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THE COMPETITIVE EFFECTS OF LINKING ELECTRICITY MARKETS ACROSS SPACE

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Abstract

Major barriers to adoption of an efficient wholesale electricity market design are the perceived distributional effects of charging consumers different short-term prices depending on their location in the network. Forward financial contracts for wholesale electricity in locational marginal pricing markets typically settle against a quantity-weighted average of short-term prices, and customers are often charged a quantity-weighted average of short-term prices for their short-term market purchases. We evaluate the competitive effects of such forward and short-term pricing mechanisms in locational pricing markets. In particular, short-term markets are more efficient under regional compared to forward contracts that clear against local prices.

Keywords: Electricity markets, equity, market design, market power, regional markets.

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I. INTRODUCTION

Locational marginal pricing or nodal pricing is used to operate all offer-based wholesale electricity markets in the United States.[1] Locational marginal prices (LMPs) are computed by minimizing the as-offered cost of serving demand at all locations in the transmission network subject to all relevant generation unit and transmission network constraints. The 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. This process can give rise to thousands of potentially different LMPs within the geographic footprint of the wholesale market each pricing period.[2] If all suppliers submit each generation unit's marginal cost as its offer price, then each LMP is the economically efficient price signal for that location in the transmission network during that pricing period. Under perfect competition, these LMPs make it unilaterally profit-maximizing for each generation unit to produce at a level of output that minimizes the total variable cost of serving demand at all locations in the transmission network.[3]

Restructured wholesale electricity markets in many other parts of the world rely on much less sophisticated methods than locational marginal pricing for allocating generation resources to serve locational demands. In such markets, the algorithms used to calculate market prices and output levels routinely fail to account for important constraints in transmission network operation. However, many of these jurisdictions are becoming increasingly aware of the inefficiencies associated with market designs that neglect fundamental constraints on system operation. The costs of operating such electricity markets have increased as a consequence of energy policies through which countries become more and more reliant on intermittent renewable energy. The variability of wind and solar generation unit output levels can accentuate the impact of transmission network operating constraints, which substantially increases the cost of maintaining a reliable supply of electricity. Yet, it has been extremely difficult to implement market designs with granular prices outside the US despite the efficiency properties of wholesale market designs based on locational marginal prices.[4]

A fundamental barrier to adoption has been the potential of the LMP market design to set different prices at different locations in the transmission network. A major argument against this design rests on the notion that locational wholesale market prices will reduce the liquidity of financial markets and make it more expensive for consumers to

[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] Bohn et al. (1984) characterize the mathematical programming problem solved to compute market-clearing quantities and LMPs.

[3] This result holds as long as "make-whole payments" are made to generation unit owners to account for non-convexities in production. Graf et al. (2021) discuss the role of make-whole payments in achieving an efficient market outcome in LMP markets.

[4] Wolak (2011) finds that the transition from a zonal to a nodal market design in California was associated with annual savings in the variable cost of serving demand of over $100 million annually. Triolo and Wolak (2021) estimate that the transition to an LMP market design in Texas produced more than $300 million in annual variable cost savings during the first twelve months of operation.

hedge electricity prices in the forward market. A second argument against charging final consumers a wholesale price that reflects the LMP at their location in the transmission network is based on the view that it is unfair to charge customers in major load centers higher wholesale prices than customers at less supply-constrained locations in the transmission network.[5]

Actual LMP markets address liquidity and equity issues to varying degree. Forward contracts often settle against trading-hub prices instead of individual LMPs. A trading-hub price is calculated as the volume-weighted average of the LMPs at all locations that jointly form the trading hub.[6] This construction is thought to increase liquidity in the forward market by reducing the importance of any single LMP in determining the profitability of forward contracting. Regulators and market operators have addressed equity concerns in LMP markets by requiring that all customers within a given geographical area purchase wholesale electricity at a price based on the volume-weighted average of all locational prices in that geographic area.[7] We show that these regional features of LMP market designs have important consequences for the performance of imperfectly competitive short-term wholesale electricity markets that employ location-based pricing.

Our basic insight is that linking M local markets through a *regional forward market* in which contracts have a settlement price equal to the quantity-weighted average of the locational short-term prices across all M markets, increases the equilibrium quantity of forward contracts held by retailers and large consumers beyond what would occur if there were *M local forward markets* each with a settlement price equal to the locational short-term price in that market. As is well-known, fixed-price forward contracts can improve short-term market performance. Producers then have an incentive to increase output in the short-term market because the associated reduction in the short-term price increases the forward market profit by reducing the settlement price of the forward contract.[8] The increase in forward market liquidity (the equilibrium quantity of forward contracts) under the regional contract reduces short-term prices below the level that would exist under forward contracts settled against individual locational short-term prices in local markets.

[5]More sophisticated versions of this argument claim that a very different network would have been built had a locational marginal pricing market design been in place when the network was originally constructed.

[6]Regional forward contracts are common also in other commodity markets. For instance, IntercontinentalExchange (`https://www.theice.com/about/exchanges-clearing`) trades futures for cocoa, coffee, sugar and other agricultural products with delivery locations at any approved port in the US and Europe.

[7]For example, all retail customers in the service territory of each of the three large investor-owned utilities in California pay a wholesale price equal to the quantity-weighted average of LMPs at all load withdrawal locations in that utility's service territory. All customers of each utility purchase their wholesale electricity at the same Load Aggregation Point (LAP) price for their utility regardless of where they are located in the utility's service territory. Singapore operates a nodal pricing market, and all loads purchase their wholesale electricity at the Uniform Singapore Electricity Price (USEP) which is equal to the quantity-weighted average of the LMPs in Singapore.

[8]Wolak (2000) demonstrates the empirical relevance of this mechanism for a large supplier in an Australian wholesale electricity market. United States regulators also recognize that suppliers with the ability to exercise unilateral market power submit offer prices into the short-term market closer to their marginal cost if they have substantial fixed-price forward contract commitments. As Wolak (2003) notes, this mechanism is a major lesson from the California electricity crisis.

To assess the implications of market design for efficiency, we develop a model of a wholesale electricity market in which producers and consumers interact in a three-stage game. Producers post forward prices in stage one, consumers buy forward quantities in stage two, production and consumption occurs in the short-term (spot) market in stage three.

The market consists of $M \geq 2$ local markets with local market-clearing spot prices. Electricity flows freely within each local market, but there is no flow of electricity between them. A fixed number of generation owners possess market power in each local short-term market.[9] Each producer with market power owns generation capacity only in one local market.[10] There is a fixed number of industrial consumers and independent retailers in each local market. These have constant demand for electricity. Each local market has a competitive fringe that supplies electricity to the short-term market at increasing marginal cost. Given the constant demand, it is the marginal cost of the competitive fringe that creates the price sensitivity of residual demand facing producers with market power. Market participants are forward-looking and rational. All trade takes place under complete information.[11] The game is solved for subgame-perfect equilibrium by backward induction.

The equilibrium quantity of forward contracting that emerges from this model reveals a mechanism that seems to have gone unnoticed in the literature. It builds on the notion that forward contracting mitigates exploitation of market power in the spot market. The pro-competitive effect in the spot market implies that forward-looking consumers are willing to pay a premium over the settlement price on forward contracts. This forward premium makes it profitable for a monopoly producer to participate in the forward market.[12] A forward contract is a mechanism that enables market participants to reduce distortions associated with market power in the spot market and share those efficiency gains. A larger forward quantity commits a producer with market power to supply more electricity to the short-term market. The forward premium distributes the efficiency benefits across consumers and the producer in such a way as to make everyone better off.

The trade-offs facing producers and consumers in the forward and spot market depend on market design. A given forward quantity has a smaller pro-competitive effect under a regional than a local forward contract because a larger output in the spot market only reduces the settlement price by a fraction of the local spot price change under the former design. The smaller competitive benefit reduces the forward premium compared to the local forward contract because of consumers' lower willingness to pay for a regional forward contract. The smaller forward premium makes it less profitable to sell

[9]Concentrated ownership is increasingly relevant to the extent that local markets are defined at the nodal level, where each generation unit interconnection point is a separate market.

[10]The assumption of local market presence is a reflection of the geographically concentrated ownership of generation assets found in most restructured electricity markets.

[11]This common assumption is innocuous for most of the analysis by the assumption that only one producer exercises market power in each local short-term market. It is only in case of strategic interaction in the short-term market that assumptions about observability of forward contract positions matter.

[12]Forward premia in wholesale electricity markets are identified, for instance, by Borenstein et al. (2008) and Ito and Reguant (2016). Both papers attribute the price differences between the forward and the short-term market to market power.

forward contracts. However, the demand for a regional forward contract is substantially more price sensitive than the demand for a local forward contract, which tends to increase forward contracting under a regional compared to a local forward contract. We show that the price sensitivity dominates to such an extent that the spot market is more efficient under the regional than the local forward contract because of a much higher liquidity in the regional forward market. Our model therefore predicts LMP markets in which forward contracts settle against trading-hub prices to be more liquid and efficient than LMP markets where forward markets settle against individual LMPs.

The incentive for independent retailers and large industrial consumers to purchase forward contracts depends on whether they pay the local short-term price for their electricity consumption or a volume-weighted average of short-term prices. In the second case of a *regional short-term market* for consumption, forward quantities purchased by local consumers have positive spill-over effects on consumers in other local markets through a reduction in the regional purchase price of electricity in the spot market. This spill-over effect does not occur in a *local short-term market* for consumption. Consequently, the willingness to pay for forward contracts is smaller in a regional compared to a local short-term market for consumption, which translates into a smaller quantity of forward contracts sold in the former than the latter type of market. Our model therefore predicts a regulatory mandate that addresses equity concerns of the nodal market design by requiring all loads to purchase their wholesale electricity at a quantity-weighted average of LMPs within a service territory, to be less efficient than LMP markets where consumers pay the local spot price for their electricity.

LMP markets that feature both trading-hub forward prices and geographically averaged consumer prices can be more or less efficient than LMP markets with local forward contracts and local consumer prices. The pro-competitive effects of regional forward contracting dominates, in particular if local forward markets are illiquid.

Related literature Allaz and Vila (1993) establish that producers operating in an oligopoly spot market have a strategic incentive to sell forward contracts. A larger forward quantity represents a commitment to increase output in the spot market, which causes competitors to reduce their production in response.[13] Bessembinder and Lemon (2002) show in a model of perfect competition that forward contracting enables efficient risk-sharing under uncertainty. The mechanisms in Allaz and Vila (1993) and Bessembinder and Lemon (2002) do not apply in our context because there is only one producer with market power in each local spot market, and the market is deterministic. In our mech-

[13] In Allaz and Vila (1993), producers are locked in a prisoners' dilemma in the forward market that increases efficiency in the short-term market. Mahenc and Salanié (2004) find forward contracting to reduce market performance if firms compete in prices instead of quantities in the spot market. Holmberg (2011) establishes conditions under which forward contracting improves market performance when firms compete in supply functions. These papers suggest that results can be sensitive to the mode of competition in the short-term market. We establish fundamental results under local monopoly conditions that are robust to strategic decisions in the short-term market. Our extension to local oligopoly markets is based on the assumption of quantity-setting competition. This model 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, 2022), the German market (Willems et al., 2009) and the Nordic market (Lundin and Tangerås, 2020).

anism, the demand for forward contracts comes from forward-looking consumers who realize that forward contracting reduces the spot price of electricity (Anderson and Hu, 2008; Ruddell et al., 2018). The burgeoning literature on forward contracting is based on the analysis of a single spot market. Motivated by standard design features of restructured electricity markets in the US, our contribution is to investigate how regional aspects of forward and wholesale markets affect market performance.[14]

The rest of the paper is organized as follows. Section 2 introduces the baseline model featuring two symmetric local markets and one producer with market power in each local market. Section 3 compares the efficiency properties of the different market designs within the baseline model. Section 4 presents results of five extensions of the symmetric model. First, efficiency results are robust to introducing more general cost and demand functions than the linear specification of the baseline model. Second, regional forward contracting reduces the volume-weighted average of short-term prices compared to the benchmark of spatially independent markets even when there is an arbitrary number of asymmetric local markets. Third, short-term prices are higher when producers have market power in multiple shot-term markets. Fourth, a market design in which local markets are linked through a regional forward contract yields lower prices than a spatially independent market design also in an oligopoly setting in the short-term market. Fifth, increasing the number of trading periods for forward contracts reduces prices in the short-term market. Section 5 concludes with a discussion of policy implications of our results for electricity market design.

II. THE BASELINE MODEL

We here introduce the simplest possible setting that generates the key mechanisms of our paper. The model features two symmetric short-term markets that are local in the sense that there is free flow of electricity within each local market but no exchange 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.

Each local market features one large producer with market power, a competitive fringe, and $H \geq 1$ retailers or industrial consumers. Each producer with market power 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. Each large consumer is also active only in one local market. The forward market is decentralized, whereas an independent system operator (ISO) organizes trade in the short-term market. This is consistent with how short-term markets for electricity work in restructured electricity markets, for instance in the US.

[14] 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 in a spatial context and thus leave aside the question of how different market designs affect collusion.

Modeling assumptions of the forward market In stage one of the game, each producer with market power in local market $m = 1, 2$ announces a forward price $f_m \geq 0$ per MWh of electricity. Each producer commits to serving all demand for forward contracts at its posted price. The two producers announce f_1 and f_2 simultaneously and independently. In stage two of the game, each consumer h in local market m decides the forward quantity $k_{hm} \in \mathbb{R}$ to purchase from producer m. Consumers choose quantities simultaneously and independently. The total forward quantity equals $k_m = \sum_{h=1}^{H} k_{hm}$ in local market m. We let $k_{-hm} = k_m - k_{hm}$ be the forward quantity purchased by all consumers in local market m except consumer h. Consumers only purchase forward contracts in the local market in which they are active, the fringe does not participate in the forward market, and there are no speculative traders. These assumptions do not restrict the analysis, as shall see below.

Modeling assumptions of the short-term (spot) market The spot market clears in stage three. To capture the fact that short-term demand for electricity is highly price inelastic, we let the local demand for electricity be constant and equal to $D > 0$. Consumers are symmetric, so each large consumer's electricity demand equals $\frac{D}{H}$. Consumers value electricity usage at $v > 0$ per MWh. By assumption, this valuation is so high that rationing of demand will never occur in equilibrium. Each consumer faces an additional cost $\psi \times (\frac{D}{H} - k_{hm})$, $\psi \geq 0$, of being short in the forward market relative to its consumption of electricity, $k_{hm} < \frac{D}{H}$. This term captures an economic effect on the consumer of forward contracting besides the forward and spot market profit. It could for instance represent the imbalance fee commonly imposed on individual retailers and large customers whenever their electricity consumption differs from the contract positions they have taken prior to the short-term market.[15] Local demand must be met entirely by local supply by our assumption of physically separated local markets, but local production is a homogeneous good by our assumption of a free flow of electricity within each local market. The producer with market power in local market $m = 1, 2$ produces $q_m \in \mathbb{R}$ MWh electricity at constant marginal cost $c \geq 0$. The competitive fringe in market m supplies the residual demand net of producer m's supply, $D - q_m \in \mathbb{R}$, at upward-sloping linear marginal cost $b(D - q_m)$, $b > 0$, so the market-clearing short-term price equals $p_m = b(D - q_m)$.[16] If we define $a = bD > \max\{2c; c + 4\psi\}$, then the inverse demand curve facing the producer with market power in short-term market m equals $P(q_m) = a - bq_m$. The slope of the inverse demand curve $P(q_m)$ comes from the slope of the marginal cost curve of the competitive fringe. Consumption and production of electricity are both deterministic.

[15] In standard market designs, large consumers have an incentive to procure too little of their expected short-term demands in the forward energy market because of price caps in the spot market (Wolak, 2022). We can alternatively think of ψ as the reduced form marginal benefit to the individual consumer of reducing the reliability externality associated with insufficient incentives to procure electricity demand in the forward market. A full analysis would require a model with uncertainty.

[16] We permit negative production, which we can think of as flexible consumption. Spot prices can therefore be negative, which is allowed in many actual market designs. By way of these assumptions, we can conveniently neglect non-negativity constraints on quantities and spot prices. Strict concavity of all objective functions then allows us to apply an unconstrained first-order approach in stage two and three throughout the analysis. All quantities and prices in the forward and short-term market are positive in equilibrium by our assumptions on the parameters of the model.

III. A TAXONOMY OF MARKET DESIGNS

The efficiency of electricity supply will depend on the design of the short-term and forward markets, specifically whether each of these markets is *local* or *regional*. In a local short-term market, generation owners in each local market receive the local short-term price of electricity for their production, and local consumers pay the local short-term price of electricity for their consumption, as in the usual nodal pricing design. A regional short-term market consists of a collection of local short-term markets. All consumers within the region pay the same regional short-term price for their consumption, which is calculated as the volume-weighted average of the local short-term prices within the region. Production is still paid according to the local short-term price. This design is known as generator nodal pricing. In a local forward market, the settlement price for forward contracts is defined as the local short-term price of electricity. In a regional forward market, the settlement price for forward contracts is instead defined as the regional short-term price of electricity.

The benchmark case of *spatially independent markets* refers to a market design with local forward and local short-term markets. This the default market design for all LMP markets in the United States. An alternative design is to *link forward markets across space* through a regional forward contract, but maintain local short-term markets for production and consumption. As mentioned in the introduction, such contracts are common in US LMP markets where settlement prices for forward contracts refer to trading-hub prices. Examples include the PJM Interconnection Western Hub and California ISO NP15 and SP15 EZ Gen Hub forward contracts.[17] A third possibility is to *link forward and short-term markets across space* through a regional forward and a regional short-term market. Examples include NYISO (New York) and ISO-NE (New England) in the US. The wholesale electricity markets in Italy and Singapore are other examples. The fourth, hypothetical construct, is to *link short-term markets across space* through a regional short-term market, but maintain local forward markets. We can display the different market designs in a table:

Table 1: A taxonomy of market designs

	Local forward markets	**Regional forward market**
Local short-term markets	Default US market design	PJM, CAISO
Regional short-term market	Hypothetical	NYISO, ISO-NE, Singapore, Italy

The following four sections analyze each of the four market designs in Table 1. We then compare their efficiency properties in Section 3.5. In particular, linking markets through a regional forward contract, increases competition in the short-term market beyond what is possible if forward markets are local. Producers with market power sell relatively more forward contracts in a regional forward market compared to local

[17]The New Zealand Electricity Market (NZEM) is another relevant example. The short-term market is LMP, but the underlying commodity of trade in the financial market is electricity produced at two reference point nodes, Benmore Base and Otahuhu. Prices at these nodes are used as indicators of local market prices in the South Island (Benmore Base) and in the upper North Island (Otahuhu).

forward markets because the demand for forward contracts is relatively more price sensitive in the former case. The increased forward quantity is sufficient to reduce short-term prices despite the fact that marginal changes in forward quantities have a smaller pass-through effect to short-term prices market under regional compared to local forward contracting.

3.1. Spatially independent markets

Forward and spot markets are both local under this market design. Since the two local markets are identical by symmetry, we skip subscript m otherwise used for identifying individual local markets. By backward induction, we begin with an analysis of the short-term market.

Equilibrium in the local short-term market The producer with market power moves in the third (production) stage of the game by choosing the quantity q to produce for the short-term market. The third-stage profit of this producer equals

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

The first term measures the forward market profit if the producer has sold contracts for k MWh electricity in the forward market at a price of f per MWh. The settlement price is the local short-term price $P(q)$, and the firm produces q MWh electricity. The second term is the profit in the short-term market, and is equal to the price-cost margin in the short-term market multiplied by the quantity produced.

Maximizing the profit function (1) over quantity q yields the first-order condition

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

for profit maximization in the short-term market. The producer has an incentive to withhold output q to sustain a higher price and thereby increase profit in the short-term market. This incentive is muted if the producer has sold fixed-price forward contracts, so that $k > 0$. An increase in output then increases the forward market profit by reducing the settlement price $P(q)$. The magnitude of this effect on the forward profit is larger when the producer has sold a larger forward quantity k. The production decision is independent of the forward price f because the forward market revenue fk is sunk at the production stage.

By way of $P(q) = a - bq$ and $P'(q) = -b$, we can use the first-order condition (2) to solve for the output

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

of the producer with market power, as a function of forward quantity 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 quantity of electricity in the forward market.

Substituting the quantity $q(k)$ into the profit function (1) yields the profit

$$\Pi(k, f) = [f - P(q(k))]k + [P(q(k)) - c]q(k) \tag{5}$$

of the monopolist, written as a function of the forward quantity k and the forward price f.

The demand for local forward contracts In stage 2, each large consumer h chooses the forward quantity k_h to maximize its profit

$$\Omega_h^I(k_h, k_{-h}, f) = -[f - p(k)]k_h + [v - p(k)]\frac{D}{H} - \psi[\frac{D}{H} - k_h] \tag{6}$$

taking the forward quantity k_{-h} of all other large consumers, and the forward price f as given. Superscript I indicates that the profit function is obtained under a spatially independent market design. The first term in (6) is consumer h's forward deficit if the forward price equals f per MWh, the settlement price of the local forward contract is $p(k) = P(q(k))$, and the consumer has purchased forward contracts for k_h MWh electricity. The second term in (6) is consumer h's profit in the short-term market. It is equal to the value v per MWh of electricity consumed minus the spot price $p(k)$ of electricity, multiplied by the individual consumption $\frac{D}{H}$ of electricity. The third term in (6) measures the cost of being short in the forward market.

The H consumers move simultaneously in the second stage of the game. The marginal effect on consumer h's profit of increasing the forward quantity k_h is

$$\frac{\partial \Omega_h^I}{\partial k_h} = -[f - p(k)] - p'(k)(\frac{D}{H} - k_h) + \psi. \tag{7}$$

An increase in the demand k_h for electricity in the forward market has a direct effect by increasing consumer h's forward market deficit. The marginal forward deficit is the first term on the right-hand side of the marginal profit expression above. An increase in demand k_h also reduces the short-term price of electricity. The marginal value of this pro-competitive effect of forward contracting, is measured by the second term in (7). The final term is the marginal benefit of reducing the imbalance between consumption and the forward quantity.

Consumer h's profit function is strictly concave in k_h, $\frac{\partial^2 \Omega_h^I}{\partial k_h^2} = -b < 0$, by $p'(k) = -\frac{b}{2}$. The solution $\frac{\partial \Omega_h^I}{\partial k_h}|_{k_h = \beta_h} = 0$ to consumer h's first-order condition for profit maximization then yields the consumer's best-reply function

$$\beta_h(k_{-h}, f) = \frac{(H+1)a + Hc + 2H(\psi - f)}{2bH} - \frac{1}{2}k_{-h}, \tag{8}$$

where we have substituted in the explicit expression for $p(k)$ established in (4) into consumer h's first-order condition. A marginal increase in the forward quantity k_{-h} purchased from the monopoly producer by the other large consumers reduces consumer h's profit-maximizing forward quantity. A larger quantity k_{-h} increases the forward premium, $f - p(k)$, by reducing the settlement price $p(k)$ of the forward contract. The larger premium makes it more costly for consumer h to purchase forward contracts, so the demanded forward quantity falls. Forward quantities therefore display strategic substitutability.

Symmetry of consumers implies that they all demand the same forward quantity, $k_h = \frac{k}{H}$, in equilibrium. We can then use the first-order condition, $\frac{\partial \Omega_h^I}{\partial k_h}|_{k_h=\frac{k}{H}} = 0$, to derive the equilibrium relationship

$$f - p(k) = \frac{b}{2}\frac{D-k}{H} + \psi \tag{9}$$

in the forward market. In Bessembinder and Lemmon (2002), consumers are willing to pay a premium on the expected spot price because they are risk averse and want to hedge uncertain future electricity prices. Equation (9) shows that large consumers may be willing to pay a positive forward premium, $f - p(k) > 0$, even if there is no uncertainty about the spot price. The first term on the right-hand side of (9) represents the marginal value of the pro-competitive effect of forward contracting in the short-term market. It is positive if the total forward quantity is smaller than total consumption, $k < D$. The second term in (9) is the marginal benefit of reducing the imbalance of the forward position relative to demand.

The forward premium in (9) is larger when H is smaller, so that there are fewer retailers or large consumers in the market for forward contracts. Specifically, the fixed-price forward contracts purchased by each consumer conveys a positive benefit to all consumers in the form of lower short-term prices. To the extent that there are fewer large consumers in a local market, any large consumer that purchases a forward contract captures a greater share of the short-term price benefits from its forward contract purchases. The willingness to pay a premium for forward contracts therefore is larger when H is smaller.

The forward premium implies that speculators apparently could enter the forward market to conduct arbitrage. Arbitrage trading would then eliminate any forward premium. However, forward contracts sold by a large local producer and those sold by other participants in the forward market are different products. Only contracts sold by a producer with local market power reduce prices in the local short-term market. Neither speculators, members of the competitive fringe, nor producers with market power in other local markets can sell local forward contracts at a premium to local buyers because those contracts cannot reduce local short-term prices.[18] This mechanism can explain why consumers would prefer purchasing forward contracts directly from producers instead of through an exchange. Consistent with this prediction, organized forward markets struggle with liquidity, for instance in the European electricity market.[19]

[18]See Ruddell et al. (2018) for additional discussion of speculative trade in the forward market.

[19]If consumers were forced to purchase forward contracts through an exchange, this might leave room for speculators to sell worthless (in our model) forward contracts unless the exchange itself matched local consumers with large local producers. Matching local buyers and sellers in this way would be in the self-interest of the exchange by increasing consumers' willingness to pay for forward contracts.

By applying symmetry to the best-reply function, we can solve for the demand

$$K^I(f) = \frac{(H+1)a + Hc + 2H(\psi - f)}{b(H+1)} \tag{10}$$

for forward contracts in a spatially independent market. This demand is linearly decreasing in the forward price f.

The price of local forward contracts The producer with market power moves in the first stage of the game by choosing the linear forward price $f \geq 0$. Substitute the demand $k = K^I(f)$ for forward contracts from (10) into $\Pi(k, f)$ defined in (5) to get the profit

$$\Pi^I(f) = [f - P(q(K^I(f)))]K^I(f) + [P(q(K^I(f))) - c]q(K^I(f)) \tag{11}$$

of the monopoly producer as a function of the forward price f.

Differentiating (11) with respect to f yields the marginal effect

$$\Pi^{I'}(f) = \underbrace{k + [f - p(k)]K^{I'}(f)}_{\text{Marginal forward profit}} + \underbrace{[-P'(q)k + P(q) - c + P'(q)q]q'(k)K^{I'}(f)}_{\text{Marginal profit in the short-term market}} \tag{12}$$

on profit of an increase in the forward price. The marginal profit in the short-term market is of second-order importance by the first-order condition (2). The equilibrium forward price f^I maximizes the producer's forward profit by solving the first-order condition $\Pi^{I'}(f^I) = 0$ and is characterized by

$$\frac{f^I - p(k^I)}{f^I} = \frac{1}{-K^{I'}(f^I)\frac{f^I}{k^I}}, \tag{13}$$

where $k^I = K^I(f^I)$ is the forward quantity sold by the monopoly producer in equilibrium.[20] The markup of the forward price over the settlement price of the forward contract is inversely proportional to the price elasticity of the demand for forward contracts.

However, it is not the forward price that is of primary concern for efficiency, but the forward quantity. By substituting the forward premium characterized in (9) into the marginal profit expression (12) and using $K^{I'}(f) = -\frac{2}{b}\frac{H}{H+1}$ from the demand function (10) for forward contracts, we can solve the first-order condition directly to get:

Proposition 1 *The equilibrium forward quantity equals*

$$k^I = \frac{D + 2H\frac{\psi}{b}}{H+2} \tag{14}$$

in a spatially independent market design.

[20]The optimum is unique by strict concavity, $\Pi^{I''}(f) = (2 - p'(k)k'(f))k'(f) = -\frac{2}{b}\frac{H+2}{H+1}\frac{H}{H+1} < 0$, of the producer's first-stage profit function.

Substituting k^I from (14) into (3) returns the producer's equilibrium output

$$q^I = q(k^I) = \frac{a-c}{2b} + \frac{1}{2}\frac{D + 2H\frac{\psi}{b}}{H+2}. \tag{15}$$

We can plug this quantity into the inverse demand function $P(q)$ to derive the equilibrium price in the short-term market:

$$p^I = P(q^I) = \frac{a+c}{2} - \frac{1}{2}\frac{a + 2H\psi}{H+2} > c. \tag{16}$$

The associated forward premium is

$$f^I - p^I = \frac{H+1}{H+2}\frac{a+2H\psi}{2H} > \psi. \tag{17}$$

A new mechanism for forward contracting There is trade of forward contracts in equilibrium despite the assumption that only one producer has market power in the spot market and the assumption of no uncertainty about future electricity prices. Hence, the mechanism that generates forward contracting in this model is fundamentally different from Allaz and Vila (1993), where forward contracts serve a strategic purpose as a commitment to behave more aggressively in the spot market, and from Bessembinder and Lemmon (2002), where producers and consumers hedge price uncertainty through forward contracts. Here, *a forward contract is a mechanism for reducing inefficiencies arising from imperfect competition in the spot market and for sharing the associated benefits*. The forward quantity k^I creates an incentive for the producer to increase output in the spot market. The forward premium $f^I - p^I$ distributes the efficiency gain across the large market participants to benefit them all. We demonstrate the latter point below.

If there was no trade of forward contracts, then the producer with market power would produce $q(0) = \frac{a-c}{2b}$ MWh electricity for the short-term market, sell it at the short-term price $p(0) = \frac{a+c}{2}$, and earn the associated profit $\pi_0 = (p(0) - c)q(0) = \frac{(a-c)^2}{4b}$. The surplus for each individual consumer would equal $\omega_0 = (v - p(0))\frac{D}{H} - \psi\frac{D}{H}$ in an equilibrium without forward contracting. By substituting the equilibrium prices and quantity expressions into $\Pi^I(f)$, we can write the equilibrium profit of the producer as

$$\pi^I = \pi_0 + \frac{1}{4b}\frac{(a+2H\psi)^2}{H(H+2)} > \pi_0.$$

The producer can always earn π_0 by charging a forward price $\tilde{f}$ that generates zero demand, $K^I(\tilde{f}) = 0$, for forward contracts. By revealed preference, $f^I < \tilde{f}$, the monopoly producer profits from stimulating demand for forward contracts. The profit in the forward market arising from large consumers' willingness to pay a forward premium is sufficient to compensate the producer for the fact that selling such contracts will reduce profit in the spot market below the monopoly level.

Consumers also benefit from forward contracting. We can substitute the equilibrium forward price and quantity into $\Omega_h^I(k_k, k_{-h}, f)$ to get consumer h's equilibrium profit

$$\omega^I = \omega_0 + \frac{(H^2 + H - 1)a + 2H\psi}{2bH^2(H+2)^2}(a + 2H\psi) > \omega_0.$$

Each individual consumer benefits from other consumers' buying forward contracts because of the resulting reduction in the spot price of electricity, $\Omega_h^I(0, k_{-h}, f) > \omega_0$, $k_{-h} > 0$. Rather than not buying any forward contracts, consumer h benefits by revealed preference from purchasing forward quantity $\frac{k^I}{H}$ at the forward price f^I given that every other consumer has purchased that same forward quantity. The increased consumer surplus in the spot market associated with a lower spot price of electricity, is sufficient to cover the cost of buying forward contracts at a premium.[21]

Because of their mutual gains, both sides have a joint interest in developing markets for forward contracts. This feature is similar to Bessembinder and Lemmon (2002), where mutual gains arise from efficient risk sharing. In Allaz and Vila (1993), however, all gains of forward contracting accrue to consumers because producers are caught in a prisoners' dilemma that reduces industry profit. In that model, generation owners with market power have a joint interest in not developing any forward market.

Market power in the spot market extends the producer's market power to the forward market, but this aspect of imperfect competition does not matter directly for efficiency, which ultimately depends on the output in the spot market. The competitive effect of forward contracting is weaker, in the sense that $p^I - c$ is larger, if H is larger so that more consumers are present in the market for forward contracts, because then the willingness to pay for forward contracts is smaller. Yet, forward contracting improves efficiency and benefits both the large producer and all consumers for any bounded H compared to a market without forward contracting. The only case when forward contracting does not increase efficiency is when there are no large retailers or consumers in the local market ($H \to \infty$).

Notwithstanding the competitive benefits 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 quantity equal to the producer's output.[22] Instead, the equilibrium contract coverage is only partial:

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

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

3.2. Linking forward markets across space

Consider the consequences of linking the local markets through a *regional forward contract*. In our simple model, this is a forward contract with a settlement price defined as the average $\frac{1}{2}(p_1 + p_2)$ of the short-term market prices in the two local markets. This change in market design affects both competition in the forward and the short-term market. We maintain the assumption that consumers pay the local short-term price for

[21] Strategic buyers in the forward market were introduced by Anderson and Hu (2008) and Ruddell et al. (2018) in a framework with duopoly production. In both models, consumers gain in equilibrium whereas producers lose from forward contracting.

[22] If $k = q$ in (2), then $P(q) = c$ solves the producer's first-order condition in the short-term market.

the electricity they use, and generation owners receive the local short-term price for the electricity they produce.

Equilibrium in the local short-term market The profit of producer $m = 1, 2$ equals

$$[f_m - \frac{1}{2}\{P(q_1) + P(q_2)\}]k_m + [P(q_m) - c]q_m. \tag{18}$$

at the production stage of the game if it has sold forward contracts for k_m MWh electricity at the forward price f_m per MWh, and it produces q_m MWh electricity for the short-term market. Forward contracts in (18) settle against the average of the short-term prices in the two local markets whereas forward contracts in (1) settle against the local forward price.

Producer m's first-order condition for profit maximization in the short-term market is

$$-\frac{1}{2}P'(q_m)k_m + P(q_m) - c + P'(q_m)q_m = 0. \tag{19}$$

The competitive effect of forward contracting in the short-term market is muted under a regional forward contract compared to the case of local forward markets elucidated in (2). The reason is that the marginal effect of an increase in q_m is smaller when the settlement price of the forward contract is defined as the weighted average of multiple short-term prices. By comparing (19) with (2), we see that producer m 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 m equals

$$q_m(k_m) = q(\frac{k_m}{2}) = \frac{1}{2}\frac{a - c}{b} + \frac{1}{2}\frac{k_m}{2} \tag{20}$$

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

$$p_m(k_m) = P(q_m(k_m)) = p(\frac{k_m}{2}) = \frac{a + c}{2} - \frac{b}{2}\frac{k_m}{2}. \tag{21}$$

Substituting the quantities $q_1(k_1)$ and $q_2(k_2)$ into profit function (18) returns the profit

$$\Pi_1(k_1, k_2, f_1) = [f_1 - \frac{1}{2}\{P(q_1(k_1)) + P(q_2(k_2))\}]k_1 + [P(q_1(k_1)) - c]q_1(k_1) \tag{22}$$

of the monopoly producer in local market $m = 1$ as a function of the pair (k_1, k_2) of forward quantities and its forward price f_1. An analogous profit expression $\Pi_2(k_2, k_1, f_2)$ holds for the monopoly producer in local market $m = 2$.

The demand for regional forward contracts In stage 2, each large consumer h in local market 1 chooses the forward quantity k_{h1} to maximize its profit

$$\begin{aligned}\Omega^{RI}_{h1}(k_{h1}, k_{-h1}, k_2, f_1) = &- [f_1 - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\}]k_{h1} \\ &+ [v - p_1(k_1)]\frac{D}{H} - \psi[\frac{D}{H} - k_{h1}],\end{aligned} \tag{23}$$

subject to the forward quantity k_{-h1} purchased by all other large consumers in local market 1, the forward quantity k_2 in local market 2, and the forward price f_1 of local producer 1. Superscript RI identifies a market design with a regional forward market and a local short-term market. Contrary to the consumer profit (6) in a spatially independent market, forward contracts here settle against the quantity-weighted average of the short term prices $p_1(k_1)$ and $p_2(k_2)$ in the two local markets, where $p_m(k_m) = P(q_m(k_m))$, $m = 1, 2$. The profit in the spot market is qualitatively the same under both market designs.

The first term in the marginal profit

$$\frac{\partial \Omega_{h1}^{RI}}{\partial k_{h1}} = -[f_1 - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\}] - p_1'(k_1)(\frac{D}{H} - \frac{1}{2}k_{h1}) + \psi. \tag{24}$$

is the marginal effect of the increased forward quantity on the forward market deficit, the second term is the marginal competitive effect of forward contracting on the short-term price in local market 1, and the third term is the marginal benefit of a smaller contract imbalance.[23]

The equilibrium forward quantities are symmetric by symmetry of the large consumers, so $k_{h1} = \frac{k_1}{H}$ for all h. We can then use the first-order condition $\frac{\partial \Omega_{h1}^{RI}}{\partial k_{h1}}|_{k_{h1}=\frac{k_1}{H}} = 0$ and $p_m'(k_m) = -\frac{b}{4}$ from (21) to solve for the forward premium

$$f_1 - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\} = \frac{b}{4}\frac{2D - k_1}{2H} + \psi \tag{25}$$

in local market 1. A similar expression holds for the forward premium in local market 2.

The demand for forward contracts depends on forward prices in both markets because the settlement price is the quantity-weighted average of the spot prices in the two markets. We can combine the two expressions for the forward premia from the two local markets and use the explicit expression (21) for the short-term price, to solve for the demand

$$K_m^{RI}(f_m, f_{-m}) = \frac{2}{b}\frac{(2H+1)a + 2Hc + 4H(\psi - f_m + H(f_{-m} - f_m))}{2H+1} \tag{26}$$

for forward contracts in local market m. The demand for forward contracts is linearly decreasing in the own forward price and linearly increasing in the forward price of the other local producer:

$$\frac{\partial K_m^{RI}}{\partial f_m} = -\frac{8H}{b}\frac{H+1}{2H+1} < 0, \; \frac{\partial K_{-m}^{RI}}{\partial f_m} = \frac{8H}{b}\frac{H}{2H+1} > 0. \tag{27}$$

The positive cross-price elasticity of demand is *not* a result of local producers competing for consumers in the regional forward market because consumers only purchase forward contracts from their local monopoly producer. The cross effect occurs because a higher forward price f_m increases the settlement price $\frac{1}{2}(p_1 + p_2)$ of the regional forward contract through a reduction in the local demand k_m for forward contracts. This

[23]Consumer h's best reply is unique by strict concavity, $\partial^2 \Omega_{h1}^{RI}/\partial k_{h1}^2 = -\frac{b}{4} < 0$, of h's profit function.

results in a smaller forward premium in local market $-m$, which increases the demand for forward contracts in that local market.

Notice finally that consumers in one local market have no incentive to purchase contracts from the producer in the other local market because doing so only increases the forward market premium by reducing the settlement price of the regional forward contract, without generating any pro-competitive effect on the spot price in the own local market.

Prices in the regional forward market Consider the profit-maximizing choice of forward prices by the two local producers in the first stage of the game. By substituting the local demand $k_1 = K_1^{RI}(f_1, f_2)$ for forward contracts in market 1 and $k_2 = K_2^{RI}(f_2, f_1)$ in market 2 into the profit function defined in (22), we get the profit

$$\Pi_1^{RI}(f_1, f_2) = \Pi_1(K_1^{RI}(f_1, f_2), K_2^{RI}(f_2, f_1), f_1)$$

of local producer 1. This profit depends on the forward price of both local producers because forward markets are linked through the regional forward contract. Producer 1 maximizes its profit over $f_1 \geq 0$ taking f_2 as given, whereas producer 2 behaves in a symmetric fashion.

A small increase in the forward price f_1 has a marginal effect on profit in the forward and the short-term market,

$$\begin{aligned} \frac{\partial \Pi_1^{RI}}{\partial f_1} &= \underbrace{[1 - \frac{1}{2}P'(q_2)q_2'(k_2)\frac{\partial K_2^{RI}}{\partial f_1}]k_1 + [f_1 - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\}]\frac{\partial K_1^{RI}}{\partial f_1}}_{\text{Marginal forward profit}} \\ &+ \underbrace{[-\frac{1}{2}P'(q_1)k_1 + P(q_1) - c + P'(q_1)q_1]q_1'(k_1)\frac{\partial K_1^{RI}}{\partial f_1}}_{\text{Marginal profit in the short-term market}}, \end{aligned} \tag{28}$$

although the marginal profit in the short-term market is only of second-order effect by (19). A new term arises in (28) compared to the expression (12) for marginal profit in the spatially independent market. The larger forward price f_1 increases the demand for forward contracts in local market 2 through the positive cross-price effect. The increased forward quantity in local market 2 reduces the spot price of electricity in local market 2, which reduces the settlement price of the regional forward contract. The direct effect of a marginally higher forward price plus the marginal reduction in the settlement price of the regional forward contract, multiplied by the forward quantity constitute the marginal effect on the forward premium in local market 1 identified by the first term in the marginal forward profit in (28).

Use the first-order condition (19) from the short-term market to eliminate the second row of (28), and set the marginal profit (28) of producer 1 to zero to get the characterization

$$\frac{f^{RI} - p^{RI}}{f^{RI}} = \frac{1}{-\frac{\partial K_1^{RI}}{\partial f_1}\frac{f^{RI}}{k^{RI}}}[1 - \frac{1}{2}P'(q^{RI})q_2'(k^{RI})\frac{\partial K_2^{RI}}{\partial f_1}] \tag{29}$$

of the markup of the forward price over the settlement price in symmetric equilibrium, $f_1 = f_2 = f^{RI}$. In this expression, $k^{RI} = K_m^{RI}(f^{RI}, f^{RI})$ is the forward quantity sold, and $q^{RI} = q_m(k^{RI})$ is the quantity produced in equilibrium by each producer with local market power.[24] The short-term price is the same in both local markets and given by $p^{RI} = p_m(k^{RI})$. The markup is proportional to the inverse of the own-price elasticity of the demand for forward contracts multiplied by the marginal forward premium.

The forward quantity is of main concern for efficiency, not the forward price. Substitute the first-order condition (19) and the forward premium (25) into the marginal profit expression (28). Then use $P'(q_2) = -b$, $q_2'(k_2) = \frac{1}{4}$, and the marginal demand expressions (27) to solve the first-order condition $\frac{\partial \Pi_1^{RI}}{\partial f_1} = 0$ directly for the equilibrium forward quantity:

Proposition 2 *Linking two symmetric local markets through a regional forward contract with a settlement price equal to the quantity-weighted average of the short-term prices in those two markets, more than doubles the equilibrium forward quantity k^{RI} sold by each producer with market power,*

$$k^{RI} = \frac{2D + 8H\frac{\psi}{b}}{H+2} \geq \frac{2D + 4H\frac{\psi}{b}}{H+2} = 2k^I, \tag{30}$$

compared to the benchmark of spatially independent markets. The increase in the forward quantity has a pro-competitive effect in the short-term market:

$$c < p^{RI} = \frac{a+c}{2} - \frac{1}{2}\frac{a + 4H\psi}{H+2} \leq p^I. \tag{31}$$

The inequalities are strict for all $\psi > 0$.

Proposition 2 predicts forward contracts with a settlement price equal to the volume-weighted average of short-term prices across multiple local markets, to be substantially more liquid than forward contracts that settle against local short-term prices. This increase in liquidity is sufficient to improve the performance of the short-term market.

Let us examine the mechanisms underlying Proposition 2. The cross-price effect in the first row of the marginal profit expression (28) reinforces the incentive to increase the forward price compared to a spatially independent market design. What is holding producer 1 back, is the loss associated with a reduced demand for forward contracts, the second marginal effect on the first row of (28). That marginal loss is larger if the forward premium is larger and the demand for forward contracts is more sensitive to marginal changes in the forward price.

To compare forward premiums under the two market designs, let $\hat{f}$ be the symmetric forward price which generates demand for forward contracts in the regional forward market that is twice the forward demand in a spatially independent market design. Substitute $k_1 = 2k$ into (25) to obtain the forward premium

$$\hat{f} - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\} = \frac{b}{4}\frac{D-k}{H} + \psi = \frac{f - p(k) + \psi}{2} \geq \frac{1}{2}(f - p(k)) \tag{32}$$

[24] Strict concavity, $\partial^2 \Pi_1^{RI} / \partial f_1^2 = (2 + H\frac{H-1}{2H+1})\frac{\partial K_m^{RI}}{\partial f_m} < 0$, of the producer's profit function implies that the symmetric forward price indeed represents an equilibrium.

associated with the forward price $\hat{f}$. Equation (32) shows that producers jointly need to reduce the forward premium by less than one half to double the forward quantity compared to the equilibrium in a spatially independent market. Furthermore, linking forward contracts across space substantially increases the price-sensitivity of demand for forward contracts,

$$\frac{\partial K_1^{RI}}{\partial f_1} = -\frac{8H}{b}\frac{H+1}{2H+1} < -\frac{8H}{b}\frac{1}{H+1} = 4K^{I'}(f),$$

compared to the case of spatially independent markets. An increase in the forward price f_1 increases the demand for forward contracts in local market 2. The larger forward quantity k_2 increases the forward premium in local market 1 by reducing the settlement price of the regional forward contract. The larger forward premium further reduces the demand for forward contracts in local market 1. The interactions across local markets create a multiplier effect which accentuates the marginal own-price effect on the demand for forward contracts in a regional forward market compared a local forward market. The relatively large forward premium and the increased sensitivity of demand for forward contracts drive down the equilibrium forward price to such an extent that local producers with market power sell more than double the forward quantity, $k^{RI} \geq 2k^I$, when markets are linked through a regional forward contract compared to the spatially independent market design.

3.3. Linking forward and short-term markets across space

Consider a market design with a regional short-term as well as a regional forward market. The difference between this design and the one in the previous section, is that now consumers pay the average short term price $\frac{1}{2}(p_1 + p_2)$ instead of the local short-term price for their consumption. Local production is remunerated on the basis of the local short-term price.

Equilibrium in the regional short-term market The profit of producer m at the production stage of the game is the same as in the previous section, and defined by (18). Holding the total forward quantities (k_1, k_2) in each local market constant, a regional short-term market does not affect the profit-maximizing production compared to the previous section, because the demand for electricity is constant, and producers still receive the local short-term price for their output. The producer with market power in local market m therefore produces $q_m(k_m)$ MWh electricity, characterized in (20), for the short-term market. The corresponding price $p_m(k_m)$ in the short-term market is characterized in (21).

The demand for regional forward contracts Consumer h in local market 1 maximizes its profit

$$\begin{aligned}\Omega_{h1}^R(k_{h1}, k_{-h1}, k_2, f_1) = &-[f_1 - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\}]k_{h1} \\ &+ [v - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\}]\frac{D}{H} - \psi[\frac{D}{H} - k_{h1}],\end{aligned} \tag{33}$$

over k_{h1}, taking all other forward quantities and the forward price as given. We use superscript R to identify a market design with a regional forward and a regional short-term market. Compared with (23), the consumer now pays the average short-term price instead of the local short-term price for its electricity consumption $\frac{D}{H}$.

Maximization of (33) yields the forward premium

$$f_1 - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\} = \frac{b}{4}\frac{D - k_1}{2H} + \psi \tag{34}$$

in local market 1 if all consumers in that local market purchase the same forward quantity. A similar expression holds for the forward premium in local market 2. All else equal, the forward premium is smaller when consumers pay a regional short-term price for their consumption relative to when they pay the local short-term price, as can be verified by comparing (34) to (25). In a market design where the short-term price of electricity consumption is measured by the quantity-weighted average of prices in the short-term market, consumers in one local market exert a positive externality on consumers in the other local market by purchasing forward contracts. The reason is that the price of consumption falls in both local markets. This externality reduces the willingness to pay for forward contracts compared to the case of a local short-term price where all the pro-competitive benefits of forward contracting arise in the own local market.

Combine the forward premia from the two local markets to solve for the demand

$$K^R_m(f_m, f_{-m}) = \frac{1}{b}\frac{(2H+1)a + 4Hc + 8H(\psi - f_m) + 8H^2(f_{-m} - f_m)}{2H+1} \tag{35}$$

for forward contracts in local market m. A comparison of (35) with (26) reveals that the demand for forward contracts is smaller if consumers pay the regional short-term price compared to the local short-term price for their consumption. The reason is the positive regional short-term price externality. Observe that the slopes of demand are the same as in (27).

Prices in the regional forward market The producer with market power in local market 1 maximizes its first-stage profit $\Pi^R_1(f_1, f_2) = \Pi_1(K^R_1(f_1, f_2), K^R_2(f_2, f_1), f_1)$ over its forward price f_1, taking f_2 as given. Local producer 2 does the same. We can then follow similar steps as in the previous section to solve for the equilibrium quantity k^R in the forward market.

Proposition 3 *Let two symmetric local markets be linked through a regional forward contract that settles against the quantity-weighted average of the short-term prices in those two markets, and let consumers in both markets pay that quantity-weighted average price for their consumption. The equilibrium quantity*

$$k^R = \frac{D + 8H\frac{\psi}{b}}{H+2} \in [k^I, k^{RI}) \tag{36}$$

of electricity sold forward by each producer with market power is sufficiently large ($k^R > 2k^I$) to reduce the spot price

$$p^R = \frac{a+c}{2} - \frac{1}{4}\frac{a+8H\psi}{H+2} \tag{37}$$

of electricity compared to the case of spatially independent markets, if and only if $\frac{\psi}{b} > \frac{D}{4H}$.

Regional forward contracting increases liquidity in the forward market compared to the case of independent markets also when consumer prices are required to be identical in both local markets through a regional short-term price. This increase in liquidity may or may not be sufficient to compensate for the effect that regional forward contract volumes have a weaker effect on prices in the short-term market than forward contracts with an settlement price equal to the local short-term price. In particular, the equilibrium spot price is smaller than in a design with spatially independent markets if the number H of strategic consumers is sufficiently large. Similar to in the previous section,

$$\hat{f} - \frac{1}{2}\{p_1(k_1) + p_2(k_2)\} = \frac{b}{4}\frac{D-2k}{2H} + \psi = \frac{1}{2}(f - p(k)) + \frac{b}{2}(\frac{\psi}{b} - \frac{D}{4H})$$

characterizes the forward premium in each local market which ensures that the demand for forward contracts equals $2k$ in each local market. In particular, this forward premium is larger than $\frac{1}{2}(f - p(k))$ if the number H of strategic consumers is sufficiently large. This is precisely when the spatially independent market design leads to non-competitive outcomes.[25]

3.4. Linking short-term markets across space

The final market design we consider, is the hypothetical case where consumers pay the quantity-weighted average of the prices in the short-term market for their electricity consumption. Everything else is the same as in the spatially independent market design: Forward markets are local, and producers receive the local short-term price for the electricity they generate.

Equilibrium in the short-term market Holding forward quantities constant, the assumption that consumers pay a regional price for their usage of electricity has no bearing on allocations in the short-term market compared to the spatially independent market design, because the demand for electricity in the short-term market is constant. Since forward markets are local, producer $m = 1, 2$ supplies $q(k_m)$ to the short-term market, where $q(k)$ was defined in (3). The corresponding short-term price is $p(k_m)$, with $p(k)$ defined in (4).

The demand for local forward contracts Consumer h in local market 1 obtains profit

$$\Omega_h^{IR}(k_{h1}, k_{-h1}, k_2, f_1) = -[f_1 - p(k_1)]k_{h1} + [v - \frac{1}{2}\{p(k_1) + p(k_2)\}]\frac{D}{H} - \psi(\frac{D}{H} - k_{h1})$$

[25]Differentiation of the price-cost margin in (16) yields $\frac{\partial}{\partial H}(p^I - c) = \frac{1}{2}\frac{a-4\psi}{(H+2)^2} > 0$.

by purchasing $k_{h1} \geq 0$ MWh electricity in the forward market from the monopoly producer in local market 1, at price f_1 per MWh, if all other consumers purchase forward contracts for k_{-h1} in local market 1 and for k_2 in local market 2. Superscript IR identifies a market design with a local forward and a regional short-term market. This profit expression differs from (6) in the sense that consumers under the present market design pay the quantity-weighted average of the two local prices for their consumption, instead of the local short-term price.

Maximize Ω_h^{IR} over k_{h1} and impose symmetry, $k_{h1} = \frac{k}{H}$, to obtain the demand

$$K^{IR}(f) = \frac{(2H+1)a + 2Hc + 4H(\psi - f)}{2b(H+1)} \tag{38}$$

for forward contracts as a function of the price f the local monopoly producer charges per MWh electricity sold in the forward market. Holding the forward price constant, this demand is smaller than the demand (10) for forward contracts in the spatially independent market because of the positive externality on the spot price in local market 2.

The price of the local forward contract Maximizing the monopoly profit $\Pi^{IR}(f) = \Pi(K^{IR}(f), f)$ over f yields:

Proposition 4 *Linking two symmetric local markets through a regional consumer price equal to the quantity-weighted average of the short-term prices in those two markets, reduces the profit maximizing volume k^{IR} of forward contracts sold by each producer with market power,*

$$k^{IR} = \frac{1}{2}\frac{D + 4H\frac{\psi}{b}}{H+2} < k^I,$$

compared to the benchmark of spatially independent markets. The reduction in the volume of forward contracts also has an anti-competitive effect in the short-term market,

$$p^{IR} = \frac{a+c}{2} - \frac{1}{4}\frac{a + 4H\psi}{H+2} \geq p^R,$$

compared to a market design with a regional forward and a regional short-term market.

3.5. Comparison of market designs

In the previous sections, we examined market designs that differ in the extent to which forward or short-term markets were regional or local. Such market designs have properties that correspond with those found in actual LMP markets. We display those designs in the below matrix, along with the relevant price comparisons.

The two columns display market designs under which the settlement price of the forward contract is either the local short-term price or the quantity-weighted average of short-term prices. The two rows show market designs under which consumers either

Table 2: Comparison of short-term prices under different market designs

	Local forward markets	**Regional forward market**
Local short-term markets	$p^I < p^{IR}$	$p^{RI} \leq p^I$
Regional short-term market	$p^{RI} < p^R \leq p^{IR}$	$(p^I - p^R)(\frac{\psi}{b} - \frac{D}{4H}) \geq 0$

pay the local short-term price or the quantity-weighted average of short-term prices for their electricity usage.

Introducing a regional forward market (moving from the left to the right column in Table 2) increases liquidity in the forward market and is pro-competitive regardless of the design of the short-term market: $p^{RI} \leq p^I$ and $p^R \leq p^{IR}$, with strict inequalities for $\psi > 0$. The increased price sensitivity of demand for regional compared to local forward contracts causes producers to sell relatively more forward contracts under the former design.

Introducing an "equity-based" regional short-term market (moving from the top to the bottom row in Table 2) is anti-competitive regardless of the design of the forward market: $p^{IR} > p^I$ and $p^R > p^{RI}$. The spill-over effect of lower consumer prices into the other markets reduces the willingness to pay for forward contracts and therefore the liquidity of the forward market in a regional short-term market.

Introducing a design with a regional forward market and regional consumer prices (moving diagonally from the top left to the bottom right in Table 2) increases liquidity in the forward market compared to a design with spatially independent markets, but is pro-competitive in the short-term market if and only if the underlying characteristics of the markets fulfill specific conditions.

One can also rank the four different market designs in terms of their competitiveness. The most competitive market design is the one in which forward markets are regional and consumers pay the local short-term price for their electricity ($p^{RI} \leq \min\{p^I; p^R; p^{IR}\}$). The least competitive design is the one with a local forward market and a regional consumer price ($p^{IR} \geq \max\{p^I; p^R; p^{RI}\}$).

IV. EXTENSIONS

This section briefly discusses extensions to the model. We first consider more general cost and demand functions than the linear specifications used so far. We then generalize the model to an arbitrary number of asymmetric short-term markets. In a third extension, we allow producers to exercise market power in more than one local market. A fourth extension is to analyze oligopoly instead of monopoly in each local market. We finally investigate the consequences of increasing the number of trading periods in the forward market. These extensions are analyzed in detail in our online appendix (Tangerås and Wolak, 2023) which also contains proofs of all formal statements below.

4.1. General cost and inverse demand functions

The pro-competitive effect of regional forward contracting established in Proposition 2 is *not* an artifact of assuming a constant marginal production cost c of the producer with market power and a linear residual inverse demand function $P(q) = a - bq$ for electricity in the short-term market. Let $\{C(q), P(q)\}$ be a pair of twice continuously differentiable cost and inverse demand functions. These functions yield regular demand and profit functions in our context if the following four technical conditions are satisfied: (i) both the spatially independent market design and the one where local markets are linked through a regional forward contract feature an interior symmetric equilibrium; (ii) the demand $K_m^{RI}(f_m, f_{-m})$ for forward contracts in a regional forward market is strictly decreasing in the own forward price f_m; (iii) the forward demand function $K_m^{RI}(f, f)$ is strictly decreasing in the symmetric forward price f; (iv) the producer's marginal profit function $\partial\Pi_m^{RI}(f, f)/\partial f_m$ is strictly decreasing in the symmetric forward price f. Under these assumptions, Tangerås and Wolak (2023) verify:

Proposition 5 *Linking two symmetric markets through a regional forward contract is pro-competitive relative to a spatially independent market design, $k^{RI} \geq 2k^I$, with strict inequality if $\psi > 0$, for any pair $\{C(q), P(q)\}$ of twice continuously differentiable cost and inverse demand functions that yield regular demand and profit functions.*

Tangerås and Wolak (2023) also show that one can generalize the imbalance cost $\psi \times (\frac{D}{H} - k_{hm})$, $\psi > 0$, without altering results.

4.2. Multiple asymmetric local markets

This section generalizes the model to an arbitrary number $M \geq 2$ of local markets that are heterogeneous in terms of demand characteristics and production costs. We maintain the assumption of one producer with market power and H large consumers in each local market. Linking local markets through a forward contract with a settlement price equal to the quantity-weighted average of the short-term prices in the M local markets, strengthens producers' unilateral incentives to sell forward contracts even in this generalized setting. We establish an average pro-competitive effect by showing that the volume-weighted average of the short-term prices is smaller under a regional forward contract than in the spatially independent market design where forward contracts settle against the local short-term prices.

Index local markets (and individual producers with market power) by $m \in \mathcal{M} = \{1, ..., M\}$. In the first stage, each producer m sets a forward price f_m per MWh at which it is willing to sell an unlimited forward quantity. In the second stage, each large consumer $h \in \{1, ..., H\}$ in local market m purchases forward quantity k_{hm} from producer m.[26] Denote by $k_m = \sum_h k_{hm}$ the total forward quantity sold by producer m. In the third stage, each producer m decides how much electricity, q_m, to produce for the short-term market at constant marginal cost c_m. Each large consumer in m uses $\frac{D_m}{H}$ MWh electricity, so that the total demand for electricity in local market m equals D_m.

[26]We could allow a heterogeneous number H_m of large consumers in each local market m without affecting any of the results.

Let $D = \frac{1}{M}\sum_m D_m$ be the average demand for electricity across the M local markets. The residual demand $D_m - q_m$ in each local market is covered by a local competitive fringe that supplies electricity at linear marginal cost $b_m(D_m - q_m)$. The inverse demand curve facing the producer in the short-term market m can then be written as $P_m(q_m) = a_m - b_m q_m$, where $a_m = b_m D_m$.

In a spatially independent market design, all forward contracts sold by producer m settle against the local spot price p_m. The analysis is qualitatively the same as in Section 3.1 with adjustment for notation. The equilibrium short-term price equals

$$p_m^I = \frac{a_m + c_m}{2} - \frac{1}{2}\frac{a_m + 2H\psi}{H+2} \tag{39}$$

in short-term market m. This expression generalizes the short-term price p^I characterized in (16) under symmetry.

Let forward contracts instead settle against the quantity-weighted average, $\frac{1}{M}\sum_m \frac{D_m}{D} p_m$, of the spot prices in all M local markets. The analysis is qualitatively the same as in Section 3.2. The equilibrium short-term price in local market m equals

$$p_m^{RI} = \frac{a_m + c_m}{2} - \frac{1}{2}\frac{a_m + 2MH\frac{D}{D_m}\psi}{H+2}. \tag{40}$$

This expression generalizes the short-term price in (31) to $M \geq 2$ asymmetric markets.

Comparison of this equilibrium price with (39) in a spatially independent market yields:

Proposition 6 *Consider an electricity market with $M \geq 2$ local markets. Let there be one producer with market power in each local market, and assume that each producer is active only in one local market. Linking the M local markets through a regional forward contract with a settlement price equal to the quantity-weighted average of the shot-term prices in those M markets, increases competition in the short-term markets by reducing the quantity-weighted average of the short-term prices,*

$$\frac{1}{M}\sum_{m=1}^{M}\frac{D_m}{D}(p_m^I - p_m^{RI}) = \frac{M-1}{H+2}H\psi \geq 0, \tag{41}$$

compared to the benchmark of spatially independent markets. The inequality is strict if $\psi > 0$.

Proposition 6 generalizes Proposition 2 to the case of multiple asymmetric markets if one uses the quantity-weighted average of the local spot prices as a benchmark for comparison. An alternative formulation is that consumers' total spot market purchases across the M local markets are cheaper under a regional forward contract, compared to a design with M local forward markets.

The proposition also speaks to the efficiency of bundling local forward markets through a regional forward contract. Loosely speaking, the average pro-competitive effect is stronger when more markets are linked because the right-hand side of (41) is increasing in M. To derive a formal result, consider a collection $\mathcal{O}$ of O local markets indexed by o. Assume that $\mathcal{O}$ initially is partitioned into two regional forward markets, $\mathcal{M}$ and $\mathcal{N}$. The first regional forward market encompasses M local markets indexed by m, and the other consists of N local markets indexed by n. Let the average electricity demand per local market be equal to D_M in $\mathcal{M}$ and D_N in $\mathcal{N}$.

Corollary 1 *Merging two regional forward markets $\mathcal{M}$ and $\mathcal{N}$ into a larger regional forward market $\mathcal{O} = \mathcal{M} \cup \mathcal{N}$ reduces consumers' total spot market expenditures on electricity across the $O = M + N$ short-term markets that constitute the geographical footprint of the enlarged regional forward market by*

$$\sum_{m \in \mathcal{M}} D_m p_m^{RI} + \sum_{n \in \mathcal{N}} D_n p_n^{RI} - \sum_{o \in \mathcal{O}} D_o p_o^{RI} = \frac{HMN}{H+2} \frac{D_M + D_N}{MD_M + ND_N} \psi \geq 0,$$

with strict inequality if $\psi > 0$.

By this corollary it would be globally efficient to link all local markets through one global forward market.

4.3. Producers active in more than one local market

We now extend the model in Section 4.2 of multiple asymmetric short-term markets to allow producers to own generation assets and exercise market power in more than one local short-term market. This change in ownership structure implies that producers internalize more of the demand effects of selling forward contracts, which tends to increase prices in the short-term market.

Let there be $1 \leq S \leq M$ large producers with market power in the entire market, and assume that each producer s is active in a subset $\mathcal{M}_s$ of the M local markets. Let M_s be the cardinality of $\mathcal{M}_s$ and therefore measure the number of local spot markets in which producer s exercises market power. We maintain the assumption of only one producer with market power in each local market. These modifications to the model do not matter for the spatially independent market design because all local markets then are functionally independent from one another. The analysis in Section 3.1 still applies. We only analyze the case of a regional forward market in more detail.

In a market design in which local markets are linked through a regional forward contract, producer s has total profit

$$[f_s - \frac{1}{M} \sum_n \frac{D_n}{D} P_n(q_n)]k_s + \sum_{m \in \mathcal{M}_s} [P_m(q_m) - c_m]q_m$$

in the third stage of the game. In the above profit expression, $k_s = \sum_{m \in \mathcal{M}_s} k_m$ measures the total forward quantity sold by producer s in all local markets in which it owns generation capacity. Profit maximization delivers the quantity $q_m(k_s)$ sold by producer s in local short-term market $m \in \mathcal{M}_s$ and the associated spot price $p_m(k_s)$:

$$q_m(k_s) = \frac{1}{2} \frac{a_m - c_m}{b_m} + \frac{1}{2} \frac{D_m}{D} \frac{k_s}{M}, \; p_m(k_s) = \frac{a_m + c_m}{2} - \frac{b_m}{2} \frac{D_m}{D} \frac{k_s}{M}.$$

Seeing as the spot price in local market m depends on k_s, producer s cannot charge different forward prices across the local markets in which it owns generation capacity. Attempts at price differentiation would be arbitraged away by consumers indifferent between which of the $\mathcal{M}_s$ markets to buy forward contracts.

Maximization of consumer profit yields the demand $K_s^{RI}(\boldsymbol{f})$ for forward contracts sold by producer s as a function of the S forward prices $(f_s, \boldsymbol{f}_{-s})$ charged by the large producers. At the first-stage, producer s maximizes

$$\Pi_s^{RI}(\boldsymbol{f}) = [f_s - \frac{1}{M}\sum_{t=1}^{S}\sum_{n\in\mathcal{M}_t}\frac{D_n}{D}p_n(k_t)]k_s + \sum_{m\in\mathcal{M}_s}[p_m(k_s) - c_m]q_m(k_s)$$

over $f_s \geq 0$ subject to the demand $k_t = K_t^{RI}(\boldsymbol{f})$ for forward contracts for all large producers t. Profit-maximization yields the equilibrium forward quantity

$$k_s^{RI} = \frac{MD + 2M^2HM_s\frac{\psi}{z_s}}{M_sH + 2}, \; z_s = \sum_{m\in\mathcal{M}_s} b_m(\frac{D_m}{D})^2.$$

of producer s. We can then calculate the quantity-weighted average of the short-term prices in the M_s local markets that comprise the geographical footprint of regional monopoly s:

$$\frac{1}{M}\sum_{m\in\mathcal{M}_s}\frac{D_m}{D}p_m^{RI} = \frac{1}{M}\sum_{m\in\mathcal{M}_s}\frac{D_m}{D}\frac{a_m + c_m}{2} - \frac{1}{2M}\frac{z_sD + 2MHM_s\psi}{M_sH + 2}.$$

Comparing this average price with the average price in a spatially independent market design yields ambiguous results. Regional monopolies are still anti-competitive in the following sense

Proposition 7 *Merging two producers s and t into a larger unit u, such that $\mathcal{M}_u = \mathcal{M}_s \cup \mathcal{M}_t$, increases the quantity-weighted average of spot prices in the subset $\mathcal{M}_u$ of short-term markets if local markets are linked by a regional forward contract, but has no implications for prices in a spatially independent market.*

A merger reduces efficiency in the short-term market even if it does not affect market concentration in the local short-term market, but strategic interaction occurs in a regional forward market. Proposition 7 therefore suggests that competition authorities should look beyond the effects on ownership concentration in markets for produced goods when evaluating the competitive effects of mergers.

4.4. Oligopoly in the local short-term market

We extend the model with $M \geq 2$ symmetric markets to the case when there are $L \geq 2$ producers with market power in each local market, under the maintained assumption that all producers are active in one local market only.

In the spatially independent market design, the short-term price $p(k)$ depends on the aggregate forward quantity k sold by all producers in the local market. Forward quantities are perfect substitutes, so consumers buy all their forward contracts from the producer with the smallest forward price. Bertrand competition in the forward market drives the equilibrium forward price down to the marginal production cost, $f^I = c$. The large amount of forward contracts sold at this price implies that electricity is supplied at a price below marginal producers, $p^I < c$, in the short-term market. Producers might be collectively better off not selling any forward contracts, but as in Allaz and Vila (1993), zero forward contracting cannot be sustained as an equilibrium.

The increased price-sensitivity of forward demand under a regional forward contract drives the forward price even further down to

$$f^{RI} = c - \frac{M-1}{M}(c - p(\frac{k^{RI}}{M}))$$

in an interior equilibrium. This reduction in the equilibrium forward price implies:

Proposition 8 *Consider an electricity market with $M \geq 2$ symmetric local markets. Let there be $L \geq 2$ producers with market power in each local market, and assume that each producer is active in one local market. Linking the M local electricity markets through a regional forward contract that has a settlement price equal to the average of the short-term prices in those M markets, increases the symmetric equilibrium forward quantity k^{RI} sold in each local market by at least a factor M, compared to the benchmark k^I of spatially independent markets, $k^{RI} \geq Mk^I$. The inequality is strict if $\psi > 0$.*

As electricity is already priced below marginal cost c in the spot market, introducing a regional forward market reduces efficiency in this case by driving down the spot price of electricity even further. However, Bertrand competition in the forward market reduces the equilibrium forward price to an implausible level. One might want to consider a model in which switching costs or other transaction costs soften competition in the forward market. Based on the above result, we conjecture that regional forward contracting would increase efficiency in a market with sufficiently horizontally differentiated forward contracts.

4.5. Multiple trading periods in the forward market

In their seminal contribution, Allaz and Vila (1993) show that the quantity of electricity sold in the forward market increases with the number of trading periods in the forward market. Production becomes fully efficient in the limit when there are infinitely many trading periods. Increasing the number of trading periods has a pro-competitive effect also in our model, although the motive for forward contracting is different than in Allaz and Vila (1993).

Proposition 9 *Assume that there is one producer with market power in each local market. Under a spatially independent market design, more electricity is traded in the forward market if there are two trading periods for forward contracts instead of just one.*

Repeated interaction in the forward market enables market participants to internalize more of the efficiency benefits of forward contracting. The monopoly producer can always ensure the same profit if forward contracts are traded in two periods compared to one period by charging a forward price $\tilde{f}_1$ in period 1 that generates zero demand, $K_1^I(\tilde{f}_1) = 0$, for forward contracts in trading period 1. By revealed preference, $f_1^I < \tilde{f}_1$, the monopoly strictly benefits from introducing an additional trading period.[27] However, the effect on consumers is ambiguous. Tangerås and Wolak (2023) show that consumer profit is smaller under two-period trading of forward contracts compared to one-period trading if and only if $H \geq 3$ and $\frac{a}{\psi}$ is sufficiently large. Increased trade by the other consumers in trading period 1 then reduces the profit of consumer h. Consumers would be collectively better off by a market design with only one single trading period for forward contracts in that case.

V. CONCLUSIONS

A key problem with market performance in restructured electricity markets is the high degree of market concentration that sometimes arises when transmission constraints create local markets with one or a few large producers in each. Increased market concentration strengthens suppliers' incentives to exercise market power. Improving competition through entry or market integration is problematic in many jurisdictions because economic or political constraints represent barriers to large supplier entry or limit transmission capacity expansion.

We show that changes to market design can reduce exploitation of market power without supplier entry or network expansion. Specifically, a regional forward contract with a settlement price equal to 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 settle against the individual location-specific short-term prices.

"Equity-based" pricing under which consumers pay the quantity-weighted average of a set of locational marginal prices increases short-term prices compared to the case when consumers pay individual LMP prices for their electricity. However, this market rule is likely to facilitate retailer entry into more local markets by vertically integrated retailers. Regional retail prices reduce local consumers' efficiency benefits of signing retail contracts with local producers. They also mitigate a major source of risk retailers face in entering a local market where they do not own generation units: spatial price risk between where they own generation units and this local market. This spatial price risk has led many vertically integrated firms to focus their retailing efforts on the local markets where they own generation units to avoid such risk. Moreover, an effective entry deterrence strategy by vertically integrated retailers with generation units in the same local market as their retail customers, is to use their ability to exercise unilateral market power to spike the local wholesale price and effectively eliminate any retail profit margin a new entrant without local generation capacity could earn from selling retail electricity.[28] Requiring all retailers to purchase the wholesale electricity sold to

[27]By way of a similar argument, we conjecture that the monopoly producer would always benefit from introducing an additional trading period if there were already T trading periods for forward contracts.

[28]Consistent with such entry deterrence incentives, Wolak (2009) presents empirical evidence demonstrating that over his sample period, the four large vertically integrated retailers in the New Zealand wholesale electricity market concentrated their retailing activities in the regions where they owned generation units.

final consumers at a quantity-weighted average of all LMPs significantly limits the spatial price risk any supplier faces from entering any local market, which should increase the competitiveness of retail markets in particular.

Current discussion in Europe illustrates the policy relevance of our findings. Aggressive renewables policies across the European Union (EU) have significantly increased the cost of making generation schedules that emerge from the day-ahead market operational in real-time.[29] Transitioning to an LMP market design would eliminate the vast majority of these physical feasibility costs. The Agency for the Cooperation of Energy Regulators in the EU recently proposed a move in this direction by suggesting to split several EU member states into multiple bidding zones (ACER, 2022). Germany, for instance, could be divided into as many as five bidding zones under this proposal. Implementation of national bidding zone configurations ultimately resides with the individual EU member states. Major barriers to adopting appropriate locational pricing in these countries are fears that more granular prices increase consumers' costs of hedging electricity prices and the perceived unfairness of charging different wholesale prices to consumers at different locations in the transmission network. Such arguments received a lot of attention when the Swedish wholesale electricity market was divided into four bidding zones in 2011. Previously, Sweden had constituted a single bidding zone.

In a proposal for a reformed electricity market, the European Commission (2023) introduces so-called regional virtual hubs for the forward market. Our results suggest that dividing EU member states into multiple bidding zones, while allowing producers and consumers to write forward contracts based on the quantity-weighted average of those zonal prices, would indeed increase liquidity in the forward market and also reduce spot prices by improving local competition. Our model indicates that a single regional forward market would minimize consumers' spot market expenditures. However, an EU-wide forward contract would make it difficult for market participants to hedge spatial price risk. The efficient scope of a regional forward market would most likely balance the marginal benefit of improved competition against the marginal cost of increased spatial price risk.[30] The market design could address consumer spatial price risk by introducing complementary regional consumer prices. Charging retail prices based on the quantity-weighted average of zonal spot prices would also address equity concerns across consumers. A thorough analysis incorporating spatial price risk would require a model with uncertainty. We leave this topic for future research.

More generally, our results argue that introducing an LMP market where all relevant operating constraints are explicitly priced, all generation units are paid their locational marginal price, forward contracts clear against the quantity quantity-weighted average of LMPs, and all loads pay that quantity-weighted average for their consumption, can increase market efficiency relative to an LMP market where all suppliers and loads face

[29]ENTSO-E (2018) notes the annual costs of making day-ahead generation schedules feasible for real-time system operation in 2017 was more than 1 billion Euros in Germany, more than 400 million in the United Kingdom, and 80 million in Spain.

[30]Fundamental results from financial economics show that complete financial markets that enable agents to write contracts on all uncertainty, are efficient in otherwise well-functioning markets: see, for instance, Huang and Litzenberger (1988). Our results suggest that predictions about efficient makret completeness can be different under imperfect competition in the spot market.

their local price. Since the default LMP design with local prices is more efficient than any non-LMP market design, our results show that it is possible to increase market efficiency through locational pricing, while still ensuring liquid forward markets and equity-based consumer prices.

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