The Competitive Effects of Vertical Integration Under Incomplete Hedging

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Abstract

Vertical integration is often thought to mitigate market power in electricity markets since integrated generators that also purchase power for retail customers have less incentive to raise wholesale prices. We show that vertical integration between generators and retailers can be anti-competitive if firms are risk averse and only have access to standard forward contracts that provide incomplete insurance. Because standard forward contracts hedge price fluctuations for a fixed quantity, risk-averse integrated firms have an incentive to hedge retail obligations by taking long positions. This hedging incentive can make integrated generators net suppliers in the spot market, softening competition. Using unit-hour level auction data, we estimate forward positions and find integrated firms indeed hold large long positions and bid less competitively than their generation-only rivals. Using our estimated model, we find that the introduction of more complete forward contracts, in the form of load-following contracts, reduces hedging by integrated firms and intensifies spot-market competition, lowering consumer costs and increasing total welfare.

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1 Introduction

This paper studies how vertical integration affects competition when firms use forward contracts for both risk hedging and strategic commitment. Vertical integration and forward contracting have each been the topic of long and distinguished literatures in economics, but the topics are rarely studied together. Yet both vertical integration and forward contracting are observed in many wholesale markets, including electricity, agriculture, and airlines. When analyzed separately, forward contracts and vertical integration are each thought to increase competition by lowering wholesalers' exposure and incentives to raise spot prices. However, the forward position of an integrated firm may reflect hedging considerations driven by their retail demand in addition to wholesale pricing incentives, altering the firm's net exposure to spot prices. We analyze how forward positions, shaped by wholesale and retail considerations, determine the effect of vertical integration on competition.

We show that vertical integration can be anti-competitive when firms are risk-averse and only standard forward contracts, or price-only swaps, are available to manage risk. A standard swap pays the difference between the spot price and a pre-set base price for a fixed quantity of units. While this contract hedges the risk of holding financial assets or inventory, it provides an imperfect hedge for firms with variable quantities. For example, consider an electricity retailer. The retailer procures electricity, paying the spot price multiplied by realized demand, but their swap contracts pay spot prices multiplied by a constant quantity that does not vary with demand. Since forward contract payouts adjust to demand only through prices, and not quantities, the retailer faces right-tail asymmetric residual risk: when demand is high, spot prices rise sharply, creating large losses on the unhedged quantity; when demand is low, prices fall less dramatically, yielding smaller gains.

We develop a theoretical model that characterizes the optimal swap positions of vertically integrated firms. A risk-averse integrated firm responds to this asymmetric exposure by *over-hedging*—buying swap contracts to cover a higher quantity than expected retail demand. The additional forward payments provide partial insurance in precisely the high-demand, high-price states where the residual risk is greatest. However, over-hedging also causes the integrated firm to enter the spot market with substantial long exposure, creating an incentive to raise spot prices and weakening competition. The model shows that this over-hedging incentive disappears when more flexible "load-following" contracts, which index contracted quantities to realized demand, are introduced. We provide empirical evidence supporting

these predictions using data from before and after the introduction of load-following contracts in the electricity market in Alberta, Canada.

Vertical integration between generators and retailers is common in many deregulated electricity markets, reflecting both the legacy of integrated monopolies and retail firms' incentives to hedge risk by securing long-term reliable access to generation. In theory, vertical integration can also be anti-competitive due to foreclosure of rivals or increasing their operating and entry costs (Joskow (2008); Rey and Tirole (2007)). In restructured electricity markets, however, opportunities for vertical foreclosure are limited because wholesale dispatch and network access are coordinated by independent system operators, and strict regulatory oversight ensures nondiscriminatory access to the network (Mansur (2007); Bushnell et al. (2008)). Instead, vertical integration is usually viewed as pro-competitive (Bushnell et al. (2008)). Since an integrated firm earns the wholesale price on its generation but pays that price on the electricity needed to serve retail demand, its net exposure to wholesale prices is reduced, weakening incentives to raise wholesale prices. This logic has become influential both in subsequent empirical work and in policy analysis, where vertically integrated firms are often treated as more competitive once retail obligations are netted out of their wholesale positions.[1]

This dominant view, however, ignores a central feature of modern electricity markets: forward contracting. Electricity prices are highly volatile due to non-storability and inelastic short-run demand (Borenstein (2002)), and most deregulated markets are therefore accompanied by active forward markets. In standard oligopoly models, short forward positions can intensify wholesale-market competition by committing producers to larger effective quantities (Allaz and Vila (1993)), reinforcing the view that forward commitments, like vertical integration, discipline market power. Although the magnitudes differ, the pro-competitive impact holds across a wide range of market structures (Miller and Podwol (2020), and regardless of whether standard swaps or load following futures contracts are used (Brown and Sappington (2023)).[2]

[1]For example, see Brown et al. (2023); Fabra and Reguant (2014); Mansur (2007); Lundin and Tangerås (2020); Simshauser (2020); Bosco et al. (2013); NERA Economic Consulting (2025); Frontier Economics (2017).

[2]Brown and Sappington (2023) contrast the effect of load following and swap contracts for risk neutral generation only firms, focusing on the strategic role similar to Allaz and Vila (1993). However, they model load following contracts that cover the quantities produced by the strategic firms (excluding the competitive fringe) whereas in practice these contracts cover retailer demand. Their assumption means contract volumes are a function of the firms' production, and as a result the load following contracts are more effective for

The natural conclusion of these benchmark models is that both vertical integration and forward contracting are pro-competitive. We show that this prediction need not hold. The main missing force is risk aversion. In electricity markets, retailers' losses are concentrated in extreme states where prices and quantities are jointly high, threatening solvency rather than simply reducing profits. This risk is not merely theoretical: during the 2000-2001 California electricity crisis, several major retailers entered bankruptcy or came close to failure, and the 2021 ERCOT crisis led multiple Texas retailers to bankruptcy or market exit. The risk of retailer insolvency reflects a well-established corporate finance rationale for hedging: when adverse states are disproportionately costly, hedging creates firm value.[3]

We begin by separately analyzing simple models of the two main forces that drive forward contracting. Strategic commitment incentives push the integrated firm toward shorter, more negative net positions that intensify spot-market competition. In contrast, risk-hedging incentives push the integrated firm to over-hedge its downstream retail obligations by taking long forward positions, which soften spot-market competition. Over-hedging arises because the hedge available is an incomplete form of insurance.

Figure 1 provides a graphical illustration of the hedging problem. The retailer's procurement cost is the spot price $p^s(\varepsilon)$ multiplied by realized demand $q^r(\varepsilon)$. For simplicity, suppose the retailer's demand is $q^r(\varepsilon) = E[q^r(\varepsilon)] + \beta\varepsilon$, where $\beta\varepsilon$ represents their share of the market-level demand shock. The retailer receives payment $p^s(\varepsilon)f$ from forward contracts with fixed quantity f. If the retailer sets $f = E[q^r(\varepsilon)]$ to hedge their expected demand, they can offset the variation in $-\Delta\pi = -p^s(\varepsilon)E[q^r]$. However, this leaves the retailer exposed to the unhedged interaction term $-p^s(\varepsilon) \cdot \beta\varepsilon$. This interaction term creates asymmetric risk. For example, with convex supply curves, When demand is high ($\varepsilon \gg 0$), spot prices rise sharply, creating large losses $-p^s(\varepsilon) \cdot \beta\varepsilon$ on the unhedged quantity. When demand is low ($\varepsilon \ll 0$), prices fall less dramatically, yielding smaller gains. The retailer can reduce this asymmetric exposure by over-hedging: setting $f^* > E[q^r(\varepsilon)]$ generates additional forward payments $\Delta\pi^{\text{over}}$ precisely when demand and prices are both high, providing insurance

reducing output than the standard swap.

[3]Smith and Stulz (1985) show that hedging is valuable when financial distress costs are convex. Stulz (1990) and Bessembinder (1991) model settings in which low-cash-flow states induce underinvestment due to monitoring and contracting frictions or debt overhang near default. Froot et al. (1993) show that when external finance is costly, hedging reallocates internal funds toward low-cash-flow states. Consistent with these motives, electricity retailer hedging has been extensively studied (Willems and Morbee, 2010; Oum and Oren, 2009; Zhou et al., 2017; Winzer et al., 2024; Flottmann et al., 2025).

against the costliest states.

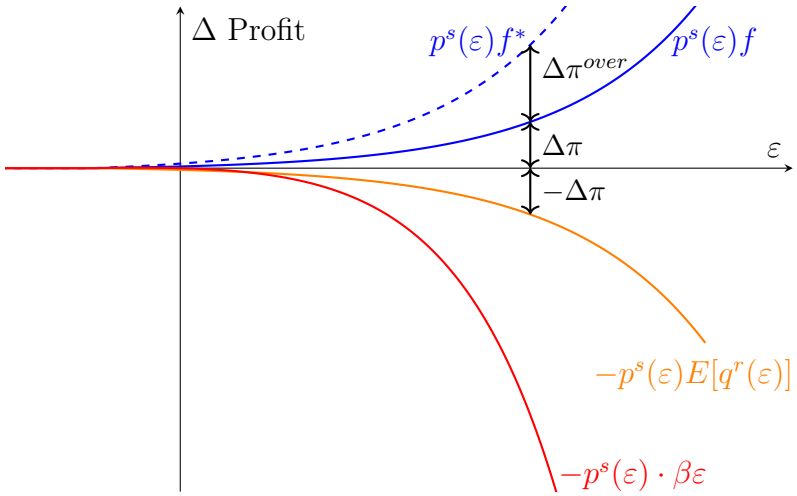


Figure 1: Asymmetric Shock Exposure and Over-hedging of Forward Positions

Notes: The figure illustrates how a demand shock ε affects a retailer's exposure to procurement costs and forward payoffs. The vertical distance of each curve from the horizontal axis represents the effect of a given realization of ε on profits. In the absence of higher-order effects (i.e., without the interaction term $-p^s(\varepsilon)\cdot\beta\varepsilon$), the retailer can fully hedge procurement risk by setting forward positions equal to expected demand, $f = \mathbb{E}[q^r(\varepsilon)]$. In this case, the linear components of profit offset exactly across states. When higher-order effects are present, exposure becomes asymmetric: losses in high-demand states are amplified relative to gains in low-demand states. As a result, the variance-minimizing forward position exceeds expected demand, $f^* > \mathbb{E}[q^r(\varepsilon)]$, generating endogenous over-hedging. The figure depicts the case of convex spot prices. The same intuition applies under symmetric price functions when the demand shock distribution is skewed.

A similar hedging incentive appears in agriculture markets (e.g., McKinnon (1967),Rolfo (1980), Hirshleifer (1988)). Farmers face market level output shocks that are correlated with their own production, for example favorable weather conditions boost everyone's yield simultaneously. These shocks induce a negative correlation between price and output through the downward sloping demand curve which creates an incentive for farmers to under-hedge their production. In addition, similar hedging motives arising from skewness in the distribution of equilibrium prices have been documented in electricity markets Bessembinder and Lemmon (2002).[4]

A natural question is why perfect insurance does not exist. In electricity markets, complete load-following contracts are largely absent from centralized trading.[5] They may be

[4]Bessembinder and Lemmon (2002) analyze a period where forward contracts were much less widely traded, thus their paper focuses on imperfect arbitrage, rather than imperfect spot-market competition.

[5]In industry and regulatory practice, these contracts are also sometimes referred to as full-requirements or full-load contracts.

negotiated bilaterally, but they are not standardized or liquid, and an industry report notes that such products are not traded in any North American market (Alberta Utilities Commission (2018)). A key barrier is asymmetric information. Delivery must condition on the buyer's realized retail demand, which is private, limiting wide trade. Practical frictions reinforce this. Risk sharing requires counterparties (or intermediaries) willing to absorb correlation risk, credible information-sharing to verify demand, and strong default safeguards such as collateral. These costs make centralized market design costly and keep trading thin.

We use our model to derive theoretical predictions on the equilibrium forward contract positions in four different scenarios that vary the type of contracts available and whether firms face strategic or risk-hedging incentives. We find that with strategic incentives only, both integrated and generation-only firms have similar (short) forward positions. Under risk aversion, the generation only firm takes a short position but the integrated firm over-hedges their retail demand. With load following contracts in either strategic or risk-hedging case, both integrated and generation firms take similar short forward positions.

Guided by these predictions, we study the five largest firms in the Alberta electricity market: four generation-only firms and one vertically integrated firm using unit-hour auction data. Alberta provides a well-suited environment for this analysis. The wholesale market clears through a single hourly uniform-price auction, generators do not receive any capacity payments, and an active exchange-traded forward market operates alongside the wholesale market. We first measure spot-market competition directly, computing markups as the wedge between bid prices and engineering marginal costs. Prior to the introduction of load-following contracts, the vertically integrated firm exhibited the highest markups. Following the introduction, markups declined for the vertically integrated firm but not for generation-only firms. To isolate the role of forward contracts in driving this change in markups, we estimate forward positions, controlling for confounding factors such as generation portfolio composition and demand elasticity. The dominant empirical approach, following Bushnell et al. (2008) would predict that the vertically integrated firm holds the shortest net position once retail obligations are accounted for. We find the opposite. The vertically integrated firm bids least competitively and holds the longest forward position, consistent with the model's risk-hedging channel. After load-following contracts are introduced, the firm's long hedging position declines substantially while those of generation-only firms remain stable, and its bidding behavior becomes markedly more competitive, consistent with the model's

predictions.

Using the model, we quantify the welfare implications of the interaction between vertical structure and risk hedging. When only standard (price-only) forward contracts are available, vertical integration increases average wholesale prices by 3.4 CAD/MWh (approximately 4 percent), raising consumer costs by approximately 64 million CAD per year and generating total welfare losses of 27 CAD million per year. However, introducing more flexible contracts reduces wholesale prices by 2.8 CAD/MWh, lowering consumer costs by 53 million CAD per year and producing total welfare gains of 25 million CAD per year. These results indicate that the adverse effects arise from the interaction between vertical integration and contract incompleteness. This implies that vertical integration is not, by itself, the sole source of the welfare losses. Instead, the losses reflect limitations in the contracts available in forward markets and can be mitigated by increasing contract completeness.

2 Institution and Data

We focus on Alberta, which has several attractive features for our analysis. The market is quite concentrated, there is a single vertically integrated firm, bidding data is widely available, and the regulator worked with the firms to develop novel forward contracts, that better hedge quantity risk. We use several datasets on the Alberta energy market from 2018-2021. First, we use data from the Alberta Electric System Operator (AESO) on the hourly price and quantity bids for all generation units, the ownership of the assets, and observed market demand. We combine this with data from Brown et al. (2023) on the marginal costs of generation units, which we use to verify our model estimates. These are noisy estimates of the hour-specific marginal costs for each plant, constructed using information on gas prices, taxes, and heat rates. Finally, we leverage forward contract pricing information from Olmstead and Yatchew (2025).

2.1 Electricity Spot Market

The wholesale electricity market in Alberta is a single real-time hourly uniform-price multi-unit auction. There are no day-ahead or capacity markets. There is an ancillary services market to match short term fluctuations. Generators submit bids in the hourly-auction as step-functions. That is, each generator provides a set of up to seven price, quantity

pairs at which they are willing to supply electricity. The price they quote must be in $[0,999.99]/MWh and the generators must provide quotes for all available capacity (i.e., the largest quantity must equal the capacity). The AESO sorts the bids by price to construct an aggregate demand curve. In each minute of the hour, there is a system-marginal price, the most expensive bid that is used to clear the market. All bids with prices below this market clearing price are dispatched. Participants are paid the pool price, the time-weighted average of the system marginal price within the hour for all units dispatched. The generation market in Alberta has no location marginal prices. The AESO plans transmission investments according to a no-congestion standard, ensuring sufficient capacity to provide reasonable access to all in-merit generation (AESO (2022); Wolak (2015)). Consistent with this policy, the Market Surveillance Administrator reports that constrained-down generation accounts for only 0.2% of total load, with congestion arising primarily from discrete planned or forced transmission outages rather than insufficient baseline capacity (MSA (2014)).

The market is quite concentrated, with four large firms making up 48% of the generation capacity (see Table 1). These large firms are TransAlta, ATCO, ENMAX, and Capital Power. There is also a competitive fringe consisting of 38 smaller firms MSA (2018). The market is about half natural gas generation, and coal and renewables make up around 30, and 10 percent of generation respectively. Finally, there are also bids from the balancing pool, a government entity which manages assets subject to a divestiture at the time the electricity market underwent restructuring Brown et al. (2023).[6] Alberta has limited interconnection with other Canadian provinces and the United States. The total transmission import capacity is around 1100MW, and net imports account for only about 5% of Alberta's demand AESO (2022).

Approximately 80% of retail electricity demand is non-residential with 61% from large industrial consumers MSA (2015). Alberta has a competitive retail market, where firms offer both fixed or variable rate contracts. There is also a default option. During the period of the study, the default option had a variable price, depending on forward market and wholesale electricity prices based on a formula determined by the regulator MSA (2015).

[6]In around 2000, generation asset divestiture was done via power purchase agreement (PPA) auctions to reduce concentration. The auctions offered 6250MW of coal and gas capacity (roughly 64% of the market at the time). The unsold PPA capacity from these auctions (roughly 2000MW) was transferred to the balancing pool, and the government managed these assets to maintain operation in a commercial manner Brown et al. (2023).

Table 1: Summary Statistics

Variable	Mean	Median	SD	Min	Max
Panel A: Hourly Market Data					
Pool price (CAD/MWh)	63.46	35.07	106.74	0.00	999.99
Total dispatched (MWh)	8340	8369	829	5855	16506
Gas dispatched	4812	4754	631	2982	9366
Coal dispatched	2609	2597	788	866	6168
Wind dispatched	583	489	448	0	3299
Hydro dispatched	176	147	102	34	636
Solar dispatched	17	0	47	0	302
Other	143	147	24	52	338
Panel B: Monthly Retail Consumption					
Total (GWh)	3964.36	3936.31	241.06	3540.89	4472.95
Vertically integrated firm	1346.47	1380.16	152.15	1046.43	1625.39
Panel C: Market Share					
3 Generation-only large firms		39% of total capacity			
Vertically integrated firm		9% of total capacity			

Notes: Sample from 2018 to 2021.

2.2 Forward Markets

There is an active financial market for electricity futures in Alberta. The main trading platforms are the Natural Gas Exchange (NGX) and over-the-counter broker markets (MSA, 2010). On NGX, contracts are quoted and traded anonymously, and NGX acts as a clearinghouse that assumes counterparty risk. As with many financial exchanges, this is possible because NGX requires participants to post margin. Since these contracts are standardized and centrally cleared, participants can easily offset a forward position by taking on a new position in the opposite direction.

The most commonly traded forward contract is a spot-forward. These are also referred to as contracts for difference. To settle the contract, one party pays the other the difference between the agreed upon price, and the hourly pool price for the contract period. Participants in the forward market include not only generators and retailers, but also financial intermediaries and hedge funds. There are both flat forwards (covering every hour, each day in the contract period), as well as on-peak, off-peak, extended peak, extended off-peak and

super peak contracts which provide some variation in the set of covered hours. Monthly, quarterly, and yearly flat contracts are most common. Monthly contracts account for 40% of the market, quarterly contracts for approximately 25%, and annual contracts for the remaining 35%. Financial participants and electricity firms each comprise roughly equal shares of total market activity MSA (2010). [7] These features, especially the exchange trading, and high participation of financial participants suggest that the forward market is competitive.

2.2.1 Testing for Arbitrage

Since our theoretical model assumes no arbitrage between the spot and forward markets, we begin by empirically verifying that this condition holds in the data. Following Longstaff and Wang (2004), we test whether the mean of the difference between spot and forward prices is zero. In this test we use heteroskedasticity and autocorrelation standard errors. A histogram of the price differences is presented in Appendix Figure 10. The average difference is -2.22, but the standard error of the estimate is 2.87, yielding a p-value of 0.44. Olmstead and Yatchew (2025) provide a different test of the so-called unbiasedness hypothesis i.e., if p^f_{tM} is the forward price at time t for delivery in month M, and p^s_M the spot price in month M, and unbiasedness requires $\beta_0 = 0, \beta_1 = 1$ in the regression $p^s_M = \beta_0 + \beta_1(\frac{1}{T}\sum p^f_{t,M}) + \epsilon_M$. They do not reject the null on the full sample: $\hat{\beta}_0 = -0.02\,(6.41)$ and $\hat{\beta}_1 = 1.02\,(0.09)$, yielding a p-value of 0.855, suggesting unbiasedness, which implies no arbitrage. In some sub-samples they find evidence that this prediction is violated. In particular they find larger slopes, and negative intercepts far before the contract is delivered. This does not suggest a violation of arbitrage, it may simply reflect price discovery, since prices far ahead are compressed towards the unconditional average, because much of the relevant information has not yet arrived.

2.2.2 Load-Following Contracts

Part way through the sample period the government intervened in the forward market, introducing a new type of forward contract. This new contract pays the spot price minus the contracted price (like the contract for differences) but this time instead of being a contract for a fixed quantity, this price gap is paid on the retail demand of the firm on which the contract is

[7] Jha and Wolak (2023) provide evidence that introducing purely financial participation in California's wholesale electricity market improved agreement between day-ahead and real-time prices and reduced production costs, suggesting that financial participants can play an important role in improving forward market efficiency.

written. This intervention was motivated by a desire to efficiently price the regulated option. Any consumer not on a competitive electricity plan is served by the regulated option. Prices for this are set at a procurement cost, reflecting forward market prices, plus a small markup to the retailer for their servicing costs. In each region of the province one retailer acts as the provider of the regulated option plan. The government imposes many requirements on this plan, setting prices, and forcing the retailers to follow an agreed upon hedging strategy in their Energy Price Setting Plan (EPSP) which must be approved by the Alberta Utilities Commission (AUC) through regulatory proceedings approximately every three years.

The government worked with the retail firms and outside contractors to develop a contract form, and then held centralized auctions to help generate sufficient liquidity to sell these contracts. Initially this move was lead by EPCOR, another large retailer (which is not vertically integrated). EPCOR transitioned to using load following futures, sold at auctions in 2018. The vertically integrated retailer followed, with the first auction held in September of 2020 for delivery in December (see e.g., Brown et al. (2022)).

There were several frictions that made the adoption of these contracts difficult, and which may explain why despite success in government-run auctions they did not arise alone in the market. First, these contracts transfer large financial risks onto the financial players (since prices and quantities are high on the same day) requiring larger margin/collateral be kept by the market maker or inducing substantial counterparty risk if contracted bilaterally NERA Economic Consulting (2019). Second, these products transfer larger risks to the firm and that may change the set of firms interested in supplying the product. Third, these products contract on the retail demand of a firm. This information is the private information of the firm and may be subject to manipulation without some trusted verification system NERA Economic Consulting (2019). Fourth, these products require good data and different modeling ability and may be complicated to price (e.g., Beblow (2017)). Finally, because the market is still not liquid unlike a standard forward contract these contracts are difficult to unwind (one cannot simply go to the exchange and purchase an offsetting position in the other direction). Despite these challenges, the regulator has found success in encouraging the adoption of these contracts in Alberta and they now form part of the tools used for managing risks. Similar contracts have also been adopted in other markets with government support (e.g., procurement via government run auctions) in several electricity markets including Pennsylvania, Ohio and New Jersey. Similar demand-shaped forward

contracts have also been proposed for long-term resource adequacy in markets with significant intermittent renewables, where they discourage the exercise of unilateral market power when realized demand exceeds forecasts (Wolak (2022); Thurber et al. (2022); Shaffer and Wolak (2024)).

3 Simple Model

This section presents a simple model of optimal forward positions in swaps and load-following forward contracts (LFFCs) for producers and vertically integrated (VI) firms. The goal is to build intuition by isolating the main economic forces—strategic incentives and risk-based hedging—cleanly and separately. We combine both incentives in a richer quantitative model calibrated to deliver empirical predictions in Section 5. We present four results, all proofs are in Appendix A. The first and second results isolate the strategic and risk-based hedging respectively in the case with swap contracts only. The third and fourth results repeat the same exercise, with load following contracts instead of swaps.

In the first case, with only strategic behavior (i.e., risk neutral firms and imperfect competition in the spot market) production firms sell forward contracts, pre-committing to offer larger quantities (as in Allaz and Vila (1993)). The integrated firm uses forward contracts to obtain the same net-exposure to the spot market prices as the production-only firm, (but for the integrated firm this requires shading its forward sales to offset its expected retail exposure). On the other hand, with risk aversion, no strategic interactions (i.e., a competitive spot market), and swap contracts, the production-only firm takes a forward position equal to their expected production plus a small additional hedging term and the integrated firm aggressively over-hedges their expected retail demand. This over-hedging arises since retail profits depend on spot prices (which depend on demand shocks), multiplied by the demand shock, while swap forward contract payouts are spot prices times a constant, and so they cannot perfectly insure retail profits. If demand uncertainty is right-skewed, or if prices are convex in demand, then the integrated firm can increase their payments in the high-price states where they would otherwise face large losses, by over-hedging their retail exposure.

In the competitive case, introducing load following contracts causes a small change in positions. However, with risk aversion, the introduction of load following contracts reduces

the short position of production-only firms and eliminates the overhedging behavior of the integrated firm, so that the integrated firm hedges similarly to the production only firm.

3.1 Strategic Incentives and Swap Forward Contracts

Spot Market Equilibrium. We begin with the conventional view of forward contracts and vertical integration following Allaz and Vila (1993) and Bushnell et al. (2008), establishing why forward commitments and VI are generally regarded as pro-competitive. Throughout this section, f_i denotes firm i's short forward position (forward sales), with $f_i < 0$ representing a long position. Subscripts "N" and "A" denote the risk-neutral and risk-averse cases, respectively. Firm i chooses production q_i at the production stage. Retail sales and the retail price are denoted q_i^r and p_i^r, respectively. Firm i maximizes profits:

$$\Pi_i = \underbrace{p_i^r q_i^r - p^s q_i^r}_{\text{Retail Profit}} + \underbrace{p^s q_i - C_i(q_i)}_{\text{Generation Profit}} + \underbrace{p^f f_i - p^s f_i}_{\text{Forward Profit}}$$

where $C_i(q_i) = b_i q_i + \frac{q_i^2}{2k_i}$ denotes total costs, and p^s and p^f are the spot and forward prices. Following Allaz and Vila (1993) and Bushnell et al. (2008), retail quantities (q_i^r)[8] and prices (p_i^r), as well as forward quantities (f_i) and prices (p^f), are sunk at the time production decisions are made and therefore drop out of the optimization over output. The maximization problem thus reduces to:

$$\max_{q_i} \; -p^s q_i^r + p^s q_i - C_i(q_i) - p^s f_i$$

The first-order condition is:

$$\underbrace{p^s - C_i'(q_i)}_{\text{Markup}} = \underbrace{(q_i - f_i - q_i^r)}_{\text{Net position}} \cdot \left(-\frac{\partial p^s}{\partial q_i} \right)$$

This condition clarifies the standard argument for why forward contracts and vertical integration are pro-competitive: as the short forward position or retail quantity increases, the firm's incentive to raise the spot price diminishes. Note that $q_i - f_i - q_i^r$ may be negative, in which case the firm would prefer to drive spot prices *below* competitive levels. The key question, therefore, is how net forward positions $f_i + q_i^r$ are determined in equilibrium.

[8] A generation-only firm corresponds to the special case $q_i^r = 0$.

Forward market equilibrium. We consider a two-player, two-period model in which player 1 is a generation-only firm and player 2 is a VI firm. In the first period, both players trade forward contracts calling for delivery of electricity to be produced in the second period. These contracts serve as precommitments to supply. In the second period, both players choose production quantities.

In period 1, agents face uncertainty over the residual demand state, which is resolved in period 2. We assume the forward market is efficient – equivalently, the perfect arbitrage condition holds, so that expected forward profits are zero. This requires only at least one risk-neutral speculator. Following Bushnell et al. (2008), we also assume that expected retail profits are zero, with retail rates adjusted to reflect expected wholesale prices and retail demand. Retail demand is exogenously determined.

Residual demand in the second-stage production game is:

$$p^s(Q,\varepsilon) = a + \varepsilon - Q \quad \text{and} \quad Q(p^s,\varepsilon) = a + \varepsilon - p^s$$

where Q denotes aggregate system-wide quantity, a is average system-wide demand, and ε is a mean-zero random demand shock with variance σ^2. Demand is inelastic, but the duopolists face a downward-sloping residual demand because fringe suppliers produce as long as price exceeds their marginal costs. The VI firm serves exogenous retail demand $q_2^r = \theta + e$, where θ is average retail demand and e is a mean-zero retail demand shock. For technical simplicity, we assume the retail demand shock is proportional to the system demand shock: $e = \beta\varepsilon$. However, our proofs in Appendix A do not require this assumption.

In the first stage, both firms take into account both periods. By backward induction, equilibrium quantities q_1^*, q_2^* and the spot price p^s at the production stage are functions of f_1 and f_2. With swaps, the contract quantities f_1 and f_2 are non-random, and the first-stage problems are:

$$\text{Producer: } \max_{f_{1,N}} \mathbb{E}\Big[p^s q_1^* - C_1(q_1^*) + (p^f - p^s) f_{1,N}\Big]$$

$$\text{VI: } \max_{f_{2,N}} \mathbb{E}\Big[p_2^r q_2^r - p^s q_2^r + p^s q_2^* - C_2(q_2^*) + (p^f - p^s) f_{2,N}\Big]$$

For technical simplicity, consider the symmetric technology case ($b_1 = b_2 = b$, $k_1 = k_2 = k$), with $0 < b < a$ and $k > 0$.

Result 1 (Strategic Incentives with Swap Contracts)**.** *The equilibrium swap forward positions are:*

$$f^*_{1,N} = \frac{k^2}{5k^2 + 5k + 1}(a - b), \qquad f^*_{2,N} = f^*_{1,N} - \theta$$

Allaz and Vila (1993) is a special case of this result. If we assume constant marginal cost ($k \to \infty$) and generation-only firms ($q^r_2 = 0$), we obtain $f^*_{1,N} = f^*_{2,N} = \frac{a-b}{5}$, matching their Proposition 2.3. Both firms are always net short ($f^*_{1,N} = f^*_{2,N} + \mathbb{E}[q^r_2] > 0$). The immediate implication is that equilibrium pre-committed quantities are identical in expectation across the producer and the VI firm (i.e., $f^*_{1,N} = f^*_{2,N} + \mathbb{E}[q^r_2]$). The intuition is straightforward: risk-neutral symmetric firms make strategic commitments targeting the same expected production level, so the VI firm reduces its forward position by exactly its expected retail quantity. This means the forward market continues to deliver the improvement in competition over the one-period Cournot game highlighted by Allaz and Vila (1993).

The result also tells us that conditional on equilibrium forward market behavior, vertical integration has no effect on the level of spot market competition. Net pre-committed quantities match those implied by the producer-only game. As a result, VI is neither pro nor anti-competitive in this setting.

3.2 Hedging Incentives and Swap Forward Contracts

We now consider firms that use forward contracts solely as hedging instruments rather than strategic commitment devices. For this exercise, we adopt the extreme assumption that both firms are price takers and that the spot price clears the following exogenous demand:

$$Q(\varepsilon) = a + \varepsilon$$

While it is an important simplification of wholesale electricity markets, this assumption is standard in the finance literature on risk hedging (see Bessembinder and Lemmon (2002)) and greatly simplifies the analysis of how hedging incentives determine forward positions. As before, we assume that the VI firm faces exogenous retail demand $q^r_1 = \theta + \beta\varepsilon$, where θ is average retail demand and $\beta\varepsilon$ is a mean-zero shock proportional to the market demand shock.

Under the price-taking assumption ($\frac{\partial p^s}{\partial q_i} = 0$), the first-order condition at the production stage yields:

$$\frac{\partial \Pi_i}{\partial q_i} = p^s - C_i'(q_i) = 0 \iff q_i = k(p^s - b) \quad \text{for } i = 1, 2$$

Equating total production to total demand gives $a+\varepsilon = 2k(p^s - b)$, so the market-clearing spot price and equilibrium quantities are:

$$p^s = \frac{a+\varepsilon}{2k} + b, \qquad q_1^* = \frac{a+\varepsilon}{2}, \qquad q_2^* = \frac{a+\varepsilon}{2}$$

In the first stage, both firms anticipate second-stage outcomes. Since production-stage outcomes q_1^*, q_2^*, p^s are now independent of f_1 and f_2, expected profits $\mathbb{E}[\Pi_i]$ do not depend on f_i. The firms' sole concern is risk reduction, and they minimize profit variance:

$$\text{Producer: } \min_{f_{1,A}} \operatorname{Var}\Big[p^s q_1^* - C_1(q_1^*) + (p^f - p^s) f_{1,A}\Big]$$

$$\text{VI: } \min_{f_{2,A}} \operatorname{Var}\Big[p_2^r q_2^r - p^s q_2^r + p^s q_2^* - C_2(q_2^*) + (p^f - p^s) f_{2,A}\Big]$$

Result 2 (Hedging Incentives with Swap Contracts)**.** *The equilibrium swap forward positions are:*

$$f_{1,A}^* = \mathbb{E}[q_1^*] + \frac{\mathbb{E}[\varepsilon^3]}{4\,\mathbb{E}[\varepsilon^2]}, \qquad f_{2,A}^* \approx f_{1,A}^* - \theta - \underbrace{\frac{\mathbb{E}[\varepsilon^2 \cdot \beta\varepsilon]}{\mathbb{E}[\varepsilon^2]}}_{\textit{Over-hedge}}$$

As in Result 1, the VI firm reduces its forward position relative to the production only firms by their expected retail quantity. However, in this setting the VI firm reduces their position *further* due to the over-hedging term $\frac{\mathbb{E}[\varepsilon^2 \cdot \beta\varepsilon]}{\mathbb{E}[\varepsilon^2]} > 0$, an ε^2-weighted average of the retail demand shock $\beta\varepsilon$.

The over-hedging term is driven by the fact that swap contracts provide incomplete insurance. To see why, focus on the retail cost and forward contract terms in the integrated firms problem i.e., $-p^s(\varepsilon)q_2^r(\epsilon) + (p^f - p^s(\varepsilon))f_{2,A}$. In the retail cost term, $p^s(\varepsilon)q_2^r(\varepsilon)$, spot market prices (which depend on the residual demand state in equilibrium) are multiplied by the residual demand shock –which shifts $q_2^r(\varepsilon)$ directly. However, there is no analogous higher-order interaction with the residual demand shock in the contract payout term $(p^f - p^s(\varepsilon))f_{2,A}$, where prices are multiplied by the same constant in all demand states. This means swap futures do not perfectly insure the price times shock component.

Imposing the linear forms from the simple model, the retail exposure is $p^s(\varepsilon)(\theta + \beta\varepsilon)$ and the futures payoff is $(p^f - p^s(\varepsilon))f$. If the firm chose $f = \theta$, the firm fully offsets the $p^s\theta$ variation with their contracts but they are left with $p^s(\varepsilon) \cdot \beta\varepsilon$. The crucial point is that this residual term, involves the spot price p^s multiplied by residual demand shocks, whereas in the futures payoff, p^s is only ever multiplied by a constant f. In this baseline model, if the retail shocks are proportional to the aggregate demand shocks i.e., $\beta\varepsilon$, then the residual term $p^s(\varepsilon) \cdot \beta\varepsilon$ is a quadratic function in ε. This means that if ε has a skewed distribution or $p^s(\varepsilon)$ is asymmetric in ε (say from convex supply costs due to the production technology), then the firm can reduce risk by distorting their forward position. For instance, if very high ε states are much more likely than very low ones, the firm can buy forward contracts, to get offsetting payments precisely in those more-probable expensive states.

Figure 2 illustrates this over-hedging incentive graphically. Each line in panel (a) represents the retail arm's payoff $\pi = p^r q^r - p^s q^r + (p^f - p^s)f$ for a given hedging decision f, plotted against realized market demand (Q) on the horizontal axis. Panel (b) shows the spot price implied by the supply curve, $p^s(Q)$ alongside the density of demand.

To generate realistic price and demand patterns, we draw 8760 hourly net demand observations (demand minus renewable production) from a single year. Because demand is inelastic, each draw maps to a unique point on the supply curve (red line), and the resulting pries inherit its convex shape: prices fall only slightly when demand is below average but rise dramatically in high-demand states. This pattern is typical of electricity markets and produces a similar right-tailed effect on retailer profit to the skewness in residual demand states used in the simple model ($p^s(\varepsilon) \cdot \beta\varepsilon$).

Consider, for example, a high-demand realization of $Q = 10137$ MWh, where the spot price reaches $p^s = 883$. Under no hedging ($f = 0$, blue dot), the retail arm loses 2.56 million CAD, a substantial loss from a singly hour; hedging at expected demand ($f = -E[q^r] = -2405$, purple solid) reduces the loss to 0.53 million CAD; and the variance-minimizing position ($f = f^* = 2983$, green dash) reduces it to just 0.04 million CAD. The zero line represents perfect insurance, which occurs when the forward position exactly matches retail demand ($f = -q^r$).

By construction of the retail price, all payoff profiles share the same expected profit, so differences across curves therefore reflect risk exposure rather than expected profitability. If the firm set their forward position equal to expected retail demand, their uninsured residual

retail payoffs would be larger in the high-demand states, and the firm could reduce their risk by buying linear swap contracts to increase payments in those states. Without hedging, profits fall sharply with demand: high demand coincides with high wholesale prices, generating large losses in precisely the states that matter most for a risk-averse retailer. The swap contract must be purchased before demand is realized and does not allow the retailer to adjust their long forward position $-f$ to the realized demand state q^r. Hedging at $f = -\mathbb{E}[q^r]$ reduces price exposure around typical demand levels but leaves substantial downside risk in high-demand states, where procurement exceeds the hedge and wholesale prices are highest. The optimal long position therefore exceeds expected demand. Increasing long position rotates the payoff upward in the right tail: the hedge pays off most when p^s is high, and because prices are high when demand is high, a larger long position disproportionately reduces losses in the variance-driving states. Taken together, the figure illustrates the paper's central mechanism: with right-tail asymmetric exposure to demand shocks, the retailer can reduce their payoff risk, by buying extra swaps to improve their payouts in the states where demand and prices are both high.

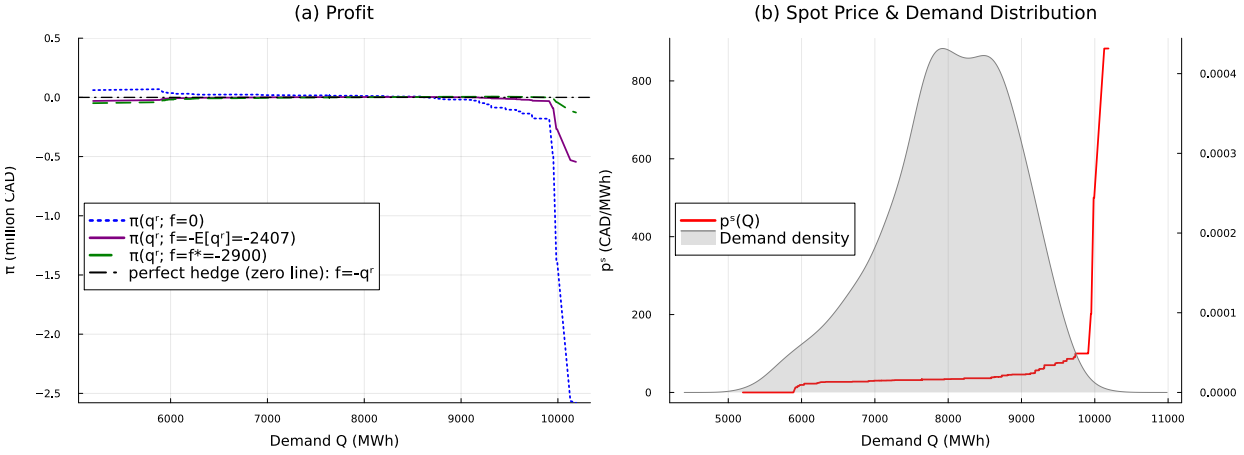


Figure 2: Retailer Payoff Profiles Under Alternative Hedging Strategies

*Notes:*This figure illustrates the over-hedging incentive in two panels. Panel (a) plots the retailer's profit across demand realizations for three forward positions: no hedging $f = 0$, hedging expected demand ($f = -E[q^r]$), and the variance-minimizing (over-hedging) position ($f = f^* < -E[q^r]$). The zero line represents the perfect hedge ($f = -q^r$), where the forward position exactly offsets the retailer's own demand, eliminating all profit variability. Panel (b) shows the convex supply curve $p^s(Q)$ alongside the distribution of demand. The convexity of the supply curve creates asymmetric exposure across demand shocks: losses in high-demand states (where both price and unhedged quantity are large) exceed gains in low-demand states (where spot prices are low and close to the forward price). Over-hedging reduces profit variance by loading additional forward payments into high-price, high-quantity states, providing insurance precisely when procurement costs are most severe.

3.3 Load Following Contracts

The preceding analysis showed that swaps cannot hedge all risk factors in electricity markets. In particular, retail quantity risk and the correlation between price and quantity risk remain unhedged, giving rise to over-hedging. A natural question is: what are the effects of introducing more complete forward contracts? Specifically, how do contracts whose quantities adjust to realized demand affect equilibrium forward positions?

In a standard swap, the payment is $(p^f - p^s) \cdot f$, where p^f and f are fixed in advance. In a more complete contract, the payment is $(p^f - p^s) \cdot lq^r$, where p^f and l are fixed in advance while p^s and q^r are realized at the production stage. Setting $l = 1$ yields the perfect hedge for the retail arm depicted in Figure 2. This contract is not merely a theoretical construct: it was recently introduced in the Alberta electricity market as a load-following forward contract (LFFC), and other markets in North America and Australia have begun adopting similar instruments (Brown and Sappington (2023)).

We first consider risk-neutral firms under imperfect competition with residual demand $Q(p^s, \varepsilon) = a + \varepsilon - p^s$. The production game is equivalent to the swap model. In the first stage, the two firms solve:

$$\text{Producer: } \max_{l_{1,N}} \mathbb{E}\Big[p^s q_1^* - C_1(q_1^*) + (p^f - p^s) l_{1,N} q_2^r\Big]$$

$$\text{VI: } \max_{l_{2,N}} \mathbb{E}\Big[p_2^r q_2^r - p^s q_2^r + p^s q_2^* - C_2(q_2^*) + (p^f - p^s) l_{2,N} q_2^r\Big]$$

Result 3 (Strategic Incentives, Load Following Contracts)**.** *The expected equilibrium LFFC forward positions are:*

$$\mathbb{E}[l_{i,N} q_2^r] = f_{i,N}^* + \frac{k^2}{5k^2 + 5k + 1} \frac{-(a-b)\beta^2\sigma^2 + \theta\beta\,\sigma^2}{\theta^2 + \beta^2\sigma^2} \quad \textit{for } i = 1, 2$$

As in Result 1, equilibrium pre-committed quantities are identical across the producer and the VI firm. The second term captures the difference between swaps and LFFCs. To build intuition for this comparison, suppose further that the retail demand shock co-moves with system demand proportionally to its mean level: $\beta = \frac{\theta}{a}$. [9] Then, we obtain $\mathbb{E}[l_{1,N} q_2^r] \approx f_{i,N}^*$ to a first-order approximation. As a result, swaps and LFFCs yield nearly identical positions

[9] We consider a more general error structure, and provide full proofs of the results, in Appendix A.

in equilibrium. Any remaining difference is second-order and therefore quantitatively small.

We next consider risk-averse, price-taking firms with residual demand $Q(\varepsilon) = a + \varepsilon$. The production game is again equivalent to the swap model. Since production-stage outcomes are independent of $l_{1,A}$ and $l_{2,A}$, expected profits do not depend on the LFFC positions, and firms minimize profit variance:

$$\text{Producer: } \min_{l_{1,A}} Var\left[p^s q_1^* - C_1(q_1^*) + (p^f - p^s) l_{1,A} q_2^r\right]$$

$$\text{VI: } \min_{l_{2,A}} Var\left[p_2^r q_2^r - p^s q_2^r + p^s q_2^* - C_2(q_2^*) + (p^f - p^s) l_{2,A} q_2^r\right]$$

Result 4 (Risk Hedging with Load Following Contracts)**.** *The expected equilibrium LFFC forward positions are:*

$$\mathbb{E}[l_{1,A} q_2^r] \approx f_{1,A}^* - \mathbb{E}[q_1^*] \frac{\mathbb{E}[\varepsilon^2 \cdot \beta\varepsilon]}{\theta\, \mathbb{E}[\varepsilon^2]}, \qquad \mathbb{E}[l_{2,A} q_2^r] \approx f_{1,A}^* - \theta - \mathbb{E}[q_1^*] \frac{\mathbb{E}[\varepsilon^2 \cdot \beta\varepsilon]}{\theta\, \mathbb{E}[\varepsilon^2]} + \left(\underbrace{\frac{\mathbb{E}[\varepsilon^2 \cdot \beta\varepsilon]}{\mathbb{E}[\varepsilon^2]}}_{\textit{Correction}} - \underbrace{\frac{\mathbb{E}[\varepsilon^2 \cdot \beta\varepsilon]}{\mathbb{E}[\varepsilon^2]}}_{\textit{Over-hedge}} \right)$$

The key insight is that LFFCs exactly correct the over-hedging term arising from swap incompleteness identified in Result 2. By replacing f, which was constant across states, by $l_{2,A} q_2^r$, these contracts introduce the missing interaction term into the forward contract, allowing contract payoffs to vary nonlinearly with demand shock. This has two important implications. First, the over-hedging term represents a long position that increases the incentive to exercise market power under imperfect competition; LFFCs eliminate this potentially anticompetitive effect. Second, whereas the VI firm held smaller precommitted quantities than the producer in the swap case, under LFFCs the two firms' precommitted quantities are approximately equal in expectation ($\mathbb{E}[l_{1,A} q_2^r] \approx \mathbb{E}[l_{2,A} q_2^r] + \mathbb{E}[q_2^r]$). Moreover, LFFCs automatically tailor producers' market exposure, reducing sensitivity when prices are high and increasing it when prices are low. Thus, if hedging incentives dominate strategic incentives, LFFCs may reduce producers' short forward positions.

Results 1 through 4 characterize equilibrium forward positions under alternative assumptions about risk preferences and market power. Figure 3 illustrates net short equilibrium positions—forward positions plus retail demand—separately for the strategic commitment

case in panel (a) and the risk-hedging case in panel (b). Blue circles represent the producer's net positions; red squares represent the VI firm's. Arrows indicate the shift from optimal swap to optimal LFFC positions. Under risk neutrality with market power (panel a), both firms hold identical net short positions under swaps. The impact of LFFCs is negligible and enters only at second order.

Under risk aversion (panel b), the producer is net short with swaps, but the VI firm may be either net short or net long depending on the magnitude of the over-hedging term. The critical observation is that risk-averse producers and VI firms hold *different* net positions: the over-hedging term drives a wedge between them, pushing the VI firm toward longer positions. This over-hedging incentive is the only mechanism in the model that can generate a net long position. LFFCs correct this wedge, moving both the producer and the VI firm toward the same net position, as shown in panel (b).

These results suggest potential anti-competitive effects arising from the interaction between vertical integration and contract incompleteness under imperfect competition. The risk-averse VI firm may substantially reduce its short position or hold long positions due to the over-hedging incentive with swap, creating an incentive to raise spot prices. However, LFFCs or structural separation can correct these adverse effects. One may wonder whether these results extend to the case where strategic and risk-based hedging are present simultaneously. In Section Appendix D, we empirically solve the structural Cournot model with risk-averse players and show that all these results continue to hold.

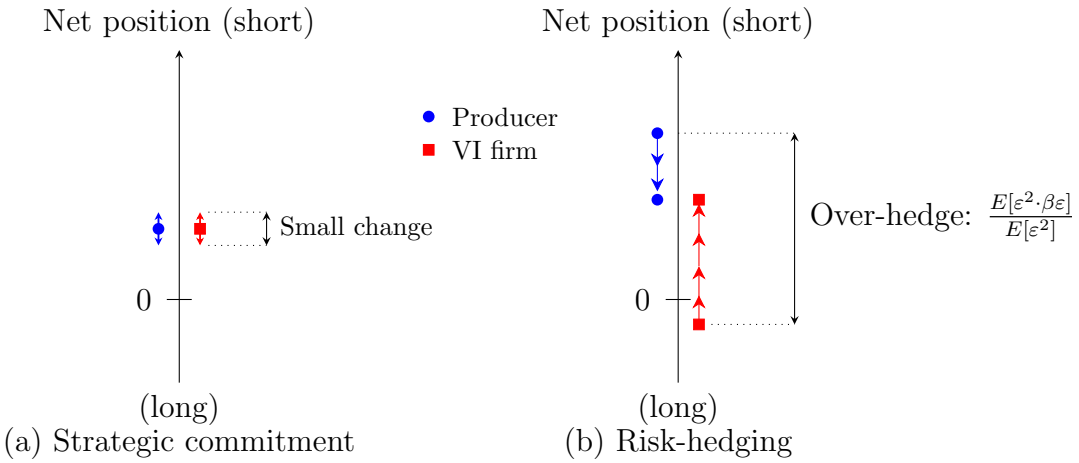


Figure 3: Graphical illustration of theoretical predictions

4 Empirical Evidence

In this section, we investigate contract positions and mark-ups of firms in Alberta, before and after the government initiated the load following forwards market. Our theoretical analysis in the previous sections, predicts that the integrated firm should over-hedge their retail exposure when only standard forward contracts are available. When the firm over-hedges, they would then have incentives to charge large markups in the spot market. After the introduction of load following contracts, the integrated firm should take a much smaller forward position and charge mark-ups similar to the other producing firms in the spot market.

We perform two exercises to verify these predictions. First, we analyze mark-ups over engineering estimates of generation unit-level marginal-costs from Brown et al. (2023). This allows us to test the model predictions about changes in mark-ups around the introduction of the new contracts. Second, since forward positions are private information of firms, we introduce a structural model of bidding, similar to Reguant (2014) and Hortaçsu and Puller (2008), to back-out the forward position that rationalizes the observed bidding behavior.

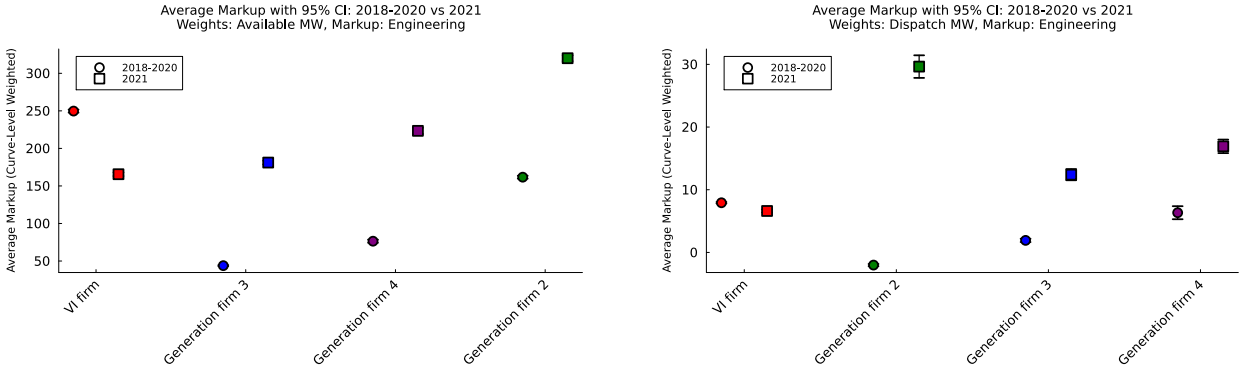
4.1 Mark-up Trends

In July 2020 the Alberta Utilities Commission approved a new hedging strategy for the regulated rate option offered by the integrated firm, which involved holding auctions for load-following forward contracts that provided quantity insurance. The first auction was held in September 2020, for contracts with delivery in December 2020. Our theoretical model predicts that the introduction of these contracts removes the incentive of the integrated firm to over-hedge their retail exposures and as a result will reduce the markups that they offer in the market.

Figure 4 plots quantity-weighted average markups (bids less engineering cost estimates) for each unit across the two periods. Panel (A) shows markups over all available quantities, while Panel (B) focuses on markups for cleared (dispatched) quantities. The results for the integrated firm are striking. They go from being the firm with the largest markups to charging the smallest markups. This is consistent with the theoretical predictions that the introduction of these contracts reduced over-hedging by the integrated firm, reducing their optimal markups. Perhaps surprisingly, the other firms increase their markups somewhat. If we consider only a competitive response to the increased competition from the change

Figure 4: Engineering Markups

This figure plots the average markups (bid price minus engineering marginal cost) weighted by quantity. Panel (A) shows markups for all available capacity offered, while Panel (B) shows markups for dispatched capacity only. Marginal cost estimates are constructed following Brown et al. (2023).



Panel (A) Panel (B)

in the integrated firms' hedging, we would expect the opposite behavior. In reality, this is driven by several changes in the market. First, PPA agreements ended,[10] which increased the concentration of assets held by the big four firms, and could have increased the optimal markups. In 2021, there was also higher demand, including new all-time records in the summer and winter due to extreme weather events, there were some untimely outages, and an increase in the carbon tax Alberta Electric System Operator (2022).

Although these markup trends are suggestive, they alone cannot test our theoretical predictions given potential changes in market structure, generation portfolio, and market competitiveness. In the next section, we explicitly account for these potential confounders to test the implications derived in Section 3.

4.2 Estimating Forward Positions

The model estimation procedure that we use to estimate forward positions closely follows Reguant (2014). However, in this setting there are no complex bids. The market uses a uniform price auction, the price is determined by the last accepted bid needed to clear the demand.

There are $i = \{1, \ldots, N\}$ firms, who each own a set of generator units that can produce

[10]These power purchase arrangements (PPA) had previously reassigned bidding control over some generating units away from their original owners, limiting the concentration of effective market control among the large incumbent firms. See Section 2.1 for institutional details on PPA agreements and Appendix F for asset-level PPA expiration dates and ownership changes.

electricity, indexed for each firm by $j = \{1, \ldots, J_i\}$. In each hourly auction (which occurs two hours before dispatch), the firms submit bids on the electricity to be produced at that hour (in MWh). Each generation unit has a minimum and maximum capacity, represented by $\underline{q}_{ij}$ and $\overline{q}_{ij}$. Whenever a unit is running, it needs to produce within the range $q_{ijh} \in [\underline{q}_{ij}, \overline{q}_{ij}]$. Each firm i chooses a bidding strategy to maximize its expected profits, conditional on a set of common public information and independent private shocks, assuming that the opposing firms submit bids according to their equilibrium strategies.

Define the collection of bids made by all firms as the array $\mathbf{b}$. Bids for each firm (i) are hour (h), unit (j), specific step functions i.e., price, quantity pairs $\{b_{ijhk}, g_{ijhk}\}$ at steps $k = 1, \ldots, K$, where K is the maximum number of steps set by the auctioneer at $K = 7$. Price bids must be between \$[0, 999.99] and the total quantity bid must be the capacity of the unit. Price bids need to be weakly increasing in quantity. Formally, bids for a given firm i are defined as:

$$\mathbf{b}_{ih} = \Bigg\{ \left(\vec{b}_{ijh}, \vec{g}_{ijh}, K_{ijh}\right) : \dim(\vec{b}_{ijh}) = \dim(\vec{g}_{ijh}) = K_{ijh} \in \{1, \ldots, 7\} \quad \forall j$$
$$b_{ijhk} \in [0, 999.99], \quad g_{ijhk} \in [\underline{q}_{ij}, \overline{q}_{ij}] \quad \forall k > 1 : b_{ijhk} > b_{ijhk-1}, \quad g_{ijhk} > g_{ijhk-1} \Bigg\}.$$

Expected profits of firm i for a given hour are:

$$\mathbb{E}_{-i}[\Pi_i(\mathbf{b})] = \mathbb{E}_{-i}\left[p_h(\mathbf{b}_h) \left(Q_{ih}(\mathbf{b}_h) - \nu_{ih}\right) - \sum_j C_{ij}(\mathbf{q}_{ij}(\mathbf{b})) \right], \tag{1}$$

where $p_h(\cdot)$ represents the equilibrium price, $Q_{ih}(\cdot)$ is the total quantity sold by firm i at hour h, ν_{ih} are the financial contracts of the firm, and $C_{ij}(\cdot)$ represents the hourly costs of unit j belonging to firm i, which depends on the hourly equilibrium quantities used. We focus on the cost structure of thermal units (coal and gas) owned by large firms. We assume the cost function for unit j is:

$$C_{ij}(\mathbf{q}_{ij}) = \alpha_{ij1} q_{ijh} + \frac{\alpha_{ij2}}{2} \tilde{q}_{ijh}^2 \tag{2}$$

where $\alpha_{ij1}, \alpha_{ij2}$ represent unit-specific marginal costs of production, and $\tilde{q}_{ijh}$ represents the quantity over the minimum production level $\underline{q}_{ij}$, i.e., $\tilde{q}_{ijh} = \max\{q_{ijh} - \underline{q}_{ij}, 0\}$. Reguant

(2014) demonstrates that ramp-up costs for gas and coal units either have no effect or offset the impact of quadratic costs, such that including a ramp-cost term does not alter estimation results. We therefore exclude these costs from our specification.

The goal of the firm is to choose its bids $\mathbf{b}_i$ to maximize its expected profit. A necessary condition for optimality is that a firm must be indifferent between raising or lowering the whole bidding offer at a given step of the supply curve, given by a bid b_{ijkh}, for unit j at step k and hour h:

$$\mathbb{E}_{-i}\left[\frac{\partial \Pi_i(\mathbf{b})}{\partial b_{ijkh}}\right] = 0. \tag{3}$$

which implies the bid is equal to the average marginal cost plus a markup

$$b_{ijkh} = \zeta_{ijkh} - \frac{\mathbb{E}_{-i}[Q_{ih} - \nu_{ih} \mid p_h = b_{ijkh}]}{\partial \mathbb{E}_{-i}[Q_{ih} \mid p_h = b_{ijkh}]/\partial b_{ijkh}}, \tag{4}$$

where $\zeta_{ijkh} \equiv \frac{\partial \mathbb{E}_{-i}[C_{ij}|p_h=b_{ijkh}]/\partial b_{ijkh}}{\partial \mathbb{E}_{-i}[Q_{ih}|p_h=b_{ijkh}]/\partial b_{ijkh}}$ is the weighted expected average marginal cost when b_{ijkh} sets the price. The markup depends on the expected infra-marginal quantity produced by the firm when the unit is accepted, divided by its effect on equilibrium quantities, which is equivalent to its effect on the residual demand.

We impose two additional restrictions on the functional form. First, the marginal costs function is assumed to be:

$$\zeta_{ijkht}(\boldsymbol{\alpha}_i) \equiv \begin{cases} \alpha_{j1}\, p_t^{fuel} + \alpha_{j2}\, p_t^{fuel} \tilde{q}_{ijht} + \epsilon_{ijkht}, & \text{if } j \text{ is a gas unit,} \\ \alpha_{j1} + \alpha_{j2}\, \tilde{q}_{ijht} + \epsilon_{ijkht}, & \text{if } j \text{ is a coal unit.} \end{cases} \tag{5}$$

where t represents the day of the sample, and the error term ϵ_{ijkht} can be interpreted as a shock on marginal costs known to the firm as well as optimization or specification error. p_{jht}^{fuel} denotes the daily spot price of natural gas sourced from the Alberta Natural Gas Exchange (NGX), reflecting short-run variation in fuel input costs. Coal-fired generators, by contrast, face no analogous spot market price: coal procurement in Alberta has historically operated through long-term contracts or mine-mouth arrangements that fix input costs over extended horizons (Independent Assessment Team (1999); Alberta Energy Regulator (2025)). Consequently, for coal units, α_{j1} and α_{j2} absorb the relevant contracted fuel costs rather than prevailing market prices.

Second, the forward contracts are assumed to be

$$\nu_{ht}(\boldsymbol{\gamma}_i) \equiv \gamma_i \bar{q}_{ht} + \varepsilon_{ht}, \tag{6}$$

where $\bar{q}_{ht}$ represents the expected quantity sold at the spot market.

We aim to estimate the parameters of the cost function $\boldsymbol{\alpha}$, and the forward positions γ_i. The estimator has two steps. First, to construct the empirical analogue of the first-order condition in equation, we first estimate its expectation terms. To do this, we follow the multi-unit auction literature and use a resampling procedure to estimate the expectation over residual demand. Then, we use a generalized method of moments estimator based on moments constructed from these first-order conditions. Given the potential endogeneity and measurement error of markup terms, we use the publicly available demand forecast as instruments.

Hours are classified into interaction categories defined by weekday group (weekday vs. weekend), hour of day (0–23), and ownership- and portfolio-based subperiods. The ownership and portfolio subperiods are defined in Appendix 4.1 such that major ownership remains stable within each subperiod (e.g., following PPA expirations and asset exits). Within each category, we match comparable hours based on the squared distance in demand forecasts and renewable generation. This approach assumes that this conditioning is the same as the conditioning performed by bidders, i.e., there is no unobserved heterogeneity that influences bidders' expectations but not those of the econometrician. The procedure is also essential for controlling for changes in market structure and competitiveness that cannot be addressed in a simple mark-up trend analysis.

Given this set of auctions, we simulate the beliefs of one firm i about the other firms' strategies by resampling (with replacement) each opponents' strategy independently from the set of similar hours. This gives a distribution of residual demand curves, with residual demand in bootstrap sample bs represented by $D_{ih}^{R,bs}(\cdot)$. In each simulated hour, the market clears where the quantity produced by firm i, $Q_{ih}(\cdot)$, equals the residual demand.

We follow a smoothing approach that has been used in the context of electricity auctions (Reguant (2014);Wolak (2007)), and approximate demand and supply as continuous functions that depend on price. For a given bootstrap sample bs, both the residual demand

faced by a firm and its supply curve are approximated as follows:

$$\hat{D}_{ih}^{R,bs}(p_h, \mathbf{b}_{-i,h} \mid s^{bs}, bw) = \sum_{l \neq i} \sum_{k} g_{ljhk} K\left(\frac{b_{ljkh} - p_h^{bs}}{bw}\right), \tag{7}$$

$$\hat{Q}_{ih}^{bs}(p_h, \mathbf{b}_{i,h} \mid s^{bs}, bw) = \sum_{j} \sum_{k} g_{ijkh} K\left(\frac{b_{ijkh} - p_h^{bs}}{bw}\right), \tag{8}$$

where K is a Kernel cumulative weight and bw is a bandwidth parameter that determines the degree of smoothing.

With this smooth representation, the empirical analogue to the first-order condition of unit j at step k in hour h can be constructed. The empirical analogue is:

$$m_{ijkht}(\boldsymbol{\alpha}_i, \boldsymbol{\gamma}_i; bw, B) \equiv \frac{1}{B} \sum_{bs=1}^{B} \mathbb{1}(j \text{ in}) \frac{\partial p_{ht}^{bs}}{\partial b_{ijkht}} \left[(b_{ijkht} - \zeta_{ijkht}(\boldsymbol{\alpha}_i)) \frac{\partial D_{iht}^{R,bs}}{\partial p_{ht}} + (Q_{ijkht}^{bs} - \nu_{iht}(\boldsymbol{\gamma}_i)) \right], \tag{9}$$

where B represents the number of bootstrap simulations taken for each hour. In equilibrium:

$$\frac{\partial p_{ht}}{\partial b_{ijkht}} = \frac{\partial Q_{ih}/\partial b_{ijkh}}{\partial D_{ih}^{R}/\partial p_h - \partial Q_{ih}/\partial p_h}, \tag{10}$$

which can be computed using the smooth approximation.

With all these elements, the moments are constructed. Given the potential endogeneity and measurement error of markup terms, we use the publicly available demand forecast as instruments, represented with $\mathbf{Z}_{ht}$. For a given firm i, the empirical moments are:

$$\sum_{t=1}^{T} \sum_{k=1}^{K} \mathbf{Z}_{ht} m_{ijkht}(\boldsymbol{\alpha}_i, \boldsymbol{\gamma}_i; bw, B) = 0, \quad \forall j, h, \tag{11}$$

which provides a consistent estimate for $\boldsymbol{\alpha}_i$ and $\boldsymbol{\gamma}_i$. Following Reguant (2014), we use two stage least squares weights.

4.2.1 Results

We estimate the model separately for the periods before and after the introduction of the load following futures contract. Figure 5 presents the GMM estimates of the forward positions. The four generation-only firms (average denoted by blue circles) pre-sell forward contracts covering a substantial share of their total generation, with only a small negative change

after 2020. The VI firm (denoted by red squares) on the other hand initially has a long position in forward contracts, but from 2021 on, hedges similarly to the generation only firms. These patterns are consistent with the predictions of our model. This analysis differs from the markup trend analysis in Figure 4 in several respects. Raw markups reflect not only forward positions but also market structure, generation portfolios, and the degree of market competitiveness. On the other hand, our GMM estimation isolates the role of forward positions and marginal costs from these confounding factors by explicitly accounting for each firm's generation portfolio and ownership structure, expected market demand, and the elasticity of residual demand.

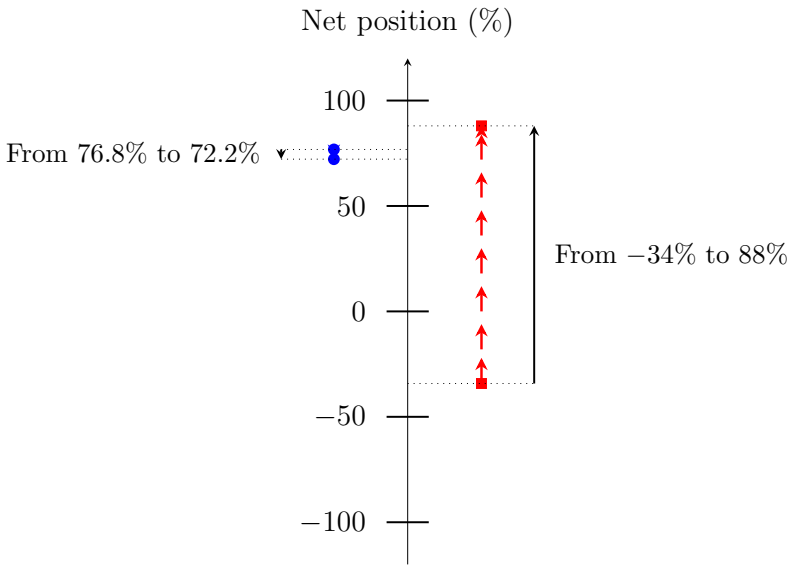


Figure 5: Net position changes with GMM estimates

Notes: The figure shows GMM estimates of net hedge ratios before 2021 and in 2021. Blue circles represent the average hedge ratio across generation-only firms, while red squares represent the vertically integrated firm. Each pair of points shows the hedge ratio before 2021 (upper/lower point) and in 2021 (lower/upper point), with arrows indicating the direction of change. Generation-only firms decreased their hedge ratio from 76.8% to 72.2%, while the VI firm increased from −34% to 88%.

Table 4 summarizes the GMM estimates of marginal costs and forward positions alongside engineering estimates of marginal costs. The results are consistent with firms' annual reports. One generation-only firm directly reports its contract positions annually, with positions of 87%, 78%, and 72% for 2018–2020, respectively, which align closely with the estimates in Table 4. While the vertically integrated firm does not directly report contract positions, it discloses the earnings impact of a 10 percent change in the forward price of electricity (i.e., $0.1 \times p \times q^f$). To recover a rough estimate of the firms' forward contract positions, we use

this formula, together with the average annual spot market prices, and the firm's reported losses from price changes. This yields an exposure of 22.7 million MWh in December 2017, covering more than one year of their retail load share (16 million MWh in our sample period). Given that the integrated firm's production is approximately 8 million MWh per year, this back-of-the-envelope estimate substantially exceeds net retail demand (retail load minus own production). In December 2020, the first month with load-following futures available for delivery, their position was 3 million MWh, covering roughly 8 months of net load ($13.4 - 8.9 = 4.5$ million MWh in that year).

Table 4 also reports average marginal cost estimates by fuel type. The increase in costs in 2021 are driven primarily by changes in gas prices and environmental compliance costs. The GMM estimates align well with engineering estimates, though some differences remain. Several factors may explain these differences. First, although engineering cost estimates provide useful reference points, heat rate data predate our sample period by 6–14 years, and thus do not reflect subsequent technology derating and upgrading. Second, engineering estimates do not capture unobserved cost shocks arising from factors such as temperature variation or emission market trading costs. These cost changes, however, are reflected in firms' bidding prices and are therefore captured by the GMM estimates. Overall, the GMM estimates provide evidence consistent with our theoretical predictions and yield reasonable estimates of marginal costs and forward positions when compared to engineering estimates and industry reports.

Table 2: Average marginal cost and forward position estimates for large firms

Firm	Fuel Type	Before 2021			2021		
		GMM MC ($/MWh)	Eng. MC ($/MWh)	GMM Forward (%)	GMM MC ($/MWh)	Eng. MC ($/MWh)	GMM Forward (%)
Generation firm 1	COAL	27.81	34.99	76.1%**	–	–	–
		(1.75)		(3.7%)			
	GAS	23.01	24.07		–	–	
		(0.68)					
Generation firm 2	COAL	20.91	29.13	66.0%**	27.96	37.34	70.2%**
		(2.43)		(16.2%)	(3.38)		(8.1%)
	GAS	24.98	18.90		41.62	32.06	
		(2.11)			(3.52)		
Generation firm 3	COAL	29.84	34.35	89.7%**	34.28	36.85	59.3%**
		(2.69)		(19.7%)	(7.27)		(13.8%)
	GAS	25.53	31.46		39.21	45.69	
		(1.80)			(3.39)		
Generation firm 4	COAL	29.28	31.72	75.6%**	42.63	38.08	87.3%**
		(2.27)		(11.9%)	(2.59)		(4.0%)
	GAS	40.45	32.85		55.53	49.01	
		(2.96)			(3.75)		
VI firm 1	GAS	24.57	19.57	-34.3%	40.94	32.99	88.0%**
		(3.96)		(19.9%)	(6.60)		(19.6%)

Notes: GMM marginal costs are computed at each unit's average output level and aggregated by fuel type and firm; unit-level estimates are reported in Appendix G. Because one generation firm exits and another enters during the sample period, the market is characterized by three dominant generation-only firms at any given point in time rather than four. Several assets are excluded from the firm-level aggregation: three assets are excluded due to the absence of engineering MC estimates, and three additional assets belonging to Generation-Only Firm 3 are excluded because they appear in only ∼1%, ∼3%, and ∼3% of that firm's total operating hours, respectively; their small sample sizes yield highly imprecise GMM MC estimates that would distort the firm-level MC estimates. All excluded assets are reported in Appendix G. Bootstrap standard errors in parentheses. For *GMM Forward* estimates, ** (*) denotes significance at the 1% (5%) level under H_0: forward position = 0.

5 Quantifying the effects of Contracts and Vertical Integration

The previous section presented evidence that the VI firm over-hedges their retail demand, and that this over-hedging is corrected following the introduction of load-following contracts, at which point the VI firm's hedging position converges to levels comparable to those of generation-only firms. We now turn to quantifying the competitive and welfare implications of these findings.

When we combine risk aversion and competition we no longer obtain analytic expressions to characterize the optimal forward contract position. Therefore, we numerically solve a richer model that combines these two forces. This allows us to empirically asses the effects that arise from the interaction between vertical integration and contract incompleteness. Our model accommodates multiple strategic firms with capacity constraints and flexible marginal costs and uses estimated residual demand, marginal cost functions and demand uncertainty.

We model 3 generation only firms and 1 VI firm that are playing a Cournot Nash equilibrium. We solve the two stage model by backward induction. We observe the VI firm's retail demand at the monthly level and thus we approximate the VI firm's hourly retail demand by scaling hourly market demand by its monthly share. At the second stage, demand uncertainty is realized and conditional on a realized level of market demand, firms choose their optimal quantities to produce given their forward commitments. The firms face a residual demand curve composed of the price inelastic market demand, less the supply of fringe suppliers. At the first stage, firms choose forward contract positions, taking into account their effects on the second-stage equilibrium. Firms take forward positions for both strategic commitment and risk-hedging purposes. Firms are risk averse and have preferences

$$\mathbb{E}[\Pi] - \lambda_i Var[\Pi_i]$$

following Allaz (1992). We assume that the generation only firms have a common risk-aversion parameter, and the vertically integrated firm may have a different level of risk aversion. Since the retail firm faces risk from high-prices in states when they also have to purchase a large quantity, we interpret the risk aversion parameter as reflecting concerns about default risk and large cash outflows. In line with this, the California electricity crisis saw several major retailers enter bankruptcy or near failure. More recently, the 2021 ERCOT crisis led multiple Texas retailers to bankruptcy or market exit. Similarly, following the 2020–2021 wholesale price spike, a substantial number of electricity retailers exited the Japanese market through bankruptcy or voluntary withdrawal.

In contrast, generation-only firms face lower default risk from price fluctuations. Since wholesale prices follow a right-skewed distribution bounded between \$0 and \$999/MWh, producers' payoffs never become negative—the zero lower bound prevents large cash outflows. Price spikes, rather than threatening generators' solvency, typically generate extremely high cash inflows. So, short-term price fluctuations are unlikely to directly cause bankruptcy

among generation firms. Given these asymmetric risk exposures, we view it as plausible that integrated firms (which incorporate both generation and retail operations) may have higher or otherwise different risk aversion than generation-only firms.

We select risk aversion parameters to match the GMM estimates of forward positions reported in Table 4. Specifically, we choose λ_{GEN} and λ_{VI} to minimize the distance between the swap forward positions implied by our simulation, $f_i(\lambda_{GEN}, \lambda_{VI})$, and those estimated by GMM, f_i^{GMM} :

$$\min_{(\lambda_{GEN},\lambda_{VI})} \sum_i \left(f_i(\lambda_{GEN}, \lambda_{VI}) - f_i^{GMM}\right)^2$$

We solve this problem by grid search. In Appendix D, we present results across a wide range of alternative risk aversion parameters, which show our conclusions are similar for a wide range of parameter values. We obtain the minimizing parameter pair $(\lambda^*_{GEN}, \lambda^*_{VI}) = (3.16 \times 10^{-8}, \infty)$. These risk aversion estimates imply that producers maximize mean–variance utility, while the VI firm effectively minimizes profit variance.[11] Although the actual hedging strategies of retailers and vertically integrated firms are not publicly observed, industry and regulatory reports indicate that minimum-variance hedging is a common benchmark and a reasonable approximation of firms' practices (see Independent Competition and Regulatory Commission (2019)). Our preferred parameter choice is therefore consistent with the institutional evidence. Generation-only firms, by contrast, effectively trade off profits against variance rather than minimizing costs.

To solve the model, we build on the algorithm of Ito and Reguant (2016). The algorithm solves a mixed-integer-linear-programming problem to solve firms' quantities from Cournot competition in the spot market given each realization of the demand shocks, then uses an outer Gauss-Seidel iteration updating each firms' choice of contracts. We provide the full details of our implementation in Appendix B. Our implementation differs from Ito and Reguant (2016) in three ways. First, rather than approximating the residual demand curve with a single linear line, we introduce a piecewise linear approximation that captures the shape of the entire residual demand curve. We find that a 5-segment approximation provides sufficient accuracy, as illustrated in Figure 6.

[11] These patterns are consistent with risk aversion arising from large cash-outflow concerns — such as bankruptcy risk or external financing costs — as retailers face greater downside risk than generation-only firms in electricity markets. To evaluate robustness, we conduct a series of sensitivity exercises across alternative risk aversion values in Appendix D. In Appendix E, we further show that as the VI firm's risk aversion parameter increases, profit variance falls sharply with modest sacrifice in expected profits.

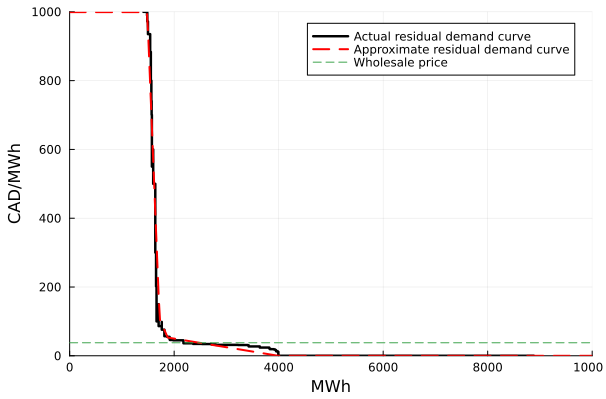


Figure 6: Residual demand approximation

This additional flexibility is important to capture the high-price, high-demand states, which play an important role, generating the risk that firms hedge. Second, since we model financial forward contract choice, rather than the day-ahead choice, choices are at a much lower frequency, and we assume that the firm faces demand realizations drawn from the annual distribution of hourly demand. Following Ito and Reguant (2016), we assume demand shocks are normally distributed and approximate this distribution using a discrete grid of quantiles. The grid consists of evenly spaced interior deciles and two extreme quantiles, calibrated so that the lower and upper tails correspond to realizations that occur with expected frequency once per year. Each quantile is weighted according to their density. Third, we introduce a risk averse utility maximization problem following Allaz (1992) and assume perfect arbitrage between the forward and spot markets (due to the presence of financial arbitrageurs). We estimate the marginal cost of all thermal generation units owned by the four firms, as described in Section 4.2.

We use this model to evaluate six scenarios:

- **Swap+VI**: Three risk-averse generation-only firms with parameter λ^*_{GEN} and one risk-averse VI firm with parameter λ^*_{VI} choose swap forward positions in the first stage and produce with market power in the second stage. This scenario most closely approximates observed firm behavior before 2021.

- **Swap+VI (Neutral)**: Identical to Swap+VI, except all firms are risk neutral. This isolates the effects attributable to risk aversion alone.

- **Swap+Gen (VI risk)**: A counterfactual separation of the VI firm, into a generation firm and a retail firm where all firms operate as generation-only. Three generators

have risk aversion λ^*_{GEN}, while the separated VI firm retains λ^*_{VI}. Firms choose swap forward positions in the first stage and produce with market power in the second stage.

- **Swap+Gen (Gen risk)**: Identical to Swap+Gen (VI risk), except the separated VI firm adopts λ^*_{GEN}. If risk aversion reflects bankruptcy and large cash outflows concerns, this parameterization is more appropriate, as the separated generation-only entity would face a risk profile similar to other generators.

- **LFFC+VI**: Identical to Swap+VI, except firms choose load-following forward contract (LFFC) positions rather than swap positions in the first stage. This scenario most closely approximates observed firm behavior in 2021.

- **First-best**: All firms offer production at marginal cost in the second stage.

Swap+VI serves as the baseline scenario in which the over-hedging incentive is present (similar to Alberta before 2021). Each alternative relaxes one dimension of the baseline. Swap+VI (Neutral) removes risk aversion, Swap+Gen removes vertical integration, and LFFC+VI removes contract incompleteness.

Figure 7 compares the wholesale price distribution from the Swap+VI simulation with actual prices in 2018. The model captures the pattern of actual price distributions reasonably well, despite the fact that no wholesale price data are used to calibrate any parameter in the simulation.[12]

[12]This differs from Ito and Reguant (2016), who use actual clearing prices to estimate the slope of the linear demand curve. Since we adopt a global approximation of demand, clearing prices are not required.



Figure 7: Simulated and Actual Price Distributions

Figure 8 presents the expected price difference relative to the first-best scenario under each market structure. In the Swap+VI case, the average price exceeds the first-best by $7.4 CAD/MWh—approximately 10 percent of the first-best price. Separating the integrated firm into retail and generation-only firms (Swap+Gen (Gen risk)) reduces prices by 7.41-4.05=$3.36 CAD/MWh, yielding the largest competitive effect among the alternatives. This effect is similar when the VI risk parameter is used for the separated firm. Switching from swaps to LFFCs achieves competitive effects similar in magnitude to this separation. The Swap+VI (Neutral) scenario indicates that risk aversion of the VI firm accounts for roughly $2 CAD/MWh of the price distortion. As shown in Figure 11, these results imply that separation or more complete contracts would reduce consumer costs by approximately $65 and $54 million CAD per year, respectively.

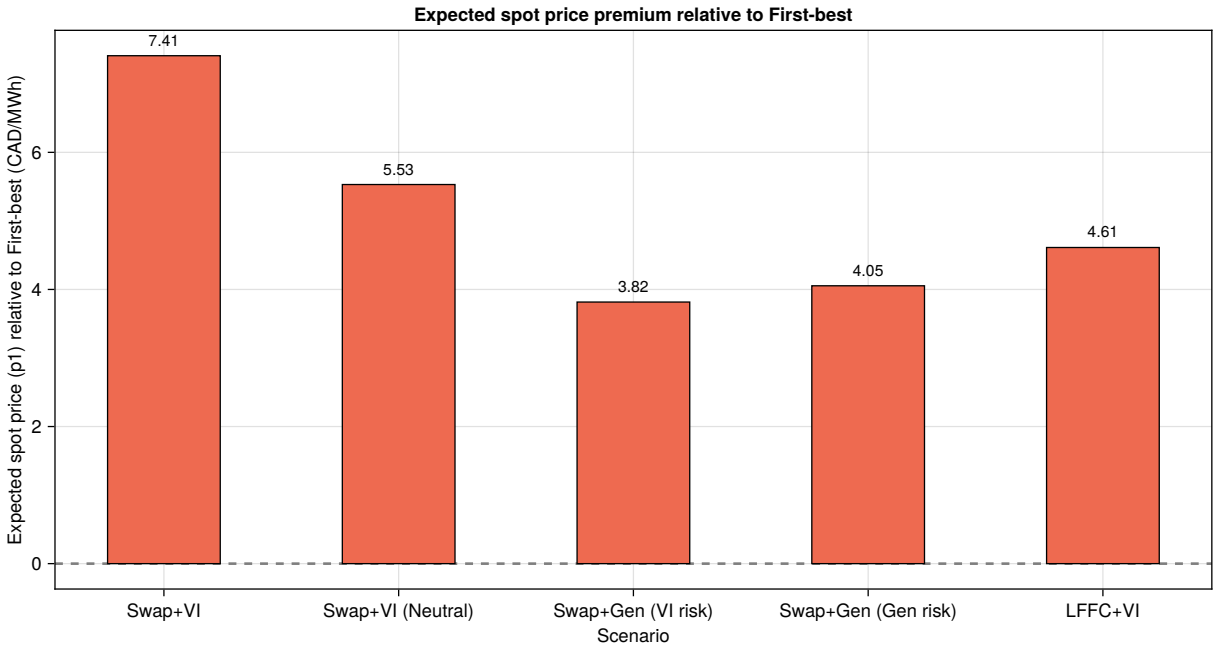


Figure 8: Average Price Increase Relative to the First Best

Notes: This figure shows the expected price under different simulation scenarios.

Figure 9 reports annual deadweight loss under each scenario. The efficiency implications mirror the competitive effects. Under Swap+VI, deadweight loss is approximately $33 million CAD per year, exceeding 2 percent of total first-best production costs. Separation of the integrated firm and LFFCs both substantially improve welfare, reducing deadweight loss to approximately $6 and $7.5 million CAD per year, respectively. The Swap+VI (Neutral) result indicates that risk aversion accounts for roughly 65 percent of the inefficiency in the Swap+VI baseline.

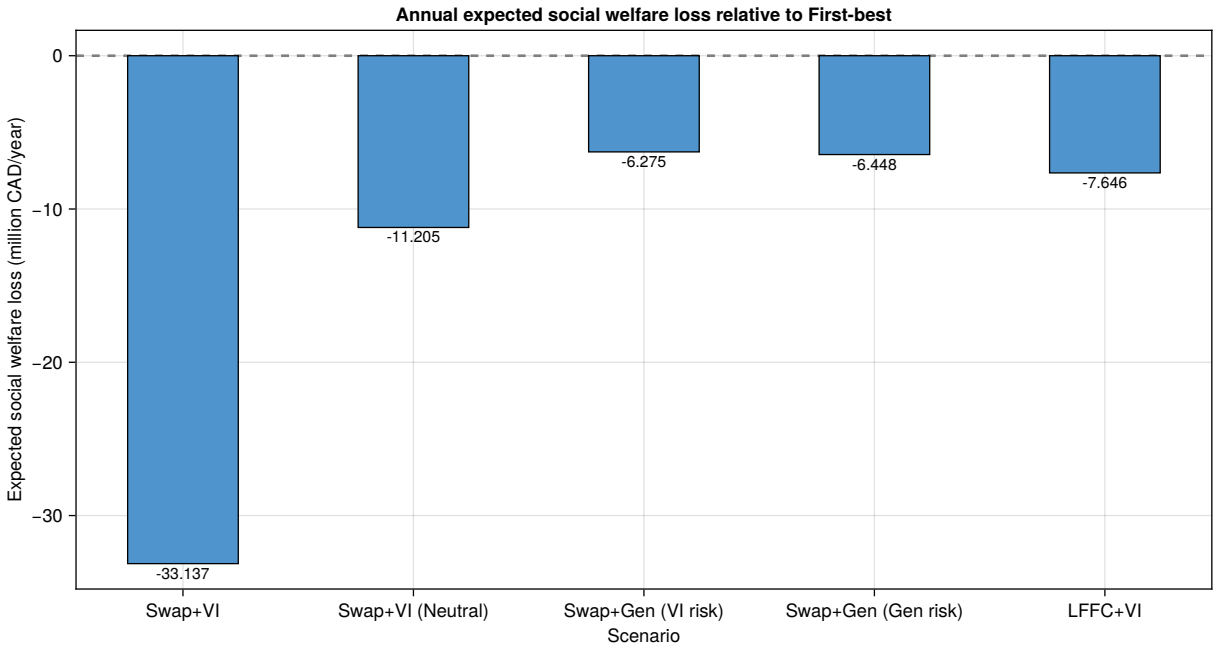


Figure 9: Average Deadweight Loss

Notes: This figure shows the expected deadweight loss under different simulation scenarios. The deadweight loss measure compares total production costs in each scenario to those in the first-best benchmark.

Table 3 summarizes the full simulation results. For each scenario, the table reports market-level outcomes—average price $E[p]$ (CAD/MWh), deadweight loss ($1000 CAD/hour), and consumer cost difference relative to the first-best ($1000 CAD/hour)—as well as firm-level outcomes (averaged over three generation-only firms versus the single VI firm): net forward position (%), thermal production (MWh), expected profit ($1000 CAD/hour), and standard deviation of profit ($1000 CAD/hour).

Several additional findings emerge beyond the welfare and competitive effects discussed above. Consistent with our theoretical predictions, the VI firm maintains a very low net forward position in the Swap+VI case. This outcome arises from the interaction of three elements: vertical integration, risk aversion, and contract incompleteness. Relaxing any one of these—through structural separation (Swap+Gen), removing risk aversion (Swap+VI Neutral), or introducing LFFCs (LFFC+VI)—yields substantially higher net forward positions.

The profit results reveal that the VI firm can substantially reduce profit variance through forward contracting with little sacrifice in expected profits. In the Swap+VI case, moving from risk-averse to risk-neutral behavior reduces the standard deviation of profits by 76 percent while decreasing expected profits by only 3.8 percent. Although counterfactual

separation and LFFCs yield similar competitive and welfare effects, they differ in their implications for firm profits. Relative to Swap+VI, both Swap+Gen (Gen risk) and LFFC+VI increase the VI firm's expected profits, but Swap+Gen (Gen risk) raises profit variance while LFFC+VI substantially reduces it. Across all scenarios, Swap+VI yields the highest profits for the generation-only firms.

Table 3: Summary of Outcomes Across Simulation Scenarios

Scenario	E[p] (CAD/MWh)	Net Position (%)	Production (Thermal) (MWh)	E[π] (k CAD/MWh)	SD(π) (k CAD/MWh)	DWL (k CAD/h)	Cons. cost Δ from FB (k CAD/h)
Swap+VI							
Gen-only (avg.)	83.1	63.0	575	61.2	60.0	3.78	16.2
VI		0.37	726	73.9	39.2		
Swap+VI (Neutral)							
Gen-only (avg.)	81.2	54.9	498	59.1	84.4	1.28	12.1
VI		72.2	1032	76.8	165		
Swap+Gen (VI risk)							
Gen-only (avg.)	79.5	61.5	488	57.9	75.2	0.72	8.32
VI		96.7	1130	75.6	2.94		
Swap+Gen (Gen risk)							
Gen-only (avg.)	79.7	64.4	507	58.2	67.9	0.74	8.84
VI		71.6	1065	75.5	70.6		
LFFC+VI							
Gen-only (avg.)	80.3	60.3	494	58.4	43.7	0.87	10.1
VI		75.1	1081	76.2	8.53		
First-best							
Gen-only (avg.)	75.7		542	55.1	172	0.00	0.00
VI			1120	71.0	687		

Note: The labels "Gen-only (avg.)" and "VI" refer to the three generation-only firms and the one vertically integrated firm observed in the data, respectively. These labels are retained across all scenarios for consistency, even in counterfactual scenarios such as Swap+Gen (VI risk) and Swap+Gen (Gen risk), where the VI firm is modeled as generation-only. Production, profits, and the standard deviation of profits are reported at the firm level. For "Gen-only (avg.)," firm-level variables are reported as averages across the three generation-only firms. Expected prices, deadweight loss, and consumer costs are reported at the market level. Deadweight loss is measured as the difference in total production costs between the market power scenario and the first-best benchmark. Changes in consumer costs are also computed relative to the first-best and represent the additional payments made by consumers compared to the first-best outcome. Consumer costs are defined as the market price multiplied by total (inelastic) demand.

6 Conclusion

This paper demonstrates that the conventional view of vertical integration as pro-competitive in electricity markets overlooks a critical interaction, from incomplete forward contracts and risk aversion. While prior literature has emphasized how vertical integration reduces firms' net exposure to spot prices and thereby intensifies competition, we show that this logic depends crucially on the availability of complete hedging instruments. When firms can

only access standard swap contracts that hedge price but not quantity, risk-averse vertically integrated retailers optimally over-hedge their retail obligations, entering the spot market with long positions that soften rather than intensify competition. Our theoretical model isolates the two competing forces—strategic commitment incentives that push toward shorter positions and risk-hedging incentives that push toward longer positions—and demonstrates conditions under which the hedging motive dominates.

We provide empirical support for this mechanism from the electricity market in Alberta, Canada. We find that the vertically integrated firm maintains the longest forward position and bids least competitively among the four largest market participants, when only standard swaps are available, contradicting the predictions of standard models that treat vertical integration as pro-competitive. Critically, when more complete forward contracts become available, that allow the integrated retailer to better hedge their quantity risk, its long position shrinks substantially and its bidding behavior becomes more competitive. This supports our theoretical prediction that contract incompleteness drives the anticompetitive effects.

The welfare effects of vertical integration under different contracts vary widely. Under the incomplete contracting regime, vertical integration increases average wholesale prices by 3.4 CAD/MWh (approximately 4 percent), with total welfare losses of 27 million CAD per year. However, introducing more complete contracts that hedge both price and quantity risk reduces wholesale prices by 2.8 CAD/MWh and generates total welfare gains of 25 million CAD per year. These findings carry important policy implications: the competitive effects of vertical integration depend critically on the design of forward markets. More broadly, our results suggest that in markets characterized by volatile prices, demand uncertainty, and convex supply curves—including agriculture, natural gas, and other commodity markets—the interaction between vertical structure and contract design may similarly influence competitive outcomes in ways not captured by existing theory.

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Appendix A Proofs of Results

Proof of Result 1: Risk-Neutral Firm with Market Power (Swap)

We consider a two-player game consisting of (i) a generation-only producer (firm 1) and (ii) a vertically integrated firm (firm 2) that operates both generation and retail activities. In addition, there is at least one risk-neutral speculator in the forward market.

Residual wholesale demand is given by

$$Q = a + \varepsilon - p^s,$$

or equivalently,

$$p^s(Q, \varepsilon) = a + \varepsilon - Q,$$

where a denotes the average market demand level and ε is an aggregate demand shock satisfying

$$\mathbb{E}[\varepsilon] = 0, \qquad \text{Var}(\varepsilon) = \sigma^2.$$

Residual demand is defined as inelastic demand a minus the quantity supplied by fringe firms, which are willing to produce at their capacity as long as the market price p exceeds their marginal cost. The shock enters through the aggregate inelastic demand level.

The VI firm's retail demand is

$$q_2^r = \theta + e,$$

where θ is the average retail demand level and e is a retail demand shock with

$$\mathbb{E}[e] = 0, \qquad \text{Var}(e) = \sigma_e^2.$$

Note that in the main text we focus on the special case $e = \beta\varepsilon$. In this appendix, we instead characterize the equilibrium forward positions for a general realization of e.

The VI firm's generation cost is quadratic:

$$C_2(q_2) = bq_2 + \frac{q_2^2}{2k_2},$$

where b is the marginal cost intercept and $k_2 > 0$ governs cost curvature.

Profit. Both firms trade forward contracts. Let f_i denote firm i's forward position, p^f the forward price, and p^s the spot price.

Producer (firm 1):

$$\Pi_1 = \underbrace{p^f f_1 - p^s f_1}_{\text{Forward profit}} + \underbrace{p^s q_1 - C_1(q_1)}_{\text{Generation profit}}.$$

Vertically integrated firm (firm 2):

$$\Pi_2 = \underbrace{p^r q_2^r - p^s q_2^r}_{\text{Retail profit}} + \underbrace{p^f f_2 - p^s f_2}_{\text{Forward profit}} + \underbrace{p^s q_2 - C_2(q_2)}_{\text{Generation profit}}.$$

Retail profit reflects the margin between the retail price p^r and the wholesale procurement cost p^s applied to realized retail demand q_2^r. Forward profit corresponds to settlement at p^f with spot adjustment at p^s. Generation profit equals wholesale revenue net of production cost.

Timing. Firms first choose forward positions (f_1, f_2). Uncertainty (ε, e) is realized. Firms then choose generation quantities (q_1, q_2) in the spot market. The spot price p^s clears the wholesale market.

Spot Market Fix forward positions $\{f_\ell\}$.

1. Producer.

The producer's spot-stage profit is

$$p^s q_1 - C_1(q_1) + (p^f - p^s) f_1 = p^s(q_1 - f_1) - b q_1 - \frac{q_1^2}{2k_1} + p^f f_1.$$

Using $\partial p^s / \partial q_1 = -1$, the first-order condition is

$$\frac{\partial \Pi_1}{\partial q_1} = p^s - (q_1 - f_1) - b - \frac{1}{k_1} q_1 = 0.$$

Rearranging yields

$$q_1^* \left(1 + \frac{1}{k_1}\right) = p^s - b + f_1,$$

so that

$$q_1^* = \frac{p^s - b + f_1}{1 + \frac{1}{k_1}}.$$

2. Vertically Integrated Firm.

The VI firm's spot-stage profit is

$$\Pi_2 = p^r q_2^r - p^s q_2^r + p^f f_2 - p^s f_2 + p^s q_2 - b q_2 - \frac{q_2^2}{2k_2}.$$

Terms independent of q_2 can be omitted. Using $\partial p^s / \partial q_2 = -1$, the first-order condition is

$$\frac{\partial \Pi_2}{\partial q_2} = p^s - (q_2 - q_2^r - f_2) - b - \frac{1}{k_2} q_2 = 0,$$

which can be written as

$$q_2^r + f_2 - q_2 + p^s - b - \frac{1}{k_2} q_2 = 0.$$

Rearranging gives

$$q_2^* \left(1 + \frac{1}{k_2}\right) = p^s - b + q_2^r + f_2,$$

and therefore

$$q_2^* = \frac{p^s - b + q_2^r + f_2}{1 + \frac{1}{k_2}}.$$

Market Clearing. For the remainder, impose symmetry in marginal-cost curvature, $k_\ell = k$ for all ℓ, and define

$$\delta := \frac{1}{1 + \frac{1}{k}}.$$

Substituting the best responses and summing outputs yields aggregate supply

$$Q^* = q_1^* + q_2^* = \delta\big(2p^s - 2b + f_1 + f_2 + q_2^r\big).$$

Market clearing requires $Q^* = a + \varepsilon - p^s$. Hence,

$$\delta\big(2p^s - 2b + f_1 + f_2 + q_2^r\big) = a + \varepsilon - p^s.$$

Collecting terms in p^s gives

$$(2\delta + 1)p^s = a + \varepsilon + \delta\big(2b - f_1 - f_2 - q_2^r\big),$$

so that the equilibrium spot price is

$$p^s = \frac{a + \varepsilon + \delta(2b - f_1 - f_2 - q_2^r)}{2\delta + 1}.$$

Individual Outputs and Forward Price. Substituting the equilibrium spot price into the firms' best responses yields output expressions.

For the VI firm,

$$q_2^* = \delta\big(p^s - b + q_2^r + f_2\big) = \frac{\big[a - b + \varepsilon - \delta f_1 + (\delta + 1)f_2 + (\delta + 1)q_2^r\big]\delta}{2\delta + 1}.$$

For the standalone producer,

$$q_1^* = \delta\big(p^s - b + f_1\big) = \frac{\big[a - b + \varepsilon - \delta f_2 + (\delta + 1)f_1 - \delta q_2^r\big]\delta}{2\delta + 1}.$$

Finally, competitive risk-neutral speculators set the forward price equal to the expected spot price,

$$p^f = \mathbb{E}[p^s] = \mathbb{E}\left[\frac{a + \varepsilon + \delta(2b - f_1 - f_2 - q_2^r)}{2\delta + 1}\right].$$

Using $\mathbb{E}[\varepsilon] = 0$ and $\mathbb{E}[q_2^r] = \theta$, this simplifies to

$$p^f = \frac{a + \delta(2b - f_1 - f_2 - \theta)}{2\delta + 1}.$$

The equilibrium spot price can be written as

$$p^s = \frac{a + \varepsilon + \delta(2b - f_2 - f_1 - \theta - e)}{2\delta + 1} \tag{12}$$

$$= \underbrace{\frac{a + \delta(2b - f_2 - f_1 - \theta)}{2\delta + 1}}_{=:\, p_0} + \underbrace{\frac{1}{2\delta + 1}}_{=:\, p_1}\varepsilon + \underbrace{\frac{-\delta}{2\delta + 1}}_{=:\, p_2} e. \tag{13}$$

The producer's equilibrium output is

$$q_1^* = \frac{\big[a - b + \varepsilon - \delta f_2 + (\delta + 1)f_1 - \delta\theta - \delta e\big]\delta}{2\delta + 1} \tag{14}$$

$$= \underbrace{\frac{\big[a - b - \delta f_2 + (\delta + 1)f_1 - \delta\theta\big]\delta}{2\delta + 1}}_{=:\, q_{1,0}} + \underbrace{\frac{\delta}{2\delta + 1}}_{=:\, q_{1,1}}\varepsilon + \underbrace{\frac{-\delta^2}{2\delta + 1}}_{=:\, q_{1,2}} e. \tag{15}$$

The VI firm's equilibrium output is

$$q_2^* = \frac{\big[a - b + \varepsilon - \delta f_1 + (\delta+1) f_2 + (\delta+1)\theta + (\delta+1)e\big]\delta}{2\delta+1} \tag{16}$$

$$= \underbrace{\frac{\big[a - b - \delta f_1 + (\delta+1) f_2 + (\delta+1)\theta\big]\delta}{2\delta+1}}_{=:\, q_{2,0}} + \underbrace{\frac{\delta}{2\delta+1}}_{=:\, q_{2,1}}\varepsilon + \underbrace{\frac{(\delta+1)\delta}{2\delta+1}}_{=:\, q_{2,2}} e. \tag{17}$$

For $\ell \in \{1, 2\}$, the price derivatives are

$$\frac{\partial p_0}{\partial f_\ell} = -\frac{\delta}{2\delta+1}, \qquad \frac{\partial p_1}{\partial f_\ell} = 0, \qquad \frac{\partial p_2}{\partial f_\ell} = 0.$$

For the producer,

$$\frac{\partial q_{1,0}}{\partial f_1} = \frac{(\delta+1)\delta}{2\delta+1}, \qquad \frac{\partial q_{1,1}}{\partial f_1} = 0, \qquad \frac{\partial q_{1,2}}{\partial f_1} = 0.$$

For the VI firm,

$$\frac{\partial q_{2,0}}{\partial f_2} = \frac{(\delta+1)\delta}{2\delta+1}, \qquad \frac{\partial q_{2,1}}{\partial f_2} = 0, \qquad \frac{\partial q_{2,2}}{\partial f_2} = 0.$$

Forward-Stage Optimization. Because $p^f = \mathbb{E}[p^s] = p_0$, the forward payoff satisfies

$$(p^f - p^s) f_\ell = -(p_1\varepsilon + p_2 e) f_\ell = \frac{-\varepsilon + \delta e}{2\delta+1} f_\ell,$$

so that

$$\mathbb{E}[(p^f - p^s) f_\ell] = 0.$$

Under risk neutrality, producers' forward positions affect expected profits only through their impact on spot market outcomes.

Producer. The producer's expected profit is

$$\mathbb{E}[\Pi_1] = \mathbb{E}\left[p^s q_1^* - \left(b q_1^* + \frac{q_1^{*2}}{2k}\right)\right].$$

Since $(p_1, q_{1,1}, p_2, q_{1,2})$ are independent of f_1, the first-order condition reduces to

$$\frac{\partial \mathbb{E}[\Pi_1]}{\partial f_1} = \frac{\partial p_0}{\partial f_1} q_{1,0} + \frac{\partial q_{1,0}}{\partial f_1} p_0 - b\frac{\partial q_{1,0}}{\partial f_1} - \frac{1}{k} q_{1,0} \frac{\partial q_{1,0}}{\partial f_1} = 0.$$

VI Firm. As discussed in the main text, and following Bushnell et al. (2008), we assume that expected retail profits are zero, with retail rates set to reflect expected wholesale prices and retail demand. Hence, $\mathbb{E}[p^r q_2^r - p^s q_2^r] = 0$. Consequently, the VI firm's forward choice affects expected profits only through its impact on spot-market outcomes.

$$\mathbb{E}[\Pi_2] = \mathbb{E}\left[p^s q_2^* - \left(b q_2^* + \frac{q_2^{*2}}{2k}\right)\right],$$

Since $(p_1, q_{2,1}, p_2, q_{2,2})$ are independent of f_2, the first-order condition reduces to

$$\frac{\partial \mathbb{E}[\Pi_2]}{\partial f_2} = \frac{\partial p_0}{\partial f_2} q_{2,0} + \frac{\partial q_{2,0}}{\partial f_2} p_0 - b\frac{\partial q_{2,0}}{\partial f_2} - \frac{1}{k} q_{2,0} \frac{\partial q_{2,0}}{\partial f_2} = 0.$$

Solving the two first-order conditions yields

$$f_1^* = \frac{(a-b)\big(k - \delta(\delta+1)\big)}{\delta\big(2\delta k + \delta + 3k + 1\big)} \qquad \text{and} \qquad f_2^* = f_1^* - \theta.$$

Thus the VI firm sells θ fewer forward units than the standalone producer, consistent with the interpretation that the VI firm's retail position partially substitutes for forward sales. Recall that

$$\delta = \frac{1}{1 + \frac{1}{k}} = \frac{k}{k+1}.$$

Substituting this expression into the general solution for f_1^* yields

$$f_1^* = \frac{k^2}{5k^2 + 5k + 1}(a - b).$$

Therefore, in the notation of Result 1,

$$f_{1,N}^* = \frac{k^2}{5k^2 + 5k + 1}(a - b), \qquad f_{2,N}^* = f_{1,N}^* - \theta.$$

This completes the proof of Result 1.

Proof of Result 2: Risk-Averse,Price-Taking Firm (Swap)

We now consider price-taking firms under swap.

Profit. Firm profits are given by

Producer (firm 1):

$$\Pi_1 = \underbrace{p^f f_1 - p^s f_1}_{\text{Forward Profit}} + \underbrace{p^s q_1 - C_1(q_1)}_{\text{Generation Profit}}.$$

Vertically integrated firm (firm 2):

$$\Pi_2 = \underbrace{p^r q_2^r - p^s q_2^r}_{\text{Retail Profit}} + \underbrace{p^f f_2 - p^s f_2}_{\text{Forward Profit}} + \underbrace{p^s q_2 - C_2(q_2)}_{\text{Generation Profit}}.$$

Demand and retail quantities. Aggregate demand is

$$Q(\varepsilon) = a + \varepsilon, \qquad \mathbb{E}[\varepsilon] = 0, \qquad \text{Var}(\varepsilon) = \sigma^2.$$

The VI firm's retail demand is

$$q_2^r = \theta + e, \qquad \mathbb{E}[e] = 0, \qquad \text{Var}(e) = \sigma_e^2.$$

Each firm has quadratic cost

$$C_i(q_i) = bq_i + \frac{q_i^2}{2k_i}.$$

Spot market Firm 1 and firm 2 are price takers in the spot market; conditional on p^s they solve

$$\max_{q_i} \ \Pi_i^s = p^s q_i - C_i(q_i) = p^s q_i - bq_i - \frac{q_i^2}{2k_i}.$$

The first-order condition yields

$$p^s - b - \frac{q_i}{k_i} = 0 \qquad \Longleftrightarrow \qquad q_i = k_i(p^s - b).$$

Assuming symmetric technologies in the spot market (so $k_1 = k_2 = k$) and using $n = 2$,

market clearing implies

$$a + \varepsilon = nk(p^s - b) \qquad \Longleftrightarrow \qquad p^s = \frac{a+\varepsilon}{nk} + b = \frac{a+\varepsilon}{2k} + b.$$

Therefore,

$$q_i = \frac{a+\varepsilon}{n} = \frac{a+\varepsilon}{2}.$$

Arbitrage With one risk-neutral speculator, the forward price satisfies

$$p^f = \mathbb{E}[p^s] = \frac{a}{2k} + b.$$

Hence,

$$p^f - p^s = -\frac{\varepsilon}{2k}.$$

Retail pricing As discussed in the main text, and following Bushnell et al. (2008), we assume that expected retail profits are zero, with retail rates set to reflect expected wholesale prices and retail demand. Hence,

$$\mathbb{E}[p^r q_2^r - p^s q_2^r] = 0$$

.

Since p^r is chosen prior to the realization of (ε, e) and $\mathbb{E}[e] = 0$, we have

$$p^r = \mathbb{E}[p^s] + \frac{\mathbb{E}[p^s e]}{\theta}$$

Thus,

$$p^r = b + \frac{a}{2k} + \frac{\mathbb{E}[\varepsilon e]}{2\theta k},$$

Forward market Using the spot-market expressions, the relevant payoffs are:

Producer (firm 1):

$$\Pi_1 = (p^f - p^s)f_1 + p^s q_1 - bq_1 - \frac{q_1^2}{2k} = -\frac{\varepsilon}{2k}f_1 + \left(\frac{a+\varepsilon}{2k} + b\right)\frac{a+\varepsilon}{2} - b\frac{a+\varepsilon}{2} - \frac{(a+\varepsilon)^2}{8k}.$$

Simplifying,

$$\Pi_1 = -\frac{\varepsilon}{2k} f_1 + \frac{(a+\varepsilon)^2}{8k}.$$

VI (firm 2):

$$\Pi_2 = p^r(\theta + e) - \left(\frac{a+\varepsilon}{nk} + b\right)(\theta + e) + (p^f - p^s) f_2 + \frac{(a+\varepsilon)^2}{8k}.$$

Using $p^f - p^s = -\varepsilon/(2k)$,

$$\Pi_2 = \left(p^r - b - \frac{a+\varepsilon}{2k}\right)(\theta + e) - \frac{\varepsilon}{2k} f_2 + \frac{(a+\varepsilon)^2}{8k}$$

Moments and optimal hedge For the producer (firm 1), expected profit is

$$\mathbb{E}[\Pi_1] = \mathbb{E}\left[\frac{(a+\varepsilon)^2}{8k} - \frac{\varepsilon}{2k} f_1\right].$$

Since $\mathbb{E}[\varepsilon] = 0$, expected profit is independent of f_1.

Keeping only the random components in Π_1:

$$\Pi_1 = -\frac{\varepsilon}{2k} f_1 + \frac{\varepsilon^2}{8k} + \frac{a\varepsilon}{4k} \; + \; \text{(non-random terms)}.$$

Equivalently,

$$\Pi_1 = \varepsilon\left[-\frac{f_1}{2k} + \frac{a}{4k}\right] + \frac{\varepsilon^2}{8k} \; + \; \text{(non-random terms)}.$$

Thus,

$$\mathrm{Var}[\Pi_1] = \left(-\frac{f_1}{2k} + \frac{a}{4k}\right)^2 \sigma^2 + \frac{1}{64k^2}\left(\mathbb{E}[\varepsilon^4] - \sigma^4\right) + 2\left(-\frac{f_1}{2k} + \frac{a}{4k}\right)\frac{1}{8k}\,\mathrm{Cov}(\varepsilon^2, \varepsilon).$$

The f_1-dependent terms are

$$\frac{\sigma^2 f_1^2}{4k^2} - \frac{2\sigma^2 f_1}{2k}\left(\frac{a}{4k}\right) - \frac{f_1}{8k^2}\,\mathbb{E}[\varepsilon^3].$$

The first-order condition is

$$2 \cdot \frac{\sigma^2 f_1}{4k^2} - \frac{2\sigma^2}{2k}\left(\frac{a}{4k}\right) - \frac{1}{8k^2}\,\mathbb{E}[\varepsilon^3] = 0,$$

so

$$f_1^* = \frac{a}{2} + \frac{\mathbb{E}[\varepsilon^3]}{4\sigma^2}.$$

For the VI firm (firm 2), profit is

$$\Pi_2 = \left(p^r - b - \frac{a+\varepsilon}{2k}\right)(\theta + e) - \frac{\varepsilon}{2k} f_2 + \frac{(a+\varepsilon)^2}{8k}.$$

Expected profit is

$$\mathbb{E}[\Pi_2] = \mathbb{E}\left[\left(p^r - b - \frac{a+\varepsilon}{2k}\right)(\theta + e) - \frac{\varepsilon}{2k} f_2 + \frac{(a+\varepsilon)^2}{8k}\right]$$

Since $\mathbb{E}[\varepsilon] = 0$, expected profit is independent of f_1.

Keeping only random components,

$$\Pi_2 = -\frac{\varepsilon e}{2k} + e\left(p^r - b - \frac{a}{2k}\right) - \frac{\theta}{2k}\varepsilon - \frac{\varepsilon}{2k} f_2 + \frac{\varepsilon^2}{8k} + \frac{a\varepsilon}{4k} \; + \; \text{(non-random terms)}.$$

Collecting the ε-linear term,

$$\Pi_2 = -\frac{\varepsilon e}{2k} + e\left(p^r - b - \frac{a}{2k}\right) + \varepsilon\left[\frac{a}{4k} - \frac{\theta + f_2}{2k}\right] + \frac{\varepsilon^2}{8k} \; + \; \text{(non-random terms)}.$$

Therefore, $\mathrm{Var}[\Pi_2]$ is a quadratic function of f_2. The f_2-dependent terms can be written as

$$\frac{\sigma^2 f_2^2}{4k^2} - \frac{\sigma^2 f_2}{k}\left(\frac{a}{4k} - \frac{\theta}{2k}\right) + \frac{f_2}{2k^2}\,\mathrm{Cov}(\varepsilon e, \varepsilon) - \left(p^r - b - \frac{a}{2k}\right)\frac{f_2}{k}\,\mathrm{Cov}(\varepsilon, e) - \frac{f_2}{8k^2}\,\mathrm{Cov}(\varepsilon^2, \varepsilon).$$

Using $\mathrm{Cov}(\varepsilon e, \varepsilon) = \mathbb{E}[\varepsilon^2 e]$, $\mathrm{Cov}(\varepsilon, e) = \mathbb{E}[\varepsilon e]$, and $\mathrm{Cov}(\varepsilon^2, \varepsilon) = \mathbb{E}[\varepsilon^3]$, this becomes

$$\frac{\sigma^2 f_2^2}{4k^2} - \frac{\sigma^2 f_2}{k}\left(\frac{a}{4k} - \frac{\theta}{2k}\right) + \frac{f_2}{2k^2}\,\mathbb{E}[\varepsilon^2 e] - \left(p^r - b - \frac{a}{2k}\right)\frac{f_2}{k}\,\mathbb{E}[\varepsilon e] - \frac{f_2}{8k^2}\,\mathbb{E}[\varepsilon^3].$$

The first-order condition is

$$2 \cdot \frac{\sigma^2 f_2}{4k^2} - \frac{\sigma^2}{k}\left(\frac{a}{4k} - \frac{\theta}{2k}\right) + \frac{1}{2k^2}\,\mathbb{E}[\varepsilon^2 e] - \left(p^r - b - \frac{a}{2k}\right)\frac{1}{k}\,\mathbb{E}[\varepsilon e] - \frac{1}{8k^2}\,\mathbb{E}[\varepsilon^3] = 0,$$

which implies

$$f_2^* = \frac{a}{2} - \theta - \frac{\mathbb{E}[\varepsilon^2 e]}{\sigma^2} + 2k\left(p^r - b - \frac{a}{2k}\right)\frac{\mathbb{E}[\varepsilon e]}{\sigma^2} + \frac{\mathbb{E}[\varepsilon^3]}{4\sigma^2}.$$

We know

$$p^r = b + \frac{a}{2k} + \frac{\mathbb{E}[\varepsilon e]}{2\theta k},$$

so that

$$2k\left(p^r - b - \frac{a}{2k}\right) = \frac{\mathbb{E}[\varepsilon e]}{\theta}.$$

Substituting yields

$$f_2^* = \frac{a}{2} - \theta - \frac{\mathbb{E}[\varepsilon^2 e]}{\sigma^2} + \frac{\mathbb{E}[\varepsilon e]^2}{\theta\sigma^2} + \frac{\mathbb{E}[\varepsilon^3]}{4\sigma^2}.$$

Approximation for the swap benchmark f_2^* (VI). Introduce normalized shocks

$$y := \frac{\varepsilon}{a}, \qquad x := \frac{e}{\theta}, \qquad v := \mathbb{E}[y^2] = \frac{\sigma^2}{a^2},$$

and the (standardized) mixed moments

$$m_{11} := \mathbb{E}[xy] = \frac{\mathbb{E}[\varepsilon e]}{a\theta}, \qquad m_{21} := \mathbb{E}[y^2 x] = \frac{\mathbb{E}[\varepsilon^2 e]}{a^2\theta}, \qquad m_{30} := \mathbb{E}[y^3] = \frac{\mathbb{E}[\varepsilon^3]}{a^3}.$$

The variance-minimizing *swap* position for the vertically integrated firm can be represented in normalized moments as

$$f_2^* = \frac{a}{2} - \theta - \theta\,\frac{m_{21}}{v} + \theta\,\frac{m_{11}^2}{v} + \frac{a}{4}\,\frac{m_{30}}{v}. \tag{18}$$

Small-noise ordering (what is first order). Define the small-noise scalings

$$\delta := \frac{\sigma}{a}, \qquad \eta := \frac{\sigma_e}{\theta},$$

and assume bounded standardized moments (so skewness, kurtosis are $O(1)$).

By Cauchy–Schwarz,

$$|m_{11}| \le \eta\delta, \qquad |m_{21}| \le O(\delta^2\eta), \qquad m_{30} = \gamma\delta^3 = O(\delta^3)$$

We also know $v = \delta^2$.

Then

$$\frac{m_{21}}{v} = O(\eta), \qquad \frac{m_{11}^2}{v} = O(\eta^2), , \qquad \frac{m_{30}}{v} = O(\delta),$$

If one wants a *first-order* approximation in (δ, η) only, drop the $O(\eta^2)$ term:

$$f_2^* = \frac{a}{2} + \frac{\mathbb{E}[\varepsilon^3]}{4\sigma^2} - \theta - \frac{\mathbb{E}[\varepsilon^2 e]}{\sigma^2} \; + \; O(\eta^2). \tag{19}$$

Using the derived result for f_1^*, we can express

$$f_2^* = f_1^* - \theta - \frac{\mathbb{E}[\varepsilon^2 e]}{\sigma^2} \; + \; O(\eta^2).$$

Therefore we have

$$f_1^* = \frac{a}{2} + \frac{\mathbb{E}[\varepsilon^3]}{4\sigma^2}, \qquad f_2^* \approx f_1^* - \theta - \frac{\mathbb{E}[\varepsilon^2 e]}{\sigma^2}$$

Finally, substituting

$$\mathbb{E}[q_i^*] = \frac{a}{2} \quad \text{and} \quad e = \beta\varepsilon$$

completes the proof of Result 2.

Proof of Result 3: Risk-Neutral Firms with Market Power (LFFC)

We now consider risk-neutral firms with market power under load-following forward contracts (LFFC). Under LFFC, firm i chooses a hedge ratio l_i that is applied to realized retail demand, $q_2^r = \theta + e$. Forward payoffs therefore scale with realized load rather than with a fixed contracted quantity.

Profit. Firm profits are given by
Producer (firm 1):

$$\Pi_1 = p^f l_1(\theta + e) - p^s l_1(\theta + e) + p^s q_1 - b q_1 - \frac{q_1^2}{2k_1}.$$

Vertically integrated firm (firm 2):

$$\Pi_2 = p^r q_2^r - p^s q_2^r + p^f l_2(\theta + e) - p^s l_2(\theta + e) + p^s q_2 - b q_2 - \frac{q_2^2}{2k_2}.$$

Relative to the swap case, the key difference is that forward positions now vary with realized retail demand $(\theta + e)$, so that spot-price exposure depends on the load shock e.

Spot Market Fix hedge ratios $\{l_i\}$.

Producer (firm 1).

Given l_1, the producer solves

$$\max_{q_1} \; p^s q_1 - bq_1 - \frac{q_1^2}{2k_1} + (p^f - p^s) l_1(\theta + e).$$

Since p^f is constant in the spot stage, this is equivalent to

$$\max_{q_1} \; p^s q_1 - bq_1 - \frac{q_1^2}{2k_1} - p^s l_1(\theta + e).$$

Using $\partial p^s / \partial q_1 = -1$, the first-order condition is

$$p^s - (q_1 - l_1(\theta + e)) - b - \frac{1}{k_1} q_1 = 0.$$

Rearranging,

$$q_1^* \left(1 + \frac{1}{k_1}\right) = p^s - b + l_1(\theta + e),$$

so that

$$q_1^* = \frac{p^s - b + l_1(\theta + e)}{1 + \frac{1}{k_1}}.$$

VI firm (firm 2).

Given l_2, the VI firm solves

$$\max_{q_2} \; (p^r q_2^r - p^s q_2^r) + p^s q_2 - bq_2 - \frac{q_2^2}{2k_2} + (p^f - p^s) l_2(\theta + e).$$

Dropping terms independent of q_2,

$$\max_{q_2} \; p^s q_2 - bq_2 - \frac{q_2^2}{2k_2} - p^s q_2^r - p^s l_2(\theta + e).$$

Using $\partial p^s / \partial q_2 = -1$, the first-order condition is

$$p^s - (q_2 - q_2^r - l_2(\theta + e)) - b - \frac{1}{k_2} q_2 = 0.$$

Rearranging,

$$q_2^* \left(1 + \frac{1}{k_2}\right) = p^s - b + q_2^r + l_2(\theta + e).$$

Since $q_2^r = \theta + e$, this becomes

$$q_2^* = \frac{p^s - b + (1 + l_2)(\theta + e)}{1 + \frac{1}{k_2}}.$$

Market Clearing. Impose symmetric curvature $k_i = k$ and define

$$\delta := \frac{1}{1 + \frac{1}{k}}.$$

Aggregating across firms gives

$$\begin{aligned} Q^* &= q_1^* + q_2^* \\ &= \delta\big(p^s - b + l_1(\theta + e) + p^s - b + (1 + l_2)(\theta + e)\big) \\ &= \delta\big(2p^s - 2b + (1 + l_1 + l_2)(\theta + e)\big). \end{aligned}$$

Market demand is

$$Q^s = a + \varepsilon - p^s.$$

Equating supply and demand yields

$$\delta\big(2p^s - 2b + (1 + l_1 + l_2)(\theta + e)\big) = a + \varepsilon - p^s$$

Collecting terms in p^s gives

$$(2\delta + 1)p^s = a + \varepsilon + \delta\big(2b - (1 + l_1 + l_2)(\theta + e)\big).$$

Hence the equilibrium spot price is

$$p^s = \frac{a + \varepsilon + \delta\big(2b - (1 + l_1 + l_2)(\theta + e)\big)}{2\delta + 1}$$

Individual Outputs. Substituting the equilibrium spot price into the firms' output choices yields expressions for equilibrium output.

VI firm (firm 2).

$$q_2^* = \frac{\delta}{2\delta+1}\Big[a - b + \varepsilon - \delta l_1(\theta+e) + (\delta+1)l_2(\theta+e) + (\delta+1)q_2^r\Big].$$

Producer (firm 1).

$$q_1^* = \frac{\delta}{2\delta+1}\Big[a - b + \varepsilon - \delta l_2(\theta+e) + (\delta+1)l_1(\theta+e) - \delta q_2^r\Big].$$

Speculators. Risk-neutral competitive speculators imply zero expected profits on load-following forward contracts:

$$\mathbb{E}\big[p^f l_i(\theta+e) - p^s l_i(\theta+e)\big] = 0.$$

Spot Price and Outputs. The equilibrium spot price becomes

$$\begin{aligned} p^s &= \frac{a + \varepsilon + \delta\big(2b - (l_1+l_2+1)(\theta+e)\big)}{2\delta+1} \\ &= \frac{a + \delta\big(2b - (l_1+l_2+1)\theta\big)}{2\delta+1} + \frac{1}{2\delta+1}\varepsilon - \frac{\delta(l_1+l_2+1)}{2\delta+1}e \\ &=: p_0 + p_1\varepsilon + p_2 e. \end{aligned}$$

The producer's equilibrium output is

$$\begin{aligned} q_1^* &= \frac{\delta}{2\delta+1}\Big[a - b + \varepsilon - \delta l_2(\theta+e) + (\delta+1)l_1(\theta+e) - \delta(\theta+e)\Big] \\ &= \underbrace{\frac{\delta}{2\delta+1}\Big[a - b - \delta l_2\theta + (\delta+1)l_1\theta - \delta\theta\Big]}_{=:q_{1,0}} + \underbrace{\frac{\delta}{2\delta+1}}_{=:q_{1,1}}\varepsilon \\ &\quad + \underbrace{\frac{\delta\big[-\delta l_2 + (\delta+1)l_1 - \delta\big]}{2\delta+1}}_{=:q_{1,2}} e. \end{aligned}$$

The VI firm's equilibrium output is

$$\begin{aligned} q_2^* &= \frac{\delta}{2\delta+1}\Big[a-b+\varepsilon-\delta l_1(\theta+e)+(\delta+1)l_2(\theta+e)+(\delta+1)(\theta+e)\Big] \\ &= \underbrace{\frac{\delta}{2\delta+1}\Big[a-b-\delta l_1\theta+(\delta+1)l_2\theta-\delta\theta\Big]+\theta\delta}_{=:q_{2,0}}+\underbrace{\frac{\delta}{2\delta+1}}_{=:q_{2,1}}\varepsilon \\ &\quad+\left(\underbrace{\frac{\delta\big[-\delta l_1+(\delta+1)l_2-\delta\big]}{2\delta+1}+\delta}_{=:q_{2,2}}\right)e \end{aligned}$$

Derivatives. For $m \in \{1,2\}$,

$$\frac{\partial p_0}{\partial l_m} = -\frac{\delta\theta}{2\delta+1}, \qquad \frac{\partial p_1}{\partial l_m} = 0, \qquad \frac{\partial p_2}{\partial l_m} = -\frac{\delta}{2\delta+1}.$$

For the producer,

$$\frac{\partial q_{1,0}}{\partial l_1} = \frac{(\delta+1)\delta\theta}{2\delta+1}, \qquad \frac{\partial q_{1,1}}{\partial l_1} = 0, \qquad \frac{\partial q_{1,2}}{\partial l_1} = \frac{(\delta+1)\delta}{2\delta+1}.$$

For the VI firm,

$$\frac{\partial q_{2,0}}{\partial l_2} = \frac{(\delta+1)\delta\theta}{2\delta+1}, \qquad \frac{\partial q_{2,1}}{\partial l_2} = 0, \qquad \frac{\partial q_{2,2}}{\partial l_2} = \frac{(\delta+1)\delta}{2\delta+1}.$$

Producer Choice of l_1. Again, by the full-arbitrage condition, expected forward profits are zero. Hence, the producer's expected profit reduces to

$$\mathbb{E}[\Pi_1] = \mathbb{E}\left[p^s q_1^* - \left(bq_1^* + \frac{q_1^{*2}}{2k_1}\right)\right].$$

Using the decompositions

$$p^s = p_0 + p_1\varepsilon + p_2 e, \qquad q_1^* = q_{1,0} + q_{1,1}\varepsilon + q_{1,2}e,$$

we obtain

$$\mathbb{E}[\Pi_1] = \mathbb{E}\Big[(p_0 + p_1\varepsilon + p_2 e)(q_{1,0} + q_{1,1}\varepsilon + q_{1,2}e) \\ - b(q_{1,0} + q_{1,1}\varepsilon + q_{1,2}e) - \frac{1}{2k_1}(q_{1,0} + q_{1,1}\varepsilon + q_{1,2}e)^2\Big].$$

Since $\mathbb{E}[\varepsilon] = \mathbb{E}[e] = 0$, only second moments remain after taking expectations.

Differentiating with respect to l_1 and using

$$\frac{\partial p_1}{\partial l_1} = \frac{\partial q_{1,1}}{\partial l_1} = 0,$$

yields

$$\frac{\partial \mathbb{E}[\Pi_1]}{\partial l_1} = q_{1,0}\left(\frac{\partial p_0}{\partial l_1} - \frac{1}{k_1}\frac{\partial q_{1,0}}{\partial l_1}\right) + \frac{\partial q_{1,0}}{\partial l_1}(p_0 - b) \\ + \left[q_{1,2}\left(\frac{\partial p_2}{\partial l_1} - \frac{1}{k_1}\frac{\partial q_{1,2}}{\partial l_1}\right) + \frac{\partial q_{1,2}}{\partial l_1}p_2\right]\sigma_e^2 \\ + \left[q_{1,1}\left(\frac{\partial p_2}{\partial l_1} - \frac{1}{k_1}\frac{\partial q_{1,2}}{\partial l_1}\right) + \frac{\partial q_{1,2}}{\partial l_1}p_1\right]\mathbb{E}[\varepsilon e].$$

The first line reflects the effect of l_1 on deterministic profits. The second and third lines capture, respectively, the variance and covariance channels arising from the load shock e and its interaction with ε.

Setting

$$\frac{\partial \mathbb{E}[\Pi_1]}{\partial l_1} = 0$$

characterizes the producer's best response l_1^*.

VI Choice of l_2. By the full-arbitrage condition and competitive retail pricing, expected forward and retail profits are zero. Therefore, the VI firm's expected profit can be written as

$$\mathbb{E}[\Pi_2] = \mathbb{E}\left[p^s q_2 - bq_2 - \frac{q_2^2}{2k_2}\right].$$

The hedge ratio l_2 affects $\mathbb{E}[\Pi_2]$ only through the equilibrium spot price and output.

Using

$$p^s = p_0 + p_1\varepsilon + p_2 e, \qquad q_2^* = q_{2,0} + q_{2,1}\varepsilon + q_{2,2}e,$$

we obtain

$$\begin{aligned}\mathbb{E}[\Pi_2] = \mathbb{E}\Big[&(p_0 + p_1\varepsilon + p_2 e)(q_{2,0} + q_{2,1}\varepsilon + q_{2,2}e) \\ &- b(q_{2,0} + q_{2,1}\varepsilon + q_{2,2}e) - \frac{1}{2k_2}(q_{2,0} + q_{2,1}\varepsilon + q_{2,2}e)^2\Big].\end{aligned}$$

Differentiating with respect to l_2 and using

$$\frac{\partial p_1}{\partial l_2} = \frac{\partial q_{2,1}}{\partial l_2} = 0,$$

yields the first-order condition

$$\begin{aligned}0 = {} & q_{2,0}\left(\frac{\partial p_0}{\partial l_2} - \frac{1}{k_2}\frac{\partial q_{2,0}}{\partial l_2}\right) + \frac{\partial q_{2,0}}{\partial l_2}(p_0 - b) \\ & + \left[q_{2,2}\left(\frac{\partial p_2}{\partial l_2} - \frac{1}{k_2}\frac{\partial q_{2,2}}{\partial l_2}\right) + \frac{\partial q_{2,2}}{\partial l_2}p_2\right]\sigma_e^2 \\ & + \left[q_{2,1}\left(\frac{\partial p_2}{\partial l_2} - \frac{1}{k_2}\frac{\partial q_{2,2}}{\partial l_2}\right) + \frac{\partial q_{2,2}}{\partial l_2}p_1\right]\mathbb{E}[\varepsilon e].\end{aligned}$$

Relative to the producer's condition, the VI first-order condition contains additional terms embedded in $q_{2,0}$ and $q_{2,2}$ that arise from the retail position. In particular, writing

$$q_{2,0} = q_{1,0} + \theta\delta, \qquad q_{2,2} = q_{1,2} + \delta,$$

Substituting into the VI first-order condition shows that it can be written as the producer first-order condition plus the incremental term

$$\delta\theta\left(\frac{\partial p_0}{\partial l_2} - \frac{1}{k_2}\frac{\partial q_{2,0}}{\partial l_2}\right) + \delta\left(\frac{\partial p_2}{\partial l_2} - \frac{1}{k_2}\frac{\partial q_{2,2}}{\partial l_2}\right)\sigma_e^2.$$

Using

$$\frac{\partial p_0}{\partial l_2} = -\frac{\delta\theta}{2\delta + 1}, \qquad \frac{\partial p_2}{\partial l_2} = -\frac{\delta}{2\delta + 1},$$

and

$$\frac{\partial q_{2,0}}{\partial l_2} = \frac{(\delta+1)\delta\theta}{2\delta+1}, \qquad \frac{\partial q_{2,2}}{\partial l_2} = \frac{(\delta+1)\delta}{2\delta+1},$$

the incremental VI term becomes

$$-\frac{\delta^2\theta^2}{2\delta+1}\left(1+\frac{\delta+1}{k_2}\right) - \frac{\delta^2}{2\delta+1}\left(1+\frac{\delta+1}{k_2}\right)\sigma_e^2.$$

This term is strictly negative. Using the producer first-order condition, the VI firms' first-order condition is

$$[a-b-\delta\theta l_2+(\delta+1)\theta l_1-\delta\theta][\delta\theta+\tfrac{1}{k_2}(\delta+1)\delta\theta]-[a+\delta(2b-(l_1+l_2+1)\theta)](\delta+1)\theta+b(2\delta+1)(\delta+1)\theta$$

$$+\{(-\delta l_2+(\delta+1)l_1-\delta)(\delta+\tfrac{1}{k_2}(\delta+1)\delta)+(\delta+1)\delta(l_1+l_2+1)\}\sigma_e^2+\left\{\tfrac{1}{k_2}(\delta+1)\delta-1\right\}\mathbb{E}[\varepsilon e]$$

$$+(2\delta+1)\delta\left[1+\frac{1}{k_2}(\delta+1)\right](\theta^2+\sigma_e^2)=0.$$

$$\Leftrightarrow$$

$$-[(\delta+1)\theta(\delta\theta+\tfrac{1}{k_2}(\delta+1)\delta\theta)+\delta(\delta+1)\theta^2+(\delta+1)(2\delta+\tfrac{1}{k_2}(\delta+1)\delta)\sigma_e^2]l_1^*$$

$$=[a-b-\delta l_2\theta-\delta\theta](\delta\theta+\tfrac{1}{k_2}(\delta+1)\delta\theta)-[a+\delta(2b-(l_2+1)\theta)](\delta+1)\theta+b(2\delta+1)(\delta+1)\theta$$

$$+\left[(-\delta l_2-\delta)(\delta+\delta\tfrac{1}{k}(\delta+1))+(\delta+1)\delta(l_2+1)\right]\sigma_e^2+\left\{\tfrac{1}{k_2}(\delta+1)\delta-1\right\}\mathbb{E}[\varepsilon e]$$

$$+(2\delta+1)\delta\left[1+\frac{1}{k_2}(\delta+1)\right](\theta^2+\sigma_e^2).$$

Two First-Order Conditions. Assume $k_1 = k_2 = k$.

From the expressions derived above, the producer's first-order condition can be written as

$$
\begin{aligned}
0 = {} & [(\delta+1)\theta(\delta\theta + \tfrac{\delta(\delta+1)}{k}\theta) + \delta(\delta+1)\theta^2 + (\delta+1)(2\delta + \tfrac{\delta(\delta+1)}{k})\sigma_e^2]\, l_1^* \\
& + [a - b - \delta l_2\theta - \delta\theta](\delta\theta + \tfrac{\delta(\delta+1)}{k}\theta) \\
& - [a + \delta(2b - (l_2+1)\theta)](\delta+1)\theta + b(2\delta+1)(\delta+1)\theta \\
& + [(-\delta l_2 - \delta)(\delta + \tfrac{\delta(\delta+1)}{k}) + (\delta+1)\delta(l_2+1)]\sigma_e^2 \\
& + \Big\{\tfrac{\delta(\delta+1)}{k} - 1\Big\}\mathbb{E}[\varepsilon e].
\end{aligned}
$$

The VI firm's first-order condition is identical except for the additional retail term:

$$
\begin{aligned}
0 = {} & [(\delta+1)\theta(\delta\theta + \tfrac{\delta(\delta+1)}{k}\theta) + \delta(\delta+1)\theta^2 + (\delta+1)(2\delta + \tfrac{\delta(\delta+1)}{k})\sigma_e^2]\, l_2^* \\
& + [a - b - \delta l_1\theta - \delta\theta](\delta\theta + \tfrac{\delta(\delta+1)}{k}\theta) \\
& - [a + \delta(2b - (l_1+1)\theta)](\delta+1)\theta + b(2\delta+1)(\delta+1)\theta \\
& + [(-\delta l_1 - \delta)(\delta + \tfrac{\delta(\delta+1)}{k}) + (\delta+1)\delta(l_1+1)]\sigma_e^2 \\
& + \Big\{\tfrac{\delta(\delta+1)}{k} - 1\Big\}\mathbb{E}[\varepsilon e] \\
& + (2\delta+1)\delta\Big(1 + \tfrac{\delta+1}{k}\Big)(\theta^2 + \sigma_e^2).
\end{aligned}
$$

Collecting terms in (l_1, l_2) and simplifying yields a linear system

$$
A\, l_1^* = B\, l_2^* + C, \qquad A\, l_2^* = B\, l_1^* + C + D,
$$

where

$$
A = \delta(\delta+1)(\theta^2 + \sigma_e^2)\Big(2 + \tfrac{\delta+1}{k}\Big),
$$

$$
B = \delta\Big(-1 + \tfrac{\delta(\delta+1)}{k}\Big)(\theta^2 + \sigma_e^2),
$$

$$
C = -[a - b - \delta\theta]\Big(\delta\theta + \tfrac{\delta(\delta+1)}{k}\theta\Big) + [a + \delta(2b - \theta)](\delta+1)\theta - b(2\delta+1)(\delta+1)\theta
$$

$$-\delta\Big(1-\tfrac{\delta(\delta+1)}{k}\Big)\sigma_e^2+\Big(1-\tfrac{\delta(\delta+1)}{k}\Big)\mathbb{E}[\varepsilon e].$$

$$D=-(2\delta+1)\delta\Big(1+\tfrac{\delta+1}{k}\Big)(\theta^2+\sigma_e^2),$$

Solving the linear system From the first equation, $l_2^*=\frac{Al_1^*-C}{B}$. Substituting into the second equation gives

$$A\left(\frac{Al_1^*-C}{B}\right)=Bl_1^*+C+D,$$

so

$$A^2l_1^*-AC=B^2l_1^*+BC+BD,$$

and therefore

$$l_1^*=\frac{BC+AC+BD}{A^2-B^2}.$$

Similarly,

$$l_2^*=\frac{BC+AC+AD}{A^2-B^2}.$$

Useful identity Note

$$\begin{aligned}A+B&=\delta(\theta^2+\sigma_e^2)\Big[(\delta+1)\Big(2+\tfrac{\delta+1}{k}\Big)+\Big(-1+\tfrac{\delta(\delta+1)}{k}\Big)\Big]\\&=\delta(\theta^2+\sigma_e^2)\Big[(2\delta+1)+\tfrac{(\delta+1)(2\delta+1)}{k}\Big]\\&=\delta(\theta^2+\sigma_e^2)(2\delta+1)\Big(1+\tfrac{\delta+1}{k}\Big).\end{aligned}$$

Hence,

$$\frac{D}{A+B}=-1.$$

Expected load-following forward positions Since $L_i=l_i(\theta+e)$ and $\mathbb{E}[e]=0$, we have $\mathbb{E}[L_i]=\theta\,l_i^*$. Using $A^2-B^2=(A-B)(A+B)$ and $\frac{D}{A+B}=1$,

$$\mathbb{E}[L_1]=\theta\left(\frac{C}{A-B}+\frac{B}{A-B}\cdot\frac{D}{A+B}\right)=\theta\left(\frac{C}{A-B}-\frac{B}{A-B}\right),$$

$$\mathbb{E}[L_2]=\theta\left(\frac{C}{A-B}+\frac{A}{A-B}\cdot\frac{D}{A+B}\right)=\theta\left(\frac{C}{A-B}-\frac{A}{A-B}\right).$$

Therefore,

$$\mathbb{E}[L_1] - \mathbb{E}[L_2] = \theta.$$

and their gap ($\mathbb{E}[L_1] - \mathbb{E}[L_2]$) is θ. This implies that, in expectation, the VI firm shades its forward position by an amount equal to its retail exposure.

Simplify LFFC

$$\mathbb{E}[L_1] = \theta \left(\frac{C}{A-B} - \frac{B}{A-B} \right)$$

with

$$A = \delta(\delta+1)\big(\theta^2 + \sigma_e^2\big) \left(2 + \frac{\delta+1}{k}\right), \qquad B = \delta \left(-1 + \frac{\delta(\delta+1)}{k}\right) \big(\theta^2 + \sigma_e^2\big),$$

$$C := -[a - b - \delta\theta]\Big(\delta\theta + \tfrac{\delta(\delta+1)}{k}\theta\Big) + [a + \delta(2b-\theta)](\delta+1)\theta - b(2\delta+1)(\delta+1)\theta$$

$$-\delta\Big(1 - \tfrac{\delta(\delta+1)}{k}\Big)\sigma_e^2 + \Big(1 - \tfrac{\delta(\delta+1)}{k}\Big)\mathbb{E}[\varepsilon e].$$

Simplification:

$$\mathbb{E}[L_1] = \frac{k^2}{5k^2+5k+1} \, \frac{\theta\big((a-b)\theta + \mathbb{E}[\varepsilon e]\big)}{\theta^2 + \sigma_e^2}$$

Let

$$S := \theta^2 + \sigma_e^2.$$

Denominator. Recall

$$A = \delta(\delta+1)S \left(2 + \frac{\delta+1}{k}\right), \qquad B = \delta \left(-1 + \frac{\delta(\delta+1)}{k}\right) S.$$

Hence,

$$A - B = \delta S \left[(\delta+1) \left(2 + \frac{\delta+1}{k}\right) - \left(-1 + \frac{\delta(\delta+1)}{k}\right) \right].$$

Distributing the minus sign yields

$$A - B = \delta S \left[(\delta+1) \left(2 + \frac{\delta+1}{k}\right) + 1 - \frac{\delta(\delta+1)}{k} \right].$$

Expanding terms,

$$(\delta+1)\left(2+\frac{\delta+1}{k}\right)=2(\delta+1)+\frac{(\delta+1)^2}{k}.$$

Therefore,

$$A-B=\delta S\left[2(\delta+1)+1+\frac{(\delta+1)^2-\delta(\delta+1)}{k}\right].$$

Since

$$(\delta+1)^2-\delta(\delta+1)=(\delta+1),$$

we obtain

$$A-B=\delta S\left[2\delta+3+\frac{\delta+1}{k}\right].$$

Writing over a common denominator k gives

$$A-B=\frac{\delta S\big(2\delta k+\delta+3k+1\big)}{k}.$$

Numerator We simplify

$$C=-[a-b-\delta\theta]\Big(\delta\theta+\tfrac{1}{k}(\delta+1)\delta\theta\Big)+[a+\delta(2b-\theta)](\delta+1)\theta-b(2\delta+1)(\delta+1)\theta$$

$$-\Big\{-\delta\Big(\delta+\tfrac{1}{k}(\delta+1)\delta\Big)+(\delta+1)\delta\Big\}\sigma_e^2-\Big\{\tfrac{1}{k}(\delta+1)\delta-1\Big\}\mathbb{E}[\varepsilon e].$$

The first line of C (terms without σ_e^2 and $\mathbb{E}[\varepsilon e]$) is

$$-[a-b-\delta\theta]\Big(\delta\theta+\tfrac{\delta(\delta+1)}{k}\theta\Big)+[a+\delta(2b-\theta)](\delta+1)\theta-b(2\delta+1)(\delta+1)\theta$$

$$=-\theta\Big\{[a-b-\delta\theta]\Big(\delta+\tfrac{\delta(\delta+1)}{k}\Big)-(\delta+1)[a+\delta(2b-\theta)]+b(2\delta+1)(\delta+1)\Big\}$$

$$=-\theta\Big[(a-b)\Big(\delta+\tfrac{\delta(\delta+1)}{k}\Big)-(\delta+1)(a-b)-\delta\theta\Big(\delta+\tfrac{\delta(\delta+1)}{k}\Big)+(\delta+1)\delta\theta\Big]$$

$$=-\theta\Big[(a-b)\Big(\tfrac{\delta(\delta+1)}{k}-1\Big)+\delta\theta\Big(1-\tfrac{\delta(\delta+1)}{k}\Big)\Big]=\theta\Big(1-\tfrac{\delta(\delta+1)}{k}\Big)\Big[(a-b)-\delta\theta\Big].$$

For the σ_e^2 term, the coefficient is

$$\delta\left(\delta+\frac{(\delta+1)\delta}{k}\right)-(\delta+1)\delta=-\delta\left[1-\frac{\delta(\delta+1)}{k}\right],$$

so the σ_e^2 contribution in C is

$$-\delta\left(1-\frac{\delta(\delta+1)}{k}\right)\sigma_e^2.$$

Finally,

$$-\Big\{\tfrac{1}{k}(\delta+1)\delta-1\Big\}\mathbb{E}[\varepsilon e]=\left(1-\frac{\delta(\delta+1)}{k}\right)\mathbb{E}[\varepsilon e].$$

Thus,

$$C=\theta\Big(1-\tfrac{\delta(\delta+1)}{k}\Big)\Big[(a-b)-\delta\theta\Big]-\delta\left(1-\frac{\delta(\delta+1)}{k}\right)\sigma_e^2+\left(1-\frac{\delta(\delta+1)}{k}\right)\mathbb{E}[\varepsilon e]$$

$$=\theta\Big(1-\tfrac{\delta(\delta+1)}{k}\Big)(a-b)-\delta\left(1-\frac{\delta(\delta+1)}{k}\right)(\theta^2+\sigma_e^2)+\left(1-\frac{\delta(\delta+1)}{k}\right)\mathbb{E}[\varepsilon e]$$

$$=\Big(\tfrac{k-\delta(\delta+1)}{k}\Big)\Big(\theta(a-b)+\mathbb{E}[\varepsilon e]\Big)+\delta\left(\frac{\delta(\delta+1)-k}{k}\right)(\theta^2+\sigma_e^2)$$

$$=\Big(\tfrac{k-\delta(\delta+1)}{k}\Big)\Big(\theta(a-b)+\mathbb{E}[\varepsilon e]\Big)+B.$$

So

$$C-B=\Big(\tfrac{k-\delta(\delta+1)}{k}\Big)\Big(\theta(a-b)+\mathbb{E}[\varepsilon e]\Big)$$

Therefore,

$$\begin{aligned}\mathbb{E}[L_1]&=\theta\left(\frac{C}{A-B}-\frac{B}{A-B}\right)\\&=\theta\Big(\frac{\Big(\frac{k-\delta(\delta+1)}{k}\Big)\Big(\theta(a-b)+\mathbb{E}[\varepsilon e]\Big)}{\frac{\delta S\left(2\delta k+\delta+3k+1\right)}{k}}\Big)\\&=\theta\Big(\frac{(k-\delta(\delta+1))\Big(\theta(a-b)+\mathbb{E}[\varepsilon e]\Big)}{\delta S\left(2\delta k+\delta+3k+1\right)}\Big)\\&=\frac{k^2}{5k^2+5k+1}\cdot\frac{\theta\big((a-b)\theta+\mathbb{E}[\varepsilon e]\big)}{\theta^2+\sigma_e^2}.\end{aligned}$$

Now subtract the swap forward position from the load-following:

$$\mathbb{E}[L_1]-f_1^*=\frac{k^2}{5k^2+5k+1}\left[\frac{\theta\big((a-b)\theta+\mathbb{E}[\varepsilon e]\big)}{\theta^2+\sigma_e^2}-(a-b)\right].$$

We can rewrite the bracketed term as

$$\frac{\theta\big((a-b)\theta+\mathbb{E}[\varepsilon e]\big)}{\theta^2+\sigma_e^2}-(a-b)=\frac{\theta\,\mathbb{E}[\varepsilon e]-(a-b)\sigma_e^2}{\theta^2+\sigma_e^2}.$$

So the wedge is exactly

$$\mathbb{E}[L_1]=f_1^*+\frac{k^2}{5k^2+5k+1}\,\frac{\theta\,\mathbb{E}[\varepsilon e]-(a-b)\sigma_e^2}{\theta^2+\sigma_e^2}$$

Equivalently,

$$\mathbb{E}[L_1]-f_1^*=\frac{k^2}{5k^2+5k+1}\,\frac{\theta\,\mathbb{E}[\varepsilon e]-(a-b)\sigma_e^2}{\theta^2+\sigma_e^2}$$

Result 3 is obtained as a special case under the assumption $e=\beta\varepsilon$.

Impose the proportionality assumption: Assume the retail demand shock is proportional to the market demand shock

$$e=\frac{\theta}{a}\varepsilon+\eta\ \text{ with }\ E[\eta]=0, E[\varepsilon\eta]=0$$

which says that the part of e that comoves with ε has slope θ/a. Plug into the condition:

$$\mathbb{E}[\varepsilon e]=\frac{a}{\theta}\sigma_e^2.$$

Then the key numerator becomes

$$\theta\,\mathbb{E}[\varepsilon e]-(a-b)\sigma_e^2=b\sigma_e^2$$

Let $\eta=\frac{\sigma_e}{\theta}$. Assume small η for approximation. We have

$$\mathbb{E}[L_1]-f_1^*=\frac{k^2}{5k^2+5k+1}\,\frac{b\sigma_e^2}{\theta^2+\sigma_e^2}=\frac{k^2}{5k^2+5k+1}\,\frac{b\eta^2}{1+\eta^2}=\frac{k^2}{5k^2+5k+1}\,\frac{O(\eta^2)}{1+O(\eta^2)}$$

Since

$$\frac{1}{1+O(\eta^2)}=1+O(\eta^2)$$

We can get

$$\mathbb{E}[L_1]-f_1^*=O(\eta^2)$$

Therefore,

$$\mathbb{E}[L_1] \approx f_1^* \qquad \text{to first order}$$

Just in case, the exact (non-approximated) results are reported below. Using $\frac{k^2}{5k^2+5k+1} > 0$

- if $b > 0$: $\mathbb{E}[L_1] - f_1^* > 0$ so LFFC > Swap;
- if $b = 0$: $\mathbb{E}[L_1] - f_1^* = 0$ so LFFC = Swap;
- if $b < 0$: $\mathbb{E}[L_1] - f_1^* < 0$ so LFFC < Swap.

This completes the proof of Result 3.

Proof of Result 4: Risk-Averse, Price-Taking Firms (LFFC)

We now consider price-taking firms under load-following forward contracts (LFFC). Under LFFC, firm i chooses a hedge ratio l_i applied to realized retail demand $(\theta + e)$. Forward payoffs therefore scale with realized load rather than being fixed quantities.

Profit. Firm profits are given by
Producer (firm 1):

$$\Pi_1 = \underbrace{p^f\, l_1(\theta + e) - p^s\, l_1(\theta + e)}_{\text{forward profit}} + \underbrace{p^s q_1 - C(q_1)}_{\text{generation profit}}.$$

Vertically integrated firm (firm 2):

$$\Pi_2 = \underbrace{p^r q_2^r - p^s q_2^r}_{\text{retail profit}} + \underbrace{p^f\, l_2(\theta + e) - p^s\, l_2(\theta + e)}_{\text{forward profit}} + \underbrace{p^s q_2 - C(q_2)}_{\text{generation profit}}.$$

Market clearing (perfect competition). Similarly to the proof of Result 2, and given that $(C(\cdot))$ is identical across firms, the spot price and output levels satisfy

$$p^s = \frac{a + \varepsilon}{2k} + b, \qquad q_1 = q_2 = \frac{a + \varepsilon}{2}.$$

Arbitrage and retail pricing Risk-neutral competitive speculators imply zero expected profits on load-following forward contracts:

$$\mathbb{E}\big[p^f l_i(\theta + e) - p^s l_i(\theta + e)\big] = 0.$$

Since l_i is chosen prior to the realization of (ε, e) and $\mathbb{E}[e] = 0$, dividing by l_i yields

$$p^f \theta = \mathbb{E}[p^s(\theta + e)] = \theta\, \mathbb{E}[p^s] + \mathbb{E}[p^s e].$$

Hence,

$$p^f = \mathbb{E}[p^s] + \frac{\mathbb{E}[p^s e]}{\theta}.$$

Substituting the equilibrium spot price under LFFC, we obtain

$$p^f = \mathbb{E}[p^s] + \frac{\mathbb{E}[p^s e]}{\theta} = \frac{a}{2k} + b + \frac{\mathbb{E}[\varepsilon e]}{2k\,\theta},$$

As discussed in the main text, and following Bushnell et al. (2008), we assume that expected retail profits are zero, with retail rates set to reflect expected wholesale prices and retail demand. Hence,

$$\mathbb{E}[p^r q_2^r - p^s q_2^r] = 0$$

.

Since p^r is chosen prior to the realization of (ε, e) and $\mathbb{E}[e] = 0$, we have

$$p^r = \mathbb{E}[p^s] + \frac{\mathbb{E}[p^s e]}{\theta}$$

Thus,

$$p^f = p^r$$

Risk aversion and objective. By the full-arbitrage condition and competitive retail pricing, expected forward and retail profits are zero. Moreover, under the price-taking assumption, forward positions do not affect spot market outcomes and hence are independent of l_1 and l_2. As a result, expected profits do not depend on l_1 or l_2 in this setup (as can be

verified analytically, following the same steps as in the proof of Result 2). Consequently, for both the producer and the vertically integrated firm, the mean–variance objective reduces to choosing l_1 and l_2 to minimize the variance of profits.

Common decomposition The forward profit is obtained using

$$p^f - p^s = \frac{1}{2k}\left(\frac{\mathbb{E}[\varepsilon e]}{\theta} - \varepsilon\right).$$

Hence,

$$\begin{aligned}(p^f - p^s)(\theta + e) &= \frac{1}{2k}\left(\frac{\mathbb{E}[\varepsilon e]}{\theta} - \varepsilon\right)(\theta + e) \\ &= \frac{1}{2k}\Big(\mathbb{E}[\varepsilon e] + R\Big),\end{aligned}$$

where the stochastic component is defined as

$$R := -\varepsilon e + \frac{\mathbb{E}[\varepsilon e]}{\theta}\, e - \theta\varepsilon.$$

The generation profit is

$$\begin{aligned}p^s q_1 - C(q_1) &= \left(\frac{a+\varepsilon}{2k} + b\right)\frac{a+\varepsilon}{2} - b\frac{a+\varepsilon}{2} - \frac{1}{2k}\left(\frac{a+\varepsilon}{2}\right)^2 \\ &= \frac{(a+\varepsilon)^2}{8k}.\end{aligned}$$

Since constants do not affect variances, we drop deterministic terms and define the stochastic generation component

$$G := \frac{\varepsilon^2 + 2a\varepsilon}{8k}.$$

Firm 1 (Producer): Optimal l_1. Firm 1's profit can be written as

$$\Pi_1 = \frac{l_1}{2k}\big(\mathbb{E}[\varepsilon e] + R\big) + \frac{(a+\varepsilon)^2}{8k}.$$

Because $\mathbb{E}[\varepsilon e]$ affects only the mean of profits, it does not enter the variance. The

variance-relevant component is therefore

$$\frac{l_1}{2k}R + G,$$

where G denotes the stochastic component of generation profits defined above.

Hence,

$$\mathrm{Var}(\Pi_1) = \mathrm{Var}\left(\frac{l_1}{2k}R + G\right).$$

Minimizing variance with respect to l_1 yields the first-order condition

$$\frac{l_1}{(2k)^2}\,\mathrm{Var}(R) + \frac{1}{2k}\,\mathrm{Cov}(R, G) = 0.$$

Multiplying through by $(2k)^2$ gives

$$l_1\ \mathrm{Var}(R) + 2k\ \mathrm{Cov}(R, G) = 0,$$

and therefore

$$l_1^* = -2k\,\frac{\mathrm{Cov}(R, G)}{\mathrm{Var}(R)}.$$

Normalization and Moments. Define the normalized shocks

$$x := \frac{e}{\theta}, \qquad y := \frac{\varepsilon}{a}, \qquad v := \mathbb{E}[y^2], \qquad v_e := \mathbb{E}[x^2].$$

Let the mixed moments be

$$m_{11} := \mathbb{E}[xy], \quad m_{21} := \mathbb{E}[y^2x], \quad m_{30} := \mathbb{E}[y^3], \quad m_{31} := \mathbb{E}[y^3x],$$

$$m_{12} := \mathbb{E}[x^2y], \quad m_{22} := \mathbb{E}[x^2y^2].$$

These normalizations imply

$$\sigma^2 = a^2v, \qquad \sigma_e^2 = \theta^2v_e, \qquad \mathbb{E}[\varepsilon e] = a\theta m_{11}, \qquad \mathbb{E}[\varepsilon^2 e] = a^2\theta m_{21},$$

$$\mathbb{E}[\varepsilon^3] = a^3m_{30}, \qquad \mathbb{E}[\varepsilon^3 e] = a^3\theta m_{31}.$$

Using these definitions, the stochastic components can be written as

$$R = a\theta S, \qquad S := -yx + m_{11}x - y,$$

$$G = \frac{a^2}{8k}T, \qquad T := y^2 + 2y.$$

Therefore,

$$\begin{aligned}\frac{\mathrm{Cov}(R,G)}{\mathrm{Var}(R)} &= \frac{\mathrm{Cov}(a\theta S,\ \frac{a^2}{8k}T)}{\mathrm{Var}(a\theta S)} \\ &= \frac{a}{8k\,\theta}\,\frac{\mathrm{Cov}(S,T)}{\mathrm{Var}(S)}.\end{aligned}$$

Substituting into the producer's first-order condition yields

$$l_1\theta = -\frac{a}{4}\,\frac{\mathrm{Cov}(S,T)}{\mathrm{Var}(S)}. \tag{20}$$

Bounding and approximation Assume small-noise scalings

$$\delta := \sqrt{v} = \frac{\sigma}{a}, \qquad \eta := \sqrt{v_e} = \frac{\sigma_e}{\theta},$$

and bounded standardized moments (bounded skewness, kurtosis, and the sixth moment)

$$\gamma := \frac{\mathbb{E}[\varepsilon^3]}{\sigma^3} = \frac{\mathbb{E}[y^3]}{v^{3/2}}, \qquad \kappa := \frac{\mathbb{E}[\varepsilon^4]}{\sigma^4} = \frac{\mathbb{E}[y^4]}{v^2}, \qquad \tau := \frac{\mathbb{E}[\varepsilon^6]}{\sigma^6} = \frac{\mathbb{E}[y^6]}{v^3}, \qquad \kappa_e := \frac{\mathbb{E}[e^4]}{\sigma_e^4} = \frac{\mathbb{E}[x^4]}{v_e^2},$$

with $\gamma, \kappa, \tau, \kappa_e = O(1)$. By Cauchy–Schwarz,

$$|m_{11}| \le \eta\delta, \qquad |m_{21}| \le O(\delta^2\eta), \qquad m_{30} = \gamma\delta^3 = O(\delta^3), \qquad |m_{31}| \le O(\delta^3\eta).$$

We compute

$$\begin{aligned}\mathrm{Cov}(S,T) &= \mathrm{Cov}(-yx + m_{11}x - y,\ y^2 + 2y) \\ &= \underbrace{-2v}_{\text{leading}} + A,\end{aligned}$$

where

$$A := -m_{30} - 2m_{21} + 2m_{11}^2 + \underbrace{\left(-m_{31} + m_{11}m_{21} + m_{11}v\right)}_{\text{higher order}}.$$

Similarly,

$$\begin{aligned}\mathrm{Var}(S) &= \mathrm{Var}(-yx + m_{11}x - y) \\ &= \underbrace{v}_{\text{leading}} + B,\end{aligned}$$

where

$$B := 2m_{21} - 3m_{11}^2 + m_{22} + \underbrace{\left(m_{11}^2 v_e - 2m_{11}m_{12}\right)}_{\text{higher order}}.$$

The bounds above imply

$$A = O(\delta^3) + O(\delta^2\eta) + O(\delta^2\eta^2) + O(\delta^3\eta), \qquad B = O(\delta^2\eta) + O(\delta^2\eta^2) + O(\delta^2\eta^3) + O(\delta^2\eta^4).$$

Approximation step. Assume δ is small and $|B| < v/2$ so that $\mathrm{Var}(S)$ is bounded away from zero. Then

$$\begin{aligned}\frac{\mathrm{Cov}(S,T)}{\mathrm{Var}(S)} = \frac{-2v + A}{v + B} &= \left(-2 + \frac{A}{v}\right)\left(1 + \frac{B}{v}\right)^{-1} \\ &= \left(-2 + \frac{A}{v}\right)\left(1 - \frac{B}{v} + O\left(\frac{B^2}{v^2}\right)\right) \\ &= -2 + \frac{A + 2B}{v} + O\left(\frac{|A||B|}{v^2} + \frac{B^2}{v^2}\right).\end{aligned}$$

Using the definitions of A and B, the leading part of $A + 2B$ is

$$A + 2B = -m_{30} + 2m_{21} - 4m_{11}^2 + 2m_{22} + (\text{higher order}).$$

Therefore,

$$\frac{\mathrm{Cov}(S,T)}{\mathrm{Var}(S)} = -2 - \frac{m_{30}}{v} + 2\frac{m_{21}}{v} - 4\frac{m_{11}^2}{v} + 2\frac{m_{22}}{v} + \mathcal{R}, \tag{21}$$

where

$$\mathcal{R} = O(\delta\eta) + O(\delta\eta^2) + O(\eta^2) + O(\eta^3) \quad \text{and also contains } O(B^2/v^2) \text{ terms.}$$

Firm 1 conclusion and comparison to the swap benchmark Combining (20) and (21) yields

$$\begin{aligned} l_1\,\theta &= -\frac{a}{4}\left(-2-\frac{m_{30}}{v}+2\frac{m_{21}}{v}-4\frac{m_{11}^2}{v}+2\frac{m_{22}}{v}+\mathcal{R}\right) \\ &= \frac{a}{2}+\frac{a}{4}\frac{m_{30}}{v}-\frac{a}{2}\frac{m_{21}}{v}+a\frac{m_{11}^2}{v}-\frac{a}{2}\frac{m_{22}}{v}-\frac{a}{4}\mathcal{R}. \end{aligned}$$

The variance-minimizing *swap* position for firm 1 is (exactly)

$$f_1^* = \frac{a}{2}+\frac{a}{4}\,\frac{m_{30}}{v}. \tag{22}$$

Taking the difference and retaining the first nontrivial term ,

$$\begin{aligned} l_1\theta - f_1^* &= -\frac{a}{2}\frac{m_{21}}{v}+O(\eta^2)+O(\delta\eta) \\ &= -\frac{a}{2}\,\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]}+O(\eta^2)+O(\delta\eta). \end{aligned}$$

This implies

$$l_1\theta \approx f_1^* - \frac{a}{2}\,\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]}$$

to first order, with the remaining approximation error of second order.

Firm 2 (VI): optimal l_2 The only difference relative to the standalone producer is the retail profit term $p^r q_2^r - p^s q_2^r$. Under competitive forward and retail markets, we have already established that $p^r = p^f$. Consequently, Firm 2's profit can be written as

$$\Pi_2 = (p^f - p^s)(\theta+e) + (p^f - p^s)\,l_2(\theta+e) + \frac{(a+\varepsilon)^2}{8k}.$$

Using the decomposition above, the variance-relevant component is

$$\frac{1+l_2}{2k}R + G.$$

Hence

$$\mathrm{Var}(\Pi_2) = \mathrm{Var}\left(\frac{1+l_2}{2k}R+G\right),$$

and the first-order condition is

$$(1 + l_2)\ \mathrm{Var}(R) + 2k\ \mathrm{Cov}(R, G) = 0, \qquad \Longleftrightarrow \qquad 1 + l_2 = -2k\,\frac{\mathrm{Cov}(R, G)}{\mathrm{Var}(R)}.$$

Using the producer characterization, this implies

$$1 + l_2^* = l_1^*.$$

Multiplying by θ,

$$l_2\,\theta = l_1\,\theta - \theta. \tag{23}$$

This shows that, in expectation, the VI firm shades its load-following forward position by the level of expected retail demand.

Firm 2 comparison to the swap benchmark The variance-minimizing *swap* position for firm 2 is (exactly)

$$f_2^* = -\theta + \frac{a}{2} + \theta\,\frac{m_{11}^2}{v} - \theta\,\frac{m_{21}}{v} + \frac{a}{4}\,\frac{m_{30}}{v}. \tag{24}$$

Combining (23) with the expansion for $l_1\theta$ and subtracting (24) yields,

$$\begin{aligned} l_2\theta - f_2^* &= \left(\theta - \frac{a}{2}\right)\frac{m_{21}}{v} + O(\eta^2) + O(\delta\eta) \\ &= \left(\theta - \frac{a}{2}\right)\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]} + O(\eta^2) + O(\delta\eta) \\ &= -\frac{a}{2}\,\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]} + \frac{\mathbb{E}[\varepsilon^2 e]}{\mathbb{E}[\varepsilon^2]} + O(\eta^2) + O(\delta\eta). \end{aligned}$$

This implies

$$l_2\theta \approx f_2^* - \frac{a}{2}\,\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]} + \frac{\mathbb{E}[\varepsilon^2 e]}{\mathbb{E}[\varepsilon^2]}$$

to first order, with the remaining approximation error of second order.

Finally, we have the following first-order approximations:

$$l_1\theta \approx f_1^* - \frac{a}{2}\,\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]},$$

$$l_2\theta \approx f_2^* - \frac{a}{2}\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]} + \frac{\mathbb{E}[\varepsilon^2 e]}{\mathbb{E}[\varepsilon^2]}.$$

Using the identity

$$l_2\theta = l_1\theta - \theta,$$

we can equivalently write

$$l_2\theta \approx f_1^* - \theta - \frac{a}{2}\frac{\mathbb{E}[\varepsilon^2 e]}{\theta\,\mathbb{E}[\varepsilon^2]}.$$

Finally, substituting

$$\mathbb{E}[l_{i,A}q_2^r] = l_i\theta, \quad e = \beta\varepsilon, \quad \text{and} \quad \mathbb{E}[q_i^*] = \frac{a}{2},$$

completes the proof of Result 4.

Appendix B Solution Algorithm

We solve a two-stage dynamic game with $N = 4$ firms competing in Alberta's electricity market. Firms make forward commitments q_{i1} in Stage 1, then compete in Cournot competition in Stage 2 after demand uncertainty ϵ is realized. One firm ($i = 3$) is vertically integrated with retail customers. The method uses a mixed-integer linear program to solve the cournot game, nested inside gauss-siedel iteration following Ito and Reguant (2016).

Appendix B.1 Spot Market Equilibrium

Market demand is specified as a piecewise linear function with 5 segments to capture realistic price ceiling and floor behavior:

$$P(Q,\epsilon) = \begin{cases} \infty & \text{if } Q \in [0,\kappa_1] \text{ (must-run)} \\ A_2/b_2 - Q/b_2 & \text{if } Q \in [\kappa_1,\kappa_2] \text{ (steep segment)} \\ A_3/b_3 - Q/b_3 & \text{if } Q \in [\kappa_2,\kappa_3] \text{ (normal segment)} \\ A_4/b_4 - Q/b_4 & \text{if } Q \in [\kappa_3,\kappa_4] \text{ (flat segment near ceiling)} \\ 999.99 & \text{if } Q \in [\kappa_4,\bar{Q}] \text{ (price ceiling)} \end{cases} \tag{25}$$

where $Q = \sum_{i,j} q_{ij} + Q_{\text{infra}} + \epsilon$ is total quantity demanded, ϵ is the realized demand shock, and Q_{infra} is non-strategic inframarginal production. The intercepts A_k and knot points κ_k

are estimated from data using spline regression.

Each firm i has a piecewise linear marginal cost curve with K segments indexed by $j = 1, \ldots, K$:

$$c_{ij}(q) = \alpha_{ij} + \beta_{ij} q \tag{26}$$

Each segment has capacity $\bar{q}_{ij}$. Marginal costs are continuous across segments: $\alpha_{ij} + \beta_{ij}\bar{q}_{ij} = \alpha_{i,j+1}$.

Appendix B.1.1 Equilibrium Conditions

Define binary variables $u_{ij}, \bar{u}_{ij} \in \{0, 1\}$ indicating whether segment (i, j) is used at all and used at full capacity, respectively. Let $\lambda_{ij} \geq 0$ be the shadow value when capacity $\bar{q}_{ij}$ binds. The equilibrium solves:

$$\text{[FOC 1]} \quad P - (q_{ij} - q_{i1})/b_k - \alpha_{ij} - \beta_{ij} q_{ij} - \lambda_{ij} \leq 0 \quad \forall i, j \tag{27}$$

$$\text{[FOC 2]} \quad P - (q_{ij} - q_{i1})/b_k - \alpha_{ij} - \beta_{ij} q_{ij} - \lambda_{ij} \geq -M u_{ij} \quad \forall i, j \tag{28}$$

$$\text{[Complementarity]} \quad \lambda_{ij} \leq M \bar{u}_{ij} \quad \forall i, j \tag{29}$$

$$\text{[Range]} \quad q_{ij} \leq \bar{q}_{ij} u_{ij}, \quad q_{ij} \geq \bar{q}_{ij} \bar{u}_{ij} \quad \forall i, j \tag{30}$$

$$\text{[Merit Order]} \quad u_{ij} \geq \bar{u}_{ij} \geq u_{i,j-1} \geq \bar{u}_{i,j-1} \quad \forall i, j \geq 2 \tag{31}$$

where M is a large constant (e.g., $M = 10^6$), b_k is the slope of demand segment k containing total quantity Q, and the term $(q_{ij} - q_{i1})/b_k$ represents the residual supply effect modified by forward commitments.

At $P = 999.99$, the residual demand curve faced by firms includes a flat segment followed by a steep downward-sloping segment. This creates a kink where the subdifferential of the profit function must contain zero. To handle this, we estimate firm-specific capacity limits $\bar{Q}_{i,\text{ceiling}}$ from observed dispatch when price = 999.99. We impose $q_i \leq \bar{Q}_{i,\text{ceiling}}$ when $P = 999.99$. If multiple solutions exist at the kink, we select the one with higher total production, since it is rare in the data to observe prices at 999.99.

Modification for forward contracts: The forward commitment q_{i1} reduces firm i's incentive to exercise market power. If $q_{i1} > 0$, the firm has sold forward and gains ($p_1 -$

$p_2) \times q_{i1}$ from higher spot prices, reducing the markup. The FOC becomes:

$$P - \frac{\partial P}{\partial q_{ij}}(q_{ij} - q_{i1}) = MC_{ij} \tag{32}$$

Vertically integrated firm: The vertically integrated firm serves retail customers whose demand is:

$$D_{\text{retail}}(\epsilon) = (\epsilon + \bar{Q}) \times \text{share}_{\text{VI}} \tag{33}$$

where $\bar{Q}$ is baseline total demand and share_{VI} is the integrated firm's retail market share (estimated from data). For the VI firm, we replace q_{i1} with $q_{i1} + D_{\text{retail}}(\epsilon)$ in the FOCs, as retail demand acts like an additional forward sale.

Appendix B.1.2 Profit Calculation

For a given realization ϵ and forward commitment q_{i1}, firm i's spot profit is:

$$\pi_{i2}(q_{i1}, \epsilon) = P(\epsilon) \times q_{i2}^* - \sum_j \left(\alpha_{ij} + \frac{\beta_{ij} q_{ij}^*}{2} \right) q_{ij}^* + P(\epsilon) \times Q_{\text{infra},i} \tag{34}$$

where $q_{i2}^* = \sum_j q_{ij}^*$ is equilibrium spot production and $Q_{\text{infra},i}$ is firm i's inframarginal quantity which includes their forward positions, retail demand, and must-run production.

Appendix B.2 Stage 1: Forward Market Equilibrium

We assume the demand shocks are normally distributed, and discretize the demand shock distribution using 11 points with probability weights w_s. These are, the deciles: $\epsilon_s = \Phi^{-1}(0.1k) \times \sigma$ for $k = 1, \ldots, 9$, two points for the extreme tails $\epsilon_1 = \Phi^{-1}(1/(2 \times 8760)) \times \sigma$ and $\epsilon_{11} = \Phi^{-1}(1 - 1/(2 \times 8760)) \times \sigma$ and w_s are assigned based on probability mass between adjacent quantiles. This captures tail events over a full year (8760 hours) while maintaining computational tractability.

Firm i's total profit consists of three components:

$$\Pi_i(q_{i1}, q_{-i,1}) = \mathbb{E}_\epsilon[\pi_{i,\text{gen}}(\epsilon) + \pi_{i,\text{forward}}(\epsilon) + \pi_{i,\text{retail}}(\epsilon)] \tag{35}$$

$$= \sum_s w_s \Big[\underbrace{P_2(\epsilon_s)q^*_{i2}(\epsilon_s) - C_i(q^*_{i2}(\epsilon_s)) + P_2(\epsilon_s)Q_{\text{infra},i}}_{\text{generation + inframarginal}} + \underbrace{(P_1 - P_2(\epsilon_s))q_{i1}}_{\text{forward}} + \underbrace{(P_1 - P_2(\epsilon_s))D_{\text{retail},i}(\epsilon_s)}_{\text{retail}} \Big] \tag{36}$$

where $P_1 = \mathbb{E}_\epsilon[P_2(\epsilon)] = \sum_s w_s P_2(\epsilon_s)$ is the expected spot price (which equals the equilibrium forward price under no arbitrage).

For generation-only firms: $D_{\text{retail},i}(\epsilon) = 0$ and the retail profit term vanishes.

For the vertically integrated firm: All three terms are active. Retail demand creates a natural hedge against spot price volatility.

Firms maximize utility:

$$U_i \approx \mathbb{E}[\Pi_i] - \frac{\lambda_i}{2}\text{Var}[\Pi_i] \tag{37}$$

We allow different risk aversion parameters, λ_{gen} for generation-only firms and λ_{VI} for the vertically integrated firm.

In the LFFC specification: forward commitments scale with realized retail demand

$$q_{i1}(\epsilon) = \theta_i \times D_{\text{retail,VI}}(\epsilon) \tag{38}$$

where θ_i is firm i's LFFC parameter (the choice variable in Stage 1). The forward price is the retail-demand-weighted average:

$$P_{1,\text{LFFC}} = \frac{\sum_s w_s P_2(\epsilon_s) D_{\text{retail,VI}}(\epsilon_s)}{\sum_s w_s D_{\text{retail,VI}}(\epsilon_s)} \tag{39}$$

Appendix B.2.1 Gauss-Seidel Algorithm

We solve for Nash equilibrium using sequential best response:

Algorithm 1 Stage 1 Equilibrium via Gauss-Seidel

Initialize $q_{i1}^{(0)} = 0$ for all i
Set tolerance $\tau = 10^{-2} \times \|q_2^{\text{spot}}\|$ where q_2^{spot} is spot-only equilibrium
iter $= 1$, crit $= \infty$
while crit $> \tau$ and iter < 20 **do**
    for $i = 1, \ldots, N$ **do**
        Fix $q_{-i,1} = q_{-i,1}^{(\text{iter})}$
        For each $q_{i1} \in [L_i, U_i]$:
            Solve Stage 2 equilibria for all shocks $\{\epsilon_s\}_{s=1}^{11}$
            Compute $U_i(q_{i1}, q_{-i,1})$
        $q_{i1}^{(\text{iter}+1)} = \arg\max_{q_{i1} \in [L_i, U_i]} U_i(q_{i1}, q_{-i,1})$
    end for
    crit $= \|q_1^{(\text{iter}+1)} - q_1^{(\text{iter})}\|$
    iter $=$ iter $+ 1$
end while

Define $K_i = \sum_j \bar{q}_{ij}$ as the total capacity. We bound the total swap-forward positions of generation only firms at $q_{i1} \in [0, K_i]$ of vertically integrated firms at $q_{i1} \in [-3K_i, K_i]$ and in the load following market by $\theta_i \in [-1, 1]$ for VI firm and $\theta_i \in [0, 1]$ for others.

Appendix C Additional Figures

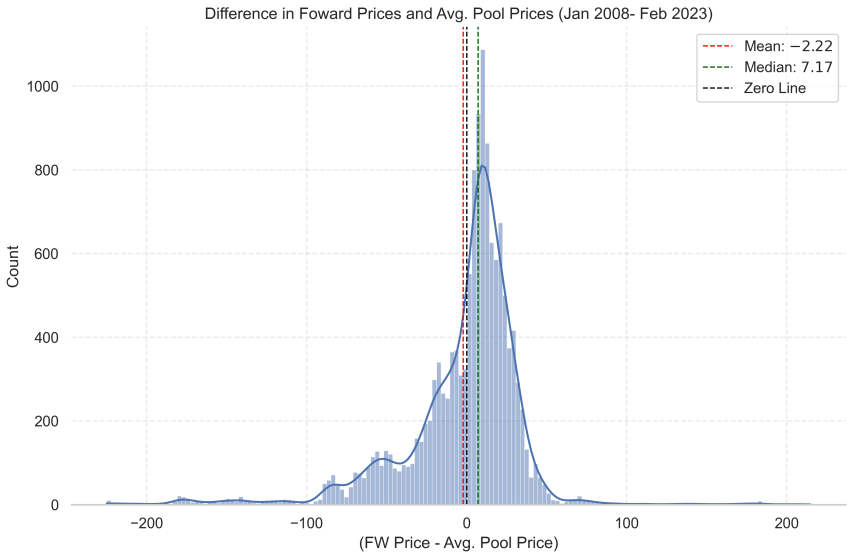


Figure 10: Forward vs Spot Prices

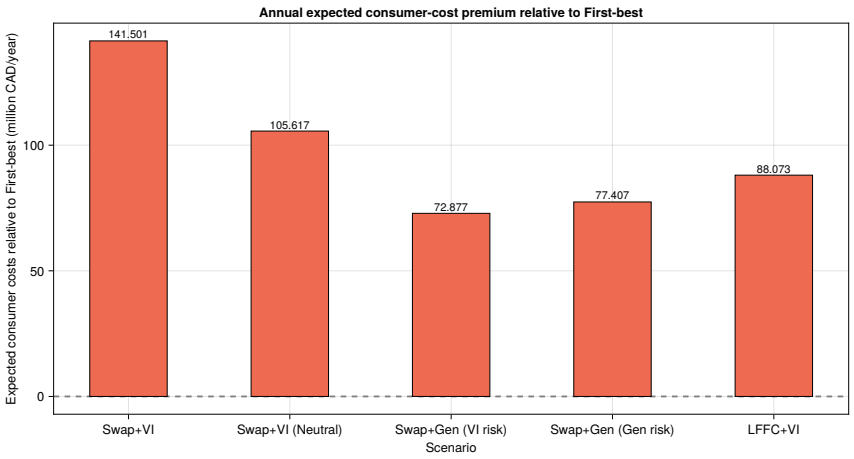


Figure 11: Average Annual Consumer Cost Increase Relative to the First-Best

Appendix D Empirical Application: Combining Risk Aversion and Imperfect Competition

We present equilibrium forward positions over a wide grid of risk-aversion parameters for generation-only firms and the vertically integrated firm separately. Starting from the risk neutral benchmark i.e., $\lambda_i = 0$, we extend the grid until the results become insensitive to further increases in risk aversion. Additional results for even larger risk-aversion values are reported in Section Appendix E.

In practice, firms are heterogeneous, so we report net equilibrium forward positions relative to expected production (i.e., equilibrium hedge ratios).

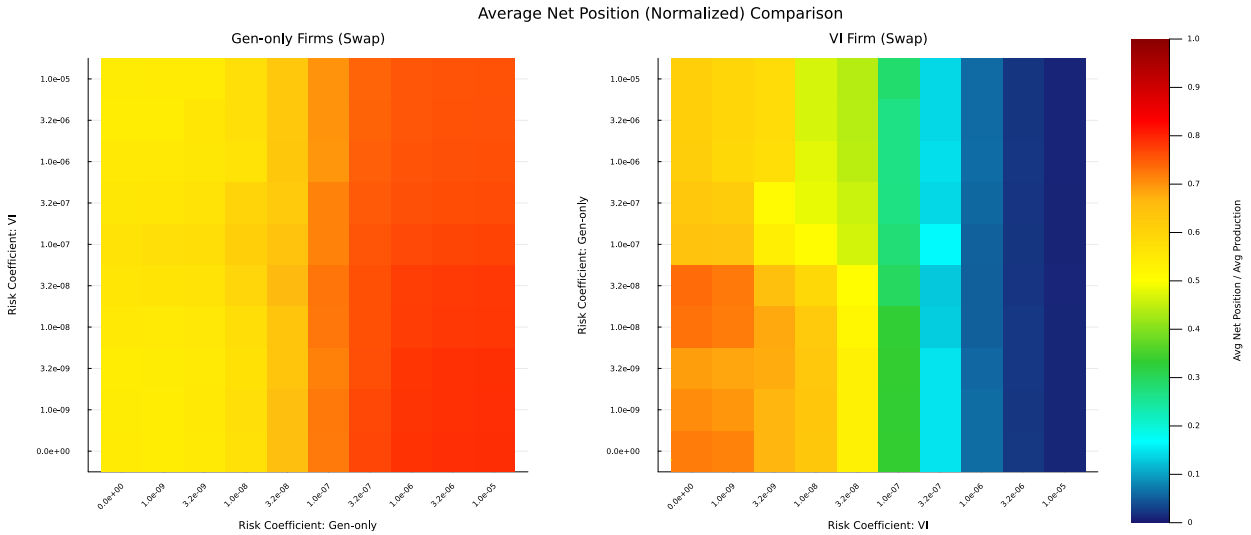


Figure 12: Optimal swap forward position relative to expected production

Notes: We use the simulations described in Section 5 to compute equilibrium swap forward positions. The figure reports equilibrium forward positions relative to expected production (i.e., equilibrium hedge ratios) for each pair of risk-aversion parameters for generation-only firms and the vertically integrated firm. The left panel shows the average optimal hedge ratio across the three generation-only firms, while the right panel shows the optimal hedge ratio for the vertically integrated firm.

Figure 12 shows the equilibrium swap hedge ratios for generation-only firms and the vertically integrated firm. The left panel shows the average equilibrium swap hedge ratio across generation-only firms for each pair of risk-aversion parameters. The model predicts hedge ratios of roughly 50–80 percent, which fall within a reasonable range compared with existing estimates in the literature (e.g., Reguant (2014)); Wolak (2007)) and industry reports. The right panel shows the equilibrium hedge ratio for the VI firm. When risk aversion is low, the VI firm holds a forward position comparable to that of generation-only firms. As risk aversion increases, however, the VI firm's hedge ratio declines substantially, reflecting the over-hedging effect. These patterns are consistent with the predictions of our simple theoretical model. Generation-only firms increase their short forward positions when using swaps for both strategic commitment and risk-hedging purposes. In contrast, while the VI firm increases its short position for strategic reasons, higher risk aversion can lead it to reduce its short position for risk-hedging purposes, due to over-hedging induced by contract incompleteness.

Figure 13 presents equilibrium LFFC hedge ratios. The left panel shows hedge ratios for generation-only firms, while the right panel shows those for the vertically integrated firm. Relative to the swap case, the VI firm's equilibrium hedge ratios become substantially

closer to those of generation-only firms. Moreover, the comparative statics with respect to the VI firm's risk aversion are reversed: the equilibrium hedge ratio now increases with risk aversion. Overall, these results are consistent with the theoretical prediction that load-following forward contracts correct the VI firm's over-hedging incentives and align its hedge ratio more closely with that of generation-only firms.

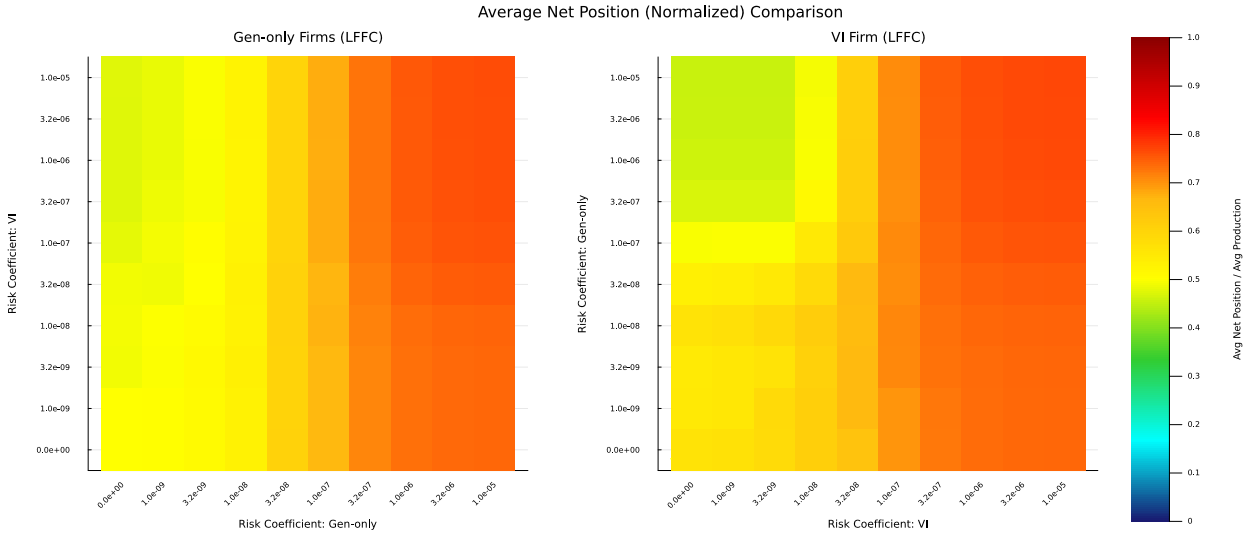


Figure 13: Optimal LFFC forward position relative to expected production

Notes: We use the simulations described in Section 5 to compute equilibrium LFFC forward positions. The figure reports equilibrium forward positions relative to expected production (i.e., equilibrium hedge ratios) for each pair of risk-aversion parameters for generation-only firms and the vertically integrated firm. The left panel shows the average optimal hedge ratio across the three generation-only firms, while the right panel shows the optimal hedge ratio for the vertically integrated firm.

Appendix E Robustness of Risk Aversion Parameters

We use the simulation model described in Section 5 to assess the robustness of our results to alternative risk aversion parameters. Specifically, we solve

$$\min_{(\lambda_{GEN},\lambda_{VI})} \sum_i \left(f_i(\lambda_{GEN},\lambda_{VI}) - f_i^{GMM}\right)^2$$

by grid search. The minimizing parameter pair is $(\lambda_{GEN},\lambda_{VI}) = (3.16\times10^{-8},\infty)$. Under this specification, producers maximize mean–variance utility, while the VI firm effectively minimizes profit variance.

Although the actual hedging strategies of retailers and vertically integrated firms are not

publicly observed, industry and regulatory reports indicate that minimum-variance hedging is a common benchmark and provides a reasonable approximation to firms' heuristic practices (see Independent Competition and Regulatory Commission (2019)). Our preferred parameter choice is therefore consistent with institutional evidence. To evaluate robustness, we conduct a series of sensitivity exercises across alternative risk aversion values.

Figure 14 reports the norm distance between the GMM-implied and model-predicted forward positions across a wide grid of parameter pairs. The red star denotes the minimizing pair. Although the optimum occurs at $\lambda_{VI} = \infty$, the norm distance becomes nearly flat for $\lambda_{VI} \gtrsim 1.0 \times 10^{-5}$. Beyond this threshold, the variance component of the objective dominates the expected profit term, so further increases in λ_{VI} have negligible effects on the fit.

In contrast, the generation-only risk parameter exhibits a well-defined interior minimum. The optimal λ_{GEN} lies between the risk-neutral benchmark and the pure variance-minimizing benchmark.

Figures 15 and 16 show that both average profits and profit standard deviations become essentially flat once $\lambda_{VI} \gtrsim 1.0 \times 10^{-5}$. Thus, the results are largely insensitive to a wide range of risk-aversion parameters in this region of the grid.

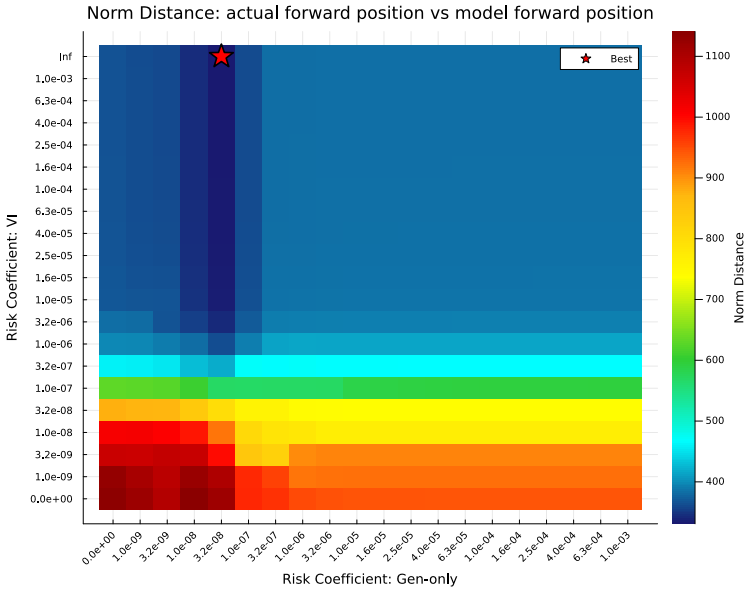


Figure 14: Norm Distance Between GMM and Model-Implied Forward Positions

*Notes:*This figure illustrates the norm distance between the GMM-implied and model-predicted forward positions, defined as $\sqrt{\left(f_i(\lambda_{GEN}, \lambda_{VI}) - f_i^{GMM}\right)^2}$. The simulation model is described in Section 5. The red star denotes the parameter pair $(\lambda_{GEN}, \lambda_{VI})$ that minimizes the norm distance.

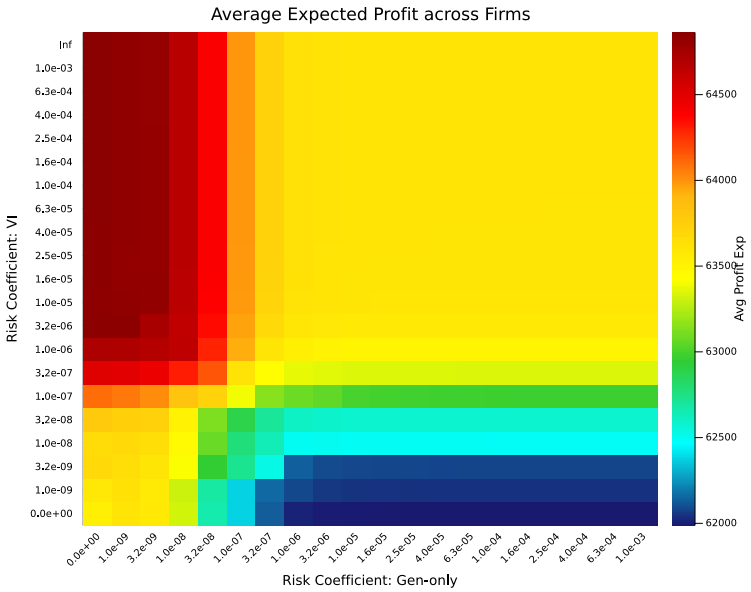


Figure 15: Average Profit Across Firms Under Alternative Risk Aversion Parameters

Notes: We use the simulation model described in Section 5. The figure reports the average expected profit across firms for alternative pairs of risk aversion parameters, $(\lambda_{GEN}, \lambda_{VI})$.

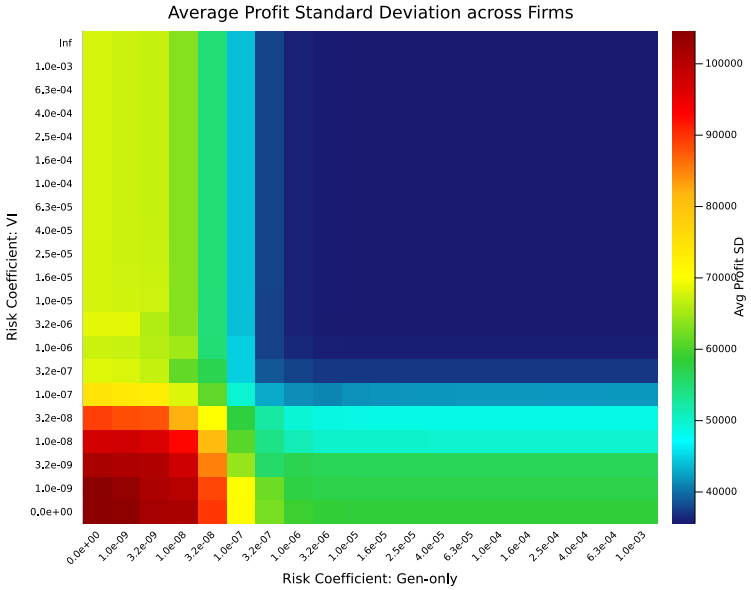


Figure 16: Average Profit Standard Deviation Across Firms Under Alternative Risk Aversion Parameters

*Notes:*We use the simulation model described in Section 5. The figure reports the average profit standard deviaion across firms for alternative pairs of risk aversion parameters, $(\lambda_{GEN}, \lambda_{VI})$.

As shown in Figures 17 and 18, increases in the VI firm's risk aversion parameter have only a modest effect on expected profits, while substantially reducing the variance of profits.

This pattern indicates that the VI firm can achieve significant risk reduction with little sacrifice in expected profitability.

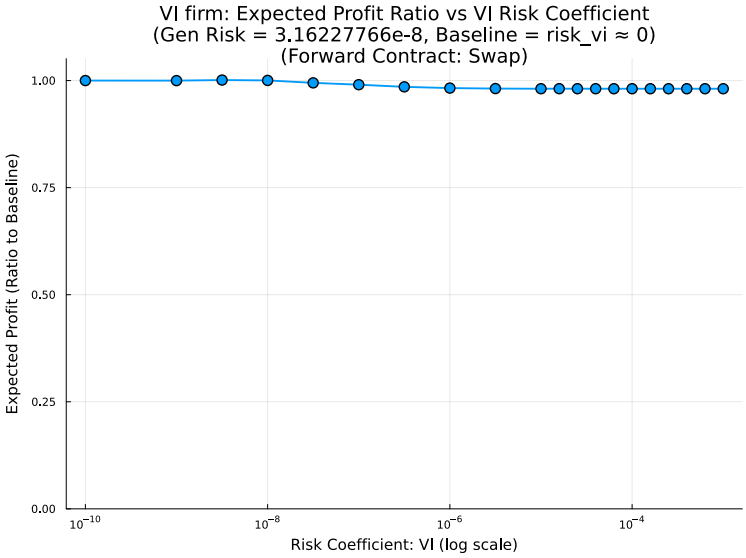


Figure 17: Expected Profit of the VI Firm Across VI Risk Aversion Parameters

*Notes:*This figure reports the VI firm's expected profit relative to the benchmark in which the VI firm is risk neutral. The producer's risk aversion is fixed at $\lambda_{GEN} = 3.16 \times 10^{-8}$, the value that best matches the GMM estimates.

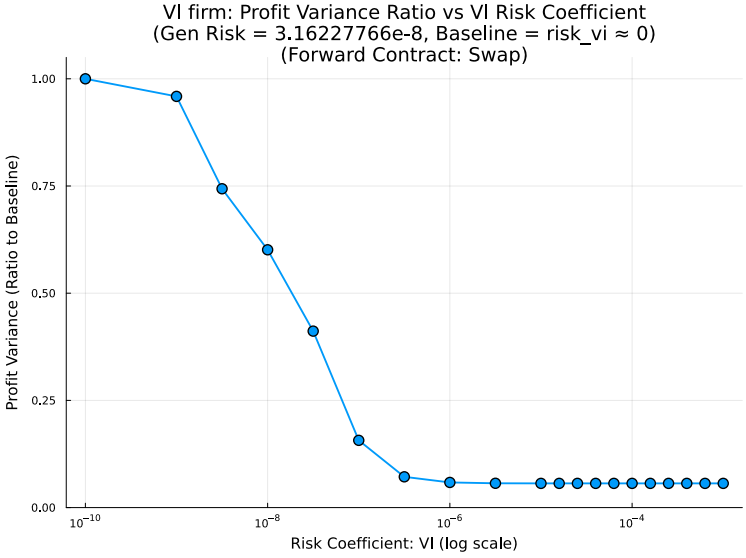


Figure 18: Profit Variance of the VI Firm Across VI Risk Aversion Parameters

*Notes:*This figure reports the VI firm's profit variance relative to the benchmark in which the VI firm is risk neutral. The producer's risk aversion is fixed at $\lambda_{GEN} = 3.16 \times 10^{-8}$, the value that best matches the GMM estimates.

Appendix F Track Ownership Changes of Assets

This appendix documents ownership changes for major thermal generation assets during the sample period. The table focuses on thermal assets owned by ATCO, Heartland Generation Ltd., ENMAX, Capital Power, TransAlta, and the Balancing Pool, which constitute the primary large firms in the Alberta market examined in the paper.

Timeline of Ownership and Asset Status Changes

- **2018-01-01**: Beginning of the analysis period.
- **2018-04-01**: Power Purchase Agreements (PPAs) for SD4, SD5, and SD6 expired; SD3 and SD5 exited the market.
- **2018-10-01**: PPA for BR5 expired.
- **2019-10-01**: Joint ownership of GN3 and KH3 was dissolved. GN3 became wholly owned by Capital Power, and KH3 became wholly owned by TransAlta.
- **2019-11-07**: ATCO's thermal assets were transferred to Heartland Generation Ltd.
- **2019-12-15**: BR3 exited the market.
- **2021-01-01**: PPAs for SH1, SH2, GN1, GN2, KH1, and KH2 expired.
- **2021-03-11**: HSM1 exited the market.
- **2021-12-31**: End of the analysis period. “‘

Based on these ownership transitions and asset exits, we redefine the re-sampling pool accordingly to ensure that firm ownership and asset availability are correctly aligned with each subperiod of the analysis.

Appendix G Unit-Level Marginal Cost Estimates

Table 4: Unit-Level Marginal Cost Estimates for Large Firms

			Before 2021			In 2021		
Firm	Unit	Fuel	GMM MC ($/MWh)	(SE)	Eng. MC ($/MWh)	GMM MC ($/MWh)	(SE)	Eng. MC ($/MWh)
Generation firm 1	Unit 1	GAS	15.37	(0.73)	19.40	–	–	–
	Unit 2	GAS	17.61	(1.45)	25.23	–	–	–
	Unit 3	COAL	19.33	(4.32)	37.48	–	–	–
	Unit 4	GAS	19.98	(0.76)	32.81	–	–	–
	Unit 5	GAS	20.18	(1.86)	25.23	–	–	–
	Unit 6	GAS	24.09	(0.86)	15.50	–	–	–
	Unit 7	GAS	26.25	(1.61)	19.98	–	–	–
	Unit 8	GAS	27.25	(2.39)	25.23	–	–	–
	Unit 9	GAS	27.27	(1.58)	25.23	–	–	–
	Unit 10	COAL	27.47	(2.06)	31.46	–	–	–
	Unit 11	GAS	29.09	(1.08)	28.02	–	–	–
	Unit 12	COAL	36.61	(0.47)	36.02	–	–	–
Generation firm 2	Unit 1	COAL	23.30	(2.68)	–	–	–	–
	Unit 2	COAL	20.91	(2.43)	29.13	27.88	(3.72)	34.93
	Unit 3	COAL	–	–	–	26.77	(4.04)	38.55
	Unit 4	GAS	20.66	(2.17)	14.55	34.41	(3.62)	24.10
	Unit 5	COAL	–	–	–	29.21	(4.01)	38.55
	Unit 6	GAS	27.04	(2.31)	21.08	45.04	(3.84)	36.04
	Unit 7	GAS	27.26	(2.68)	21.08	45.41	(4.47)	36.04
Generation firm 3	Unit 1	GAS	16.77	(1.10)	25.86	24.86	(1.83)	36.80
	Unit 2	GAS	21.98	(1.62)	41.85	32.57	(2.70)	60.49
	Unit 3	COAL	27.47	(2.06)	31.39	–	–	–
	Unit 4	GAS	24.74	(1.15)	21.21	36.67	(1.92)	29.91
	Unit 5	GAS	24.90	(4.82)	36.61	36.91	(8.04)	52.74
	Unit 6	COAL	32.20	(4.74)	37.30	–	–	–
	Unit 7	GAS	26.96	(4.11)	32.85	39.67	(6.85)	46.45
	Unit 8	COAL	–	–	–	34.28	(7.27)	36.85
	Unit 9	GAS	29.83	(2.55)	31.28	44.60	(4.24)	45.15
	Unit 10	GAS	33.49	(2.10)	26.55	49.64	(3.49)	37.83
	Unit 11	GAS	–	–	–	48.74	(7.55)	51.89
	Unit 12	GAS	43.21	(13.67)	32.81	64.04	(22.78)	47.10
	Unit 13	GAS	54.99	(133.01)	32.81	81.50	(221.59)	47.10
	Unit 14	GAS	139.39	(311.75)	32.81	206.59	(519.37)	47.10
Generation firm 4	Unit 1	COAL	27.03	(0.80)	29.13	–	–	–
	Unit 2	COAL	27.77	(0.57)	–	27.77	(1.17)	–
	Unit 3	COAL	29.38	(3.77)	31.35	32.05	(6.45)	35.63
	Unit 4	COAL	31.42	(3.18)	34.69	41.89	(3.60)	42.11
	Unit 5	COAL	–	–	–	39.54	(2.90)	38.95
	Unit 6	GAS	–	–	–	41.25	(2.61)	45.87
	Unit 7	COAL	–	–	–	42.43	(1.74)	36.85
	Unit 8	GAS	–	–	–	45.42	(4.87)	51.83
	Unit 9	GAS	40.45	(2.96)	32.85	59.53	(4.94)	46.45
	Unit 10	COAL	–	–	–	57.24	(4.97)	36.85
	Unit 11	GAS	–	–	–	75.91	(8.39)	51.89
VI firm	Unit 1	GAS	15.28	(1.70)	20.93	25.46	(2.83)	34.73
	Unit 2	GAS	15.33	(1.88)	15.56	25.53	(3.13)	25.78
	Unit 3	GAS	17.62	(1.74)	14.55	29.36	(2.90)	24.10
	Unit 4	GAS	26.29	(6.72)	22.12	43.80	(11.19)	37.77
	Unit 5	GAS	29.01	(7.81)	22.12	48.33	(13.02)	37.77
	Unit 6	GAS	43.91	(7.59)	22.12	73.15	(12.64)	37.77

Notes: The sample covers 2018–2021. Marginal costs are estimated at the unit level using the GMM estimator. The GMM marginal costs are computed at each unit's average output level. Generation Firm 1 exits during the sample period. Several assets either retire or convert to different fuel types. Engineering cost estimates are unavailable for two assets.