'s seminal investigation of SFCs. Like Allaz and Vila and much of the ensuing literature, we assume industry participants are risk neutral in order to focus on the strategic role of forward contracting rather than its risk-hedging properties.[6,7]

Several studies examine the strategic role that financial instruments other than SFCs can play. For example, Willems (2006) permits firms to sign SFCs and call options before engaging in Cournot competition. The author finds that, in equilibrium, call options enhance the pro-competitive effect of forward contracts.[8] Holmberg and Willems (2015) allow firms to choose SFCs and a portfolio of call options before competing via supply functions in the wholesale market. In this setting, firms commit to produce less output as the prevailing wholesale price increases. This commitment to downward-sloping supply functions enhances profit by reducing the intensity of wholesale market competition.[9,10]

[5]Unilateral adoption of LFFCs enhances a generator's expected profit. In contrast, ubiquitous adoption of LFFCs by all generators reduces expected industry profit below the levels that arise in the absence of forward contracting (as in Allaz and Vila's (1993) model of swap forward contracting).

[6]Empirical studies document the pro-competitive strategic effects of forward contracts in electricity markets (e.g., Wolak, 2000, 2007; Bushnell et al., 2008).

[7]Several studies analyze the risk-hedging role that forward contracts can play (e.g., Bessembinder and Lemmon, 2002; Longstaff and Wang, 2004; Aid et al., 2011). Eijkel et al. (2016) find that forward contracts provide both strategic and risk-hedging benefits in Dutch natural gas wholesale markets.

[8]Willems and Morbee (2010) extend Bessembinder and Lemmon (2002)'s model to include both swap contracts and option contracts. The authors find that welfare and capacity investment generally increase as the number of financial instruments expands due to the associated enhanced risk-hedging capabilities.

[9]Newbery (1998), Green (1999), and Holmberg (2011) also examine settings where firms compete by choosing supply functions. The authors find that forward contracting is weakly pro-competitive in a setting where forward contracting is limited to SFCs.

[10]Willems et al. (2006) examine the extent to which models with supply function competition and models

Other studies identify additional means by which forward contracts can limit the intensity of competition. Mahenc and Salanie (2004) demonstrate how firms can purchase forward quantities to commit themselves to subsequently set higher prices for their differentiated products. Liski and Montero (2006) and Green and Le Coq (2010) conclude that forward contracting can reduce the critical discount factor above which collusive agreements are sustainable in infinitely-repeated games.

Our analysis complements these studies in three primary ways. First, to the best of our knowledge, we are the first to analyze formally the endogenous choice of LFFCs and SFCs. We thereby contribute to the literature that examines how an expanded set of forward contracts affects strategic firm behavior and associated industry outcomes. Second, our analysis provides a nuanced view of how expanded forward contracting affects the intensity of wholesale market competition. We show that LFFCs can simultaneously produce relatively intense competition when market demand is high while inducing relatively limited competition when demand is low. Third, our analysis can help policymakers better understand the benefits and costs of LFFCs. This information is important because LFFCs are increasingly being advocated for use by electric distribution companies, particularly those that serve as default suppliers in settings with retail competition (NERA, 2017).[11]

Our analysis proceeds as follows. Section 2 describes our model. Section 3 explains how LFFCs affect equilibrium outcomes by altering generators' reactions functions. Section 4 examines the effects of LFFCs numerically in a setting designed to reflect conditions in Alberta's wholesale electricity market. Section 5 concludes.

with Cournot competition are consistent with observed data. The authors set relevant parameters exogenously to match equilibrium behavior to observed market outcomes in a model where firms can sign SFCs and LFFCs. In contrast, we model the endogenous choices of SFCs and LFFCS in a setting where firms subsequently compete in wholesale markets via Cournot competition.

[11]Ongoing concerns about limited competition in retail electricity markets (e.g., Littlechild, 2018; ACIL, 2020) have led to increasing calls for incumbent utilities to serve as default suppliers of electricity and for the corresponding expanded use of LFFCs by utilities.

2 Model Elements

We consider a setting with two electricity generators (G1 and G2) and one aggregate electricity consumer. Gi produces electricity at constant marginal cost $c_i > 0$ ($i \in \{1, 2\}$).[12] The consumer's demand function and inverse demand function for electricity are, respectively

$$Q(P, \varepsilon) \;=\; a + \varepsilon - b\,P \quad \text{and} \quad P(Q, \varepsilon) \;=\; \frac{a+\varepsilon}{b} - \frac{1}{b}\,Q \tag{1}$$

where Q denotes quantity, P denotes price, a and b are constants, and $a > b\,c_i > 0$ for $i \in \{1, 2\}$. $\varepsilon \in [\,\underline{\varepsilon}, \overline{\varepsilon}\,]$ is the realization of a random demand parameter with zero mean and strictly positive variance. $H(\varepsilon)$ is the cumulative distribution function for ε.

The generators sell electricity in a wholesale market. They can also sign forward contracts before the wholesale market operates. A swap forward contract (SFC) imposes a financial obligation on a generator to deliver one unit of electricity at fixed price $p^S > 0$ immediately after the wholesale price of electricity is determined. A load-following forward contract (LFFC) imposes a financial obligation on a generator to deliver a load strip at a fixed unit price for electricity, p^L, immediately after the wholesale price of electricity is determined. A load strip is the fraction $\alpha \in (0, 1)$ of the realized consumption of electricity.[13]

$q_i^*(\varepsilon)$ is Gi's equilibrium output when demand parameter ε is realized.[14] $Q^*(\varepsilon) = q_1^*(\varepsilon) + q_2^*(\varepsilon)$ and $P^*(\varepsilon) = P(Q^*(\varepsilon), \varepsilon)$ are the corresponding total output and wholesale price of electricity, respectively. When Gi signs S_i SFCs and L_i LFFCs, its equilibrium profit when ε is realized is:

$$\pi_i^*(\varepsilon) \;=\; P^*(\varepsilon)\,[\,q_i^*(\varepsilon) - L_i\,\alpha\,Q^*(\varepsilon) - S_i\,] - c_i\,q_i^*(\varepsilon) + p^S\,S_i + p^L\,L_i\,\alpha\,Q^*(\varepsilon)\,. \tag{2}$$

$q_i - L_i\,\alpha\,Q - S_i$ is the amount of Gi's output that is exposed to (i.e., ultimately sold at) the wholesale price. $p^S\,S_i + p^L\,L_i\,\alpha\,Q$ is Gi's revenue from forward sales of electricity.

[12] We consider constant marginal costs for analytic tractability. The numerical solutions derived in Section 4 admit non-constant marginal costs.

[13] Formally, if it signs S_i SFCs, Gi secures net payment $\left[\,p^S - P\,\right] S_i$ when wholesale price P is realized. Similarly, if it signs L_i LFFCs, Gi secures net payment $\left[\,p^L - P\,\right] L_i\,\alpha\,Q$ when wholesale price P and equilibrium consumption Q are realized.

[14] Here and throughout the ensuing discussion, the superscript "$*$" denotes an equilibrium outcome. We analyze subgame perfect Nash equilibria.

The forward positions of generators are observed publicly. Furthermore, forward markets are efficient, so the unit price of electricity in a SFC is the expected wholesale price of electricity.[15] Formally:

$$p^S \;=\; E\,\{\,P^*(\varepsilon)\,\} \tag{3}$$

where $E\{\cdot\}$ denotes expectation with respect to ε. Similarly, the expected payment for a load slice in a LFFC is the expected wholesale revenue from the load slice, i.e.,

$$p^L\,E\,\{\,\alpha\,Q^*(\varepsilon)\,\} \;\;=\;\; E\,\{\,P^*(\varepsilon)\,\alpha\,Q^*(\varepsilon)\,\}$$

$$\Rightarrow\;\; p^L \;=\; \frac{E\,\{\,P^*(\varepsilon)\,Q^*(\varepsilon)\,\}}{E\,\{\,Q^*(\varepsilon)\,\}} \;=\; E\,\{\,P^*(\varepsilon)\,\} + \frac{cov\,(P^*(\varepsilon),\,Q^*(\varepsilon)\,)}{E\,\{\,Q^*(\varepsilon)\,\}} \tag{4}$$

where $cov\,(\,\cdot\,)$ denotes "covariance."[16]

Equations (2) – (4) imply that Gi's expected equilibrium profit when it signs S_i SFCs and L_i LFFCs is:

$$\begin{aligned} E\,\{\,\pi_i^*(\varepsilon)\,\} \;\;&=\;\; E\,\{\,P^*(\varepsilon)\,[\,q_i^*(\cdot) - L_i\,\alpha\,Q^*(\varepsilon) - S_i\,] - c_i\,q_i^*(\varepsilon)\,\} + E\,\{\,P^*(\varepsilon)\,\}\,S_i \\ &+\;\; E\,\{\,P^*(\varepsilon)\,L_i\,\alpha\,Q^*(\varepsilon)\,\} \;\;=\;\; \int_{\underline{\varepsilon}}^{\overline{\varepsilon}} [\,P^*(\varepsilon) - c_i\,]\,q_i^*(\varepsilon)\,dH(\varepsilon)\,. \end{aligned} \tag{5}$$

The timing in the model is as follows. Initially, G1 makes a binding commitment to (L_1, S_1) and G2 makes a binding commitment to (L_2, S_2), simultaneously and non-cooperatively. Then the demand parameter (ε) is realized. Next, G1 chooses q_1 and G2 chooses q_2, simultaneously and non-cooperatively. Finally, the market-clearing wholesale price of electricity is established, output is purchased in the wholesale market, and the terms of all forward contracts are fulfilled.

[15] Holmberg and Willems (2015, pp. 241-2) observe that forward markets will be efficient when risk-neutral, non-strategic actors with rational expectations ensure the price of each forward contract reflects the expected value of the contract. The authors explain why the assumption often constitutes a reasonable caricature of electricity forward markets and observe that the assumption is common in the literature.

[16] The expression in (4) reflects the fact that for two random variables X and Y, $cov\,(X,Y) \,=\, E\,\{X\,Y\} - E\,\{X\}\;E\,\{Y\}$.

3 Strategic Effects of Forward Contracts

A generator can employ forward contracts to enhance its aggression in the wholesale market (Allaz and Vila, 1993). To determine how SFCs and LFFCs differ in this regard, it is instructive to consider two benchmark settings. In Setting N, no forward contracting is permitted, so the generators sell all of the output they produce in the wholesale market. In Setting SO, generators can sell output in the wholesale market and sign SFCs (but not LFFCs). In Setting M, the setting of primary interest, generators can sell output in the wholesale market and sign either SFCs or LFFCs or both.[17] The ensuing analysis employs the superscript "n" to denote outcomes in Setting N, the superscript "s" to denote outcomes in Setting SO, and the superscript "m" to denote outcomes in Setting M.

Lemma 1 characterizes the generators' reaction functions in Settings N, SO, and M.[18] Generator i (Gi)'s reaction function specifies Gi's profit-maximizing output ($q_i(\varepsilon)$) when demand parameter ε is realized for each level of output ($q_j(\varepsilon)$) the rival generator, Gj, might produce.

Lemma 1. *The output reaction functions for Generator i in Settings N, SO, and M are, respectively (for $i, j \in \{1, 2\}$ $(j \neq i)$):*

$$q_i^n(\varepsilon) = \frac{1}{2}\left[a + \varepsilon - b\, c_i \right] - \frac{1}{2}\, q_j^n(\varepsilon)\,;$$

$$q_i^s(\varepsilon) = \frac{1}{2}\left[a + \varepsilon - b\, c_i + S_i^s \right] - \frac{1}{2}\, q_j^s(\varepsilon)\,;$$

$$q_i^m(\varepsilon) = \frac{1}{2}\left[a + \varepsilon - b\, c_i + S_i^m \right] + \frac{\alpha\, L_i^m \left[S_i^m + b\left(p^L - c_i\right) \right]}{2\left[1 - \alpha\, L_i^m \right]} - \left[\frac{1 - 2\,\alpha\, L_i^m}{1 - \alpha\, L_i^m} \right] \frac{1}{2}\, q_j^m(\varepsilon). \quad (6)$$

It is well known that the generators' outputs are strategic substitutes in Setting N, i.e., $\frac{\partial q_i^n(\cdot)}{\partial q_j^n(\cdot)} < 0$ (Bulow et al., 1985). As one generator increases its output, the wholesale price of electricity ($P(\cdot)$) declines. The reduction in $P(\cdot)$ reduces the rate at which the rival

[17] "N" denotes no forward contracting. "SO" denotes SFCs only. "M" denotes the feasibility of multiple types of forward contracts.

[18] Lemma 1 considers parameter values for which the profit-maximizing outputs of G1 and G2 are both strictly positive. See the Appendix for the proof of Lemma 1 and all subsequent formal conclusions.

generator's profit increases as its output increases. Consequently, the rival generator reduces its output.

Allaz and Vila (1993) demonstrate that the generators' outputs are also strategic substitutes in Setting SO. Furthermore, it is apparent from Lemma 1 that outputs are strategic substitutes in Setting M if each generator's load-following forward (LFF) commitment is less than one half of realized demand, as Corollary 1 reports.

Corollary 1. *(i)* $\frac{\partial q_i^n(\cdot)}{\partial q_j^n(\cdot)} < 0$*; (ii)* $\frac{\partial q_i^s(\cdot)}{\partial q_j^s(\cdot)} < 0$*; and (iii)* $\frac{\partial q_i^m(\cdot)}{\partial q_j^m(\cdot)} < 0$ *if* $\alpha L_i^m \in (0, \frac{1}{2})$ *for* $i, j \in \{1, 2\}$ *(*$j \neq i$*).*

When a generator (Gi) has signed LFFCs, an increase in its output (q_i) has two countervailing effects. First, the increased output reduces the wholesale price, $P(\cdot)$. Second, by increasing equilibrium consumption, the enhanced output increases the generator's LFF commitment. This expanded commitment reduces the generator's exposure to $P(\cdot)$, i.e., reduces the amount of output the generator will sell in the wholesale market at unit price $P(\cdot)$. The first effect reduces the rate at which the generator's profit increases with its output. The second effect increases this rate. The first effect dominates the second when a generator's LFF commitment is less than one half of realized consumption. Consequently, in this case, a generator reduces its output in response to increased output by the rival generator. Each generator in fact implements a LFF commitment that is less than one half of realized demand in all the equilibria that arise in the setting considered in Section 4. Therefore, we focus on these equilibria in the ensuing analysis.[19]

Corollary 2 reports that after a generator (Gi) signs LFFCs ($L_i \in (0, \frac{1}{2\alpha})$), it reduces its output more slowly as the rival generator increases its output. In this sense, LFFCs induce a generator to become less accommodating of an increase in its rival's output. Formally, as illustrated in Figure 1, Gi reduces the slope of its reaction function in (q_j, q_i) space by

[19] In principle, the consumer might agree to purchase from a generator (e.g., G1) at a specified forward price more than half of the consumer's ultimate demand. In this event, G1 would increase its output in response to increased output by G2 (q_2) because the predominant effect of an increase in q_2 would be to reduce the amount of output G1 sells in the wholesale market at price $P(\cdot)$, rather than to reduce $P(\cdot)$.

signing LFFCs ($L_i^m \in (0, \frac{1}{2\,\alpha})$).

Corollary 2. *Suppose* $\alpha\, L_i^m \in (0, \frac{1}{2})$ *for* $i = 1, 2$. *Then* $\left|\frac{\partial q_i^n(\cdot)}{\partial q_j^n(\cdot)}\right| = \left|\frac{\partial q_i^s(\cdot)}{\partial q_j^s(\cdot)}\right| = \frac{1}{2}$ *and* $\left|\frac{\partial q_i^m(\cdot)}{\partial q_j^m(\cdot)}\right| \in \left(0, \frac{1}{2}\right)$ *for* $i, j \in \{1, 2\}$ *(*$j \neq i$*).*

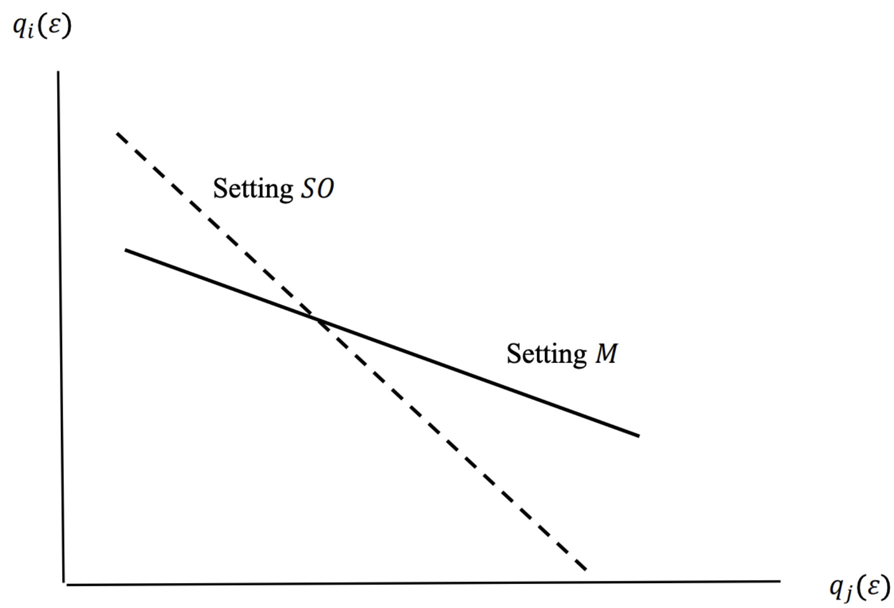


Figure 1: Generator i's Reaction Function in Settings SO and M with $L_i^m \in \left(0, \frac{1}{2\alpha}\right)$.

LFFCs render a generator less accommodating for the following reason. When $L_i^m > 0$, Gi's LFF commitment increases as its rival's output (q_j) increases because equilibrium consumption (and thus Gi's LFF commitment) increases as q_j increases. The increased LFF commitment reduces Gi's exposure to the wholesale price ($P(\cdot)$), thereby ensuring that Gi's profit declines more slowly as $P(\cdot)$ declines. The reduced sensitivity of Gi's profit to reductions in $P(\cdot)$ increases the rate at which Gi's profit increases as its output increases. Consequently, Gi produces more output than it would produce in the absence of a LFF commitment, *ceteris paribus*.

Next we examine how the shape and position of reaction functions change as the extent of forward contracting increases. Corollary 3 reviews the effects of increased swap forward contracting on a generator's reaction function in Setting SO. Proposition 1 characterizes the corresponding effects in Setting M. The proposition abstracts from the impact of SFCs on p^L, the unit price of electricity in a LFFC.[20]

Corollary 3. *(Allaz and Vila, 1993).* $\frac{\partial q_i^s(\cdot)}{\partial S_i^s} = \frac{1}{2} > 0$ *and* $\frac{\partial}{\partial S_i^s}\left|\frac{\partial q_i^s(\cdot)}{\partial q_j^s(\cdot)}\right| = 0$ *for* $i,\, j \in \{1,2\}$ *($j \neq i$), so expanded swap forward contracting shifts a generator's reaction function outward in parallel fashion in Setting SO.*

Proposition 1. *Suppose* $\alpha\, L_i^m \in (0, \frac{1}{2})$ *for* $i = 1, 2$. *Then: (i)* $\left.\frac{\partial q_i^m(\cdot)}{\partial S_i^m}\right|_{dp^L = 0} > 0$*; (ii)* $\left.\frac{\partial^2 q_i^m(\cdot)}{\partial \left(S_i^m\right)^2}\right|_{dp^L = 0} = 0$*; and (iii)* $\frac{\partial}{\partial S_i^m}\left|\frac{\partial q_i^m(\cdot)}{\partial q_j^m(\cdot)}\right|_{dp^L = 0} = 0$ *for* $j \neq i$ *($i, j \in \{1,2\}$).*

Proposition 1 reports that expanded swap forward contracting shifts a generator's reaction function outward in a parallel manner in Setting M, just as it does in Setting SO. This conclusion reflects the following considerations. As Gi's swap forward commitment (S_i^m) increases, Gi's exposure to the wholesale price ($P(\cdot)$) declines, causing Gi's profit to decline less rapidly as $P(\cdot)$ declines. The reduced sensitivity of Gi's profit to $P(\cdot)$ induces Gi to increase its output (which reduces $P(\cdot)$) for any given level of its rival's output, q_j. In the presence of linear demand, Gi's profit-maximizing output increases with S_i^m at the same rate for all levels of q_j. Consequently, an increase in S_i^m shifts Gi's reaction function outward in parallel fashion.

Proposition 2 reports that expanded LFF contracting has related, but distinct, effects on reaction functions.

Proposition 2. *Suppose* $\alpha\, L_i^m \in (0,\, \frac{1}{2})$ *and* $p^L > c_i$ *for* $i \in \{1,2\}$. *Then* $\left.\frac{\partial q_i^m}{\partial L_i^m}\right|_{dp^L = 0} > 0$ *and* $\left.\frac{\partial^2 q_i^m}{\partial \left(L_i^m\right)^2}\right|_{dp^L = 0} > 0$.

Proposition 2 reports that, abstracting from the impact of expanded forward contracting on p^L,[21] increases in $L_i^m \in (0,\, \frac{1}{2\,\alpha})$ shift Gi's reaction function outward at an increasing rate

[20] This impact is considered in Proposition 4.

[21] Proposition 4 considers the impact of L_i^m on p^L.

when p^L exceeds Gi's marginal cost (c_i).[22] As L_i^m increases, more of Gi's output is sold at forward price $p^L > c_i$ and less is sold at the wholesale price ($P(\cdot)$). Therefore, Gi's profit declines less rapidly as $P(\cdot)$ declines and Gi's profit-maximizing level of output increases for any specified level of its rival's output. Gi's profit-maximizing output increases with L_i^m at an increasing rate because the larger is L_i^m, the more rapidly Gi's LFF commitment increases as equilibrium output increases. The more rapid increase in Gi's LFF commitment reduces Gi's exposure to $P(\cdot)$ and increases its forward sales more rapidly. Both these effects increase the rate at which Gi's profit increases with its output.

Proposition 3 identifies the effects of LFFCs on the slope of Gi's reaction function.

Proposition 3. *Suppose* $\alpha\, L_i^m \in (0, \frac{1}{2})$ *for* $i = 1, 2$. *Then for* $i, j \in \{1, 2\}$ *(*$j \neq i$*),* $\frac{\partial}{\partial L_i^m} \left| \frac{\partial q_i^m}{\partial q_j^m} \right|_{dp^L = 0} < 0$ *and* $\frac{\partial}{\partial L_i^m} \left| \frac{\partial}{\partial L_i^m} \left| \frac{\partial q_i^m}{\partial q_j^m} \right| \right|_{dp^L = 0} > 0.$

Proposition 3 reports that increases in L_i^m reduce the slope of Gi's reaction function (in (q_j, q_i) space) at an increasing rate. In this sense, a generator becomes less accommodating at an increasing rate as it signs more LFFCs. As L_i^m increases, Gi's LFF commitment increases, thereby reducing Gi's exposure to the wholesale price ($P(\cdot)$). The reduced exposure ensures that Gi's profit declines less rapidly as $P(\cdot)$ declines. The reduced sensitivity of profit to reductions in $P(\cdot)$ increases the rate as which Gi's profit increases with q_i. Consequently, as $L_i^m \in (0, \frac{1}{2\alpha})$ increases, Gi reduces q_i more slowly as q_j increases, as illustrated in Figure 2.

This reduced accommodation becomes more pronounced as L_i^m increases. The larger is L_i^m, the more rapidly Gi's LFF commitment increases as q_j increases (which increases equilibrium output and thereby increases Gi's LFF commitment). The more rapid increase in Gi's LFF commitment reduces Gi's exposure to $P(\cdot)$ to a greater extent, thereby increasing the rate at which Gi's profit increases as q_i increases.

SFCs differ from LFFCs in part by requiring a generator to remove the same fixed amount of output from exposure to the wholesale price for all demand realizations (ε). Consequently,

[22] p^L always exceeds each generator's marginal cost in the Alberta setting described in Section 4.

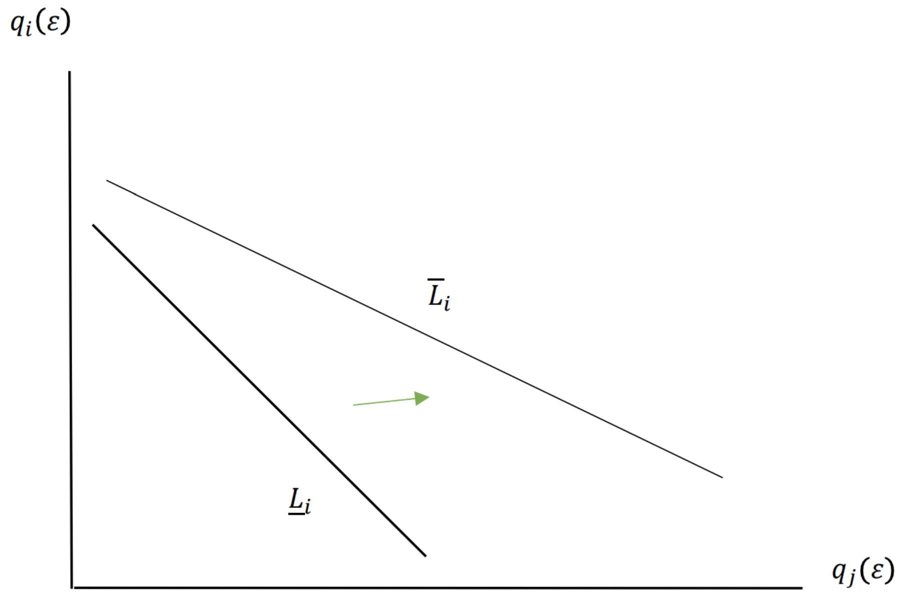


Figure 2: The Effect of Increased LFFCs ($\overline{L}_i > \underline{L}_i$) on G$i$'s Reaction Function.

when SFCs constitute the only source of forward commitment, a generator that wishes to commit to remove a large amount of output from exposure to the wholesale price when ε is high must remove the same large output from such exposure when ε is low. Yet the benefits of reduced exposure to $P(\cdot)$ vary with ε. When ε is high, the equilibrium wholesale price, and thus a generator's profit margin, typically are relatively large. Consequently, the generator's profit increases relatively rapidly as its output increases (despite the associated reduction in $P(\cdot)$). In contrast, the generator's profit margin typically is relatively small when ε is low. Consequently, the generator's profit increases relatively slowly as its output increases. Therefore, reduced exposure to $P(\cdot)$, which induces increased output, tends to be particularly valuable to a generator when ε is high.[23]

LFFCs enable a generator to remove more output from exposure to $P(\cdot)$ as ε increases. A generator's forward commitment under an LFFC increases as ε, and thus realized consumption, increases. Consequently, by signing LFFCs, a generator can commit to remove a relatively

[23] When ε is particularly low, a large forward commitment can induce a generator to become a net buyer of wholesale electricity rather than a net seller. In this event, the generator will prefer a lower wholesale price to a higher wholesale price, which can encourage particularly pronounced output expansion (Hortaçsu and Puller, 2008).

large amount of output from exposure to $P(\cdot)$ precisely when the associated commitment to increase output relatively rapidly is particularly profitable.

The foregoing observations suggest three reasons why generators might rely extensively, if not exclusively, on LFFCs to establish their forward commitments in Setting M. First, LFFCs serve two strategic functions whereas SFCs serve only one such function. LFFCs and SFCs both shift a generator's reaction function outward, thereby committing the generator to expand its equilibrium output. However, only LFFCs also render a generator less accommodating of increases in its rival's output, thereby further enhancing a generator's commitment to expand its equilibrium output.

Second, the strategic commitment effects of LFFCs strengthen as a generator's LFF commitment increases. The increasing marginal effectiveness of LFFCs can promote their predominant, or even exclusive, use.

Third, LFFCs enable generators to tailor their forward commitments to realized demand (ε) whereas SFCs do not admit such tailoring. In particular, LFFCs enable a generator to commit to increase its output particularly aggressively when ε, and thus the generator's profit margin ($P(\cdot) - c_i$), are high, which is precisely when the generator's profit increases relatively rapidly as its output increases.

LFFCs allow generators to secure the large forward commitments they find profitable when ε is relatively high while implementing smaller forward commitments when ε is relatively low. Consequently, the equilibrium expected forward coverage – the ratio of expected forward output to expected total output – may be smaller in Setting M than in Setting SO. Formally, $\frac{S_1^m + S_2^m + \alpha \left[L_1^m + L_2^m \right] E\{ q_1^m + q_2^m \}}{E\{ q_1^m + q_2^m \}}$ may be smaller than $\frac{S_1^s + S_2^s}{E\{ q_1^s + q_2^s \}}$ in equilibrium.

The analysis to this point has abstracted from the impact of expanded forward contracting on p^L, the unit price of electricity under an LFFC. Proposition 4 reports that p^L declines as the number of SFCs or LFFCs increases in Setting M as long as the intercept of the demand curve is sufficiently large relative to the generators' marginal costs.[24]

[24]This sufficient (but not necessary) condition helps ensure that equilibrium profit is maximized at strictly positive output levels.

Proposition 4. *Suppose* $a > b\,[\,c_1 + c_2\,]$ *and* $\alpha\, L_i^m \in (0, \frac{1}{2})$ *for* $i = 1, 2$*. Then* $\frac{\partial p^L}{\partial S_i^m} < 0$ *and* $\frac{\partial p^L}{\partial L_i^m} < 0$.

For the reasons explained above, wholesale market competition intensifies as the number of SFCs or LFFCs increases in Setting M. The more intense competition reduces the expected wholesale price of electricity, and thus the unit price of electricity under SFCs and LFFCs.

Propositions 1 – 4 indicate that although expanded forward contracting can enhance a generator's profit by helping it to commit to produce a relatively large level of output, expanded forward contracting can diminish a generator's profit by reducing both the wholesale price and the forward price of electricity. Furthermore, as expanded forward contracting by one generator increases (or reduces) its profit, the expanded contracting can reduce (or increase) the rival's profit. These varied and often countervailing effects of expanded forward contracting complicate the derivation of general analytic conclusions about equilibrium levels of forward contracts and corresponding equilibrium outcomes. Therefore, we examine these outcomes numerically in settings designed to reflect key elements of actual industry conditions.

4 Application: The Alberta Electricity Market

We now examine the effects of LFFCs in a generalization of our model that is designed to reflect key elements of Alberta's wholesale electricity market. The generalization allows for more than two generators, increasing marginal costs, and must-run (e.g., wind) generation.

4.1 Alberta's Electricity Market and Data

Alberta's wholesale electricity market operates as a single real-time hourly uniform-price procurement auction.[25] A generator can submit as many as seven price-quantity offer blocks for each of its generation units in each auction. An offer price, which must lie between \$0/MWh and \$999.99/MWh, represents the price at which a generator is willing to supply

[25]Many jurisdictions operate both day-ahead and real-time balancing wholesale makets.

the specified amount of electricity.

In each auction, the generators' bids are arranged in order of increasing unit price. Throughout the hour, the Alberta Electric System Operator (AESO) calls upon generation units to supply electricity in order of their offer prices (lowest to highest) until sufficient supply has been acquired to match prevailing demand. The price bid by the last unit to be called upon serves as the system marginal price (SMP). Each generation unit that is called upon to supply electricity is paid the pool price, which is the average SMP.[26]

Aside from the $999.99/MWh upper bound, bid prices are not restricted in the Alberta market (MSA, 2011, 2020b).[27] Consequently, generators may have the ability to exercise considerable market power during periods of peak demand (Brown and Olmstead, 2017). This renders the Alberta market well-suited to analyze strategic generator behavior.

The five largest generators in Alberta are TransAlta, ATCO, ENMAX, Capital Power, and Suncor. In 2019, these generators accounted for 21.0%, 12.7%, 9.3%, 7.2%, and 7.4% of market capacity, respectively (MSA, 2020a).[28] A competitive fringe consisting of thirty-seven smaller firms accounted for the remaining capacity.[29] Natural gas, coal, and wind units account for 46.2%, 34.7%, and 10.1%, respectively. 70.7% of the natural gas capacity (32.7% of market capacity) reflects cogeneration facilities that generate electricity as a by-product of on-site industrial processes (e.g., mining in Alberta's oil sands) (AUC, 2020). Such generation capacity is best viewed as "must-run" (and typically is bid at $0/MWh) rather

[26] A SMP reflects the lowest bid that ensures market supply is sufficient to meet the prevailing market demand. The SMP adjusts as demand and supply conditions change. The pool price for a specified hour is the time-weighted average of the SMPs during the hour.

[27] Bid prices often are restricted in markets where generators receive explicit capacity payments in addition to revenue from electricity sales (Cramton et al., 2013).

[28] The majority of ATCO's assets were sold to Heartland Generation on September 30, 2019 (MSA, 2020a). For expositional ease, we treat the assets as being owned by a single entity (that we refer to as "ATCO") throughout 2019.

[29] A large firm called the Balancing Pool (BP) had offer control of 14.7% of market capacity in 2019 (MSA, 2020a). The BP is a government entity that effectively serves as the owner of several large coal units that were previously subject to Power Purchase Arrangements (PPAs). The PPAs were organized during the period of market restructuring in the early 2000's to reduce market concentration. The BP has no explicit mandate that governs its bids. However, observed behavior and discussions with regulators suggest the BP tenders bids that reflect prevailing short-run marginal costs, thereby behaving like a perfectly competitive firm.

than dispatchable (flexible). Suncor's capacity consists entirely of cogeneration facilities, so we focus on the four remaining major generators with flexible capacity.

We employ data from the AESO on hourly bids, unit level production, import supply, import capacity limits, and market demand for the period January 1, 2019 – December 31, 2019.

4.2 Empirical Model and Solution Approach

We assume four competing generators (G1, G2, G3, G4) supply electricity during T periods. In the first stage in each period, generators choose SFCs and LFFCs simultaneously and non-cooperatively.[30] In the second-stage, after demand is realized, generators determine their wholesale quantities simultaneously and independently, taking as given the established forward positions.

Let $C_{it}(q)$ denote Gi's total cost of producing q units of flexible output in period t. In addition to delivering flexible output (q_{it}) in period t, Gi delivers $q_{it}^{mr} \geq 0$ units of must-run generation (e.g., wind and cogeneration) at zero marginal cost. The total output of the four large generators in period t is $Q_t = \sum_{i=1}^{4} (q_{it}^{mr} + q_{it})$. $P_t(Q_t, \varepsilon_t)$ denotes the inverse residual demand function the four large generators face collectively in period t. Residual demand is total demand less the sum of supply delivered by the price-taking fringe and net imports from neighboring jurisdictions.[31] $\varepsilon_t \in [\,\underline{\varepsilon}_t, \overline{\varepsilon}_t\,]$ is the realization of a stochastic, additive component of demand in period t. $H_t(\varepsilon_t)$ denotes the distribution function for ε_t in period t.

The model is solved via backward induction in this *Alberta setting*. In period t in Setting M, Gi takes its SFCs (S_{it}) and LFFCs (L_{it}) as given and chooses q_{it} to maximize:[32]

$$\pi_{it}(q_{1t}, ..., q_{4t}) \;=\; P_t(Q_t, \varepsilon_t)\,[\,q_{it} + q_{it}^{mr} - \alpha\, L_{it}\, Q_t - S_{it}\,] - C_{it}(q_{it}) + p_t^L\, L_{it} + p_t^S\, S_{it}$$
$$\text{subject to:} \quad q_{it} \;\geq\; 0\,. \tag{7}$$

Let $\lambda_{it} \geq 0$ denote the Lagrange multiplier associated with the constraint in (7). Also let

[30] Generators can and do sign SFCs and LFFCs in Alberta (MSA, 2010; NERA, 2019).

[31] This formulation assumes the large generators base their production decisions on accurate beliefs about the supply function of the competitive fringe and imports from neighboring jurisdictions.

[32] For expositional ease, the notation in this section does not employ the superscript m.

$\perp$ denote complementarity. Then expression (7) implies that Gi's choice of output in period t is determined by:

$$\frac{\partial P_t(\cdot)}{\partial Q_t} \left[q_{it} + q_{it}^{mr} - \alpha \, L_{it} \, Q_t - S_{it} \right] + P_t(Q_t, \varepsilon_t) \left[1 - \alpha \, L_{it} \right] - C'_{it}(q_{it}) + \lambda_{it} \;=\; 0 \, ;$$

$$q_{it} \;\geq\; 0 \quad \perp \quad \lambda_{it} \;\geq\; 0 \quad \text{for} \;\; i \;=\; 1, ..., 4 \, . \tag{8}$$

Each generator's choice of forward position is specified as a stochastic mathematical program with equilibrium constraints (SMPEC), treating the equilibrium conditions in expression (8) as constraints for each realization of ε_t. Assuming forward markets are efficient, equation (5) implies that Gi's choice of S_{it} and L_{it} in period t is determined by:

$$\underset{S_{it}, \, L_{it}}{\text{Maximize}} \;\; E \left\{ \pi_{it}(\cdot) \right\} \;\;=\;\; \int_{\underline{\varepsilon}_t}^{\overline{\varepsilon}_t} \left\{ \, P_t(Q_t(\varepsilon), \varepsilon) \left[\, q_{it}(\varepsilon) + q_{it}^{mr}(\varepsilon) \, \right] - C_{it}(q_{it}(\varepsilon)) \, \right\} H_t(\varepsilon) \tag{9}$$

subject to the constraints in expression (8) for each $\varepsilon_t \in [\, \underline{\varepsilon}_t, \overline{\varepsilon}_t \,]$.[33]

Because Gi's forward market decisions are represented by the SMPEC in (9), the overall problem is a stochastic equilibrium problem with equilibrium constraints (SEPEC). A solution to this SEPEC requires solving a set of interconnected SMPECs. The solution to this SEPEC characterizes a Nash equilibrium in which no generator has an incentive to unilaterally alter its forward or wholesale market decisions (Hu and Ralph, 2007).

The stochastic demand component ε_t complicates the solution of the SEPEC. We follow the stochastic programming literature (e.g., Yao et al., 2007; Birge and Louveaux, 2011) and approximate the continuous density for ε_t with $1,000$ equally likely, discrete potential realizations. The support of this density (i.e., the values of $\underline{\varepsilon}_t$ and $\overline{\varepsilon}_t$) reflects the dispersion of the residuals of the estimated fringe supply function, as described further below. We solve the SEPEC by reformulating the problem as a mixed nonlinear complementarity program (Hu, 2002; Xian et al., 2004; Hu and Ralph, 2007).[34]

Following Green et al. (2014) and Reguant (2019), we utilize a k-means algorithm to

[33] The foregoing discussion pertains to Setting M. The analysis for Setting SO is analogous. The analysis for Setting N only requires solving for wholesale market outputs for each possible ε_t realization.

[34] See Brown and Sappington (2021) for details.

reduce the dimensionality of our data. We place data from each of the $8,760$ hours in the year into one of 25 representative hours.[35] We then estimate for each hour the values of the parameters in the residual demand and marginal cost functions that are described in Sections 4.3 and 4.4. We take the average of these parameters within a cluster. The k-means algorithm we employ identifies hours with similar attributes based on key variables that reflect prevailing industry conditions. These variables include demand forecasts, wind generation, import capacities, fringe supply, the prices of coal and natural gas, generators' must-run outputs, the pool price, and the prevailing supply cushion (which reflects the difference between the available supply of electricity and the prevailing demand for electricity). For each representative hour, expected outcomes (e.g., welfare) reflect the average across the $1,000$ possible ε_t realizations.

4.3 Residual Demand

The residual demand the large generators face in the Alberta setting is taken to be the difference between the price-inelastic market demand ($\overline{Q}_t$) and the sum of the price-elastic supply of the thirty-seven fringe suppliers and the price-elastic imports from neighboring jurisdictions.[36] We estimate the following fringe and import supply function, using the observations from the $8,760$ hours in the year:

$$\begin{aligned} Q_t^f \;=\;& \beta_0 + \beta_1\, p_t + \vec{\gamma}\ \text{ImportCap}_t + \vec{\omega}\ h(temp_t) \\ &+ \sum_{m=2}^{12} \delta_m\ \text{Month}_{mt} + \sum_{j=2}^{7} \phi_j\ \text{Day}_{jt} + \sum_{h=2}^{24} \eta_h\ \text{Hour}_{ht} + \mu\ \text{Holiday}_t + \varepsilon_t\,. \end{aligned} \tag{10}$$

In equation (10): p_t is the wholesale price of electricity in hour t; ImportCap_t reflects the available import capacities from British Columbia, Montana, and Saskatchewan in hour t; $h(temp_t)$ is a nonlinear function of the temperature in each neighboring jurisdiction during hour t; and Month_{mt}, Day_{jt}, Hour_{ht}, and Holiday_t are indicator variables for each month,

[35] 25 representative hours were chosen to enhance tractability while limiting relevant variation within each representative hour. See the Appendix for additional detail.

[36] This formulation, like our overall empirical approach, parallels the methodologies in Bushnell (2007), Bushnell et al. (2008), and Brown and Eckert (2017).

day of the week, hour, and holiday in Alberta. We employ temperatures in neighboring jurisdictions as well as hour of the day and day of the week fixed effects to control for regional wholesale prices of electricity that can affect exporters' supply decisions.[37] Fringe supply and imports can vary with the wholesale market price and with cost shocks that are captured by the calendar fixed effects.

We employ the hourly day-ahead demand forecast as an instrument for the endogenous wholesale price. The forecast is a valid instrument in the Alberta setting because electricity demand is largely insensitive to the prevailing wholesale price.[38] This is the case because consumers generally face retail prices that vary at most monthly.[39] We estimate the fringe and import supply functions using an instrumental variables approach with Newey-West heteroskedastic and autocorrelation robust standard errors with 24 lags.

The coefficient estimates from equation (10) are employed to construct the following demand and inverse demand functions facing the four large generators:[40]

$$\begin{aligned} Q_t(p_t, \varepsilon_t) \; &= \; \overline{Q}_t - \left(\widehat{Q}^f_t(p_t) + \varepsilon_t \right) \; = \; \overline{Q}_t - \left(\widehat{a}_t + \widehat{\beta}_1 \, p_t + \varepsilon_t \right) \\ \Rightarrow \quad P_t(Q_t, \varepsilon_t) \; &= \; \frac{\overline{Q}_t - \widehat{a}_t - \varepsilon_t}{\widehat{\beta}_1} - \frac{1}{\widehat{\beta}_1} \, Q_t \, . \end{aligned} \tag{11}$$

In equation (11), $\widehat{a}_t$ is the intercept (on the quantity axis) of the estimated fringe and import supply function. This estimated function for period t generates a distribution of residuals with mean 0 and standard deviation σ_t. We set $\overline{\varepsilon}_t = 2\,\sigma_t$ and $\underline{\varepsilon}_t = -2\,\sigma_t$ to capture the extent of the exogenous stochastic variation in the demand the large generators face.

[37] We employ quadratics of hourly cooling degrees (degrees above 18.33 °C $\approx$ 65 °F) and hourly heating degrees (degrees below 18.33 °C). The temperature data – for Vancouver, Saskatoon, and Billings – are derived from Environment Canada and the U.S. National Oceanic and Atmospheric Administration. Our estimates are robust to the use of higher order polynomials and temperature data from other large cities in British Columbia, Saskatchewan, and Montana.

[38] Alberta only has a small amount of price-responsive load (less than 2% of total load, on average).

[39] Because demand only affects imports and fringe supply through its impact on the wholesale market price, the exclusion restriction is satisfied.

[40] The key coefficient estimates are reported in Table B1 in the Appendix. Brown and Sappington (2021) present additional coefficient estimates.

4.4 Marginal Cost

We adopt the standard engineering approach to specify the marginal cost of production by fossil fuel generation unit i in period t as:

$$c_{it} \; = \; VOM_i \, + \, HR_i \cdot p_t^{fuel} \, + \, e_i \, . \tag{12}$$

In equation (12), VOM_i reflects unit i's variable operating and maintenance (O&M) cost. HR_i is the unit's heat-rate, which measures its efficiency in converting fuel to electricity. p_t^{fuel} is the relevant input commodity price (coal or natural gas) in period t. e_i is an environmental compliance cost that varies with unit i's technology.[41] Unit-level heat rates are available from the AESO and the Alberta Utilities Commission. The U.S. Energy Information Administration (EIA, 2020) provides data on variable O&M costs. Hourly natural gas prices reflect volume-weighted average daily prices on Alberta's Natural Gas Exchange. The weekly coal price in Wyoming's Powder River Basin is employed to approximate the price of coal in Alberta because coal from the Basin has heat-rate content similar to the sub-bituminous coal in Alberta (Alberta Energy, 2020).[42]

We take the short-run marginal cost of wind and cogeneration units to be zero. In practice, output from these units typically is bid at \$0/MWh. One firm in the sample, TransAlta, operates several hydroelectric units. The majority of output from these units is bid at \$0/MWh in Alberta. Consequently, we treat TransAlta's hydro output as must-run.[43]

We estimate a linear marginal cost function for each hour and each generator to approximate the generator's actual step-wise discontinuous marginal cost function. Discontinuities arise in practice because different generation units entail different marginal costs of production and each unit has finite capacity. Marginal cost increases discontinuously as output increases sufficiently to require the operation of an additional unit with a higher marginal cost. Our

[41] See Brown et al. (2018) for details.

[42] We translate variable O&M costs and coal prices from U.S. dollars to Canadian dollars using Bank of Canada Exchange rates.

[43] Borenstein et al. (2002) also treat hyrdoelectric units as price-taking suppliers. On occasion, TransAlta bids a subset of its hydro capacity at non-zero prices. However, these bids are sufficiently high (often near the \$999.99/MWh maximum bid) that they are never accepted. We remove these MWs from TransAlta's available capacity.

linear approximation fits the data reasonably well. The average R^2 values for ATCO, Capital Power, TransAlta, and ENMAX are 0.80, 0.71, 0.81, and 0.74, respectively.[44] For each of the 25 representative hours determined via the k-means clustering algorithm, we take the average of the estimated intercept and slope parameters across all hours in a cluster. Doing so provides a generator-specific representative linear marginal cost function for each cluster.

4.5 Findings

Table 1 reports equilibrium outcomes in the Alberta setting, averaged across the 25 representative hours. In the table, S denotes $S_1 + ... + S_4$, L denotes $L_1 + ... + L_4$, $E\{\Pi\}$ denotes $E\{\pi_1 + ... + \pi_4\}$, and $E\{FC\}$ denotes expected forward coverage.[45] Formally, $E\{FC\}$ is $\frac{S}{E\{Q\}}$ in Setting SO and $\frac{S+\alpha E\{Q\}L}{E\{Q\}}$ in Setting M.[46] Table 2 records percentage changes in the average equilibrium outcomes reported in Table 1 across settings.

Setting	L	S	$E\{Q\}$	$E\{P\}$	$E\{\Pi\}$	$E\{CS\}$	$E\{W\}$	$E\{FC\}$
N	0	0	3,369.97	116.69	356,773	603,935	960,708	0
			(475.19)	(15.72)	(91,212)	(164,542)	(255,608)	
SO	0	2,795.29	3,910.95	60.89	182,639	811,134	993,773	0.71
		(408.77)	(554.68)	(8.03)	(42,321)	(222,842)	(264,317)	(0.008)
M	63.03	0	3,718.07	68.26	207,834	783,705	991,539	0.63
	(0.98)		(924.52)	(8.95)	(49,514)	(214,841)	(263,672)	(0.009)

Notes. The numbers in parentheses are standard deviations. The entries are rounded.

Table 1: Average Equilibrium Outcomes in the Alberta Setting.

Four elements of Tables 1 and 2 and the findings that underlie the tables warrant emphasis. First, generators sign LFFCs but do not sign SFCs in Setting M. For the reasons identified in Section 3, LFFCs offer strategic advantages that SFCs do not. The additional advantages of LFFCs lead to their exclusive use in the Alberta setting.

Second, the average expected wholesale price of electricity is considerably lower in Settings SO and M than in Setting N. Thus, forward contracting reduces expected wholesale prices

[44] See the Appendix for additional discussion of the estimated marginal cost functions.

[45] Recall that expected forward coverage is the ratio of expected forward output to expected total output.

[46] $\alpha = 0.01$ in the Alberta setting.

Setting	$E\{P\}$	$E\{\Pi\}$	$E\{CS\}$	$E\{W\}$
SO Relative to N	-47.77	-48.44	34.22	3.45
	(1.80)	(2.22)	(0.64)	(0.15)
M Relative to N	-41.45	-41.43	29.70	3.22
	(1.61)	(1.98)	(0.61)	(0.14)
M Relative to SO	12.13	13.63	-3.37	-0.22
	(0.84)	(1.14)	(0.09)	(0.02)

Notes. The numbers in parentheses are standard deviations.

Table 2: Average Percentage Changes in the Alberta Setting.

substantially (more than 40% on average) in the Alberta setting.[47] The relatively low prices in Settings SO and M lead to substantially lower expected profit and considerably higher expected consumer surplus. Forward contracting does not increase expected welfare dramatically in the Alberta setting. However, it does induce a pronounced transfer of expected surplus from producers to consumers.

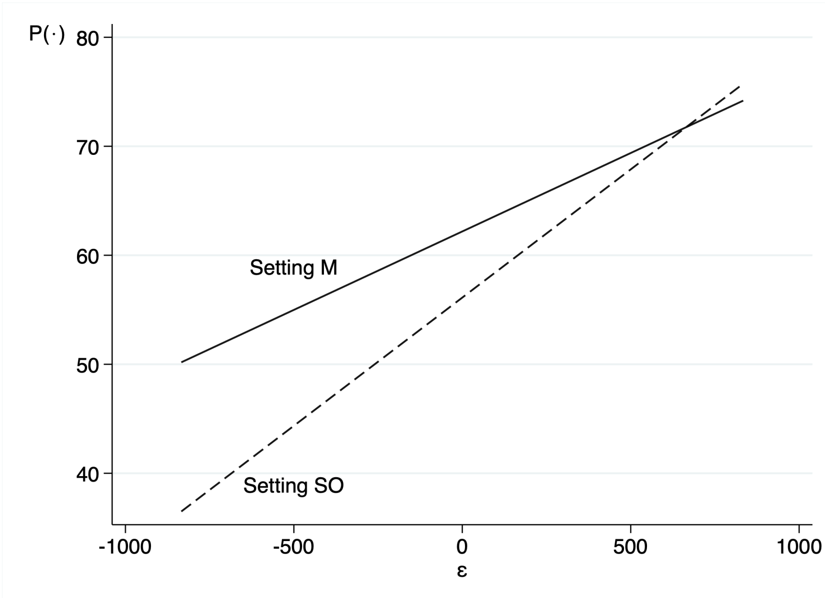
Third, in each of the 25 representative hours, the expected forward coverage is substantial both in Setting SO and in Setting M, but is less pronounced in Setting M than in Setting SO.[48] The less pronounced expected forward coverage in Setting M reflects in part the fact that LFFCs tailor a generator's forward commitment to realized demand (ε), thereby allowing generators to implement a relatively limited forward commitment when ε is low while securing a relatively pronounced forward commitment when ε is high.

Fourth, the expected wholesale price is higher in Setting M than in Setting SO in each of the 25 representative hours. In each case, the difference in expected wholesale price is a relatively small percentage. However, the higher expected price in Setting M represents a considerable transfer of surplus from consumers to producers. The higher expected price

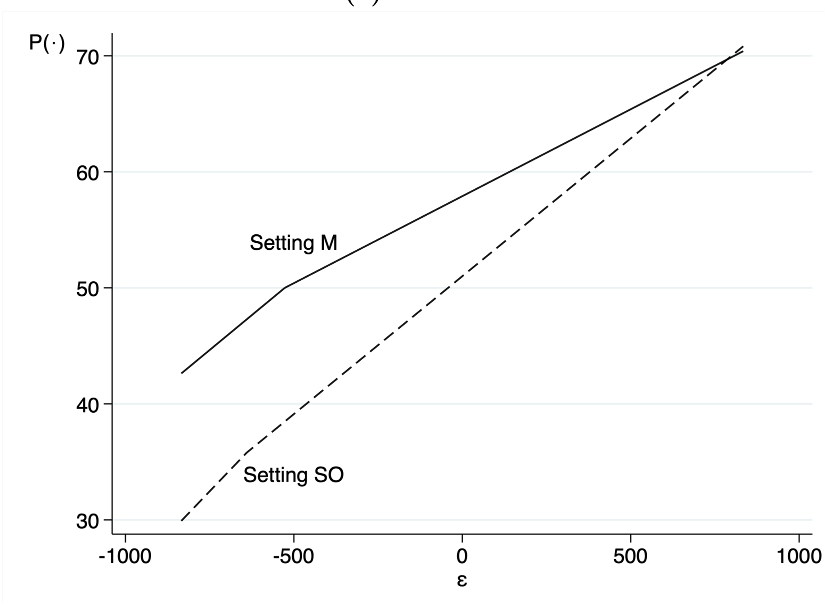
[47] The average expected price in Setting M in our model is reasonably close to the average wholesale price of electricity in Alberta in 2019 ($70.92/MWh). This proximity lends credence to our model and is consistent with prior research which finds that a Cournot model approximates observed behavior in electricity markets reasonably well once firms' forward positions are accounted for (Brown and Eckert, 2017, Bushnell et al., 2008).

[48] Across the 25 representative hours, the expected forward coverage varies between 0.594 and 0.642 in Setting M, and between 0.689 and 0.725 in Setting SO.

leads to lower expected consumer surplus and welfare in Setting M than in Setting SO. Thus, adding LFFCs to the set of feasible forward contracts (which includes SFCs) reduces expected consumer surplus and welfare. These reductions reflect in part the smaller equilibrium expected forward coverage in Setting M than in Setting SO.



(a) Hour 12



(b) Hour 17

Figure 3: The Wholesale Price $P(\cdot)$ ($/MWh).

The levels and changes reported in Tables 1 and 2 are averaged across all demand (ε)

realizations. To better understand the varying effects of SFCs and LFFCs on equilibrium outcomes, it is helpful to examine how the equilibrium wholesale price and forward coverage vary with ε in Settings SO and M. Figures 3 and 4 illustrate this variation for two of the 25 representative hours: hours 12 and 17.[49] Hour 12 represents the 5^{th} percentile of the distribution of representative hours, ranked according to the percentage difference in the expected wholesale price between Settings M and SO. Hour 17 represents the 95^{th} percentile of this distribution.

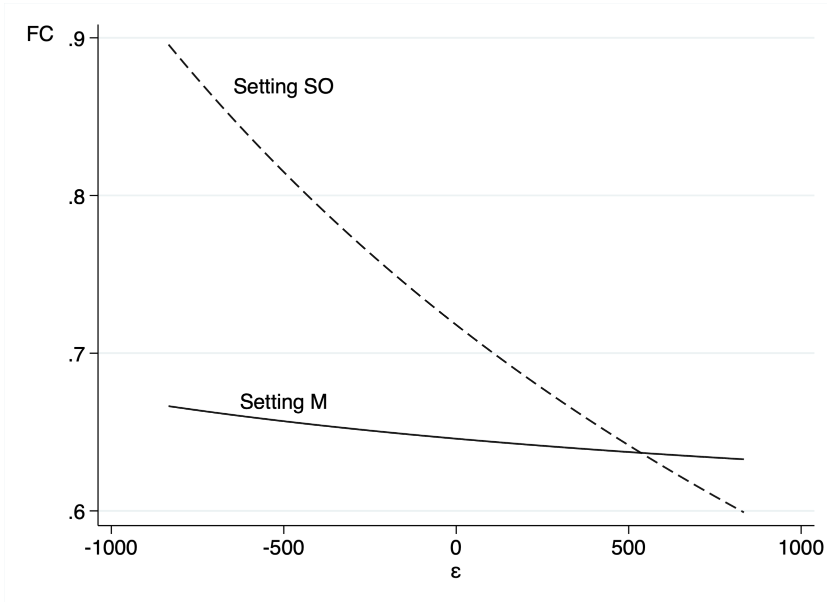
Figure 3 demonstrates that the equilibrium wholesale price is substantially higher in Setting M than in Setting SO for the smallest ε realizations. In contrast, the equilibrium wholesale price is lower in Setting M than in Setting SO for the highest ε realizations. The equilibrium price is higher in Setting M than in Setting SO when ε is relatively small because equilibrium consumption, and thus each generator's LFF commitment, is relatively small when ε is small. In contrast, when ε (and thus equilibrium consumption) is large, each generator's LFF obligation is relatively large, which induces the generators to expand their outputs relatively aggressively.[50]

Figure 4 reveals that the generator's forward coverage varies with ε more substantially in Setting SO than in Setting M. The more pronounced variation arises because SFCs require a generator to deliver the same amount of output at forward price p^S for all demand (ε) realizations. Consequently, the ratio of the generator's forward output to total output declines relatively rapidly as ε (and thus total output) increases. In particular, when a generator signs a relatively large number of SFCs to commit to produce a relatively large level of output when ε (and thus the generator's profit margin) is high, the generator ends up with a particularly pronounced forward coverage when ε is low.

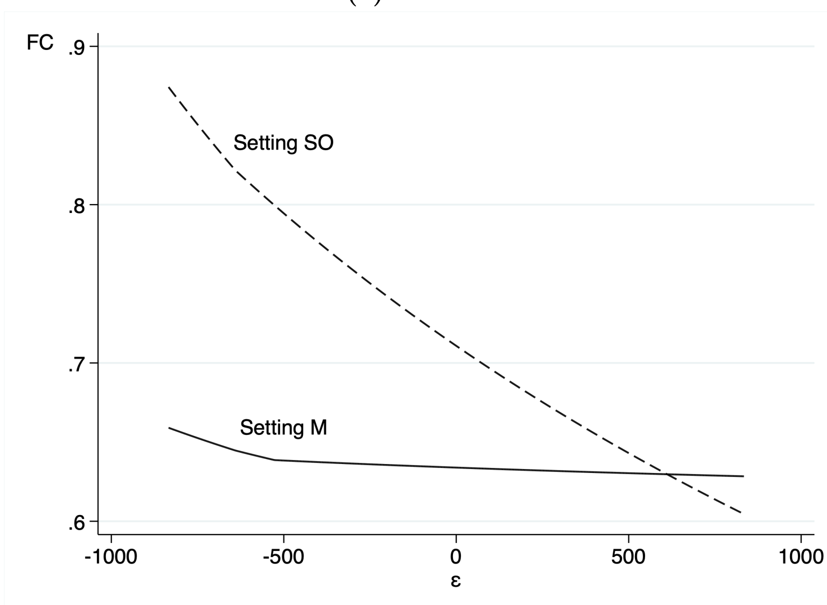
In contrast, LFFCs link a generator's forward output to realized demand. Specifically,

[49] The variation in forward coverage in Figure 4 is reported for ATCO. The corresponding variation for the other generators is similar.

[50] The kink in the wholesale price function in Setting M in Figure 3b arises because a generator finds it most profitable to produce no dispatchable output when realized demand (ε) is sufficiently small.



(a) Hour 12



(b) Hour 17

Figure 4: Forward Coverage (FC) for ATCO.

the generator's forward commitment increases as ε increases, so the ratio of forward output to total output varies less with ε in Setting M (where generators sign LFFCs) than in Setting SO. The tailoring of forward obligation to realized demand that LFFCs permit enable a generator to commit to produce a relatively high level of output when ε is high without mandating the same commitment when ε is low (and so the benefit of increased output is less pronounced).

In summary, forward contracting leads to substantially lower expected wholesale prices and substantially higher expected consumer surplus in the Alberta setting. However, expected forward coverage is lower in Setting M than in Setting SO, which leads to higher expected wholesale prices and lower expected consumer surplus in Setting M than in Setting SO. Thus, expected wholesale prices rise and expected consumer surplus declines in the Alberta setting when generators are able to sign both LFFCs and SFCs rather than only SFCs.

5 Conclusions

We have analyzed equilibrium outcomes in a setting where electricity generators can sign forward contracts before choosing their outputs in a wholesale market. Like many studies in the literature, we found that forward contracting generally enhances welfare. However, we also found that expanding the set of feasible forward contracts can increase wholesale prices and reduce consumer surplus and welfare. In particular, allowing suppliers to sign both LFFCs and SFCs can reduce expected consumer surplus and welfare below the levels that prevail when suppliers can only sign SFCs. The reductions arise because LFFCs induce a relatively limited level of forward contracting, and thus relatively limited competitive aggression, when realized demand is low.

Although LFFCs can increase expected wholesale prices and reduce expected consumer surplus, LFFCs can reduce the extent to which the wholesale price changes as realized demand (ε) changes. LFFCs induce more aggressive competition as ε increases by linking a generator's forward commitment to the level of realized consumption. The enhanced aggression can reduce the rate at which the equilibrium wholesale price increases with ε, as illustrated in Figure 3. Consequently, expanding the set of feasible forward contracts to include LFFCs might warrant consideration in settings where reduced variation in the wholesale price of electricity is valued. Because LFFCs can enhance generators' profits, LFFCs might also serve to enhance capacity investment.[51]

[51] Willems and Morbee (2010) examine how options affect investment in the electricity sector.

In addition to considering risk aversion and endogenous capacity investment, future research might consider additional types of forward contracts, alternative cost and demand structures, and different institutional settings.[52] Future research might also consider the implications of our analysis for the study of competition in retail electricity markets. In many such markets, some suppliers are vertically-integrated producers (VIPs) and the retail price of electricity diverges from the wholesale price for extended periods of time. When a VIP decides to serve a new customer in such a setting, the revenue the VIP receives from serving the customer does not vary with the prevailing wholesale price of electricity. The reduced exposure to the wholesale price can enhance the VIP's incentive to supply output in the wholesale market, much like a LFFC enhances a generator's incentive to increase output in our model. Thus, a VIP's decision about how many retail customers to serve shares important features with a generator's decision about how many forward contracts to sign.

[52]Multiple periods of forward contracting might also be considered. The welfare gains introduced by forward contracting often increase as the number of forward trading periods increases (e.g., Allaz and Vila, 1993; Breitmoser, 2012, 2013).

Appendix

Part A of this Appendix presents the proofs of the formal conclusions in the text. Part B provides additional detail regarding the analysis of the Alberta setting.

A. Proofs of Formal Conclusions.

Proof of Lemma 1. (1) and (2) imply that at an interior solution:

$$\frac{\partial \pi_i(\cdot)}{\partial q_i} = \frac{\partial P(\cdot)}{\partial Q}\,[\, q_i - L_i\,\alpha\,(\, q_i + q_j\,) - S_i\,] + P(Q,\varepsilon)\,[\, 1 - L_i\,\alpha\,] - c_i + p^L\, L_i\,\alpha \;=\; 0 \tag{13}$$

$$\Rightarrow\; -\frac{1}{b}\,[\, q_i - L_i\,\alpha\,(\, q_i + q_j\,) - S_i\,]$$

$$+\left[\frac{a+\varepsilon}{b} - \frac{1}{b}\,q_i - \frac{1}{b}\,q_j\right][\, 1 - L_i\,\alpha\,] - c_i + p^L\, L_i\,\alpha \;=\; 0$$

$$\Rightarrow\; -\,[\, q_i - L_i\,\alpha\,(\, q_i + q_j\,) - S_i\,] + [\, a + \varepsilon - \, q_i - \, q_j\,]\,[\, 1 - L_i\,\alpha\,]$$

$$-\, b\, c_i + b\, p^L\, L_i\,\alpha \;=\; 0$$

$$\Rightarrow\; [\, a + \varepsilon\,]\,[\, 1 - L_i\,\alpha\,] - b\, c_i + b\, p^L\, L_i\,\alpha + S_i - q_j\,[\, 1 - 2\, L_i\,\alpha\,] \;=\; 2\, q_i\,[\, 1 - L_i\,\alpha\,]$$

$$\Rightarrow\; q_i \;=\; \frac{[\, a + \varepsilon\,]\,[\, 1 - L_i\,\alpha\,] - b\, c_i + b\, p^L\, L_i\,\alpha + S_i}{2\,[\, 1 - L_i\,\alpha\,]} - \frac{1 - 2\, L_i\,\alpha}{2\,[\, 1 - L_i\,\alpha\,]}\; q_j\,. \tag{14}$$

Observe that:

$$\frac{[\, a + \varepsilon\,]\,[\, 1 - L_i\,\alpha\,] - b\, c_i + b\, p^L\, L_i\,\alpha + S_i}{2\,[\, 1 - L_i\,\alpha\,]}$$

$$= \frac{a+\varepsilon}{2} - \frac{b\, c_i}{2\,[\, 1 - L_i\,\alpha\,]} + \frac{S_i}{2\,[\, 1 - L_i\,\alpha\,]} + \frac{b\, p^L\, L_i\,\alpha}{2\,[\, 1 - L_i\,\alpha\,]}$$

$$= \frac{a + \varepsilon - b\, c_i + S_i}{2} - \frac{b\, c_i}{2\,[\, 1 - L_i\,\alpha\,]} + \frac{S_i}{2\,[\, 1 - L_i\,\alpha\,]} + \frac{b\, c_i}{2} - \frac{S_i}{2} + \frac{b\, p^L\, L_i\,\alpha}{2\,[\, 1 - L_i\,\alpha\,]}$$

$$= \frac{a + \varepsilon - b\, c_i + S_i}{2} - \frac{b\, c_i\,[\, 1 - (\, 1 - \alpha\, L_i\,)\,]}{2\,[\, 1 - L_i\,\alpha\,]} + \frac{S_i\,[\, 1 - (\, 1 - \alpha\, L_i\,)\,]}{2\,[\, 1 - L_i\,\alpha\,]} + \frac{b\, p^L\, L_i\,\alpha}{2\,[\, 1 - L_i\,\alpha\,]}$$

$$= \frac{a + \varepsilon - b\, c_i + S_i}{2} + \frac{\alpha\, L_i}{2\,[\, 1 - \alpha\, L_i\,]}\,\left[\, S_i + b\left(p^L - c_i\right)\right]. \tag{15}$$

The expression for $q_i^m(\varepsilon)$ in (6) follows from (14) and (15). The other reaction functions in (6) follow immediately from (14). ■

Proof of Corollaries 1 – 3 and Proposition 1. The conclusions follow directly from (6). ■

Proof of Proposition 2. (6) implies that under the specified conditions:

$$\left.\frac{\partial q_i^m(\varepsilon)}{\partial L_i^m}\right|_{dp^L=0} = \frac{\alpha\left[\,S_i^m + b\left(p^L - c_i\right)\right]}{2}\,\frac{1}{[\,1-\alpha\,L_i^m\,]^2} > 0$$

$$\Rightarrow \quad \left.\frac{\partial^2 q_i^m(\varepsilon)}{\partial\left(L_i^m\right)^2}\right|_{dp^L=0} = \frac{\alpha\left[\,S_i^m + b\left(p^L - c_i\right)\right]}{2}\,\frac{2\,\alpha}{[\,1-\alpha\,L_i^m\,]^3} > 0\,. \quad ■$$

Proof of Proposition 3. (6) implies that the absolute value of the slope of Gi's reaction function in (q_j, q_i) space (holding p^L constant) is:

$$x \equiv \frac{1}{2}\left[\frac{1-2\,\alpha\,L_i^m}{1-\alpha\,L_i^m}\right]$$

$$\Rightarrow \quad \frac{\partial x}{\partial L_i^m} = \frac{1}{2}\,\frac{[\,1-\alpha\,L_i^m\,][\,-2\,\alpha\,] + \alpha\,[\,1-2\,\alpha\,L_i^m\,]}{[\,1-\alpha\,L_i^m\,]^2} = -\,\frac{\alpha}{2\,[\,1-\alpha\,L_i^m\,]^2}$$

$$\Rightarrow \quad \frac{\partial}{\partial L_i^m}\left|\frac{\partial x}{\partial L_i^m}\right| = \frac{\alpha}{2}\left[\,-2\,(\,1-\alpha\,L_i^m\,)^{-3}\,\right][\,-\alpha\,] = \frac{\alpha^2}{[\,1-\alpha\,L_i^m\,]^3} > 0\,. \quad ■$$

Proof of Proposition 4. (6) implies that in equilibrium:

$$\begin{aligned} q_1 &= \frac{[\,a+\varepsilon\,][\,1-L_1\,\alpha\,] - b\,c_1 + b\,p^L\,L_1\,\alpha + S_1}{2\,[\,1-L_1\,\alpha\,]} \\ &\quad - \frac{1-2\,L_1\,\alpha}{2\,[\,1-L_1\,\alpha\,]}\left[\frac{(\,a+\varepsilon\,)(\,1-L_2\,\alpha\,) - b\,c_2 + b\,p^L\,L_2\,\alpha + S_2}{2\,(\,1-L_2\,\alpha\,)} - \frac{1-2\,L_2\,\alpha}{2\,(\,1-L_2\,\alpha\,)}\;q_1\right] \end{aligned}$$

$$\begin{aligned} \Rightarrow \quad & q_1\left[\frac{4\,(\,1-L_1\,\alpha\,)(\,1-L_2\,\alpha\,) - (\,1-2\,L_1\,\alpha\,)(\,1-2\,L_2\,\alpha\,)}{4\,(\,1-L_1\,\alpha\,)(\,1-L_2\,\alpha\,)}\right] \\ &= [\,a+\varepsilon\,]\left[\frac{1-L_1\,\alpha}{2\,(\,1-L_1\,\alpha\,)} - \frac{(\,1-2\,L_1\,\alpha\,)(\,1-L_2\,\alpha\,)}{4\,(\,1-L_1\,\alpha\,)(\,1-L_2\,\alpha\,)}\right] \\ &\quad - b\left[\frac{c_1 - p^L\,L_1\,\alpha}{2\,(\,1-L_1\,\alpha\,)} - \frac{(\,1-2\,L_1\,\alpha\,)\left[\,c_2 - p^L\,L_2\,\alpha\right]}{4\,(\,1-L_1\,\alpha\,)(\,1-L_2\,\alpha\,)}\right] \\ &\quad + \frac{S_1}{2\,[\,1-L_1\,\alpha\,]} - \frac{[\,1-2\,L_1\,\alpha\,]\,S_2}{4\,[\,1-L_1\,\alpha\,][\,1-L_2\,\alpha\,]}\,. \end{aligned} \tag{16}$$

Observe that:

$$4\,[\,1 - L_1\,\alpha\,]\,[\,1 - L_2\,\alpha\,] - [\,1 - 2\,L_1\,\alpha\,]\,[\,1 - 2\,L_2\,\alpha\,]$$

$$= \; 4\left[\,1 - L_1\,\alpha - L_2\,\alpha + L_1\,L_2\,\alpha^2\,\right] - \left[\,1 - 2\,L_2\,\alpha - 2\,L_1\,\alpha + 4\,L_1\,L_2\,\alpha^2\,\right]$$

$$= \; 3 - 2\,L_1\,\alpha - 2\,L_2\,\alpha \; = \; 3 - 2\,\alpha\,[\,L_1 + L_2\,]\,. \tag{17}$$

(16) and (17) imply:

$$q_1\left[\frac{3 - 2\,\alpha\,(\,L_1 + L_2\,)}{4\,(\,1 - L_1\,\alpha\,)\,(\,1 - L_2\,\alpha\,)}\right]$$

$$= \; \frac{1}{4\,[\,1 - L_1\,\alpha\,]\,[\,1 - L_2\,\alpha\,]}\Big\{\,[\,a + \varepsilon\,][\,1 - L_2\,\alpha\,]$$

$$- \, b\left[\,2\,(\,1 - L_2\,\alpha\,)\left(c_1 - p^L\,L_1\,\alpha\right) - (\,1 - 2\,L_1\,\alpha\,)\left(c_2 - p^L\,L_2\,\alpha\right)\,\right]$$

$$+ \; 2\,[\,1 - L_2\,\alpha\,]\,S_1 - [\,1 - 2\,L_1\,\alpha\,]\,S_2\,\Big\}$$

$$\Rightarrow \quad q_1^* \; = \; \frac{1}{3 - 2\,\alpha\,[\,L_1 + L_2\,]}\Big\{\,[\,a + \varepsilon\,][\,1 - L_2\,\alpha\,] - b\,[\,2\,(\,1 - L_2\,\alpha\,)\,c_1 - (\,1 - 2\,L_1\,\alpha\,)\,c_2\,]$$

$$+ \; b\,p^L\,\alpha\;[\,2\,(\,1 - L_2\,\alpha\,)\,L_1 - (\,1 - 2\,L_1\,\alpha\,)\,L_2\,]$$

$$+ \; 2\,[\,1 - L_2\,\alpha\,]\,S_1 - [\,1 - 2\,L_1\,\alpha\,]\,S_2\,\Big\}$$

$$\Rightarrow \quad q_1^* \; = \; \frac{1}{3 - 2\,\alpha\,[\,L_1 + L_2\,]}\Big\{\,[\,a + \varepsilon\,][\,1 - L_2\,\alpha\,] - b\,[\,2\,(\,1 - L_2\,\alpha\,)\,c_1 - (\,1 - 2\,L_1\,\alpha\,)\,c_2\,]$$

$$+ \; b\,p^L\,\alpha\;[\,2\,L_1 - \;L_2\,] + 2\,[\,1 - L_2\,\alpha\,]\,S_1 - [\,1 - 2\,L_1\,\alpha\,]\,S_2\,\Big\}. \tag{18}$$

Symmetry implies:

$$q_2^* \; = \; \frac{1}{3 - 2\,\alpha\,[\,L_1 + L_2\,]}\Big\{\,[\,a + \varepsilon\,]\,[\,1 - L_1\,\alpha\,] - b\,[\,2\,(\,1 - L_1\,\alpha\,)\,c_2 - (\,1 - 2\,L_2\,\alpha\,)\,c_1\,]$$

$$+ \; b\,p^L\,\alpha\;[\,2\,L_2 - \;L_1\,] + 2\,[\,1 - L_1\,\alpha\,]\,S_2 - [\,1 - 2\,L_2\,\alpha\,]\,S_1\,\Big\}. \tag{19}$$

(18) and (19) imply that equilibrium total output ($Q^* = q_1^* + q_2^*$) is:

$$Q^* \; = \; \left[\frac{1}{3 - 2\,\alpha\,(\,L_1 + L_2\,)}\right]\Big\{\;[\,a + \varepsilon\,]\,[\,1 - L_2\,\alpha\,] - b\,[\,2\,(\,1 - L_2\,\alpha\,)\,c_1 - (\,1 - 2\,L_1\,\alpha\,)\,c_2\,]$$

$$+ \;\; b\,p^L\,\alpha\;[\,2\,L_1 - \;L_2\,] + \;\; 2\,[\,1 - L_2\,\alpha\,]\,S_1 - [\,1 - 2\,L_1\,\alpha\,]\,S_2$$

$$+ [a+\varepsilon][1-L_1\alpha] - b[2(1-L_1\alpha)c_2 - (1-2L_2\alpha)c_1]$$
$$+ b p^L \alpha [2L_2 - L_1]$$
$$+ 2[1-L_1\alpha]S_2 - [1-2L_2\alpha]S_1 \Big\}$$

$$= \left[\frac{1}{3-2\alpha(L_1+L_2)}\right]\Big\{ [a+\varepsilon][2-\alpha(L_1+L_2)] + b p^L \alpha [L_1+L_2]$$
$$- b[2(1-L_2\alpha)c_1 - (1-2L_1\alpha)c_2 + 2(1-L_1\alpha)c_2 - (1-2L_2\alpha)c_1]$$
$$+ S_1[2(1-L_2\alpha) - (1-2L_2\alpha)] + S_2[2(1-L_1\alpha) - (1-2L_1\alpha)] \Big\}$$

$$= \frac{[a+\varepsilon][2-\alpha(L_1+L_2)] - bc_1 - bc_2 + S_1 + S_2 + b p^L \alpha [L_1+L_2]}{3-2\alpha[L_1+L_2]}. \tag{20}$$

(1) and (20) imply:

$$P(Q^*,\varepsilon) = \frac{a+\varepsilon}{b} - \frac{[a+\varepsilon][2-\alpha(L_1+L_2)] - bc_1 - bc_2 + S_1 + S_2 + b p^L \alpha [L_1+L_2]}{b[3-2\alpha(L_1+L_2)]}$$

$$= \left[\frac{1}{b(3-2\alpha[L_1+L_2])}\right]\Big\{ [a+\varepsilon][3-2\alpha(L_1+L_2)] - [a+\varepsilon][2-\alpha(L_1+L_2)]$$
$$+ bc_1 + bc_2 - S_1 - S_2 - b p^L \alpha [L_1+L_2] \Big\}$$

$$= \left[\frac{1}{b(3-2\alpha[L_1+L_2])}\right]\Big\{ [a+\varepsilon][1-\alpha(L_1+L_2)]$$
$$+ bc_1 + bc_2 - S_1 - S_2 - b p^L \alpha [L_1+L_2] \Big\}. \tag{21}$$

(20) and (21) imply:

$$P(Q^*,\varepsilon)\, Q^* = \left[\frac{1}{b(3-2\alpha[L_1+L_2])^2}\right]\Big\{ [a+\varepsilon][1-\alpha(L_1+L_2)]$$
$$+ bc_1 + bc_2 - S_1 - S_2 - b p^L \alpha [L_1+L_2] \Big\}$$
$$\cdot \Big\{ [a+\varepsilon][2-\alpha(L_1+L_2)] - bc_1 - bc_2 + S_1 + S_2 + b p^L \alpha [L_1+L_2] \Big\}$$

$$= \left[\frac{1}{b(3-2\alpha[L_1+L_2])^2}\right]\Big\{ a[1-\alpha(L_1+L_2)] + bc_1 + bc_2 - S_1 - S_2$$
$$+ \varepsilon[1-\alpha(L_1+L_2)] - b p^L \alpha [L_1+L_2] \Big\}$$

$$\cdot \Big\{ a\,[\,2-\alpha\,(\,L_1+L_2\,)\,] - b\,c_1 - b\,c_2 + S_1 + S_2$$
$$+\ \varepsilon\,[\,2-\alpha\,(\,L_1+L_2\,)\,] + b\,p^L\,\alpha\ [\,L_1 +\ L_2\,] \Big\}$$

$$= \ \left[\frac{1}{b\,(\,3-2\,\alpha\,[\,L_1+L_2\,]\,)^2} \right]$$
$$\cdot \Big\{ [\,a\,(\,1-\ \alpha\,[\,L_1+L_2\,]\,) +\ b\,c_1 + b\,c_2 - S_1 - S_2\,]$$
$$\cdot [\,a\,(\,2-\alpha\,[\,L_1+L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$
$$+\ \varepsilon\,[\,a\,(\,1-\ \alpha\,[\,L_1+L_2\,]\,) +\ b\,c_1 + b\,c_2 - S_1 - S_2\,]\ [\,2-\alpha\,(\,L_1+L_2\,)\,]$$
$$+\ \varepsilon\,[\,1-\alpha\,(\,L_1+L_2\,)\,]\,[\,a\,(\,2-\alpha\,[\,L_1+L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$
$$+\ \varepsilon\,[\,1-\alpha\,(\,L_1+L_2\,)\,]\,b\,p^L\,\alpha\,[\,L_1 +\ L_2\,]$$
$$+\ \varepsilon^2\,[\,1-\alpha\,(\,L_1+L_2\,)\,]\,[\,2-\alpha\,(\,L_1+L_2\,)\,]$$
$$+\ b\,p^L\,\alpha\,[\,a\,(\,1-\alpha\,[\,L_1+L_2\,]\,) +\ b\,c_1 + b\,c_2 - S_1 - S_2\,]\ [\,L_1 +\ L_2\,]$$
$$-\ b\,p^L\,\alpha\,[\,L_1 +\ L_2\,]\ [\,a\,(\,2-\alpha\,[\,L_1+L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$
$$-\ \ \varepsilon\,b\,p^L\,\alpha\,[\,L_1 +\ L_2\,]\ [\,2-\alpha\,(\,L_1+L_2\,)\,] - b^2\,(p^L)^2\,\alpha^2\,[\,L_1 +\ L_2\,]^2 \Big\}. \tag{22}$$

Denoting $Q^*(L_1, L_2, S_1, S_2, \varepsilon)$ by $Q^*(\cdot)$, (3) and (4) imply the forward prices are:

$$E\,\{\,p^S\,S_i - P(Q^*(\cdot),\varepsilon)\,S_i\,\} \ = \ 0 \quad \Rightarrow \quad p^S \ = \ E\{\,P(Q^*(\cdot),\varepsilon)\,\}\,; \text{ and}$$

$$E\,\{\,p^L\,L_i\,\alpha\,Q^*(\cdot) - P(Q^*(\cdot),\varepsilon)\,L_i\,\alpha\,Q^*(\cdot)\,\} \ = \ 0$$

$$\Rightarrow \quad p^L\,E\,\{\,Q^*(\cdot)\,\} \ = \ E\,\{\,P(Q^*(\cdot),\varepsilon)\,Q^*(\cdot)\,\} \quad \Rightarrow \quad p^L \ = \ \frac{E\,\{\,P(Q^*(\cdot),\varepsilon)\,Q^*(\cdot)\,\}}{E\{\,Q^*(\cdot)\,\}}. \tag{23}$$

(20) and (22) imply that when $E\{\,\varepsilon\,\} = 0$:

$$E\{\,Q^*(\cdot)\,\} \ = \ \frac{a\,[\,2-\alpha\,(\,L_1+L_2\,)\,] - b\,c_1 - b\,c_2 + S_1 + S_2 +\ b\,p^L\,\alpha\ [\,L_1 +\ L_2\,]}{3-2\,\alpha\,[\,L_1+L_2\,]}\,. \tag{24}$$

$$E\{\,P(Q^*(\cdot),\varepsilon)\,Q^*(\cdot)\} = \ \left[\frac{1}{b\,(\,3-2\,\alpha\,[\,L_1+L_2\,]\,)^2} \right]$$
$$\cdot \Big\{ [\,a\,(\,1-\ \alpha\,[\,L_1+L_2\,]\,) +\ b\,c_1 + b\,c_2 - S_1 - S_2\,]$$
$$\cdot\ [\,a\,(\,2-\alpha\,[\,L_1+L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$

$$+\; E\{\,\varepsilon^2\,\}\;[\,1 -\; \alpha\,(\,L_1 + L_2\,)\,]\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,]$$

$$+\; b\,p^L\,\alpha\,[\,a\;(\,1 -\; \alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,]\,[\,L_1 +\; L_2\,]$$

$$-\; b\,p^L\,\alpha\,[\,L_1 +\; L_2\,]\;[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$

$$\left. -\; b^2\,(p^L)^2\,\alpha^2\,[\,L_1 +\; L_2\,]^2\;\right\}. \qquad (25)$$

(23) – (25) imply:

$$p^L\,E\{\,Q^*(\cdot)\,\} \;=\; E\{\,P(Q^*(\cdot),\varepsilon)\,Q^*(\cdot)\,\}$$

$$\Rightarrow\quad p^L\left[\,\frac{a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2 +\; b\,p^L\,\alpha\,(\,L_1 +\; L_2\,)}{3 - 2\,\alpha\,(\,L_1 + L_2\,)}\,\right]$$

$$= \;\left[\,\frac{1}{b\,(\,3 - 2\,\alpha\,[\,L_1 + L_2\,]\,)^2}\,\right]$$

$$\cdot\left\{\,[\,a\,(\,1 -\; \alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,]\right.$$

$$\cdot\;[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$

$$+\; E\{\,\varepsilon^2\,\}\;[\,1 - \alpha\,(\,L_1 + L_2\,)\,]\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,]$$

$$+\; b\,p^L\,\alpha\,[\,a\;(\,1 -\; \alpha\,[\,L_1 + L_2\,]\,) +\; b\,c_1 + b\,c_2 - S_1 - S_2\,]\,[\,L_1 +\; L_2\,]$$

$$-\; b\,p^L\,\alpha\,[\,L_1 +\; L_2\,]\;[\,a\;(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$

$$\left. -\; b^2\,(p^L)^2\,\alpha^2\,[\,L_1 +\; L_2\,]^2\;\right\}$$

$$\Rightarrow\quad p^L\,b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]$$

$$\cdot\;\left[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2 + b\,p^L\,\alpha\,(\,L_1 +\; L_2\,)\,\right]$$

$$= \;\;[\,a\,(\,1 - \alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,]$$

$$\cdot\;[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$

$$+\; E\{\,\varepsilon^2\,\}\;[\,1 - \alpha\,(\,L_1 + L_2\,)\,]\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,]$$

$$+\; b\,p^L\,\alpha\,[\,a\;(\,1 -\; \alpha\,[\,L_1 + L_2\,]\,) +\; b\,c_1 + b\,c_2 - S_1 - S_2\,]\,[\,L_1 +\; L_2\,]$$

$$-\; b\,p^L\,\alpha\,[\,L_1 +\; L_2\,]\;[\,a\;(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]$$

$$-\; b^2\,(p^L)^2\,\alpha^2\,[\,L_1 +\; L_2\,]^2$$

$$
\begin{aligned}
\Rightarrow \quad & b^2 (p^L)^2 \alpha^2 [L_1 + L_2]^2 + b^2 (p^L)^2 \alpha [3 - 2\alpha (L_1 + L_2)] [L_1 + L_2] \\
& + p^L b [3 - 2\alpha (L_1 + L_2)] [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& - b p^L \alpha [a (1 - \alpha [L_1 + L_2]) + b c_1 + b c_2 - S_1 - S_2] [L_1 + L_2] \\
& + b p^L \alpha [L_1 + L_2] [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& - [a (1 - \alpha [L_1 + L_2]) + b c_1 + b c_2 - S_1 - S_2] \\
& \qquad \cdot [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& - E\{\varepsilon^2\} [1 - \alpha (L_1 + L_2)] [2 - \alpha (L_1 + L_2)] = 0
\end{aligned}
$$

$$
\begin{aligned}
\Rightarrow \quad & b^2 (p^L)^2 \alpha [L_1 + L_2] [\alpha (L_1 + L_2) + 3 - 2\alpha (L_1 + L_2)] \\
& + p^L b \Big\{ [3 - 2\alpha (L_1 + L_2)] [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& \qquad - \alpha [a (1 - \alpha [L_1 + L_2]) + b c_1 + b c_2 - S_1 - S_2] [L_1 + L_2] \\
& \qquad + \alpha [L_1 + L_2] [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \Big\} \\
& - [a (1 - \alpha [L_1 + L_2]) + b c_1 + b c_2 - S_1 - S_2] \\
& \quad \cdot [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& - E\{\varepsilon^2\} (1 - \alpha [L_1 + L_2]) [2 - \alpha (L_1 + L_2)] = 0
\end{aligned}
$$

$$
\begin{aligned}
\Rightarrow \quad & b^2 (p^L)^2 \alpha [L_1 + L_2] [3 - \alpha (L_1 + L_2)] \\
& + p^L b \Big\{ [3 - 2\alpha (L_1 + L_2)] [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& \qquad - \alpha [a (1 - \alpha [L_1 + L_2]) + b c_1 + b c_2 - S_1 - S_2] [L_1 + L_2] \\
& \qquad + \alpha [L_1 + L_2] [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \Big\} \\
& - [a (1 - \alpha [L_1 + L_2]) + b c_1 + b c_2 - S_1 - S_2] \\
& \quad \cdot [a (2 - \alpha [L_1 + L_2]) - b c_1 - b c_2 + S_1 + S_2] \\
& - E\{\varepsilon^2\} [1 - \alpha (L_1 + L_2)] [2 - \alpha (L_1 + L_2)] = 0
\end{aligned}
$$

$$
\Rightarrow \quad A (p^L)^2 + B p^L + C = 0 \qquad (26)
$$

where:

$$A \;\equiv\; b^2\,\alpha\,[\,L_1 +\, L_2\,]\,[\,3 - \alpha\,(\,L_1 + L_2\,)\,]\,;$$

$$\begin{aligned} B \;\equiv\; b\Big\{\, & [\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\ & - \alpha\;[\,a\,(\,1 -\, \alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,]\,[\,L_1 +\, L_2\,] \\ & + \alpha\,[\,L_1 +\, L_2\,]\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,]\;\Big\} \\ =\; & b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\ & + b\,\alpha\,[\,L_1 + L_2\,]\,\Big\{\,a\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,] - b\,c_1 - b\,c_2 + S_1 + S_2 \\ & \qquad - a\,[\,1 - \alpha\,(\,L_1 + L_2\,)\,] - b\,c_1 - b\,c_2 + S_1 + S_2\,\Big\} \\ =\; & b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\ & + b\,\alpha\,[\,L_1 + L_2\,]\,[\,a\, - 2\,b\,c_1 - 2\,b\,c_2 + 2\,S_1 + 2\,S_2\,]\,; \end{aligned}$$

$$\begin{aligned} C \;\equiv\; & -\,[\,a\,(\,1 -\, \alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,] \\ & \cdot\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\ & - E\{\,\varepsilon^2\,\}\,[\,1 - \alpha\,(\,L_1 + L_2\,)\,]\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,]\,. \end{aligned} \tag{27}$$

(26) implies that for $x \in \{S_1, S_2, L_1, L_2, \}$:

$$\big[\,2\,A\,p^L + B\,\big]\,d\,p^L + \left[\,\frac{d\,A}{d\,x}\,(p^L)^2 + \frac{d\,B}{d\,x}\,p^L + \frac{d\,C}{d\,x}\,\right]\,d\,x \;=\; 0$$

$$\Rightarrow \quad \frac{dp^L}{dx} \;=\; -\,\frac{\frac{dA}{dx}\,(p^L)^2 + \frac{dB}{dx}\,p^L + \frac{dC}{dx}}{2\,A\,p^L + B}\,. \tag{28}$$

(27) implies:

$$\frac{dA}{dS_i} \;=\; 0\,; \tag{29}$$

$$\frac{dA}{dL_i} \;=\; b^2\,\alpha\,\{\,-\,\alpha\,[\,L_1 +\, L_2\,] + 3 - \alpha\,[\,L_1 + L_2\,]\,\} \;=\; b^2\,\alpha\,[\,3 - 2\,\alpha\,(\,L_1 +\, L_2\,)\,]\,. \tag{30}$$

$$\frac{dB}{dS_i} \;=\; b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,] + 2\,b\,\alpha\,[\,L_1 + L_2\,] \;=\; 3\,b\,. \tag{31}$$

$$\begin{aligned}
\frac{dB}{dL_i} \;&=\; -\,a\,\alpha\,b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,] - 2\,\alpha\,b\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\
&\qquad + \,b\,\alpha\,[\,a\; - 2\,b\,c_1 - 2\,b\,c_2 + 2\,S_1 + 2\,S_2\,] \\
&=\; -\,a\,\alpha\,b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,) + 4 - 2\,\alpha\,(\,L_1 + L_2\,) - 1\,] \\
&=\; -\,a\,\alpha\,b\,[\,6 - 4\,\alpha\,(\,L_1 + L_2\,)\,] \;=\; -\,2\,a\,\alpha\,b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,.
\end{aligned} \tag{32}$$

$$\begin{aligned}
\frac{dC}{dS_i} \;&=\; -\;[\,a\,(\,1 - \;\alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,] \\
&\qquad + \,a\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,] - b\,c_1 - b\,c_2 + S_1 + S_2 \\
&=\; a - 2\,b\,c_1 - 2\,b\,c_2 + 2\,S_1 + 2\,S_2\,.
\end{aligned} \tag{33}$$

$$\begin{aligned}
\frac{dC}{dL_i} \;&=\; a\,\alpha\,[\,a\,(\,1 - \;\alpha\,[\,L_1 + L_2\,]\,) + b\,c_1 + b\,c_2 - S_1 - S_2\,] \\
&\qquad + \,a\,\alpha\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\
&\qquad + \,\alpha\,E\{\,\varepsilon^2\,\}\,[\,1 - \alpha\,(\,L_1 + L_2\,) + 2 - \alpha\,(\,L_1 + L_2\,)\,] \\
&=\; a^2\,\alpha\,[\,3 - 2\,\alpha\,(\,L_1 + \,L_2\,)\,] + \alpha\,E\{\,\varepsilon^2\,\}\,[\,3 - 2\,\alpha\,(\,L_1 + \,L_2\,)\,] \\
&=\; \alpha\,\left[a^2 + E\{\,\varepsilon^2\,\}\,\right]\,[\,3 - 2\,\alpha\,(\,L_1 + \,L_2\,)\,]\,.
\end{aligned} \tag{34}$$

Because $\alpha \in (0,1)$ and $L_i \in (0, \frac{1}{2\,\alpha})$ for $i \in \{1,2\}$:

$$3 - \alpha\,[\,L_1 + L_2\,] \;>\; 3 - 2\,\alpha\,[\,L_1 + L_2\,] \;>\; 3 - 2\,\alpha\left[\frac{1}{2} + \frac{1}{2}\right] \;=\; 3 - 2\,\alpha \;>\; 0\,. \tag{35}$$

(27) and (35) imply that under the specified conditions:

$$\begin{aligned}
A \;&\equiv\; b^2\,\alpha\,[\,L_1 + \,L_2\,]\,[\,3 - \alpha\,(\,L_1 + L_2\,)\,] \;\stackrel{s}{=}\; 3 - \alpha\,[\,L_1 + L_2\,] \;>\; 0\,; \\
B \;&\equiv\; b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \\
&\qquad + \,b\,\alpha\,[\,L_1 + L_2\,]\,[\,a\; - 2\,b\,c_1 - 2\,b\,c_2 + 2\,S_1 + 2\,S_2\,] \\
&>\; b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,[\,a\,(\,2 - \alpha\,[\,L_1 + L_2\,]\,) - b\,c_1 - b\,c_2 + S_1 + S_2\,] \;>\; 0\,.
\end{aligned} \tag{36}$$

The last inequality in (36) holds because:

$$a\,[\,2 - \alpha\,(\,L_1 + L_2\,)\,] - b\,c_1 - b\,c_2 + S_1 + S_2 \;>\; a\left[2 - \alpha\left(\frac{1}{2} + \frac{1}{2}\right)\right] - b\,c_1 - b\,c_2 + S_1 + S_2$$

$$= \; a\,[\,2-\alpha\,] - b\,c_1 - b\,c_2 + S_1 + S_2 \;\geq\; a\,[\,2-\alpha\,] - b\,c_1 - b\,c_2$$

$$> \; a - b\,[\,c_1 + c_2\,] \;>\; 0\,.$$

(28), (29), (31), (33), and (36) imply that under the specified conditions:

$$\frac{dp^L}{dS_i} \;=\; -\,\frac{\frac{d\,A}{d\,S_i}\,(p^L)^2 + \frac{d\,B}{d\,S_i}\,p^L + \frac{d\,C}{d\,S_i}}{2\,A\,p^L + B} \;\stackrel{s}{=}\; -\left(\frac{dA}{dS_i}\,(p^L)^2 + \frac{dB}{dS_i}\,p^L + \frac{dC}{dS_i}\right)$$

$$= \; -\,\big(\,3\,b\,p^L + a - 2\,b\,c_1 - 2\,b\,c_2 + 2\,S_1 + 2\,S_2\big) \;<\; 0\,.$$

(28), (30), (32), and (34) – (36) imply that under the specified conditions:

$$\frac{dp^L}{dL_i} \;=\; -\,\frac{\frac{d\,A}{d\,L_i}\,(p^L)^2 + \frac{d\,B}{d\,L_i}\,p^L + \frac{d\,C}{d\,L_i}}{2\,A\,p^L + B} \;\stackrel{s}{=}\; -\left(\frac{dA}{dL_i}\,(p^L)^2 + \frac{dB}{dL_i}\,p^L + \frac{dC}{dL_i}\right)$$

$$= -\Bigg(\,b^2\,\alpha\,[\,3 - 2\,\alpha\,(\,L_1 +\; L_2\,)\,]\,\big(p^L\big)^2 -\; 2\,a\,\alpha\,b\,[\,3 - 2\,\alpha\,(\,L_1 + L_2\,)\,]\,p^L$$
$$+\;\alpha\,\big[\,a^2 + E\{\,\varepsilon^2\,\}\,\big]\,[\,3 - 2\,\alpha\,(\,L_1 +\; L_2\,)\,]\Bigg)$$

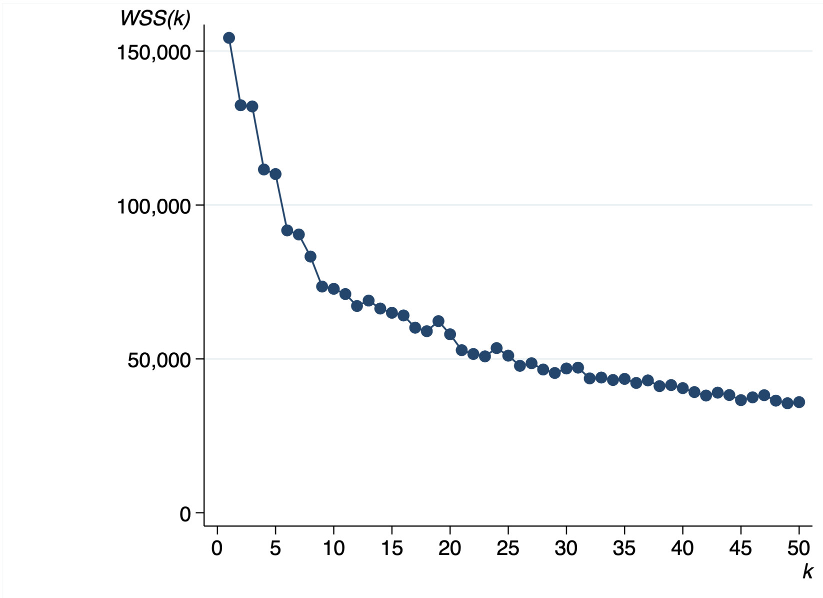
$$= \; -\,\alpha\,[\,3 - 2\,\alpha\,(\,L_1 +\; L_2\,)\,]\,\Big[\,b^2\,\big(p^L\big)^2 - 2\,a\,b\,p^L + a^2 + E\{\,\varepsilon^2\,\}\,\Big]$$

$$\stackrel{s}{=} \; -\,\Big[\,b^2\,\big(p^L\big)^2 - 2\,a\,b\,p^L + a^2 + E\{\,\varepsilon^2\,\}\,\Big] \;=\; -\,\Big[\,\big(\,a - b\,p^L\,\big)^2 + E\{\,\varepsilon^2\,\}\,\Big] \;<\; 0\,. \quad \blacksquare$$

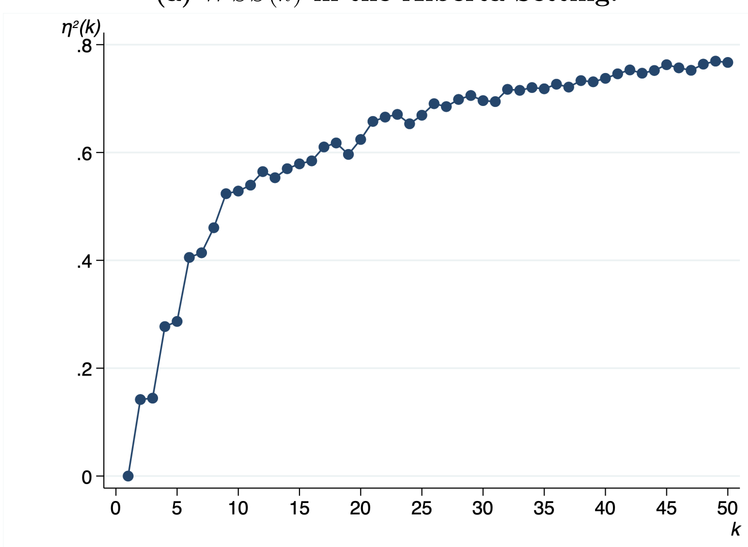
B. Analysis of the Alberta Setting.

The clustering analysis we employ in analyzing the Alberta setting is designed to reduce the dimensionality of the analysis while maintaining much of the richness of the full data set. To determine an appropriate number of clusters (i.e., an appropriate number of hours to employ to represent the $8,760$ hours in the sample), we follow Makles (2012) in calculating $WSS(k)$ for integer values of k. $WSS(k)$ is the sum of squared deviations from the average values of the variables under consideration within a cluster in the presence of k clusters. Higher values of $WSS(k)$ denote greater variability of the variables within a cluster. We then compute $\eta^2(k) \;=\; 1 - \frac{WSS(k)}{WSS(1)}$. Note that $WSS(1)$ is the sum of squared deviations from the average values of the variables in the full data set (where effectively there is a single cluster). Thus, $\eta^2(\cdot) \in [\,0, 1\,]$, and higher values of $\eta^2(\cdot)$ denote less within-cluster variation in key variables used to define the clusters.

Figure B1 depicts the values of $WSS(k)$ and $\eta^2(k)$ as the number of clusters (k) increases from 1 to 50 in the Alberta setting. The marginal reduction in $WSS(k)$ from introducing an additional cluster begins to decline markedly as k increases above 8. This analysis leads us to conclude that 25 clusters in the Alberta setting permit a tractable analysis while ensuring that the hours within each cluster are not too diverse. ($\eta^2(25) = 0.68$.)



(a) $WSS(k)$ **in the Alberta Setting.**



(b) $\eta^2(k)$ **in the Alberta Setting.**

Figure B1: Clustering Performance as the Number of Clusters (k) Varies.

Following Reguant (2019), we present Figure B2 to provide additional information about how well the 25 clusters we employ reflect the variation in the broader data set. Figure B2a reports for the entire data set the Pearson correlation coefficients for the key variables in the analysis. Figure B2b reports the corresponding correlations in the clustered data set. The figures identify some variation in the correlations, but suggest the clustered data generally reflects the relevant relations in the entire data set reasonably well.

The analysis of the Alberta setting employs the estimated fringe and import supply function specified in equation (10). Table B1 records the key coefficient estimates.[53] The first column of data in the table presents estimates from the ordinary least squares (OLS) regression. The last two columns of data in Table B1 report estimates from the first and second stages of the instrumental variable (IV) estimation. The OLS findings indicate that failure to account for the endogeneity of the wholesale price introduces attenuation bias. For the IV estimation, the Kleibergen-Paap (K-P) F-statistic strongly rejects the null hypothesis that the excluded instrument is weak. The second stage of the IV estimation finds a positive and statistically significant relationship between the wholesale price and fringe supply.

	OLS Q_t^f	IV First Stage p_t	IV Second Stage Q_t^f
Price	0.3074*** (0.1295)		9.6954*** (1.7319)
Demand Forecast		0.0489*** (0.008)	
K-P Wald Statistic		37.34***	
Calendar Fixed Effects	Y	Y	Y
Temperature Controls	Y	Y	Y
Sample Size	8,760	8,760	8,760

Notes. The calendar fixed effects include Hour, Month, Day (of the week), and Holiday. Standard errors appear in parentheses. *** denotes significance at the 1% level.

Table B1: Key Estimated Coefficients for the Fringe and Import Supply Function.

The estimated fringe and import supply function is employed to specify the residual demand function for each of the 25 representative hours. The average price elasticity of the estimated residual demand functions is -0.11, which is consistent with estimates for other geographic regions, including the north-eastern U.S. states (Bushnell et al., 2008).

Figure B3 illustrates an actual and an estimated marginal cost function in a selected representative hour for each of the major generators in the Alberta setting.

[53] Table TA1 in Brown and Sappington (2021) reports additional coefficient estimates.

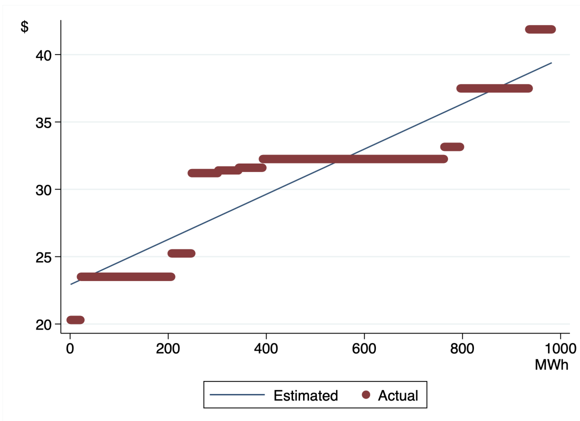
	BCImport	MTImport	SKImport	Price	DemandForecast	SupplyCushion	FringeSupply	ATCO_MustRun	CP_MustRun	ENMAX_MustRun	TA_MustRun	WindOutput	CoalPrice
MTImport	0.920												
SKImport	-0.101	-0.066											
Price	-0.113	-0.106	0.066										
DemandForecast	0.097	0.111	0.169	0.357									
SupplyCushion	0.342	0.316	-0.109	-0.463	-0.583								
FringeSupply	0.015	0.031	0.275	0.431	0.762	-0.696							
ATCO_MustRun	0.225	0.203	-0.206	0.017	0.187	0.069	0.114						
CP_MustRun	0.121	0.127	0.278	-0.008	0.246	0.056	0.150	0.351					
ENMAX_MustRun	0.211	0.189	-0.075	-0.120	-0.094	0.171	-0.141	0.089	0.027				
TA_MustRun	-0.030	-0.020	-0.596	0.021	-0.020	-0.099	-0.151	0.072	-0.183	0.030			
WindOutput	0.115	0.112	0.305	-0.049	0.176	0.080	0.080	0.303	0.922	0.090	-0.172		
CoalPrice	-0.075	-0.081	0.099	-0.022	-0.116	-0.042	0.008	-0.263	-0.471	-0.026	-0.142	-0.394	
GasPrice	0.155	0.188	0.382	0.197	0.482	-0.155	0.519	0.208	0.404	-0.075	-0.417	0.304	-0.150

(a) Full Data Set (Pre-Clustering).

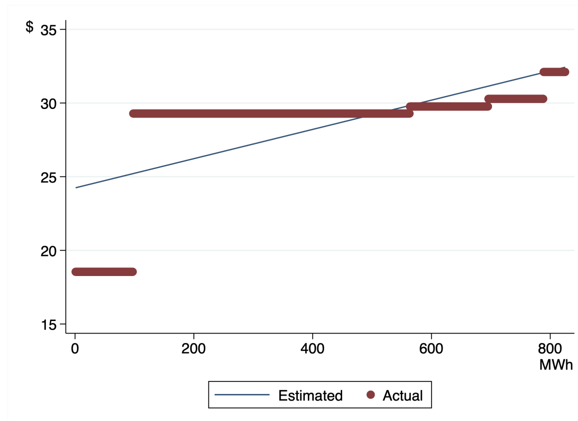
	BCImport	MTImport	SKImport	Price	DemandForecast	SupplyCushion	FringeSupply	ATCO_MustRun	CP_MustRun	ENMAX_MustRun	TA_MustRun	WindOutput	CoalPrice
MTImport	0.904												
SKImport	-0.199	-0.119											
Price	-0.087	-0.051	0.103										
DemandForecast	0.112	0.162	0.286	0.448									
SupplyCushion	0.619	0.545	-0.320	-0.569	-0.481								
FringeSupply	0.034	0.092	0.447	0.662	0.790	-0.654							
ATCO_MustRun	0.271	0.233	0.044	0.206	0.521	0.006	0.405						
CP_MustRun	0.254	0.281	0.282	0.147	0.405	0.076	0.328	0.564					
ENMAX_MustRun	0.192	0.130	0.151	0.014	0.138	0.003	0.068	0.181	-0.012				
TA_MustRun	-0.213	-0.152	-0.281	0.377	0.121	-0.400	0.151	0.194	-0.130	0.184			
WindOutput	0.234	0.238	0.397	0.070	0.399	0.042	0.306	0.577	0.920	0.249	-0.054		
CoalPrice	-0.083	-0.115	-0.016	-0.189	-0.331	0.016	-0.177	-0.474	-0.806	-0.099	-0.258	-0.753	
GasPrice	0.246	0.303	0.472	0.176	0.682	-0.141	0.657	0.360	0.517	0.111	-0.313	0.509	-0.234

(b) Clustered Data Set (Post-Clustering).

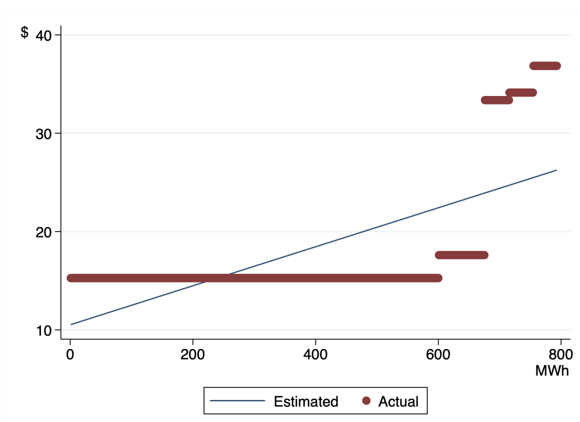
Figure B2: Correlation Matrices.



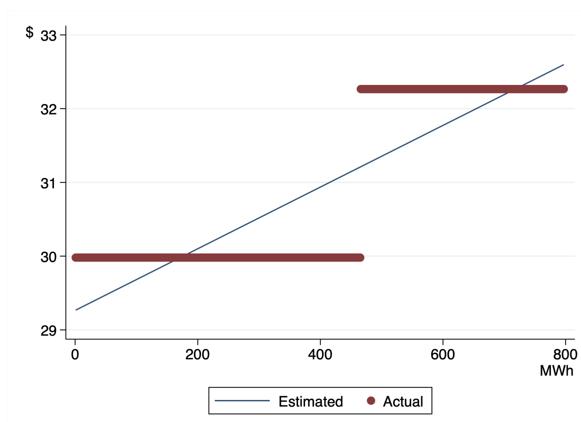
(a) ATCO



(b) Capital Power



(c) ENMAX



(d) TransAlta

Figure B3: Representative Actual and Estimated Marginal Cost Functions.

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