The Competitive Effects of Linking Electricity Markets Across Space and Time*

Thomas P. Tangerås† and Frank A. Wolak‡

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Abstract

We show that a common feature of electricity markets that use location-based pricing increases the performance of imperfectly competitive wholesale electricity markets. A forward contract that clears against the quantity-weighted average of a set of locational short-term prices increases competition compared to a set of local forward contracts that clear against individual location-specific prices. In contrast, linking locational markets through a long-term contract that clears against the quantity-weighted average of short-term prices either has no effect on, or reduces average wholesale market performance. These results demonstrate that an appropriate design of forward markets can enhance efficiency in wholesale electricity markets.

Key Words: Electricity markets, equity, market design, market performance, market power, vertical integration.
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†Research Institute of Industrial Economics (IFN) P.O. Box 55665, 10215 Stockholm, Sweden, e-mail: thomas.tangeras@ifn.se. Associated researcher, Energy Policy Research Group, University of Cambridge. Faculty affiliate, Program on Energy and Sustainable Development, Stanford University.

‡Program on Energy and Sustainable Development and Department of Economics, Stanford University, 579 Serra Mall, Stanford, CA 94305-6072, e-mail: wolak@stanford.edu.

1 Introduction

Locational marginal pricing or nodal pricing is used to manage transmission congestion in all formal wholesale electricity markets in the United States.[1] Locational prices and generation unit-level energy sales are computed by minimizing the as-offered cost of serving demand at all locations in the transmission network subject to all relevant operating constraints on the network. This process can give rise to thousands of different locational prices within the geographic footprint of the wholesale market each pricing period.

The locational marginal price (LMP) at a location or node in the transmission network is equal to the increase in the minimized as-offered cost of withdrawing an additional megawatt-hour (MWh) at that node. Therefore, if all suppliers submit a generation unit's marginal cost as its offer price to the Independent System Operator (ISO), each LMP is the economically efficient price signal for that location in the transmission network.[2]

Despite these market efficiency properties of LMP pricing, it has been extremely difficult for regulators in the United States to charge electricity consumers a retail price that reflects the LMP at their location in the transmission network. The potential of the LMP market design to set different prices at different locations in the transmission network has been a major barrier also to the adoption of this market design in many countries, despite demonstrated market efficiency benefits from doing so.[3] The arguments against charging final consumers a retail price that reflects the LMP at their location in the transmission network are typically based on the view that it is unfair to charge customers in major load centers higher prices than customers withdrawing energy from other nodes in the transmission network, even though LMPs in load centers are usually higher than prices at other nodes.

This paper demonstrates that a common feature of US LMP markets reduces the negative consequences for consumers of LMP pricing in imperfectly competitive electricity markets by improving the performance of short-term markets. US LMP markets often create trading hub prices, which are quantity-weighted averages of LMPs in a sub-region of the market. Because these hub prices are typically less volatile than any individual component LMP, market participants manage their short-term price risk by purchasing forward contracts that

[1]PJM Interconnection, California Independent System Operator (ISO), ISO-New England, New York ISO, Midcontinent ISO, and Electricity Reliability Council of Texas (ERCOT) all use locational marginal pricing for their day-ahead and real-time markets.

[2]Specifically, if these LMPs are set at each node in the transmission network, then all suppliers will find it unilaterally profit-maximizing to produce at a level of output that minimizes the total variable cost of serving demand at all locations in the transmission network.

[3]Wolak (2011) finds that the transition from a zonal to a nodal market design was associated with annual savings in the variable cost of serving demand of over 100 million dollars annually.

clear against these trading hub prices.

Our basic insight is that linking M local markets through a single forward contract that clears against the quantity-weighted average of the locational short-term prices over all M markets, increases the amount of forward contracts beyond the level that would occur if there were M independent forward markets with the forward price in each local market clearing against the locational short-term price in that market. As is well-known, forward contracting can improve short-term market performance because an output expansion has a smaller effect on the share of output exposed to the spot price decrease if the producer has covered a larger part of its output in the forward market.[4] The associated increase in the amount of forward contracts reduces short-term prices below the level that would exist under forward contracts cleared against individual locational short-term prices.

The competitive benefits of linking forward markets across space can be substantial. In a symmetric Cournot model, linking together five local monopoly markets through a single forward contract can cause the short-term price-cost margins to drop by 5-15% in each local market. Notably, these price effects are purely the result of changes in the forward market, and do not rely on any changes in market structure.

We consider a model in which producers sell forward contracts in a first stage and produce for the short-term market in a second stage. The equilibrium amount of forward contracting that emerges from this model balances a number of opposing forces. On the one hand, a forward premium renders it profitable for the producer to increase its quantity of forward contracts. On the other hand, a larger forward quantity reduces the forward price. A third effect occurs if there are multiple producers with market power in the local market. A larger forward quantity commits the producer to supplying more output to the short-term market. This commitment triggers a strategic response by which competitors reduce their output. The profit in the short-term market increases as a consequence of the output contraction.

The incentives to buy and sell forward contracts and the implications of forward contracting for competition depend crucially on forward market design. We compare two policy relevant designs. The first is the benchmark of *spatially independent* markets. Forward markets in this setting are *local* in the sense that forward contracts clear against the locational short-term prices in each market. The second scenario is where the local markets are *linked* through a *regional* forward contract that clears against the quantity-weighted average of all locational short-term prices. A forward contract that clears against a trading hub price is an example of a regional forward contract in the context of our model.

[4] Wolak (2000) demonstrates the empirical relevance of this mechanism for a large supplier in an Australian wholesale electricity market.

A producer's forward profit equals its forward quantity multiplied by the difference between the forward price and the clearing price. The forward quantity and forward price are sunk at the production stage. An increase in production then increases the forward profit by driving down the clearing price. This mechanism is the source of the pro-competitive effect of forward contracting on short-term prices. The effect is weaker under regional compared to local forward contracting because each locational short-term price only enters as a fraction of the clearing price in the regional forward contract. Short-term prices therefore are higher under regional than local forward contracting for constant forward quantities. By implication, regional forward contracting can only be pro-competitive compared to local forward contracting if it substantially increases the amount of forward contracts in equilibrium.

The demand for forward contracts in our model comes from large industrial consumers that are forward-looking and anticipate that buying such contracts will reduce the short-term price and therefore the cost of electricity (Ruddell et al., 2018). Because of these competitive benefits, consumers are willing to pay a premium on forward contracts. However, consumers' willingness to pay for forward contracts is lower under regional than local forward contracting because the price effects in the short-term market of forward contracts are smaller under a regional forward contract. The lower willingness to pay drives down the forward premium under the regional forward contract. This partial effect reduces the profitability of selling forward contracts when markets are linked by a regional forward contract compared to the benchmark of spatially independent markets.

The incentive to sell forward contracts depends also on the effect of an increase in forward quantities on the forward price. The forward price effect spills over to all local markets when forward markets are linked through a regional forward contract. For historical reasons, producers typically own generation capacity only in a few local markets, usually their historical service territory during the former monopoly regime. Producers will not internalize the full forward price effect unless they are active (own generation capacity) in all local markets. The spill-over effect of forward prices increases the profitability of selling forward contracts under a regional forward contract compared to the benchmark of spatially independent markets.

Our main result is that the spill-over effect of regional forward contracting is so strong that it dominates the forward premium effect if all local markets feature one producer with market power and all producers are active only in one local market. Producers then sell substantially more forward contracts under regional forward contracting, which reduces the average short-term prices compared to spatially independent markets.

An additional effect of forward contracting arises if there is more than one producer with market power in the short-term market. The strategic output contraction by competitors is smaller under regional than local forward contracting because an increase in a producer's amount of forward contracts constitutes a weaker commitment to behave aggressively in the short-term market under regional forward contracts. The muted strategic effect reduces the profitability of selling forward contracts when local markets are linked by a regional forward contract compared to the case of spatially independent markets. Still, the spill-over effect is sufficiently strong to reduce equilibrium short-term prices even in oligopoly if, for instance, the local markets are sufficiently similar.

Producers internalize more of the forward price effect under regional forward contracting if they own generation assets in more than one local market. Consequently, linking markets through a regional forward contract reduces prices in the short-term market compared to the case of spatially independent markets if and only if producers with market power own production assets in a sufficiently small number of local markets.

We also consider the case when producers and consumers both can write local and regional forward contracts, to see if the market can sustain both types of contracts in equilibrium. Typically, local forward premiums are above [below] the regional forward premium in markets with above [below] average demand. Therefore, producers with market power in large [small] markets will only offer local [regional] forward contracts. Adding a regional forward market to an existing set of local forward markets therefore has no effect on short-term prices in relatively large markets, but will reduce short-term prices in relatively small markets.

We finally explore the implications of linking markets over time by way of a long-term forward contract and compare this outcome to a sequence of short-term contracts. In a long-term contract, the M markets are different versions of the same market over time, and this case is formally equivalent to all producers and all consumers participating in all M markets. The average of the short-term market prices across all periods is found to be the same under long-term and short-term forward contracts. However, short-term contracts improve market performance if producers are expected to be off-grid in some periods, for instance because of outages or scheduled maintenance. A long-term forward contract signed with a producer has no effect on short-term prices in periods when the producer is off-grid. Short-term contracts enable consumers to purchase in every period forward contracts from producers that are on-grid that period. Therefore, short-term are pro-competitive relative to long-term contracts.

Recent experience in Germany illustrates the policy relevance of our findings. Subsidies to renewable electricity generation have created a large production surplus in northern Germany (because this is where the conditions for solar and wind electricity production are the most favorable) despite the fact that a large share of demand is located in the South. Suggestions have been made to break the single German price area into smaller ones to manage these local supply and demand imbalances within Germany.[5] Our results suggest that that dividing Germany into several price areas while allowing producers and consumers to write forward contracts based on the quantity-weighted average of those area prices could improve short-term market efficiency and reduce prices in all local markets by improving local competition.

Allaz and Vila (1993) are the first to demonstrate the pro-competitive effects of forward contracting in a model with a single short-term market. Our main contribution to this literature is to show how linking forward markets across geographical locations can improve the average performance of the wholesale markets.[6] Mahenc and Salanié (2004) find forward contracting to reduce market performance if firms compete in prices in the spot market instead of in quantities as assumed here. Holmberg (2011) establishes conditions under which forward contracting improves market performance when firms compete in supply functions. These results suggest that the competitive effects of regional forward markets can be sensitive to the mode of competition in the short-term market. We establish pro-competitive effects also under local monopoly conditions, and these are invariant to the choice of price versus quantity. Moreover, Cournot competition has been used in empirical research to model strategic interaction among suppliers in many wholesale markets for electricity, including California, New England and PJM (Bushnell et al., 2008), the Midwest market (Mercadal, 2016), the German market (Willems et al., 2009) and the Nordic market (Lundin and Tangerås, 2020).

The rest of the paper is organized as follows. Section 2 introduces our setup and illustrates the mechanism in a simple symmetric example with two local markets and one producer with market power in each local market. Section 3 generalizes the model to an asymmetric setting with an arbitrary number of local markets and an arbitrary number of producers with market power in every local market. We show that the regional forward contract reduces the volume-weighted average of the short-term prices compared to the benchmark of spatially independent markets, if local markets have a sufficiently high degree of market concentration. Section 4 considers the possibility that producers own generation capacity in multiple local markets. Our main result is that linking local markets through a regional forward contract reduces short-term prices if and only if geographical concentration of asset ownership is sufficiently large. Section 5 considers the combined case of a regional and local forward markets. We show that producers in a larger market sell local forward contracts and producers in a smaller market sell regional forward contracts, with either zero or negative effects on

[5]See, for instance, Egerer et al. (2016) and references therein.

[6]Green and Le Coq (2010) show that increasing the contract length (linking electricity markets across time) has ambiguous effects on the ability to sustain collusion. We consider unilateral market power and thus leave the question of how different market designs affect collusion for future research.

prices in all short-term markets. Section 6 investigates the implications of long-term forward contracts, and shows that they either have no effect on average short-time prices or cause short-time prices to increase compared to short-term forward contracts. Section 7 concludes with a discussion of the implications of our results for the design of electricity markets. The proofs of some formal results are in an Appendix.

2 The mechanism demonstrated in a simple example

We here present the basic modeling framework we will apply throughout the analysis, but in the simplest possible setting that can generate the key mechanism of our paper. This simple model features two symmetric local markets that are functionally separate from one another. There is one producer with market power in each local market. Electricity demand comes from a number of large industrial consumers that also participate in the forward market (Ruddell et al., 2018). Unlike in Allaz and Vila (1993), a monopoly producer has an incentive to participate in the forward market because large consumers pay a forward premium over the short-term price of electricity. The premium occurs precisely because forward contracting reduces the short-term price.

Our main contribution is to show that linking electricity markets through a *regional forward contract* that clears against the quantity-weighted average of the short-term prices in the two local markets, increases competition in the short-term market beyond what is possible under *local forward contracts* that clear against the local short-term prices. Under the regional forward contract, producers with market power sell more forward contracts than in the Allaz and Vila (1993) and the Ruddell et al. (2018) model, because producers ignore the negative short-term price effect in the other local market when they increase forward sales. The effect on equilibrium forward volumes is sufficient to render the total short-term price effect negative even though the direct effect of regional forward contracting on competition in the short-term market is negative relative to local forward contracting when forward positions are held constant.

The model An electricity network is a set of nodes connected by high-voltage transmission lines. There are two types of nodes. A generation injection node is a location at which a power plant feeds electricity into the grid. A load withdrawal node is a location at which either a large industrial plant pulls electricity from the grid or a substation converts electricity to lower voltages for distribution to smaller industries and households. A *local market* is a subset of generation injection and load withdrawal nodes with the property that the transmission grid has sufficient capacity to handle all power flows between all those nodes. The free flow of power means that the price of electricity in the short-term market, the locational marginal price (LMP), will be the same at all nodes within the local market. The electricity market is the collection of local markets that covers all nodes in the network. The composition of local markets may change from period to period depending on demand and supply conditions and capacity constraints of the transmission grid.

In the simple model, we consider an electricity market that consists of two local markets. These are symmetric and functionally separate from one another in the sense that there is no flow of electricity between them. This assumption hugely simplifies the analysis, but also reveals a key insight: There can be market performance gains from financially linking markets even if there is no actual trade of goods between them. We generalize the model to an arbitrary number of asymmetric local markets in Section 3.

We analyze a two-stage game in which firms compete in quantities in the forward market in the first-stage and in quantities in the short-term market in the second stage. We consider long-term forward contracts that cover multiple production periods in Section 6.

To capture the fact that short-term demand for electricity is highly price inelastic, we let total demand D be constant and equal to $\frac{1}{2}D$ in each local market. This demand comes from H industrial consumers, half of which are located in each local market. We let D_h be the local demand by consumer $h \in \{1, ... \frac{1}{2}H\}$. Local demand $\frac{1}{2}D = \sum_{h=1}^{\frac{1}{2}H} D_h$ must be met entirely by local supply by our assumption of functionally separate local markets, but local production is a homogeneous good by our assumption of a free flow of electricity within each local market. We assume that consumption and production of electricity both are deterministic. The deterministic setup means that there is no hedging motive for trading forward contracts in the first stage.

There are two producers with market power: Producer 1 has market power in local market 1, and producer 2 has market power in local market 2. Each producer is *active* in one local market in the sense that it owns generation capacity only in one local market. As noted earlier, geographical concentration of generation assets is realistic in electricity markets where many companies are former monopolists with local production capacity and distribution networks connected to local consumers. We consider the effects of producers operating in multiple local markets in Section 4. We also assume that each local market has a number of independent producers that behave as a competitive fringe by selling electricity at marginal cost. Below we describe the interaction in local market 1. The description of local market 2 is identical by symmetry, so we leave it aside.

The producer with market power in market 1 sells forward contracts for k MWh electricity in the first stage at price f per MWh, and produces $q \in [0, \frac{1}{2}D]$ MWh electricity in the second stage at constant marginal production cost c. The competitive fringe supplies residual demand $\frac{1}{2}D - q$ at linear marginal cost $b(\frac{1}{2}D - q)$, so the market-clearing short-term price equals $p = b(\frac{1}{2}D - Q)$. If we define $a = b\frac{D}{2} > \frac{5}{3}c$, then the inverse demand curve facing the producer with market power equals $P(q) = a - bq$. The elasticity of the inverse demand curve $P(q)$ comes from the elasticity of the supply of the competitive fringe. We solve for the unique subgame-perfect equilibrium to this two-stage game by backward induction.

Equilibrium in the short-term market The second-stage profit of the producer with market power equals

$$(f - P(q))k + (P(q) - c)q. \tag{1}$$

The first term measures the forward profit in a spatially independent market where forward contract are local and clear against the local short-term price $p = P(q)$. The second term in the above equation measures the profit in the short-term market. The firm's first-order condition for profit maximization is

$$-P'(q)k + P(q) - c + P'(q)q = 0 \tag{2}$$

in interior optimum. The producer has an incentive to withhold output q to sustain a higher short-term price and thereby increase profit in the short-term market. This incentive is muted if the producer has sold forward contracts. An increase in output then increases the forward profit by driving down the clearing price $P(q)$ of the forward contract. The magnitude of this effect on the forward profit is larger when the producer has sold a larger quantity k of forward contracts. Notice also that the production decision is independent of the forward price f because the forward revenue fk is sunk at the production stage. By way of $P(q) = a - bq$ and $P'(q) = -b$, we can solve for the production

$$q(k) = \frac{1}{2}\frac{a-c}{b} + \frac{1}{2}k \tag{3}$$

of the producer with market power as a function of its forward position k. The corresponding short-term price equals

$$p(k) = P(q(k)) = \frac{a+c}{2} - \frac{b}{2}k. \tag{4}$$

Production is larger and the short-term price is smaller when the producer with market power has sold a larger volume of forward contracts.

Equilibrium in the forward market The $\frac{1}{2}H$ industrial consumers participate in the forward market. These consumers are strategic in the sense of being forward-looking and anticipating the effect of forward contracting on prices in the short-term market. If industrial consumer h purchases k_h of the total volume k of forward contracts, then its profit equals

$$U(D_h) + (P(q(k)) - f)k_h - P(q(k))D_h. \tag{5}$$

The first term is the value of electricity consumption D_h, the second term is the forward profit, or deficit, and the third term is the cost of electricity consumption. By aggregating the first-order condition

$$P(q(k)) - f + (k_h - D_h)P'(q(k))q'(k) = 0 \tag{6}$$

across all industrial consumers, and using $P'(q(k)) = -b$ and (3), we can solve for the inverse demand function $f = F(k)$ for forward contracts:

$$F(k) = P(q(k)) + b\frac{\frac{1}{2}D - k}{H}. \tag{7}$$

Industrial consumers purchase forward contracts in this model to drive down the short-term price of electricity, not because they want to hedge price uncertainty. Indeed, they pay a premium on forward contracts if contract coverage is incomplete, i.e. $k < \frac{1}{2}D$ (Ruddell et al., 2018). The forward premium converges to zero as the number H of industrial consumers grows to infinity because then individual consumers have very little influence over the short-term price. This limiting case corresponds to the zero forward premium assumption in Allaz and Vila (1993).

The first-stage profit of the generator with market power equals

$$(F(k) - P(q(k)))k + (P(q(k)) - c)q(k) \tag{8}$$

as a function of its forward position k, where $q(k)$ is given by (3), $P(q(k))$ by (4) and $F(k)$ by (7). The effect of a marginal increase in k can be written as

$$\underbrace{F(k) - p(k) + F'(k)k}_{\text{Marginal forward profit}} + \underbrace{[-P'(q)k + P(q) - c + P'(q)q]q'(k).}_{\text{Marginal profit in the short-term market}} \tag{9}$$

The effect of forward contracts on the profit in the short-term market is of second-order importance by the first-order condition (2). Hence, the optimal forward position k^I from the viewpoint of the producer with market power, is found at the point

$$F(k^I) - p(k^I) + F'(k^I)k^I = 0$$

that maximizes the forward profit, where superscript I identifies the case of spatially independent markets. By using the functional forms (4) and (7), we obtain the volume

$$k^I = \frac{D}{H+4} \tag{10}$$

of forward contracts sold in equilibrium by a producer with local market power. The producer's equilibrium output is:

$$q^I = q(k^I) = \frac{1}{2b}(\frac{H+6}{H+4}a - c), \tag{11}$$

and the corresponding price-cost margin in the short-term market is:

$$p^I - c = p(k^I) - c = \frac{a-c}{2} - \frac{a}{H+4} > 0. \tag{12}$$

The forward premium arising from industrial consumers' demand for forward contracts causes a producer with market power to supply forward contracts regardless of the fact that selling such contracts will reduce the short-term price-cost margin below the monopoly level $\frac{a-c}{2}$. The pro-competitive effect of forward contracting is stronger if there are fewer industrial consumers in the market for forward contracts, i.e. H is smaller, because then the willingness to pay for forward contracts is larger. Hence, strategic considerations by consumers in the forward market improve the efficiency in the short-term electricity market. The only case when forward contracting does not improve competition is when the number of industrial consumers in the local market is infinitely large ($H \to \infty$).

Notwithstanding the pro-competitive effects of forward contracting, the equilibrium short-term price remains inefficiently high. For the producer with market power to behave in a fully competitive manner, this would require full contract coverage, i.e. a forward contract position equal to the producer's entire output. Instead, the equilibrium contract coverage is only partial:

$$\frac{k^I}{q^I} = \frac{4a}{(a-c)(H+6)+2c} < 1.$$

This means there would be efficiency gains of reinforcing producers' incentives to sell forward contracts. The key insight of this paper is that linking markets creates such an incentive.

Linking the local markets by a regional forward contract Consider now the consequences of linking local markets through a *regional forward contract*. In our simple example, this is a forward contract that clears against the quantity-weighted average $\frac{1}{2}(p_1 + p_2)$ of the short-term market prices in the two local markets. As mentioned in the introduction, such contracts are common in US LMP markets where forward prices clear against trading-hub prices. In the Nordic market, standard forward contracts clear against the market-wide system price.

Let k_1 be the quantity of forward contracts sold by producer 1, and let $q_1 \in [0, \frac{1}{2}D]$ be the quantity it produces in local market 1. Similar notation applies for producer 2 located in local market 2. If $\bar{f}$ is the price of the regional forward contract, then the profit of producer 1 at the second stage of the game equals

$$(\bar{f} - \frac{1}{2}[P(q_1) + P(q_2)])k_1 + (P(q_1) - c)q_1,$$

and its first-order condition for profit maximization in interior equilibrium is:

$$-\frac{1}{2}P'(q_1)k_1 + P(q_1) - c + P'(q_1)q_1 = 0. \tag{13}$$

The competitive effect of forward contracting in the short-term market is weaker when the forward contract clears against the average short-term price in the two markets compared to the case of local forward markets elucidated in (2). The reason is that the marginal effect on the clearing price of an increase in q_1 is smaller when the forward contract clears against the weighted average of multiple short-term prices. By comparing (13) with (2), we see that producer 1 must sell twice the amount of the regional forward contract relative to the local forward contract for the competitive effect to be the same. Hence, the output of producer 1 equals

$$q_1 = q(\frac{k_1}{2}) = \frac{1}{2}\frac{a-c}{b} + \frac{1}{2}\frac{k_1}{2}$$

under the regional forward contract, and the short-term price in local market 1 is

$$p_1 = P(q(\frac{k_1}{2})) = \frac{a+c}{2} - \frac{b}{2}\frac{k_1}{2}$$

Analogous expressions hold for the producer with market power in local market 2 as a function of that producer's forward volume $\frac{1}{2}k_2$.

Consider now the first stage of the game where the two producers decide the forward contract volumes k_1 and k_2 of the regional forward contracts to offer to the market, and industrial consumers choose the volume of regional forward contracts to purchase. The profit of industrial consumer h located in market 1 equals

$$U(D_h) + (\frac{1}{2}[P(q(\frac{k_1}{2})) + P(q(\frac{k_2}{2}))] - \bar{f})k_{1h} - P(q(\frac{k_1}{2}))D_h. \tag{14}$$

if it buys a regional forward contract for k_{1h} MWh electricity from producer 1, and producer 1 [2] offers a total volume of k_1 [k_2] regional forward contracts. This consumer buys no forward contracts from producer 2 because it then does not receive the benefit of a reduction in its electricity cost. Summing up the first-order condition

$$\frac{1}{2}[P(q_1) + P(q_2)] - \bar{f} + \frac{1}{2}P'(q_1)q'(\frac{k_1}{2})(\frac{k_{1h}}{2} - D_h)$$

for all industrial consumers in each local market and across both local markets, returns the inverse demand

$$\bar{F}(k_1, k_2) = \frac{1}{2}[P(q(\frac{k_1}{2})) + P(q(\frac{k_2}{2}))] + \frac{b}{4H}(D - \frac{k_1 + k_2}{2}). \tag{15}$$

for the regional forward contract as a function of the two producers' forward positions k_1 and k_2. Industrial consumers' willingness to pay for a regional forward contract is smaller than the willingness to pay for a local forward contract even if the volume of regional forward contracts is so large relative to local forward contracts, $k_1 = k_2 = 2k$, that the short-term price would be the same under both types of forward contracts:

$$\bar{F}(2k, 2k) - P(q(k)) = \frac{b}{2}\frac{\frac{1}{2}D - k}{H} < b\frac{\frac{1}{2}D - k}{H} = F(k) - P(q(k)). \tag{16}$$

This is because the marginal pro-competitive effect in the short-term market of an increase in the volume of forward contracts is weaker under regional than local forward contracting.

Turning to the profit-maximizing forward quantities, producer 1's first-stage profit equals

$$(\bar{F}(k_1, k_2) - \frac{1}{2}[P(q(\frac{k_1}{2})) + P(q(\frac{k_2}{2}))])k_1 + (P(q(\frac{k_1}{2})) - c)q(\frac{k_1}{2}). \tag{17}$$

under the regional forward contract. As in the case of local forward contracts, we can partition the producer's marginal profit into an expression for marginal forward profit and an expression for marginal profit in the short-term market:

$$\underbrace{\bar{F}(k_1,k_2) - \frac{1}{2}[P(q_1)+P(q_2)] + \frac{\partial \bar{F}(k_1,k_2)}{\partial k_1}k_1}_{\text{Marginal forward profit}} + \underbrace{[-\frac{1}{2}P'(q_1)k_1 + P(q_1) - c + P'(q_1)q_1]\frac{1}{2}q'(\frac{k_1}{2})}_{\text{Marginal profit in the short-term market}}.$$

Again, the second term is of second-order effect on producer 1's profit. Producer 1's marginal profit therefore equals

$$\bar{F}(2k^I,2k^I) - p(k^I) + \frac{\partial \bar{F}(2k^I,2k^I)}{\partial k_1}2k^I$$

evaluated at $k_1 = k_2 = 2k^I$. On the one hand, the smaller forward premium under the regional forward contract, see equation (16), tends to reduce forward contracting below the level $2k^I$ that would yield the same short-term price under a regional forward contract as under spatially independent markets. On the other hand, the marginal reduction in the forward profit associated with the decrease in the forward price is smaller in magnitude under a regional forward contract than one that clears against the local price:

$$\frac{\partial \bar{F}(2k^I,2k^I)}{\partial k_1}2k^I = -\frac{b}{2}\frac{H+1}{2H}k^I > -\frac{b}{2}\frac{H+2}{H}k^I = F'(k^I)k^I. \tag{18}$$

The short-term price p_1 in local market 1 only represents a fraction of the clearing price of the regional forward contract. By construction of this forward contract, a share of the negative price effect of an increase in k_1 spills over to local market 2, where producer 1 has no market presence. This spill-over effect creates an incentive for firm 1 to increase k_1 above $2k^I$. The spill-over effect dominates the effect of a smaller forward premium, and therefore (superscript R identifies the case of a regional forward market):

Proposition 1 *Consider an electricity market with two symmetric local markets and one producer with market power in each local market. Linking the two local markets through a regional forward contract that clears against the quantity-weighted average of the short-term prices in those two markets, more than doubles the volume k^R of forward contracts sold by each producer with market power,*

$$k^R = \frac{2D}{H+3} > \frac{2D}{H+4} = 2k^I, \tag{19}$$

compared to the benchmark of spatially independent markets. This increase in the volume of *forward contracts has a pro-competitive effect in the short-term market:*

$$0 < p^R - c = \frac{a-c}{2} - \frac{a}{H+3} < \frac{a-c}{2} - \frac{a}{H+4} = p^I - c. \tag{20}$$

Proposition 1 predicts forward contracts that clear against the volume-weighted average of the short-term prices across multiple local markets to be substantially more liquid than forward contracts that clear against local short-term prices. Moreover, the forward premia on regional forward contracts will be relatively smaller. This increase in liquidity will improve the performance of the short-term market, even in the case where the local market is characterized by one single generator with the ability to exercise market power.

Proposition 1 is not an artifact of assuming local monopoly production or symmetry. We show in the next section that the pro-competitive effect of creating a regional forward contract holds also in the asymmetric case with an arbitrary number of local markets and producers.

3 Linking multiple local markets through a regional forward contract

We now generalize the highly stylized model in Section 2 to an arbitrary number M of local markets that can be asymmetric. We show that creating a regional forward contract that clears against the quantity-weighted average of the short-term price in all M local markets has competitive effect in the short-term market by its effect on firms' unilateral incentives to sell forward contracts. In particular, we demonstrate that the regional forward contract reducers the volume-weighted average of the short-term prices compared to the case of M local forward markets, if market concentration is sufficiently large in each local market m.

3.1 Spatially independent markets benchmark

The model We index local markets by $m \in \{1, ..., M\} = \mathcal{M}$ and an individual producer with market power in local market m by $l \in \{1, ..., L_m\}$. All electricity is sold at a uniform price f_m in forward market m and a uniform price p_m in short-term market m.

In the first stage, each producer l with market power supplies k_{lm} MWh of forward contracts, taking the aggregate forward positions $K_{-lm} = \sum_{i \neq l} k_{im}$ of the other $L_m - 1$ producers with market power as given. Let $K_m = k_{lm} + K_{-lm}$ be the total supply of forward contracts by the L_m producers with market power in local market m. These forward contracts are purchased by H_m large industrial consumers located in local market m.

In the second stage, each producer l in market m observes K_{-lm} and decides how much electricity, q_{lm}, to produce for the short-term market at constant marginal cost c_{lm}, taking the production $Q_{-lm} = \sum_{i \neq l} q_{im}$ of the other producers with the ability to exercise market power as given. The total production of electricity in local market m of firms with market power equals $Q_m = q_{lm} + Q_{-lm}$. Industrial consumer h located in market m has demand D_{mh} for electricity, all of which is purchased in the short-term market. Total demand in short-term market m equals $D_m = \sum_{h=1}^{H_m} D_{mh}$. The residual demand $D_m - Q_m$ is covered by a competitive fringe that supplies electricity at linear marginal cost $b_m(D_m - Q_m)$. The inverse demand curve facing the L_m producers with the ability to exercise unilateral market power in short-term market m can then be written as $p_m = P_m(Q_m) = a_m - b_m Q_m$, where $a_m = b_m D_m$.

It is straightforward to incorporate electricity flows between local markets with this more general notation. Let $E_m \gtreqless 0$ be the net export of electricity out of local market m, so that $\sum_{m=1}^{M} E_m = 0$. The residual demand facing the competitive fringe in short-term market m now becomes $D_m + E_m - Q_m$. If we define $a_m = b_m(D_m + E_m)$, then the inverse demand facing producers with market power in m still can be written as $P_m(Q_m) = a_m - b_m Q_m$. Trade flows between local markets are captured in the demand intercept a_m. Producers with market power may have an incentive to manipulate output so as to induce or alleviate transmission bottlenecks, in which case E_m would be endogenous. Borenstein et al. (2000) show that such strategic considerations play no role if the capacities of the transmission lines connecting the different local markets are sufficiently small. We leave the issue of endogenous transmission constraints aside.[7]

Equilibrium in the short-term market The second-stage profit of producer l equals

$$(f_m - P_m(Q_m))k_{lm} + (P_m(Q_m) - c_{lm})q_{lm}, \tag{21}$$

where the first term measures the forward profit when the forward market is local, and the second term the profit in the short-term market. The L_m first-order conditions

$$-P'_m(Q_m)k_{lm} + P_m(Q_m) - c_{lm} + P'_m(Q_m)q_{lm} = 0 \tag{22}$$

[7] See Holmberg and Philpott (2018) and references therein for illustrations of the complications caused by analyzing supplier behavior in imperfectly competitive electricity markets with endogenous network constraints.

for profit maximization solve for the equilibrium production $(q_{1m}, ..., q_{lm}, ..., q_{L_m m})$ of the producers with market power. Sum up those first-order conditions to obtain the total production

$$Q_m(K_m) = \frac{L_m}{L_m+1}\frac{a_m - c_m}{b_m} + \frac{K_m}{L_m+1} \tag{23}$$

of the L_m producers with market power in local market m as a function of the total volume K_m of forward contracts sold by these producers, and the average marginal production cost $c_m = \frac{1}{L_m}\sum_{l=1}^{L_m} c_{lm}$. The markup of the short-term price over c_m equals

$$p_m(K_m) - c_m = P_m(Q_m(K_m)) - c_m = \frac{a_m - c_m}{L_m+1} - \frac{b_m K_m}{L_m+1}. \tag{24}$$

We can then back out the production of producer l,

$$q_{lm}(k_{lm}, K_{-lm}) = \frac{1}{L_m+1}\frac{a_m - c_m}{b_m} + \frac{c_m - c_{lm}}{b_m} + \frac{L_m k_{lm}}{L_m+1} - \frac{K_{-lm}}{L_m+1}, \tag{25}$$

and the residual output of all producers other than l in market m:

$$Q_{-lm}(k_{lm}, K_{-lm}) = \frac{L_m-1}{L_m+1}\frac{a_m - c_m}{b_m} - \frac{c_m - c_{lm}}{b_m} - \frac{L_m-1}{L_m+1}k_{lm} + \frac{2K_{-lm}}{L_m+1}. \tag{26}$$

Producer l supplies more electricity to the short-term market when it has sold more forward contracts. The increase in forward contracting creates a strategic effect by which the other producers (if any) reduce their own output. The net effect is a reduction in the short-term price.

Equilibrium in the forward market Industrial consumer h in local market m obtains profit

$$U(D_{mh}) + (p_m(K_m) - f_m)k_{mh} - p_m(K_m)D_{mh},$$

where the first term is the value of consuming the electricity, the second term is the forward profit, or deficit, and the last term is the cost of electricity consumption. Summing up the first-order condition

$$p_m(K_m) - f_m + p'_m(K_m)(k_{mh} - D_{mh}) = 0$$

for industrial consumer h's optimal purchase of forward contracts across all H_m industrial consumers in market m yields the inverse demand $f_m = F_m(K_m)$ for forward contracts in local market m as

$$F_m(K_m) = p_m(K_m) + \frac{b_m}{L_m+1}\frac{D_m - K_m}{H_m} \tag{27}$$

when forward markets are local.

The first term in producer l's first-stage profit expression

$$(F_m(K_m) - p_m(K_m))k_{lm} + (p_m(K_m) - c_{lm})q_{lm}(k_{lm}, K_{-lm}).$$

is the forward profit, and the second term is the profit in the short-term market. The marginal effect on profit of increasing k_{lm} can be written as

$$\underbrace{F_m(K_m) - p_m(K_m) + F_m'(K_m)k_{lm}}_{\text{Marginal forward profit}} \underbrace{-(p_m(K_m) - c_{lm})\frac{\partial Q_{-lm}(k_{lm}, K_{-lm})}{\partial k_{lm}}}_{\text{Strategic effect in short-term market}} \tag{28}$$

after invoking the short-term market first-order condition (22). Compared to the marginal profit condition (9) in the single-producer case, an increase in k_{lm} has a first-order effect on producer l's profit in the short-term market. As demonstrated above, an increase in producer l's forward quantity is a credible commitment to increase output in the short-term market. Under quantity competition, this commitment triggers a strategic response by which the competing producers reduce their own output. The second term in (28) represents the marginal benefit to firm l of the competitors' aggregate output contraction.

By the properties of the price-cost margin $p_m(K_m) - c_m$ established in (24), the quantity $Q_{-lm}(k_{lm}, K_{-lm})$ established in (26) and the inverse demand for forward contracts characterized in (27), we can solve for the average volume of forward contracts sold by the L_m producers with market power in local market $m \in \mathcal{M}$:

$$\frac{K_m^I}{L_m} = \frac{(L_m+1)D_m}{(H_m+1)(L_m^2+1)+2L_m} + \frac{H_m(L_m-1)}{(H_m+1)(L_m^2+1)+2L_m}\frac{a_m - c_m}{b_m}. \tag{29}$$

Using this forward quantity, we can also solve for the average equilibrium markup in short-term market m:

$$p_m^I - c_m = \frac{(H_m+1)(a_m - c_m) - L_m c_m}{(H_m+1)(L_m^2+1)+2L_m}. \tag{30}$$

A strategic incentive makes it individually rational for producers to sell forward contracts above the level they would choose if they were the only generator with market power in the local market because forward contracting commits the producer to aggressive behavior in the short-term market.

3.2 Regional forward market

Assume that the M local markets are linked by a regional forward contract that clears against the quantity-weighted average

$$\bar{P}(\mathbf{Q}) = \sum_{m=1}^{M} \frac{D_m}{D} P_m(Q_m) \tag{31}$$

of the M short-term prices. Each short-term price $P_m(Q_m)$ is weighted by the size of local market m relative to the size of the whole market, measured in terms of the D_m MWh electricity consumed in local market m relative to system total demand $D = \sum_{m=1}^{M} D_m$. The vector $\mathbf{Q} = (Q_1, ..., Q_m, ..., Q_M)$ is the total output by generators with market power in each of the M local markets.

Equilibrium in the short-term market Producers with the ability to exercise unilateral market power take into account how their forward contract position affects their output choice in the short-term market. The second-stage profit of producer l in market m thus becomes

$$(\bar{f} - \bar{P}(\mathbf{Q}))k_{lm} + (P_m(Q_m) - c_{lm})q_{lm},$$

where $\bar{f}$ is the price of the regional forward contract, and we maintain the assumption that firms with market power are active in one local market only. The first-order condition

$$-\frac{D_m}{D} P'_m(Q_m)k_{lm} + P_m(Q_m) - c_{lm} + P'_m(Q_m)q_{lm} = 0$$

for producer l's quantity choice differs from the case of spatially independent markets, see equation (22), by an increase in production now having a relatively smaller positive effect on forward profit because of the $\frac{D_m}{D}$ term. Holding the forward contract quantity constant, the short-term market behavior by generators with market power is less competitive than under local forward markets.

Solving for the L_m linear first-order conditions yields the total output

$$Q_m(\frac{D_m}{D} K_m) = \frac{L_m}{L_m + 1} \frac{a_m - c_m}{L_m + 1} + \frac{1}{L_m + 1} \frac{D_m}{D} K_m \tag{32}$$

of the L_m producers with market power in short-term market m as a function of the total volume K_m of forward contracts sold by those producers, the average markup

$$p_m(\frac{D_m}{D}K_m) - c_m = P_m(Q_m(\frac{D_m}{D}K_m)) - c_m = \frac{a_m - c_m}{L_m + 1} - \frac{b_m}{L_m + 1}\frac{D_m}{D}K_m, \tag{33}$$

the production of generator l,

$$q_{lm}(\frac{D_m}{D}k_{lm}, \frac{D_m}{D}K_{-lm}) = \frac{1}{L_m + 1}\frac{a_m - c_m}{b_m} + \frac{c_m - c_{lm}}{b_m} + \frac{L_m}{L_m + 1}\frac{D_m}{D}k_{lm} - \frac{1}{L_m + 1}\frac{D_m}{D}K_{-lm}, \tag{34}$$

and of all other producers in local market m:

$$Q_{-lm}(\frac{D_m}{D}k_{lm}, \frac{D_m}{D}K_{-lm}) = \frac{L_m - 1}{L_m + 1}\frac{a_m - c_m}{b_m} - \frac{c_m - c_{lm}}{b_m} - \frac{L_m - 1}{L_m + 1}\frac{D_m}{D}k_{lm} + \frac{2}{L_m + 1}\frac{D_m}{D}K_{-lm}. \tag{35}$$

Note that the strategic effect is weaker than in equations (25) and (26) because an increase in k_{lm} now has a smaller effect on output q_{lm}.

Equilibrium in the forward market Industrial consumers have perfect foresight and therefore anticipate the short-term price $p_m(\frac{D_m}{D}K_m)$ in each short-term market m and the clearing price

$$\bar{p}(\mathbf{K}) = \sum_{m=1}^{M} \frac{D_m}{D} p_m(\frac{D_m}{D}K_m)$$

of the regional forward contract, where $\mathbf{K} = (K_1, ..., K_m, ..., K_M)$ is the vector of forward contract quantities in the M local markets. Industrial consumer h in market m has profit

$$U(D_{mh}) + (\bar{p}(\mathbf{K}) - \bar{f})k_{mh} - p_m(\frac{D_m}{D}K_m)D_{mh}.$$

Aggregating the first-order condition

$$\bar{p}(\mathbf{K}) - \bar{f} - \frac{D_m}{D}p'_m(\frac{D_m}{D}K_m)(D_{mh} - \frac{D_m}{D}k_{mh}) = 0$$

for profit maximization across all H_m industrial consumers in market m and across all short term markets, yields the inverse demand function

$$\bar{F}(\mathbf{K}) = \bar{p}(\mathbf{K}) + \frac{1}{H}\sum_{m=1}^{M} \frac{D_m}{D}\frac{b_m}{L_m + 1}(D_m - \frac{D_m}{D}K_m) \tag{36}$$

for the regional forward contract. The regional forward premium is a function of the total number $H = \sum_{m=1}^{M} H_m$ of industrial consumers in the overall market. To focus on supply-side heterogeneity within each local market, we assume that the number of industrial consumers is uniformly distributed across all local markets: $H_m = \frac{H}{M}$ for all $m \in \mathcal{M}$. We allow all other parameters to vary across markets.

In the first stage, each producer l in local market m chooses its forward position k_{lm} to maximize

$$(\bar{F}(\mathbf{K}) - \bar{p}(\mathbf{K}))k_{lm} + (p_m(\frac{D_m}{D}K_m) - c_{lm})q_{lm}(\frac{D_m}{D}k_{lm}, \frac{D_m}{D}K_{-lm}),$$

The marginal effect

$$\bar{F}(\mathbf{K}) - \bar{p}(\mathbf{K}) + \frac{\partial \bar{F}(\mathbf{K})}{\partial K_m}k_{lm} - (p_m(\frac{D_m}{D}K_m) - c_{lm})\frac{\partial Q_{-lm}(\frac{D_m}{D}k_{lm}, \frac{D_m}{D}K_{lm})}{\partial k_{lm}} \tag{37}$$

on profit of increasing forward sales k_{lm} trades off the marginal forward profit against the strategic effect in the short-term market. We then obtain the aggregate results (The proof is in the Appendix):

Proposition 2 *Consider an electricity market with $M \geq 2$ local markets and $L_m \geq 1$ producers with market power in each local market $m \in \mathcal{M}$. Assume that each producer is active only in one local market. Linking the M local markets through a regional forward contract that clears against the quantity-weighted average of the short-term prices in those local markets, yields a quantity-weighted average of the price-cost margins in the M short-term markets equal to*

$$\sum_{m=1}^{M} \frac{D_m}{D}(p_m^R - c_m) = \sum_{m=1}^{M} \frac{\Psi(L_m)\frac{H+1}{L_m}}{1 + \sum_{i=1}^{M} \Psi(L_i)} \frac{D_m}{D} \frac{a_m - c_m}{L_m + 1} - \frac{\sum_{i=1}^{M} \Psi(L_i)}{1 + \sum_{i=1}^{M} \Psi(L_i)} \sum_{m=1}^{M} \frac{D_m}{D} \frac{c_m}{L_m + 1}, \tag{38}$$

and where

$$\Psi(L) = \frac{L(L+1)}{H(L^2+1) + L + 1}. \tag{39}$$

Linking local markets through a regional forward contract increases competition in the short-term markets by reducing the quantity-weighted average of the short-term prices,

$$\sum_{m=1}^{M} \frac{D_m}{D} p_m^R < \sum_{m=1}^{M} \frac{D_m}{D} p_m^I,$$

compared to the benchmark of spatially independent markets, if the local markets are sufficiently concentrated in the sense that

$$L_m \leq \bar{L} = 1 + \frac{1}{2}[\sqrt{(M-H-3)^2 + 8(M-1)} + M - H - 3] \ \forall m \in \mathcal{M}. \tag{40}$$

Creating a regional forward contract may increase or decrease competition in a local short-term market compared to the case of spatially independent markets, depending on the local market conditions compared to those in the other markets. This is why we consider a measure of average market performance, in which the price-cost margin in each local short-term market is weighted by the relative size of that local market.

To assess the incentives to sell forward contracts under a regional forward contract, consider the case in which each producer takes a regional forward position that is equally competitive as under local forward markets, i.e. $k_{lm} = \frac{D}{D_m} k_{lm}^I$ for all L_m producers with market power in all M local markets. In this case, $p_m(\frac{D_m}{D} K_m) = p_m^I$ for all $m \in \mathcal{M}$, and the regional forward price satisfies

$$\bar{F}(\mathbf{K}) - \sum_{m=1}^{M} \frac{D_m}{D} f_m^I = -\frac{M-1}{H} \sum_{m=1}^{M} \frac{D_m}{D} \frac{b_m}{L_m + 1}(D_m - K_m^I) < 0,$$

where $f_m^I = F_m(K_m^I)$ is the equilibrium forward price in local market m under spatially independent markets. Regional forward positions have a weaker effect on competition in the short-term market than forward positions that clear against the local short-term price. This implies a willingness to pay for the regional contract that is smaller than the average willingness to pay for a local forward contract, as reflected by the above price difference. The lower profitability of the regional forward contracts tends to reduce forward contracting compared to the case of spatially independent markets.

If local market m features multiple producers with market power, $L_m \geq 2$, then the strategic effect of forward contracts is also relatively weak under the regional forward contract,

$$-\frac{\partial Q_{-lm}(\frac{D_m}{D} k_{lm}, \frac{D_m}{D} K_{lm})}{\partial k_{lm}} = \frac{D_m}{D} \frac{L_m - 1}{L_m + 1} < \frac{L_m - 1}{L_m + 1} = -\frac{\partial Q_{-lm}(k_{lm}, K_{lm})}{\partial k_{lm}},$$

which also tends to reduce forward contracting.

Those two effects are offset by the reduced price sensitivity of the regional forward contract with respect to increases in the forward position k_{lm},

$$\frac{\partial \bar{F}(\mathbf{K})}{\partial K_m} k_{lm} = -\frac{H+1}{H}\frac{D_m}{D}\frac{b_m}{L_m+1}k^I_{lm} > -\frac{H+M}{H}\frac{D_m}{D}\frac{b_m}{L_m+1}k^I_{lm} = \frac{D_m}{D}\frac{\partial F_m(K_m)}{\partial K_m}k^I_{lm},$$

which tends to increase forward contracting.

The third effect dominates, and the regional forward contract reduces short-term prices, precisely in the circumstances under which competition is weak, i.e. when the short-term market consists of a few producers with market power. Condition (40) is satisfied if each local market features one single generator with market power. If we consider instead the demand side and assume that there is one large industrial consumer in each local market, $H_m = 1$ for all $m \in \mathcal{M}$, then $\bar{L} = 2$ for $M = 3$, $\bar{L} = 3$ for $M = 6$, and $\bar{L} = 4$ for $M = 10$. Few local short-term markets have more than 4 producers with market power. Condition (40) is more restrictive if H is larger, but this is only a sufficient condition for regional forward contracting to reduce prices. For instance, Proposition 2 holds for arbitrary L_m if the average marginal cost c_m of producers with market power is sufficiently small relative to the demand intercept a_m.[8] It also holds if local markets are sufficiently similar, as we shall see in the next Section.

4 Producers active in multiple local markets

In this section, we allow producers with market power to own generation assets in more than one local market. This change in ownership structure implies that producers internalize more of the negative price effects of selling forward contracts. We show that a regional forward contract reduces prices if and only if asset ownership is sufficiently concentrated.

To maintain tractability, we reimpose perfect symmetry on the model, similar to Section 2. Let there be S large producers in the overall market, each of which owns generation capacity and exercises market power in $\bar{M}$ of the M local markets. These producers are symmetrically located, so that the number $L = S\frac{\bar{M}}{M}$ of producers with market power is the same in each local market. Multi-market presence does not matter when the local markets are spatially independent because each local market then is functionally independent from all the other local markets. Imposing symmetry on (30) yields:

$$p^I - c = \frac{(H+M)(a-c) - MLc}{(H+M)(L^2+1) + 2ML}.$$

[8] The demand intercept $a_m = b_m D_m$ in market m is the competitive fringe's marginal cost of supplying demand if firms with market power produce zero output, i.e. $Q_m = 0$.

The ownership structure of generation assets does not affect competition in the short-term market under regional forward contracting, because these markets clear independently of one another. Hence, the total production in short-term market m is given by

$$Q(\frac{K_m}{M}) = \frac{L}{L+1}\frac{a-c}{b} + \frac{1}{L+1}\frac{K_m}{M}$$

as a function of the total volume K_m of forward contracts sold by producers with market power in that market. The price-cost margin equals

$$p(\frac{K_m}{M}) - c = P(Q(\frac{K_m}{M})) - c = \frac{a-c}{L+1} - \frac{b}{L+1}\frac{K_m}{M},$$

in short-term market m, the production of a generator $s \in \{1, ..., S\}$ with production assets in local market m is

$$q_s(\frac{k_{sm}}{M}, \frac{K_{-sm}}{M}) = \frac{1}{L+1}\frac{a-c}{b} + \frac{L}{L+1}\frac{k_{sm}}{M} - \frac{1}{L+1}\frac{K_{-sm}}{M},$$

and of all other producers in local market m:

$$Q_{-s}(\frac{k_{sm}}{M}, \frac{K_{-sm}}{M}) = \frac{L-1}{L+1}\frac{a-c}{b} - \frac{L-1}{L+1}\frac{k_{sm}}{M} + \frac{2}{L+1}\frac{K_{-sm}}{M}.$$

The demand for the regional forward contract is also unaffected by the generation ownership structure, and equals

$$\bar{F}(\mathbf{K}) = \frac{1}{M}\sum_{m=1}^{M} p(\frac{K_m}{M}) + \frac{b}{M(L+1)H}(D - \frac{K}{M})$$

after simplification of (36), where $K = \sum_{m=1}^{M} K_m$ is the volume of regional forward contracts.

Producer s chooses its retail portfolio $(k_{s1}, ..., k_{sm}, ..., k_{sM})$ to maximize profit

$$(\bar{F}(\mathbf{K}) - \frac{1}{M}\sum_{m=1}^{M} p(\frac{K_m}{M}))k_s + \sum_{m=1}^{M} \beta_{sm}(p(\frac{K_m}{M}) - c)q_s(\frac{k_{sm}}{M}, \frac{K_{-sm}}{M}),$$

where β_{sm} is an indicator function taking the value 1 if producer s owns generation capacity in local market m and 0 if not. The variable $k_s = \sum_{m=1}^{M} k_{sm}$ denotes the position of firm s in the regional forward market. The producer only takes a forward position in those markets where it owns generation capacity.

The marginal effect on profit of increasing k_{sm} is

$$\bar{F}(\mathbf{K}) - \frac{1}{M}\sum_{m=1}^{M} p(\frac{K_m}{M}) + \frac{\partial \bar{F}(\mathbf{K})}{\partial K_m} k_s - (p(\frac{K_m}{M}) - c)\frac{\partial Q_{-s}(\frac{k_{sm}}{M}, \frac{K_{-sm}}{M})}{\partial k_{sm}}.$$

Compared to the case in which producers are active in only one market, each producer s with market power now takes into account the spill-over effects of the forward price reduction in the other markets in which it is present, as measured by the total forward position k_s. Set the marginal profit to zero, use the functional form expressions and apply symmetry to solve for the equilibrium price-cost margin

$$p^R - c = \frac{\bar{M}(H+1)(a-c) - MLc}{H(L^2+1) + (ML + 1 + (\bar{M}-1)(H+1))(L+1)}$$

under the regional forward contract. Producers internalize relatively more of the negative forward price effect when they own generation capacity in more local markets, which weakens the incentive to sell forward contracts. Hence, the effect on short-term prices of linking electricity markets through a regional forward contract is ambiguous:

Proposition 3 *Consider an electricity market with $M \geq 2$ symmetric local markets. Assume that each of the S producers with market power is active in $\bar{M}$ local markets. Linking the M local electricity markets through a regional forward contract that clears against the quantity-weighted average of the short-term prices in those markets reduces short-term prices compared to the benchmark of spatially independent markets if and only if the geographical concentration of generation ownership is sufficiently high [$p^R < p^I$ if and only if $\bar{M} < \frac{H+M}{H+1}$].*

Proof. Algebraic simplification of p^R and p^I yield

$$p^I - p^R = \frac{[(H(L-1) + M(L+1))(a-c) + M(L+1)c][H + M - (H+1)\bar{M}]L}{[(H+M)(L^2+1) + 2ML][H(L^2+1) + (ML + 1 + (\bar{M}-1)(H+1))(L+1)]}.$$

The denominator and the first term in square brackets in the numerator are both positive. Hence, the sign of $p^I - p^R$ is identical to the sign of $H + M - (H+1)\bar{M}$. ■

Producers that own generation capacity and exercise market power in multiple local markets account for a larger share of the spill-over effects of changes in the regional forward price on the other local markets. This increased internalization softens the incentive to participate in the forward market, potentially to such an extent that the regional forward contract is anti-competitive. However, this effect is unlikely to be substantial. If, for instance, all producers are active in all local markets, $\bar{M} = M$, then there are as many producers in each local market as there are producers in the overall market, $L = S$. Competition would then be quite intense in the short-term market even if producers did not sell any forward contracts at all.

Quantitative effects of forward contracting The price effects of forward contracting depend on local demand and cost conditions, market structure in the forward and short-term market and the number of local markets. Calculating the competitive effects are complicated even in the symmetric case, $a_m = a$, $b_m = b$, $c_m = c$ and $L_m = L$ for all m, by the fact that we still need demand and cost estimates to calculate the equilibrium short-term prices p^I and p^R. However, because of the linear structure of the model, we can derive lower and upper boundaries to the competitive effects that do not depend on these characteristics. Under symmetry,

$$I = 100 \times [1 - \frac{p^R - c}{p^I - c}]$$

measures the percentage reduction in the price cost margin in the short term market associated with linking local markets through a regional forward contract compared to the benchmark of spatially independent markets. On the basis of the above expressions for p^I and p^R, it is straightforward to verify the lower boundary

$$I \geq \underline{I}(h, L, M) = 100 \times \frac{M-1}{h+1} \frac{(L+1+h(L-1))L}{Mh(L^2+1)+(ML+1)(L+1)}$$

on the competitive effect if all producers with market power are active in one local market ($\bar{M} = 1$) and price cost margin are non-negative ($p^R \geq c$). This boundary is a function of the number of industrial consumers and L of producers with market power in each local market and the number M of local markets linked through the regional forward contract, but not on the demand and cost conditions (a, b, c). If we hold (L, M) constant and require non-negative price-cost margins for all $h \geq 1$, then we obtain the upper boundary

$$I \leq \bar{I}(h, L, M) = 100 \times \frac{M-1}{Mh-1} \frac{(M(L+1)+1)(L+1)+h(L-1)ML}{Mh(L^2+1)+(ML+1)(L+1)}.$$

on the competitive effect.

The solid line in Figure 1 plots the lower boundary $\underline{I}(h, 1, 5)$ of the competitive effect in the symmetric model with five local markets ($M = 5$), one producer with market power in each local market ($L = 1$), and under the assumption that all producers are active in one local market ($\bar{M} = 1$). The dashed line plots the corresponding upper boundary $\bar{I}(h, 1, 5)$ of the competitive effect. The x-axis in Figure 1 measures the competitiveness of the forward market in terms of the number h of strategic consumers in each local market.

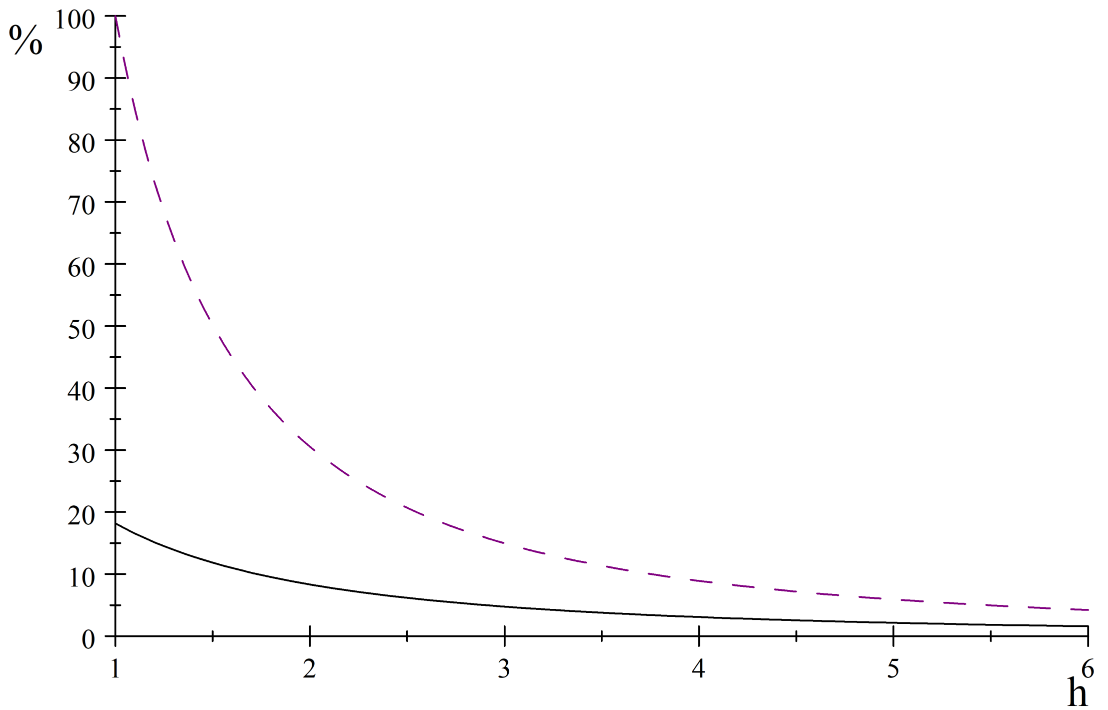

Figure 1: The competitive effects of linking symmetric markets across space $(L, M = 1, 5)$

The forward premiums are smaller if h is larger. In the polar case of $h = 1$, linking the five local electricity markets through a regional forward contract causes price-cost margins to drop by at least 18% in the short-term market compared to the benchmark of spatially independent markets. If forward markets premiums are smaller, for instance for $h = 3$, price-cost margins drop between 5% and 15% in the symmetric model depending on the cost and demand conditions. The competitive effects of regional forward contracting are negligible if h is large and forward premiums therefore very small.

5 Combined local and regional forward markets

We have previously conducted policy experiments in which forward markets are either local or regional. We examine in this section the effects of *combining* a regional forward market with local forward markets. Specifically, we allow producers with market power both to sell forward contracts that clear against the short-term price in the local market where they own production capacity and forward contracts that clear against the quantity-weighted average of all short-term market prices. We find that producers generally will participate either in the local or the regional forward market, but not both. Allowing regional forward contracting on top of local forward contracting unambiguously reduces short-term equilibrium prices.

Equilibrium in the short-term market The second-stage profit of producer l active in market m is

$$(f_m - P_m(Q_m))\hat{k}^I_{lm} + (\bar{f} - \bar{P}(\mathbf{Q}))\hat{k}^R_{lm} + (P_m(Q_m) - c_{lm})q_{lm},$$

where $\hat{k}^I_{lm}$ is its volume of local forward contracts (i.e. that clear against p_m), and $\hat{k}^R_{lm}$ is its volume of regional forward contracts. The first-order condition

$$-P'_m(Q_m)(\hat{k}^I_{lm} + \frac{D_m}{D}\hat{k}^R_{lm}) + P_m(Q_m) - c_{lm} + P'_m(Q_m)q_{lm} = 0$$

identifies producer l's optimal production as a function of total output Q_m and its *composite forward position* $k_{lm} = \hat{k}^I_{lm} + \frac{D_m}{D}\hat{k}^R_{lm}$.

Let $\hat{K}^I_m = \sum_{l=1}^{L_m} \hat{k}^I_{lm}$ and $\hat{K}^R_m = \sum_{l=1}^{L_m} \hat{k}^R_{lm}$ be the quantities of local and regional forward contracts supplied by producers in local market m. The residual supply of the two types of forward contracts is $\hat{K}^I_{-lm} = \hat{K}^I_m - \hat{k}^I_{lm}$ respective $\hat{K}^R_{-lm} = \hat{K}^R_m - \hat{k}^R_{lm}$. Let $K_m = \hat{K}^I_m + \frac{D_m}{D}\hat{K}^R_m$ be the composite forward position and $K_{-lm} = \hat{K}^I_{-lm} + \frac{D_m}{D}\hat{K}^R_{-lm}$ the residual composite forward position in market m. By way of these definitions, the total output $Q_m(K_m)$ in short-term market m is given by (23), the average price-cost margin $p_m(K_m) - c_m$ by (24), producer l's output by (25) and the residual output of all producers other than l by (26).

Forward market equilibrium Industrial consumer h located in local market m has profit

$$U(D_{mh}) + (p_m(K_m) - f_m)\hat{k}^I_{mh} + (\sum_{i=1}^{M} \frac{D_i}{D}p_i(K_i) - \bar{f})\hat{k}^R_{mh} - p_m(K_m)D_{mh}$$

if it purchases a volume of $\hat{k}^I_{mh}$ MWh forward contracts that clear against the short-term price p_m and a volume of $\hat{k}^R_{mh}$ MWh regional forward contracts, and the supply of local (regional) forward contracts is $\hat{K}^I_i$ ($\hat{K}^R_i$) in all $i \in \mathcal{M}$ local markets. Using the two first-order conditions

$$p_m(K_m) - f_m + p'_m(K_m)(\hat{k}^I_{mh} + \frac{D_m}{D}\hat{k}^R_{mh} - D_{mh}) = 0$$

and

$$\sum_{i=1}^{M}\frac{D_i}{D}p_i(K_i)-\bar{f}+\frac{D_m}{D}p'_m(K_m)(\hat{k}^I_{mh}+\frac{D_m}{D}\hat{k}^R_{mh}-D_{mh})=0$$

for the industrial consumers' profit maximization problems, we obtain the inverse demand

$$F_m(K_m)=p_m(K_m)+\frac{b_m}{L_m+1}\frac{D_m-K_m}{H_m} \tag{41}$$

for the local forward contract and the inverse demand

$$\bar{F}(\mathbf{K})=\sum_{m=1}^{M}\frac{D_m}{D}p_m(K_m)+\frac{1}{H}\sum_{m=1}^{M}\frac{D_m}{D}\frac{b_m}{L_m+1}(D_m-K_m) \tag{42}$$

for the regional forward contract. These demand functions depend only on producers' composite forward positions. The smaller effect of a regional forward position on competition in the short-term market drives the regional forward premium down below those in the local forward markets. Specifically, the regional forward premium is proportional to the quantity-weighted average of the local forward premiums:

$$\bar{F}(\mathbf{K})-\sum_{m=1}^{M}\frac{D_m}{D}p_m(K_m)=\frac{1}{M}\sum_{m=1}^{M}\frac{D_m}{D}(F_m(K_m)-p_m(K_m)). \tag{43}$$

The first stage profit of producer l equals

$$(F_m(K_m)-p_m(K_m))\hat{k}^I_{lm}+(\bar{F}(\mathbf{K})-\sum_{i=1}^{M}\frac{D_i}{D}p_i(K_i))\hat{k}^R_{lm}+(p_m(K_m)-c_{lm})q_{lm}(k_{lm},K_{-lm}),$$

where the first term is the profit of selling forward contracts that clear against p_m for $\hat{k}^I_{lm}$ MWh electricity, the second term is the profit from selling contracts for $\hat{k}^R_{lm}$ MWh electricity in the regional forward market, and the final term is the profit in the short-term market.

Consider producer l's profit-maximizing choice $\hat{k}^R_{lm}$ versus $\hat{k}^I_{lm}$ subject to holding the composite forward position constant at $k_{lm}=\hat{k}^I_{lm}+\frac{D_m}{D}\hat{k}^R_{lm}$. Rewrite the profit expression as:

$$\begin{aligned}&(F_m(K_m)-p_m(K_m))k_{lm}+(p_m(K_m)-c_{lm})q_{lm}(k_{lm},K_{-lm})\\&+\left[\bar{F}(\mathbf{K})-\sum_{i=1}^{M}\frac{D_i}{D}p_i(K_i)-\frac{D_m}{D}(F_m(K_m)-p_m(K_m))\right]\hat{k}^R_{lm}.\end{aligned} \tag{44}$$

All terms on the first row and all terms inside the square brackets on the second row of

(44) depend on l's forward contracting only through the composite forward position k_{lm}. For constant k_{lm}, firm l's profit function therefore is linear in $\hat{k}_{lm}^R$. By way of (43), the expression inside the square brackets of (44) is strictly positive for some local markets and strictly negative for other local markets unless all $\frac{D_i}{D}(F_i(K_i) - p_i(K_i))$ are identical. Such symmetry will not generally hold in equilibrium. Producers in some local markets therefore would seem to be able to make huge arbitrage profits from taking positive and very large regional forward positions $\hat{k}_{lm}^R$ and negative and very small local forward positions $\hat{k}_{lm}^I$, whereas arbitrage profits would arise from taking the opposite positions in other local markets. However, such arbitrage profits would translate into equally huge and unsustainable arbitrage losses for industrial consumers. One way of closing the model would be to impose break-even constraints on industrial consumers. We take a simpler approach by assuming that industrial consumers do not sell local or regional forward contracts, and that any given supply of forward contracts first is allocated to industrial consumers. By implication, the gains from forward contracting are shared between producers and industrial consumers. More importantly, producers cannot take negative forward positions, i.e. each producer l maximizes its profit subject to $\hat{k}_{lm}^I \geq 0$ and $\hat{k}_{lm}^R \geq 0$. Under these assumptions,

$$\hat{K}_m^I = 0 \text{ if } \frac{D_m}{D}(F_m(K_m) - p_m(K_m)) \leq \bar{F}(\mathbf{K}) - \sum_{i=1}^{M} p_i(K_i) \tag{45}$$

and

$$\hat{K}_m^R = 0 \text{ if } \frac{D_m}{D}(F_m(K_m) - p_m(K_m)) \geq \bar{F}(\mathbf{K}) - \sum_{i=1}^{M} p_i(K_i) \tag{46}$$

are optimal. To characterize the equilibria and say something about which markets will feature local versus regional forward contracting, we restrict attention to the case with two local markets ($M = 2$) and one producer with market power in each local market ($L_1 = L_2 = 1$). We prove the following result in the Appendix:

Proposition 4 *Consider an electricity market with two local markets and one producer with market power in each local market. Each producer can supply local forward contracts that clear against the short-term price in its own local market and regional forward contracts that clear against the quantity-weighted average of the short-term prices in the two local markets. Assume that producers cannot take negative forward positions. Then, there exists an equilibrium in which the producer in local market i exclusively supplies local forward contracts and the producer in local market $m \neq i$ exclusively supplies regional forward contracts if and* *only if*

$$\frac{a_i D_i}{a_m D_m} \geq 2\sqrt{\frac{H+4}{H+2}} - \frac{H+4}{H+2}. \tag{47}$$

In the combined forward market, the equilibrium price-cost margin equals

$$p_i^C - c_i = \frac{b_i}{2}[\frac{a_i - c_i}{b_i} - \frac{2D_i}{H+4}] = p_i^I - c_i \tag{48}$$

in short-term market i and

$$p_m^C - c_m = \frac{b_m}{2}[\frac{a_m - c_m}{b_m} - \frac{D_m}{H+2} - \frac{1}{H+4}\frac{a_i D_i}{a_m}] < p_m^I - c_m \tag{49}$$

in short-term market m.

The volume-weighted local forward premium in the larger market i tends to be larger than the regional forward premium, where relative market size is measured by $\frac{a_i D_i}{a_m D_m}$. Therefore, the producer in this local market tends to be better off by selling local forward contracts than participating in the regional forward market. The opposite is true in the smaller market m.[9] Introducing a regional forward contract to an existing market for local forward contracts has no effect on the larger market. However, the producer with market power in the smaller market will start trading in the regional forward market instead. This leads to a substantial increase in the volume of forward contracts sold in that market and a corresponding reduction in the short-term price. Hence, short-term prices are unaffected in some local markets and fall in other local markets as a consequence of allowing producers to trade also in regional forward contracts. The effect on the volume-weighted average short-term price is negative.

6 Linking forward markets across time

Consider now the case of linking forward markets across time through a long-term forward contract. Assume that there is a single local market, M production periods and L producers with market power. We allow demand D_m to fluctuate across time, but assume it to be deterministic. Denote by k_{lm} the forward position of producer l in period m and by K_m the total forward position in period m of all L producers with market power.

The output q_{lm} of producer l that maximizes its period m profit is independent of the forward price f_m that period, so the quantities and prices in the short-term market in period

[9] By condition (47), this type of forward market specialization is sustainable also for $a_i D_i < a_m D_m$ if the two markets are similar in size. The game thus has multiple equilibria in this case.

m are given by (24)-(26) as a function of the total amount K_m of forward contracts in that period, and where the number of producers with market power and the number of industrial consumers is the same in all periods: $L_m = L$ and $H_m = H$ for all $m \in \{1, ..., M\}$. A set of M short-term forward contracts is formally equivalent to a set of M spatially independent forward contracts. By way of (29) and (30), we get the producers' average forward position

$$\frac{K_m^I}{L} = \frac{L+1}{(H+1)(L^2+1)+2L}\frac{a_m}{b_m} + \frac{H(L-1)}{(H+1)(L^2+1)+2L}\frac{a_m - c_m}{b_m}. \tag{50}$$

in short-term market m and the price-cost margin:

$$p_m^I - c_m = \frac{(H+1)(a_m - c_m) - Lc_m}{(H+1)(L^2+1)+2L}. \tag{51}$$

6.1 Long-term forward contracts

Let firms supply long-term forward contracts in period 1 that are valid for M periods. Long-term contracts typically clear against the quantity-weighted average of the forward contract quantities. Consistent with actual forward contracting, we assume that a producer's forward obligations are constant throughout the duration of the forward contract, i.e. $k_{lm} = k_l$ and $K_m = K = \sum_{l=1}^{L} k_l$ for all L producers and M periods. Then $K_{-l} = K - k_l$ is the residual supply of long-term forward contracts by all producers with market power other than l.

The profit of industrial consumer h equals

$$\sum_{m=1}^{M} U_{mh}(D_{mh}) + (\frac{1}{M}\sum_{m=1}^{M} p_m(K) - \bar{f})Mk_h - \sum_{m=1}^{M} p_m(K)D_{mh}.$$

if it purchases long-term forward contracts for k_h MWh electricity and the total supply of long-term contracts is K, under the assumption of no discounting of profits. Different from the case of spatial contracting, it is as if the industrial consumer is present in all local markets. The term in the middle is the forward profit, or loss, of the industrial consumer because the forward contract clears against the average short-term price. We sum up the H first-order conditions

$$(\frac{1}{M}\sum_{m=1}^{M} p_m(K) - \bar{f})M + \sum_{m=1}^{M} p'_m(K)(k_h - D_{mh}) = 0$$

to obtain the inverse demand

$$\bar{F}(K) = \frac{1}{M}\sum_{m=1}^{M} p_m(K) + \frac{1}{M}\sum_{m=1}^{M} \frac{b_m}{L+1}\frac{D_m - K}{H} \tag{52}$$

for long-term forward contracts.

The first stage profit of producer l equals

$$(\bar{F}(K) - \frac{1}{M}\sum_{m=1}^{M} p_m(K))Mk_l + \sum_{m=1}^{M}(p_m(K_m) - c_{lm})q_{lm}(k_l, K_{-l}).$$

The first term in this expression is the forward profit, and the second term equals the total profit in the short-term markets summed up over all M production periods. The producer's multi-period presence implies that producers will internalize more of the price effects of any change in its forward position k_l. The marginal effect

$$[\bar{F}(K) - \frac{1}{M}\sum_{m=1}^{M} p_m(K)]M + \bar{F}'(K)Mk_l - \sum_{m=1}^{M}(p_m(K_m) - c_{lm})\frac{\partial Q_{-lm}(k_l, K_{-l})}{\partial k_l}.$$

on profit of increasing k_l is the sum of the marginal forward profit and the marginal value of the contraction of competitors' output in all subsequent periods. Set this expression to zero, sum up over all L producers with market power, and define the average demand intercept $a = \frac{1}{M}\sum_{m=1}^{M} a_m$, slope coefficient $b = \frac{1}{M}\sum_{m=1}^{M} b_m$ and marginal production cost $c = \frac{1}{M}\sum_{m=1}^{M} c_m$ to get the average long-term forward position

$$\frac{K^M}{L} = \frac{L+1}{(H+1)(L^2+1)+2L}\frac{a}{b} + \frac{H(L-1)}{(H+1)(L^2+1)+2L}\frac{a-c}{b}. \tag{53}$$

of the L producers with market power. The difference between long-term and short-term forward contracting is that the equilibrium K^M under the first type of contracting depends on the average market conditions (a, b, c), whereas the short-term contract position K_m^I depends on the realized market conditions (a_m, b_m, c_m) that period. On the basis of these equilibrium properties, it is straightforward to derive the following result:

Proposition 5 *Consider an electricity market with one local market, L producers with market power and M production periods. If producers with market power sell long-term forward contracts spanning the M periods, then the average price-cost margin is the same as when* *they sell a sequence of short-term forward contracts over the same time period:*

$$\frac{1}{M}\sum_{m=1}^{M}(p_m^M - c_m) = \frac{(H+1)(a-c) - Lc}{(H+1)(L^2+1)+2L} = \frac{1}{M}\sum_{m=1}^{M}(p_m^I - c_m). \tag{54}$$

The price-cost margin in any given period can be higher or lower under short-term than long-term forward contracting depending on the demand and cost conditions of that specific period relative to the average demand and cost characteristics. Proposition 5 demonstrates that long-term contracts have no effect on average market performance because differences cancel out on average. The fact that both producers and industrial consumers internalize the effects of their decisions in the forward market in all local markets (periods) implies that all competitive effects of long-term relative to short-term forward contracting are neutralized.

6.2 Unplanned outages

Producers are not always able to supply their full generation capacity to the short-term market in every period, for instance because of unplanned outages or scheduled maintenance work on generation units. We consider now the effect of outages on the benefits of short-term relative to long-term forward contracting.

Specifically, one producer with market power must shut down its generation capacity in every period for unscheduled maintenance reasons. The probability of outages is uniformly distributed across producers in every period, and outages are i.i.d. across periods. Let there be $L+1$ producers with market power. This means that an arbitrary producer is on-grid with probability $\frac{L}{L+1}$ and off-grid with probability $\frac{1}{L+1}$ in every period m. We assume that all uncertainty about outages is resolved prior to the opening of the short-term forward market. Instead, long-term forward contracting is done before the resolution of uncertainty. By implication, market participants are relatively better informed about market conditions under short-term forward contracting.

Producer l supplies $q_{lm}(k_{lm}, K_{-lm})$ to the short-term market if on-grid in period m, the other $L-1$ producers that are on-grid produce $Q_{-lm}(k_{lm}, K_{-lm})$, and the short-term price is $p_m(K_m)$ if producer l has sold k_{lm} short-term forward contracts, and all other producers that are also on-grid have sold K_{-lm} short-term forward contracts. By way of (50), the average forward volume sold by the L producers that are on-grid in period m equals

$$\frac{K_m^I(-i)}{L} = \frac{(L+1)}{(H+1)(L^2+1)+2L}\frac{a_m}{b_m} + \frac{H(L-1)}{(H+1)(L^2+1)+2L}\frac{a_m - \frac{1}{L}\sum_{l\neq i} c_{lm}}{b_m}, \tag{55}$$

if producer i is off-grid in period m. Outages are uniformly distributed and i.i.d, so we can compute the expected (before the start of period 1) price-cost margins under short-term forward contracting:

$$\frac{1}{M}\sum_{m=1}^{M}(E[p_m^I]-c_m)=\frac{(H+1)(a-c)-Lc}{(H+1)(L^2+1)+2L}, \tag{56}$$

under short-term forward contracting.

Under long-term forward contracting, each producer l supplies the same volume k_l of forward contracts in every period. Let $\mathbf{k}=(k_1,...,k_l,...,k_{L+1})$ be the positions in the long-term forward market taken by the $L+1$ producers with market power. Then, $K=\sum_{l=1}^{L+1}k_l$ is the total volume of long-term contracts sold by those producers, and $K_{-l}=K-k_l$ is the volume of forward contracts sold by producers other than l. The short-term actions depend only on the characteristics of the producers active in the short-term market that period. If producer i is off-grid in period m, then every producer $l\neq i$ supplies $q_{lmi}(k_l,K_{-l}-k_i)$ to the short-term market, the other $L-1$ producers supply $Q_{-lmi}(k_l,K_{-l}-k_i)$, and the short-term price is $p_{mi}(K-k_i)$. In particular quantities and prices depend on the average marginal production cost $\frac{1}{L}\sum_{l\neq i}c_{lm}$ of the on-grid producers. The expected short-term price in period m equals

$$E[p_m(\mathbf{k})]=\frac{1}{L+1}\sum_{i=1}^{L+1}p_{mi}(K-k_i).$$

The expected profit of industrial consumer h equals

$$\sum_{m=1}^{M}U_h(D_{mh})+\sum_{m=1}^{M}(E[p_m(\mathbf{k})]-\bar{f})k_h-\sum_{m=1}^{M}E[p_m(\mathbf{k})]D_{mh},$$

which implies the inverse demand

$$\bar{F}(\mathbf{k})=\frac{1}{M}\sum_{m=1}^{M}E[p_m(\mathbf{k})]+\frac{L}{L+1}\frac{1}{M}\sum_{m=1}^{M}\frac{b_m}{L+1}\frac{D_m-K}{H},$$

for the long-term forward contract. The forward market premium is adjusted by $\frac{L}{L+1}$ because each producer is off-grid with probability $\frac{1}{L+1}$ in every period, in which case it is incapable of affecting prices in the short-term market.

The first-stage expected profit of producer l equals

$$\sum_{m=1}^{M}(\bar{F}(\mathbf{k})-E[p_m(\mathbf{k})])k_l+\frac{1}{L+1}\sum_{m=1}^{M}\sum_{i\neq l}(p_{mi}(K-k_i)-c_{lm})q_{lmi}(k_l,K_{-l}-k_i).$$

Solving the $L+1$ first-order conditions for long-term forward contracting yields the average equilibrium long-term forward position

$$\frac{K^O}{L+1}=\frac{L+1}{(H+1)(L^2+1)+3L+1}\frac{a}{b}+\frac{H(L-1)}{(H+1)(L^2+1)+3L+1}\frac{a-c}{b}.$$

Superscript ^{O} here refers to (unplanned) outages. On the basis of this equilibrium forward contract volume, we can derive the expected equilibrium price cost margin

$$\frac{1}{M}\sum_{m=1}^{M}(E[p_m^O]-c_m)=\frac{a-c-\frac{L}{L+1}bK^O}{L+1}=\frac{(H+2)(a-c)-Lc}{(H+1)(L^2+1)+3L+1}$$

under long-term forward contracts. Straightforward comparison of this expression with the expected average price-cost margin (56) under short-term forward contracting yields:

Proposition 6 *Consider an electricity market with one local market, $L+1$ producers with market power and M production periods. Assume that one producer with market power takes its generation capacity off-grid every period because of unplanned outages, and that the outage probability is uniformly distributed across producers and i.i.d. across periods. A long-term forward contract spanning the M periods then yields a higher average short-term price than a sequence of M short-term forward contracts:*

$$\frac{1}{M}\sum_{m=1}^{M}E[p_m^O-p_m^I]=\frac{L[((H+1)(L-1)+2)(a-c)+(L+1)c]}{[(H+1)(L^2+1)+3L+1][(H+1)(L^2+1)+2L]}>0.$$

Short-term forward contracting enables industrial consumers to purchase forward contracts precisely from those producers with market power that are on-grid the subsequent period. Conversely, some of the competitive benefits of forward contracts are with positive probability lost on off-grid producers under long-term forward contracting. This inefficiency of long-term forward contracts reduces the forward premium all else equal and causes producers to sell relatively few long-term forward contracts compared to what they would sell under short-term forward contracting. Therefore, prices are higher under long-term than short-term forward contracting when there are unplanned outages.

6.3 Planned outages

Assume now that generation capacity is taken off-grid according to a planned maintenance schedule. To minimize the number of simultaneous outages, the system operator takes one producer off-grid every period. Scheduling is done prior to market transactions, so it is common knowledge in period 1 which generators will be on-grid in all periods. To keep things as simple as possible, we assume that there are $M = L$ symmetric production periods.

The difference between unplanned and planned outages is that forward contracting is done under uncertainty in the first case. However, in the linear-quadratic framework applied here, there is no formal difference between the two. Under symmetry, therefore, the equilibrium price-cost margin under planned outages is the same as the average price-cost margin under unplanned outages, both under short-term and long-term forward contracting. Hence,

Proposition 7 *Consider an electricity market with one local market, $L+1$ symmetric producers with market power and $M = L$ symmetric production periods. Assume that outages are planned in such a way that one producer with market power is taken off-grid every period. In this case, the difference in equilibrium short-term prices under long-term relative to short-term forward contracting is exactly the same as under unplanned outages.*

The results in this section demonstrate that short-term contracts are at least weakly more competitive than long-term contracts. While there is good reason to link forward contracts across space to increase competition, there is a corresponding good reason *not* to link forward contracts across time. Our results also predict short-term forward contracts to be more liquid than long-term contracts for electricity.

7 Concluding policy discussion

A key problem with market performance in restructured electricity markets is the high degree of market concentration that sometimes arises when transmission constraints divide a region into smaller local markets with one or a few large producers in each. Increased market concentration strengthens suppliers' incentives to exercise market power in the wholesale market. Improving competition through entry or market integration is problematic in many electricity markets because of economic or political barriers to large supplier entry or network investment to expand the size of the geographic market.

We show that market design can substantially affect market power without involving supplier entry or network investment. Specifically, a single forward market in which contracts clear against the quantity-weighted average of a set of locational marginal prices (LMP) is pro-competitive compared to multiple local forward markets in which forward contracts clear against the individual location-specific short-term prices.

Our findings are highly relevant for the debate about future designs of wholesale electricity markets. Local imbalances in the supply and demand of electricity owing to increasing shares of intermittent electricity production have increased concerns about the security of electricity supply in situations with substantial shortfalls of renewable electricity production. Such security of supply problems would be reduced if prices reflected local supply and demand conditions and all relevant constraints on operating generation units and the transmission network were explicitly priced as in a system with locational marginal prices, as first discussed in Bohn et al. (1984).

As noted in the introduction, charging consumers locational electricity prices has so far been politically difficult, for instance in Europe. Critics argue that it is unreasonable for some consumers to pay more for electricity than others just because they live at a location with an "under-supply" of electricity. Such fairness arguments received a lot of public attention following the division of the Swedish day-ahead market into four price areas in 2011. Previously, Sweden had constituted a single price area.

Based on our results, consumers in all local markets could benefit from short-term pricing at a fine level of granularity despite any resulting local price differences. Enabling forward contracting at a regional level can improve competition to such an extent that consumers in all local markets experience lower prices of electricity as a result.

Appendix

A.1 Proof of Proposition 2

Characterization Substitute

$$-\frac{\partial Q_{-lm}(\frac{D_m}{D}k_{lm}, \frac{D_m}{D}K_{lm})}{\partial k_{lm}} = \frac{L_m - 1}{L_m + 1}\frac{D_m}{D}$$

into marginal profit (37), set the expression equal to zero and sum up over all L_m producers to obtain the aggregate first-order condition

$$L_m(\bar{F}(\mathbf{K}^R) - \bar{p}(\mathbf{K}^R)) + \frac{\partial \bar{F}(\mathbf{K}^R)}{\partial K_m}K_m^R + \frac{L_m^2 - L_m}{L_m + 1}\frac{D_m}{D}(p^R - c_m) = 0$$

in local market m. By way of (24) and (36),

$$\bar{F}(\mathbf{K}^R) - \bar{p}(\mathbf{K}^R) = \frac{1}{H}\sum_{m=1}^{M}\frac{D_m}{D}(p_m^R - c_m + \frac{c_m}{L_m+1})$$

and
$$\frac{\partial \bar{F}(\mathbf{K})}{\partial K_m} = \frac{\partial \bar{p}(\mathbf{K})}{\partial K_m} - \frac{1}{H}(\frac{D_m}{D})^2\frac{b_m}{L_m+1} = -\frac{H+1}{H}(\frac{D_m}{D})^2\frac{b_m}{L_m+1}$$

Substitute these expressions into the aggregate first-order condition above, and simplify expressions to get the modified optimality condition

$$L_m\sum_{i=1}^{M}\frac{D_i}{D}(p_i^R - c_i) + \frac{L_m}{\Psi(L_m)}\frac{D_m}{D}(p^R - c_m) = (H+1)\frac{D_m}{D}\frac{a_m - c_m}{L_m+1} - L_m\sum_{i=1}^{M}\frac{D_i}{D}\frac{c_i}{L_i+1},$$

where $\Psi(L)$ was defined in (39). Multiply the modified optimality condition through by $\frac{\Psi(L_m)}{L_m}$, sum up across all M local markets and rewrite to get (38).

Comparative statics Use (30) to get the weighted average

$$\sum_{m=1}^{M}\frac{D_m}{D}(p_m^I - c_m) = \sum_{m=1}^{M}\frac{D_m}{D}\frac{(H_m+1)(a_m-c_m) - L_m c_m}{(H_m+1)(L_m^2+1)+2L_m}$$

of the price-cost margin when all forward markets are spatially independent. Subtract (38) from this expression to obtain

$$\sum_{m=1}^{M}\frac{D_m}{D}(p_m^I - p_m^R) = \sum_{m=1}^{M}\left[\frac{(H_m+1)(H(L_m^2+1)+L_m+1)}{(H_m+1)(L_m^2+1)+2L_m} - \frac{H+1}{1+\sum_{i=1}^{M}\Psi(L_i)}\right]\frac{\Psi(L_m)}{L_m}\frac{D_m}{D}\frac{a_m-c_m}{L_m+1}$$
$$+\sum_{m=1}^{M}\left[\frac{\sum_{i\neq m}\Psi(L_i)}{1+\sum_{i=1}^{M}\Psi(L_i)} - \frac{L_m(L_m+1)}{(H_m+1)(L_m^2+1)+2L_m}\right]\frac{D_m}{D}\frac{c_m}{L_m+1}.$$

We can simplify the first expression in square brackets to:

$$\frac{(H_m+1)(H(L_m^2+1)+L_m+1)\sum_{i\neq m}\Psi(L_i) - 2(H-H_m)L_m}{[(H_m+1)(L_m^2+1)+2L_m][1+\sum_{i=1}^{M}\Psi(L_i)]}.$$

The denominator is positive. The numerator is positive by

$$\Psi(L) - \frac{1}{H+1} = \frac{(H+L+1)(L-1)}{(H+1)(H(L^2+1)+L+1)} \geq 0$$

and

$$
\begin{aligned}
&(H_m+1)(H(L_m^2+1)+L_m+1)\frac{M-1}{H+1}-2(H-H_m)L_m\\
=&\frac{M-1}{M}[\frac{M-1}{H+1}(H(L_m^2+1)+L_m+1)+H(L_m-1)^2+L_m+1]>0,
\end{aligned}
$$

where we have used the assumption that $H_m = \frac{H}{M}$. To evaluate the second expression in square brackets, observe first that

$$
\frac{\sum_{i=1}^{M}\Psi(L_i)}{1+\sum_{i=1}^{M}\Psi(L_i)}-\frac{M}{M+H+1}=\frac{(H+1)\sum_{i=1}^{M}(\Psi(L_i)-\frac{1}{H+1})}{(M+H+1)(1+\sum_{i=1}^{M}\Psi(L_i))}\geq 0.
$$

Next

$$
\frac{M}{M+H+1}-\frac{L_m(L_m+1)}{(H_m+1)(L_m^2+1)+2L_m}=M\frac{(2M-L_m-1)L_m-(H+M)(L_m-1)}{[M+H+1][(H+M)(L_m^2+1)+2ML_m]},
$$

where the right-hand side expression follows from substituting in $H_m = \frac{H}{M}$. The denominator is positive. The numerator is non-negative if and only if $L_m \leq \bar{L}$, where we defined $\bar{L}$ in equation (40). ■

A.2 Proof of Proposition 4

Let (k_1^{CI}, k_1^{CR}) be an equilibrium portfolio of forward positions taken by the producer with market power in local market 1, and define (k_2^{CI}, k_2^{CR}) correspondingly in local market 2. The composite forward positions in the two markets are $k_1^C = k_1^{CI} + \frac{D_1}{D}k_1^{CR}$ and $k_2^C = k_2^{CI} + \frac{D_2}{D}k_2^{CR}$ in equilibrium. The equilibrium prices of the local forward contracts are $f_1^C = F_1(k_1^C)$ and $f_2^C = F_2(k_2^C)$, and the equilibrium short-term prices are $p_1^C = p_1(k_1^C)$ and $p_2^C = p_2(k_2^C)$. The equilibrium price of the regional forward contract is $\bar{f}^C = \bar{F}(k_1^C, k_2^C)$. Let

$$
\Pi_1(\hat{k}_1^I,\hat{k}_1^R)=(F_1(k_1)-p_1(k_1))\hat{k}_1^I+(\bar{F}(k_1,k_2^C)-\frac{D_1}{D}p_1(k_1)-\frac{D_2}{D}p_2^C)\hat{k}_1^R+(p_1(k_1)-c_1)q_1(k_1)
$$

be the first stage profit of producer 1 as a function of its forward portfolio $(\hat{k}_1^I, \hat{k}_1^R)$ evaluated at producer 2's equilibrium portfolio (k_2^{CI}, k_2^{CR}), and where $k_1 = \hat{k}_1^I + \frac{D_1}{D}\hat{k}_1^R$ is 1's composite forward position. We define $\Pi_2(\hat{k}_2^I, \hat{k}_2^R)$ in an analogous manner. Recall also that

$$
\bar{F}(k_1,k_2)-\frac{D_1}{D}p_1(k_1)-\frac{D_2}{D}p(k_2)=\frac{1}{2}[\frac{D_1}{D}(F_1(k_1)-p_1(k_1))+\frac{D_2}{D}(F_2(k_2)-p_2(k_2))] \quad (57)
$$

from (43). We first derive three properties of equilibrium forward positions in three claims. We then establish necessary and sufficient equilibrium conditions.

Claim 1 *The positions* (k_1^{CI}, k_1^{CR}) *and* (k_2^{CI}, k_2^{CR}) *constitute equilibrium forward portfolios only if* $\frac{D_1}{D}(f_1^C - p_1^C) \neq \frac{D_2}{D}(f_2^C - p_2^C)$.

Proof. If $\frac{D_1}{D}(f_1^C - p_1^C) = \frac{D_2}{D}(f_2^C - p_2^C)$, then

$$\Pi_i(k_i^C - \frac{D_i}{D}\hat{k}_i^R, \hat{k}_i^R) = (f_i^C - p_i^C)k_i^C + (p_i^C - c_i)q_i^C,$$

which is independent of $\hat{k}_i^R$. Hence, $(\hat{k}_i^I, \hat{k}_i^R) = (k_i^C, 0)$ is optimal. Moreover, $\Pi_i(k_i^C, 0) \leq \Pi_i(k_i^I, 0) = \pi_i^I$ implies $k_i^C = k_i^I = \frac{2D_i}{H+4}$, where we have obtained k_i^I by substituting $L_i = 1$ and $H_i = \frac{H}{2}$ into (29). The premium on the local forward contract in market i equals

$$f_i^I - p_i^I = \frac{b_i}{2}\frac{D_i - k_i^I}{H_i} = \frac{1}{H}\frac{H+2}{H+4}a_i. \tag{58}$$

If $k_1^C = k_1^I$ and $k_2^C = k_2^I$, then

$$\frac{D_1}{D}(f_1^C - p_1^C) - \frac{D_2}{D}(f_2^C - p_2^C) = \frac{1}{DH}\frac{H+2}{H+4}(a_1 D_1 - a_2 D_2),$$

which is different from zero unless $a_1 D_1 = a_2 D_2$. To close the proof, consider the knife-edge case $a_1 D_1 = a_2 D_2$, and assume that 1 deviates from $(k_1^I, 0)$ to $\hat{k}_1^I = 0$ and $\frac{D_1}{D}\hat{k}_1^R = k_1 \geq k_1^I$. The marginal profit of this deviation evaluated at $k_1 = k_1^I$ is

$$\frac{\partial \Pi_1(0, \frac{D}{D_1}k_1^I)}{\partial \hat{k}_1^R} = \frac{a_1 D_1}{DH}\frac{1}{H+4} > 0.$$

Hence, $\frac{D_1}{D}(f_1^C - p_1^C) = \frac{D_2}{D}(f_2^C - p_2^C)$ cannot be sustained as an equilibrium even under symmetry $a_1 D_1 = a_2 D_2$. ■

Claim 2 *The positions* $(k_i^{CI}, 0)$ *and* $(0, k_m^{CR})$*,* $i \neq m$*, constitute equilibrium forward portfolios only if* $\frac{D_i}{D}(f_i^C - p_i^C) > \frac{D_m}{D}(f_m^C - p_m^C)$.

Proof. If $\frac{D_i}{D}(f_i^C - p_i^C) < \frac{D_m}{D}(f_m^C - p_m^C)$, then it is optimal for producer i to deviate to $\hat{k}_i^I = 0$ and $\hat{k}_i^R = \frac{D}{D_i}k_i^{CI}$ by (44) and

$$\bar{f}^C - \frac{D_1}{D}p_1^C - \frac{D_2}{D}p_2^C - \frac{D_i}{D}(f_i^C - p_i^C) = \frac{1}{2}[\frac{D_m}{D}(f_m^C - p_m^C) - \frac{D_i}{D}(f_i^C - p_i^C)] > 0,$$

where we have invoked (57). Hence, $\frac{D_i}{D}(f_i^C - p_i^C) > \frac{D_m}{D}(f_m^C - p_m^C)$ by Claim 1. ■

Claim 3 *The positions* $(k_i^{CI}, 0)$ *and* $(0, k_m^{CR})$, $i \neq m$, *constitute equilibrium forward portfolios only if*

$$k_i^{CI} = k_i^I \text{ and } \frac{D_m}{D} k_m^{CR} = \frac{D_m}{H+2} + \frac{1}{H+4}\frac{a_i D_i}{a_m}. \tag{59}$$

Proof. The producer with market power in market i only participates in the local forward market if $k_i^{CR} = 0$. If $k_i^{CI} \neq k_i^I$, then producer i can increase profit by a marginal increase or reduction in $\hat{k}_i^I$ from k_i^{CI} without violating the necessary condition from Claim 2. This leaves $k_i^{CI} = k_i^I$ as the only equilibrium candidate for producer i. Consider next producer m. Assume that producer i plays $(k_i^I, 0)$ and that producer m does not participate in local forward market m. The profit-maximizing regional forward position $\frac{D_m}{D}\hat{k}_m^R = k_m^*$ solves the first-order condition

$$\frac{\partial \Pi_m(0, \hat{k}_m^R)}{\partial \hat{k}_m^R} = \bar{F}(k_m^*, k_i^C) - \frac{D_m}{D} p_m(k_m^*) - \frac{D_i}{D} p_i^C - \frac{H+1}{H}\frac{b_m}{2}\frac{D_m}{D} k_m^* = 0, \tag{60}$$

where we have substituted in $\frac{\partial \bar{F}(k_1,k_2)}{\partial k_m^R} = -\frac{H+1}{H}\frac{b_m}{2}(\frac{D_m}{D})^2$. Apply (57) to obtain the modified first-order condition

$$\frac{1}{2}[\frac{D_m}{D}(F_m(k_m^*) - p_m(k_m^*)) + \frac{D_i}{D}(f_i^C - p_i^C)] - \frac{H+1}{H}\frac{D_m}{D}\frac{b_m k_m^*}{2} = 0.$$

We can then use $F_m(k_m^*) - p_m(k_m^*) = \frac{b_m}{H}(D_m - k_m^*)$ and $f_i^C - p_i^C = f_i^I - p_i^I$ characterized in (58) to solve for

$$k_m^* = \frac{D_m}{H+2} + \frac{1}{H+4}\frac{a_i D_i}{a_m}.$$

If $\frac{D_m}{D} k_m^{CR} \neq k_m^*$, then producer m can increase profit by a marginal increase or reduction in $\hat{k}_m^R$ from k_m^{CR} without violating the necessary condition from Claim 2. This leaves $\frac{D_m}{D} k_m^{CR} = k_m^*$ as the only equilibrium candidate for producer m. ■

The forward positions characterized in (59) yield the price-cost margins

$$p_i^C - c_i = \frac{b_i}{2}[\frac{a_i - c_i}{b_i} - k_i^C] = \frac{b_i}{2}[\frac{a_i - c_i}{b_i} - \frac{2D_i}{H+4}] = p_i^I - c_i. \tag{61}$$

and

$$p_m^C - c_m = \frac{b_m}{2}[\frac{a_m - c_m}{b_m} - k_m^C] = \frac{b_m}{2}[\frac{a_m - c_m}{b_m} - \frac{D_m}{H+2} - \frac{1}{H+4}\frac{a_i D_i}{a_m}]. \tag{62}$$

The price difference

$$p_m^I - p_m^C = \frac{a_m}{2(H+4)}[\frac{a_i D_i}{a_m D_m} + \frac{H+4}{H+2} - 2\sqrt{\frac{H+4}{H+2}} + 2(\sqrt{\frac{H+4}{H+2}} - 1)]$$

is positive if condition (47) holds. The premium in local forward market m is

$$f_m^C - p_m^C = \frac{b_m}{2}\frac{D_m - k_m^C}{H_m} = \frac{1}{H}\frac{H+1}{H+2}a_m - \frac{1}{H}\frac{1}{H+4}\frac{a_i D_i}{D_m}. \tag{63}$$

Subtracting this forward market premium from $f_i^C - p_i^C = f_i^I - p_i^I$ characterized in (58) yields the forward price difference:

$$\frac{D_i}{D}(f_i^C - p_i^C) - \frac{D_m}{D}(f_m^C - p_m^C) = \frac{a_m D_m}{DH}\frac{H+3}{H+4}[\frac{a_i D_i}{a_m D_m} + \frac{H+4}{H+2} - 2\sqrt{\frac{H+4}{H+2}} + 2(\sqrt{\frac{H+4}{H+2}} - \frac{H+4}{H+3})],$$

which is positive if condition (47) holds. We finally show that condition (47) is necessary and sufficient for the equilibrium characterized in (59) to hold.

Necessity We first characterize the equilibrium profits. By way of the price-cost margin identified in (61) and $q_i^C = \frac{1}{2}(\frac{a_i - c_i}{b_i} + k_i^C)$, see (23), it follows that producer i's profit in the short-term market equals

$$(p_i^C - c_i)q_i^C = \frac{b_i}{2}(\frac{a_i - c_i}{b_i} - k_i^C)\frac{1}{2}(\frac{a_i - c_i}{b_i} + k_i^C) = \frac{(a_i - c_i)^2}{4b_i} - \frac{b_i}{4}(k_i^C)^2.$$

From producer i's first-order condition

$$f_i^C - p_i^C - \frac{H+2}{H}\frac{b_i}{2}k_i^C = 0$$

in the forward market, we retrieve i's forward profit

$$(f_i^C - p_i^C)k_i^C = \frac{H+2}{H}\frac{b_i}{2}(k_i^C)^2.$$

Adding the two profit expressions returns i's total profit

$$\pi_i^C = (f_i^C - p_i^C)k_i^C + (p_i^C - c_i)q_i^C = \frac{(a_i - c_i)^2}{4b_i} + \frac{b_i}{4}\frac{H+4}{H}(k_i^C)^2 = \frac{(a_i - c_i)^2}{4b_i} + \frac{1}{H}\frac{a_i D_i}{H+4} = \pi_i^I.$$

Producer m's profit in the short-term market is qualitatively similar to that of producer i. From the first-order condition (60) we get m's forward profit

$$(\bar{f}^C - \frac{D_1}{D}p_1^C - \frac{D_2}{D}p_2^C)k_m^{CR} = \frac{1}{2}\frac{H+1}{H}b_m(k_m^C)^2.$$

Hence,

$$\pi_m^C = (\bar{f}^C - \frac{D_1}{D}p_1^C - \frac{D_2}{D}p_2^C)k_m^{CR} + (p_m^C - c_m)q_m^C = \frac{(a_m - c_m)^2}{4b_m} + \frac{b_m}{4}\frac{H+2}{H}(k_m^C)^2.$$

Producer m can always deviate to $(\hat{k}_m^I, \hat{k}_m^R) = (k_m^I, 0)$ and obtain profit π_m^I. The net benefit of this deviation satisfies

$$\frac{4H(\pi_m^I - \pi_m^C)}{b_m(H+2)} = \frac{4D_m^2}{(H+4)(H+2)} - (k_m^C)^2 = [\frac{2D_m}{\sqrt{(H+4)(H+2)}} + k_m^C][\frac{2D_m}{\sqrt{(H+4)(H+2)}} - k_m^C].$$

In particular,

$$\frac{H+4}{D_m}[\frac{2D_m}{\sqrt{(H+4)(H+2)}} - k_m^C] = 2\sqrt{\frac{H+4}{H+2}} - \frac{H+4}{H+2} - \frac{a_i D_i}{a_m D_m}.$$

It follows that $\pi_m^I > \pi_m^C$ if condition (47) is violated. In this case, the forward positions characterized in Claim 3 cannot be sustained as an equilibrium. This is the only equilibrium candidate that features $k_i^{CR} = k_i^{CI} = 0$, and therefore there can be no equilibrium with $k_i^{CR} = k_i^{CI} = 0$ if (47) is violated.

Sufficiency Consider first producer m's incentive to deviate from $(k_m^{CI}, k_m^{CR}) = (0, \frac{D}{D_m}k_m^*)$ to an arbitrary $(\hat{k}_m^I, \hat{k}_m^R)$, where $k_m = \hat{k}_m^I + \frac{D_m}{D}\hat{k}_m^R$. It is always optimal to set either $\hat{k}_m^R = 0$ or $\hat{k}_m^I = 0$ conditional on k_m, and therefore $\Pi_m(\hat{k}_m^I, \hat{k}_m^R) \leq \max\{\Pi_m(k_m, 0); \Pi_m(0, \frac{D}{D_m}k_m)\}$. By the definitions of k_m^I and k_m^*, $\Pi_m(k_m, 0) \leq \Pi_m(k_m^I, 0) = \pi_m^I$ and $\Pi_m(0, \frac{D}{D_m}k_m) \leq \Pi_m(0, \frac{D}{D_m}k_m^*) = \pi_m^C$. Hence, $\Pi_m(\hat{k}_m^I, \hat{k}_m^R) \leq \max\{\pi_m^I; \pi_m^C\}$. If condition (47) is satisfied, then $\pi_m^C \geq \pi_m^I$, in which case $\Pi_m(\hat{k}_m^I, \hat{k}_m^R) \leq \pi_m^C$. This establishes $(k_m^{CI}, k_m^{CR}) = (0, \frac{D}{D_m}k_m^*)$ as a best reply to $(k_i^{CI}, k_i^{CR}) = (k_i^I, 0)$ if condition (47) is met.

By analogous arguments, a deviation by producer i from $(k_i^{CI}, k_i^{CR}) = (k_i^I, 0)$ to an arbitrary $(\hat{k}_i^I, \hat{k}_i^R)$ yields profit $\Pi_i(\hat{k}_i^I, \hat{k}_i^R) \leq \max\{\pi_i^C; \pi_i^*\}$, where $\pi_i^* = \max_{k_i} \Pi_i(0, \frac{D}{D_i}k_i)$. We conclude the proof by demonstrating $\pi_i^C > \pi_i^*$ if condition (47) is met.

Let $k_i^* = \arg\max_{k_i} \Pi(0, \frac{D}{D_i}k_i)$. This optimal forward position is found as the solution to

i's first-order condition.

$$\bar{F}(k_i^*, k_m^C) - \frac{D_i}{D} p_i(k_i^*) - \frac{D_m}{D} p_m^C - \frac{H+1}{H} \frac{b_i}{2} \frac{D_i}{D} k_i^* = 0.$$

We can then solve for

$$k_i^* = \frac{H+3}{H+4} \frac{D_i}{H+2} + \frac{H+1}{(H+2)^2} \frac{a_m D_m}{a_i}.$$

by following the same procedure as for k_m^*. Producer i's profit of pursuing this strategy is

$$\pi_i^* = (\bar{F}(k_i^*, k_m^C) - \frac{D_i}{D} p_i(k_i^*) - \frac{D_m}{D} p_m^C) \frac{D}{D_i} k_i^* + (p_i(k_i^*) - c_i) q_i(k_i^*) = \frac{(a_i - c_i)^2}{4b_i} + \frac{b_i}{4} \frac{H+2}{H} (k_i^*)^2.$$

The net benefit of playing the equilibrium strategy relative to deviating to $(0, \frac{D}{D_i} k_I^*)$ is:

$$\frac{4H(\pi_i^C - \pi_i^*)}{b_i(H+2)} = [\frac{2D_i}{\sqrt{(H+4)(H+2)}} + k_i^*][\frac{2D_i}{\sqrt{(H+4)(H+2)}} - k_i^*].$$

After manipulating terms, we finally get

$$\begin{aligned} a_i a_m D_m (H+2)[\frac{2D_i}{\sqrt{(H+4)(H+2)}} - k_i^*] &= [2\sqrt{\frac{H+2}{H+4}} - \frac{H+3}{H+4}] \frac{a_i D_i}{a_m D_m} - \frac{H+1}{H+2} \\ &= [2\sqrt{\frac{H+2}{H+4}} - \frac{H+3}{H+4}][\frac{a_i D_i}{a_m D_m} + \frac{H+4}{H+2} - 2\sqrt{\frac{H+4}{H+2}}] \\ &+ 2\frac{2H+5}{H+4}\sqrt{\frac{H+4}{H+2}}[\sqrt{\frac{H+4}{H+2}} - \frac{2H+7}{2H+5}], \end{aligned}$$

which is strictly positive if condition (47) is met. ■

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