Unilateral Market Power in Financial Transmission Rights Auctions

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Abstract

This paper explores market participants' incentives to exercise unilateral market power in financial transmission rights (FTR) auctions. I present a model of strategic bidding in FTR auctions that illustrates how the standard market clearing mechanism for FTR auctions can facilitate substantial cross-path competition, limiting the profitability of demand reduction. Simulation evidence suggests that unilateral market power may contribute relatively little to persistent auction revenue shortfalls. These findings highlight potential adverse effects of proposed market reforms such as decentralized FTR sales and bidding-path restrictions.

Keywords: restructured electricity markets; congestion revenue; financial transmission rights; imperfect competition; multiunit auctions

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1 Introduction

Financial transmission rights (FTRs) are an important element of restructured electricity markets. Operators of restructured electricity markets in the United States (known as independent system operators or ISOs) collect congestion revenues of roughly $4B per year, or about 4% of wholesale electricity costs (Parsons, 2023). FTRs are forward claims on these revenues. While many FTRs are directly allocated to energy market participants, a large share are sold in complex auctions in which participants – including financial speculators – can potentially profit from strategic behavior. A robust empirical literature has established that purely financial participants consistently earn large trading profits in FTR auctions, raising concerns that strategic distortions could be significant.[1]

In this paper, I use economic theory to investigate the contribution of unilateral market power to so-called "auction revenue shortfalls." Building on the theory of imperfectly competitive financial markets (Rostek and Yoon, 2023), I show that the market clearing mechanism used in FTR auctions induces significant competitive pressure even when bidding activity is thinly dispersed across auction paths, weakening bidders' incentives to shade their bids. The main results suggest that in the context of a dense, real-world transmission network, rents from unilateral market power could be relatively insignificant, despite apparent market imperfections such as limited participation on some auction paths and a lack of explicit reserve prices. Well-documented auction revenue shortfalls may reflect the high costs of holding illiquid FTRs rather than insufficient competition.[2]

In a typical FTR auction, bidders submit downward-sloping demand schedules for quantities of transmission capacity on "paths" between network nodes. After receiving bids, the

[1] Estimates in the literature suggest that financial participants in FTR auctions earn trading profits on the order of $0.5B per year across all US ISOs. This includes approximately $60M/year in MISO (O'Keefe, 2024), $220M/year in PJM (Leslie, 2021), $50M/year in NYISO (Leslie, 2021), and $55M/year in CAISO (CAISO, 2019). To obtain the $0.5B dollar figure, I divide the sum of these figures by the average share of congestion revenues in these four markets among the seven ISOs (as reported in Parsons (2023)). FTRs are also referred to as congestion revenue rights (CRRs) or transmission congestion contracts (TCCs).

[2] Another potentially important form of strategic behavior involves the use of virtual bidding to influence the ex post value of FTRs (Ledgerwood and Pfeifenberger, 2013). I narrowly focus on market power to the exclusion of this and other forms of market manipulation which may be relevant to observed profits.

market operator allocates capacity across paths to maximize net revenue, subject to the constraint that all FTR allocations are *simultaneously feasible* with respect to the physical transmission constraints of the network. Due to this feature of the market, the residual supply curve faced by each bidder depends on the strategic behavior of bidders *throughout* the network, since bidders on different paths compete for capacity on common transmission elements. Thus, the *effective* level of competition faced by a bidder on any particular path can be large even if the number of bidders in direct competition for the same FTR is small.

Section 2 captures this intuition in a stylized model of an imperfectly competitive FTR auction. Because the market clearing mechanism used in the FTR auction generalizes the familiar uniform price auction, the well-known characterization of price impacts in uniform price auctions can be adapted to the context of the FTR auction. This reveals how bidders' incentives to exercise market power depend the structure of the transmission network, which mediates the strategic interaction of bidders on different paths. In a uniform price auction, bidders' price impacts depend on the level of competition and the convexity of rival bidders' preferences; in the FTR auction, bidders' price impacts depend on the level of competition and the convexity of preferences on all *strategically connected* FTR paths – those that share equilibrium binding constraints in common – with greater weight given to paths that are closer electrical substitutes. In real-world FTR auctions, nearly all FTR paths will be strategically connected, suggesting that effective levels of competition are likely to be high except in the most peripheral regions of the transmission network.

Section 3 illustrates the implications of the model numerically in the context of the six-node test network analyzed in Chao et al. (2000) and Deng et al. (2010). In this network, a "North" region with excess generation is linked to a "South" region with excess demand, resulting in congestion. Uncertainty over the level of future demand creates uncertainty over FTR payouts. Risk averse bidders compete to purchase FTRs while accounting for behavior of bidders throughout the entire transmission network. With three bidders on every FTR path, bidders behave as aggressively as if they faced 11.8 rival bidders in decentralized, path-by-path FTR auctions.

Empirically validating the model is challenging because detailed information on real-world transmission networks is generally unavailable to researchers. For instance, the key object governing the extent of cross-auction strategic interaction is the power transfer distribution factor (PTDF) matrix, which summarizes the structure of the transmission network. This matrix cannot be reliably constructed from publicly available information.[3] Lack of information on network constraints and the PTDF matrix precludes the use of structural methods to recover bidders' marginal valuations (e.g., Kastl, 2011), as such methods require complete knowledge of the market clearing procedure to simulate supply elasticities.

Nevertheless, the analysis provides several clear implications for potential market reforms to address auction revenue shortfalls. If market power rents are small, then auction revenue shortfalls may primarily reflect convexity in bidders' preferences (from risk aversion, inventory costs, or other sources). Proposed reforms that would decentralize FTR sales could significantly reduce competition without mitigating the underlying source of underpricing. On the other hand, reforms that maintain a centralized auction while prohibiting bidding on specific types of contract "paths" could inadvertently undermine competition. If such reforms are justified on other grounds, then the analysis suggests how they might be structured to best preserve the pro-competitive features of existing auction mechanisms. I discuss the policy implications of the analysis in greater detail in the conclusion.

1.1 Related Literature

ISOs accrue congestion revenues due to the use of locational marginal pricing (Schweppe et al., 1988). Hogan (1992) proposed that ISOs issue FTRs funded with congestion revenues. All seven restructured energy markets in the United States issue FTRs, typically through a combination of direct allocation and auctions.

[3]Detailed transmission network information is considered Critical Energy Infrastructure Information by the US federal government and is subject to strict non-disclosure policies. Consequently, research on large-scale power systems is typically limited to "synthetic" grids of varying complexity.

As FTR auction markets have matured, a significant empirical literature has documented across a variety of markets and over a long period of time that auction prices for FTRs tend to be "underpriced" relative to ex post congestion revenues (Bartholomew et al., 2003; Adamson and Englander, 2005; CAISO, 2016; Olmstead, 2018; Opgrand et al., 2022). Some papers have emphasized the potential for risk premia to explain underpricing (e.g., Bartholomew et al., 2003; Adamson and Englander, 2005; Baltadounis et al., 2017), while others have focused on private information (Leslie, 2021) or interactions with other market institutions (Opgrand et al., 2022). Relative to the empirical literature, my primary contribution is a novel explanation for why unilateral market power specifically may contribute little to underpricing.

The finding of persistent underpricing has motivated a robust policy debate in recent years, with some observers asserting that FTR auctions should be eliminated in favor of more extensive direct allocation (CAISO, 2017; Parsons, 2020; Monitoring Analytics, 2022) and others arguing that existing auction mechanisms provide important benefits due to the unique benefits of FTRs for hedging congestion risk (Bushnell et al., 2018; FERC, 2022). My analysis is broadly consistent with the latter perspective, but provides insights into how specific policy proposals (such as bidding restrictions) can promote competitive bidding.

In order to analytically characterize market power in an FTR auction, I adapt a workhorse model of supply function competition from the literature on imperfectly competitive financial market (Vives, 2008; Lambert et al., 2018; Rostek and Yoon, 2023). While this approach is effective for the purpose of this paper, the use of supply function equilibria has long been considered intractable for many applications in nodal power markets (including FTR markets), leading to the use of Cournot equilibria and related approaches such as conjectured supply function equilibria (Day et al., 2002). For instance, Bautista Alderete (2005) builds a model of conjectured supply function equilibria in FTR auctions. In comparison to Bautista Alderete (2005), my primary focus is the microfoundations of market power rather than computational tractability, making a supply function approach essential. Deng et al.

(2010) also studies the implications of simultaneous feasibility constraints for prices in FTR auctions, but in an environment with perfectly competitive bidding and flat demands.

Imperfect competition in deregulated energy markets has attracted significant attention both theoretically (e.g., Joskow and Tirole, 2000; Borenstein et al., 2000) and empirically (e.g., Wolfram, 1999; Borenstein et al., 2002; Hortaçsu and Puller, 2008), but relatively little of this analysis has focused on the implications of market microstructure in realistic nodal power markets. One notable exception is Mercadal (2022), which develops an empirical extension of Hortaçsu and Puller (2008)'s bidding model to the context of nodal power markets with binding transmission constraints. In comparison, I characterize bidders' residual demand curves analytically, but without simplifying the transmission network to the same extent as Joskow and Tirole (2000). In related work, several authors have analyzed the role of financial participants in energy markets (e.g., Birge et al., 2018; Jha and Wolak, 2023; Mercadal, 2022). Notably, Ledgerwood and Pfeifenberger (2013) and Birge et al. (2018) raise the possibility that financial speculators may strategically submit virtual bids in order to influence the value of their FTR portfolios. I do not consider this possibility here.

2 Market power in FTR auctions

Consider an ISO that manages a grid with N nodes linked by M transmission constraints. Suppose there are $K \leq \frac{1}{2}N\left(N-1\right)$ distinct contract paths, each with a source node $src_k \in N$ and sink node $snk_k \in N$. Each year, a congestion price vector $\zeta \in \mathbb{R}^M$ and a power transfer vector $Q \in \mathbb{R}^K$ are realized from a distribution F. After any directly allocated FTRs $\tilde{Q} \in \mathbb{R}^K$ are funded, the ISO collects residual congestion revenues $R = \left(Q - \tilde{Q}\right)' Z\xi$, where $Z \in \mathbb{R}^{K \times M}$ is a power transfer distribution factor (PTDF) matrix.

The ISO allocates residual congestion revenues in an FTR auction. In a standard FTR auction, bidders submit downward-sloping demand schedules for FTR capacity on particular contract paths. Suppose J_k bids are submitted on FTR path k, and let $q_{kj}^{-1} : \mathbb{R} \to \mathbb{R}$ denote the inverse demand function submitted by the jth bidder on k.[4] After receiving bids on all contract paths, the ISO awards FTRs in order to maximize the "economic value" of cleared bids (i.e., the willingness-to-pay expressed by the inverse demands), subject to transmission constraints:

$$\begin{aligned} \max_{\{q_{kj}\}} \quad & \sum_{k \in K} \sum_{j \in J_k} \int_0^{q_{kj}} q_{kj}^{-1}(s)\, ds \\ \text{s.t.} \quad & P_m^L \leq \sum_{k \in K} \sum_{j \in J_k} z_{km} q_{kj} \leq P_m^U \quad \forall\, m \in M \end{aligned} \tag{1}$$

In this expression, $P_m^U \in \mathbb{R}$ denotes the maximum powerflow on transmission element m and $P_m^L \in \mathbb{R}$ the minimum (i.e., the maximum powerflow in the reverse direction) after accounting for any directly allocated FTRs. z_{km} is the previously introduced power transfer distribution factor, which represents the powerflow induced on constraint m when one megawatt (MW) of power is injected at $src_k \in N$ and withdrawn at $snk_k \in N$. An allocation of FTRs which satisfies the constraints in (1) is said to be *simultaneously feasible*.

Lemma 1 establishes a well known fact regarding market clearing in the FTR auction. In particular, the path k FTR price is a linear combination of the shadow prices associated with any binding transmission constraints in (1).

Lemma 1. *The path k clearing price in (1) is $p_k = Z_k' \xi = Z_k' \left(\xi^L - \xi^U\right)$, where $\xi^L \geq 0$ and $\xi^U \geq 0$ are the vectors of Lagrange multipliers corresponding to the constraints in (1).*

The FTR auction generalizes the familiar uniform price auction. For example, in a degenerate transmission network with two nodes and a single transmission constraint m having $P_m^L = 0$, (1) coincides with the auctioneer's problem in a standard uniform price auction with a reserve price of zero. In a more complex transmission network, (1) implies that the ISO's problem is equivalent to choosing a subset of binding constraints, and then

[4] For the purpose of exposition, I assume that q_{kj}^{-1} is smooth and strictly downward sloping. In practice, bids are discrete. Negative FTR quantities can be obtained by selling previously allocated FTRs or by purchasing "counterflow" (i.e., reverse-path) FTRs.

conducting simultaneous, virtual uniform price auctions for capacity on those constraints. The price of a path k FTR is the sum of the prices that must be paid in latent constraint auctions to obtain sufficient network capacity to inject 1MW of power at src_k and withdraw it at snk_k. Thus, each FTR bid conveys many implicit bids for constraint-level capacity.

In the next section, I characterize the Bayes Nash equilibrium of an FTR auction game. Before doing so, it is helpful to introduce additional notation. In the solution to (1), let $\tilde{M}^U$ denote the subset of constraints that bind "upwards," $\tilde{M}^L$ the subset of constraints that "downwards," and $\tilde{M}$ the union of $\tilde{M}^U$ and $\tilde{M}^L$. By complementary slackness, $p_k = \tilde{Z}_k' \tilde{\xi}$ where $\tilde{Z}_k$ and $\tilde{\xi}$ are the subvectors of Z_k and ξ corresponding to $\tilde{M}$.

2.1 Price impacts under simultaneous feasibility

In a uniform price auction, the market clearing price is the price that exhausts the auctioneer's supply of the good (provided that demand exceeds supply at the reserve price). In an FTR auction, by contrast, the market clearing price is determined by the solution to (1). Bidders with market power anticipate their *price impact*s, or the elasticity of market clearing prices with respect to their bids (Rostek and Yoon, 2023). In this section, I formally characterize bidders' price impacts when market prices are determined according to (1).

For simplicity, suppose that each bidder in the FTR auction submits one and only one bid, and that no bidder has any private information regarding the ex post value of FTRs.[5] Bidder kj is the jth bidder on path k. Her expected utility is

$$u_{kj}\left(q_{kj}; p\right) = v_{kj}\left(q_{kj}\right) - p_k q_{kj} \tag{2}$$

where q_{kj} is the quantity of FTR k awarded to bidder kj, $v_{kj} : \mathbb{R} \to \mathbb{R}$ is a smooth valuation function having $v_{kj}'' = -c_{kj}$ for some constant $c_{kj} > 0$, and p_k is the price of FTR k. With

[5] In reality, bidders submit bids on many different FTRs simultaneously, and some bidders may have superior information for forecasting FTR payouts (Leslie, 2021). I discuss the implications of multi-path bidding for my main results later in the text. It appears that private information can be incorporated into the model in the standard way (Rostek and Yoon, 2023), although I do not pursue this approach here.

perfect information, optimal bidding implies that for any clearing price p_k, the marginal benefit to kj of another unit of FTR k must be equal to its marginal cost:

$$v'_{kj}(q_{kj}) = p_k + q_{\kappa j}(p_k)\,\psi_{kj} \tag{3}$$

where $\psi_{kj} = \frac{\partial p_k}{\partial q_{kj}}$ is the *price impact* of bidder kj on the price of FTR k. When $\psi_{kj} = 0$, bidder kj bids her marginal valuation – kj has no incentive to exercise market power. If $\psi_{\kappa j} > 0$ and $q_{\kappa j}(p_k) > 0$, optimal bidding exhibits *demand reduction* – bidder kj requests inefficiently few units at each price level, shifting demand inwards and reducing prices.

In a Bayes Nash equilibrium (BNE) of the FTR auction game, each bidder kj submits an inverse demand function that satisfies (3), and prices are given by Lemma 1. It is clear from the auctioneer's problem (1) that bidders on any particular FTR path must account for the strategies of bidders on other FTR paths due to simultaneous feasibility. In order to characterize the extent of *cross-path strategic interaction* induced by simultaneous feasibility, I introduce a notion of connectivity from graph theory.

Definition 1. Let $\tilde{M} \subset M$. The *FTR graph induced by* $\tilde{M}$ is an undirected graph with vertices for each FTR path in K and edges linking any two vertices k and k' such that $d_{kk'} = \max_{m\in\tilde{M}} |J_k Z_{km}|\,|J_{k'} Z_{k'm}|$ is strictly greater than zero. FTR paths k and k' are *strategically connected under* $\tilde{M}$ if they belong to the same component of this graph.

Proposition 1 uses this definition to formally relate bidder kj's price impact ψ_{kj} to the strategies of competing bidders. Before stating this result, some additional notation is useful. For any path k, let $\mathcal{C}_k$ denote the subset of FTR paths k' that are strategically connected to k under $\tilde{M}$, and $\tilde{M}_k$ the subset of $\tilde{M}$ that defines $\mathcal{C}_k$ (i.e., $|J_k Z_{km}|\,|J_{k'} Z_{k'm}| > 0$ for some k and k' in $\mathcal{C}_k$). D_k denotes an $\left|\tilde{M}_k\right| \times \left|\tilde{M}\right|$ matrix of zeros and ones such that $D_k \tilde{Z}_k$ is the subvector of $\tilde{Z}_k$ corresponding to $\tilde{M}_k$.

Proposition 1. *Suppose $\tilde{M}$ is the subset of binding transmission constraints in a BNE of the FTR auction game. Then:*

$$\psi_{kj} = \frac{-c_{kj} + 2x_k + \sqrt{c_{kj}^2 + 4x_k^2}}{2} \tag{4}$$

is the equilibrium price impact of bidder kj, where $x_k = \tilde{Z}_k' D_k' \Psi_k D_k \tilde{Z}_k$ and Ψ_k is defined by:

$$\Psi_k^{-1} = \sum_{k' \in \mathcal{C}_k} \sum_{j' \in J_{k'}} \left\{ \frac{c_{kj} + 2x_{k'} + \sqrt{c_{kj}^2 + 4x_{k'}^2}}{2} \right\}^{-1} D_k \tilde{Z}_{k'} \tilde{Z}_{k'}' D_k' \tag{5}$$

Proposition 1 is the main result of the paper. The significance of (4) is to clarify the manner in which bidder kj accounts for the relevance of particular competing bids. Specifically, (5) implies that bidder kj's equilibrium bidding strategy will depend only on competing bids on strategically connected paths. Ψ_k is the matrix equivalent of a geometric mean of the slopes of the bids on strategically connected paths, capturing the aggregate elasticity of demand in the associated virtual constraint auctions. Bidder kj's strategy will depend most heavily on the localized elasticities on constraints for which $\left|\tilde{Z}_{km}\right|$ is largest.

One important implication of Proposition 1 is that, in general, market power will tend to be lower in an FTR auction than if FTR capacity were sold in decentralized, path-by-path uniform price auctions. This type of mechanism can be re-cast as an FTR auction in which Z is the identity matrix and P^U and P^L correspond to fixed volumes of FTR capacity for each path. Holding fixed participation, such a mechanism results in weakly smaller inverse elasticities x_k on each path k, and hence weakly higher price impacts ψ_{kj} for each kj.

In a typical uniform price auction, price impacts are positive and declining in the number of bidders. In the FTR auction, price impacts are also positive, but the effects of a marginal bidder are more nuanced. If the set of binding constraints were fixed in advance, then ψ_{kj} would not only decline in the number of bidders on path k but also in the number of bidders on any strategically connected paths $k' \neq k$. In this sense, cross-path strategic interaction tends to reduce market power. In practice, however, the set of binding constraints in (1) can adjust in response to entry, potentially introducing non-monotonicity into the relationship between ψ_{kj} and entry on k and other paths. These results are implied by Corollary 1 below.

Corollary 1. *Let $J^0 = (J_1, \ldots, J_K)$ denote an entry vector, and $J^1 = (J_1, \ldots, J_{k'} + 1, \ldots, J_K)$ the entry vector when an additional bidder submits a bid on path k'. Let $\tilde{M}^0$ and $\tilde{M}^1$ denote the the induced binding constraints under J^0 and J^1, respectively. Then:*

1. $\psi_{kj}\left(J^0; \tilde{M}^0\right)$ *and* $\psi_{kj}\left(J^1; \tilde{M}^1\right)$ *are positive*
2. $\psi_{kj}\left(J^1; \tilde{M}^0\right) - \psi_{kj}\left(J^0; \tilde{M}^0\right)$ *is positive if $k' \in C_k$ and zero otherwise*
3. $\psi_{kj}\left(J^1; \tilde{M}^1\right) - \psi_{kj}\left(J^0; \tilde{M}^0\right)$ *can be positive or negative*

Proofs of Proposition 1 and Corollary 1 are provided in Appendix A.

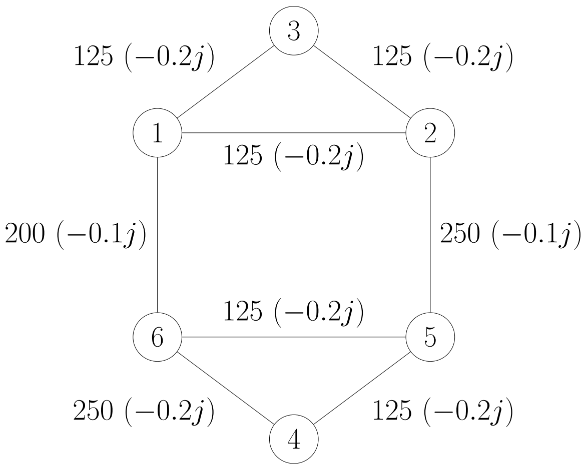
Since one would expect the PTDF matrix Z to be relatively dense in a full-scale power network, Corollary 1 suggests that bidders in real-world FTR auctions likely face a high level of effective competition, even if marginal impacts are difficult to sign due to possible adjustments in $\tilde{M}$. In reality, participants in FTR auctions often bid on many FTR paths simultaneously. Thus, the level of effective competition may be more closely related to the total number of competing firms rather than the total number of bids, but the number of competing firms is often large. Although I do not attempt to perform a comprehensive empirical validation of the model in this paper, this prediction is consistent with the stylized fact that bidders in FTR auctions who face no direct competition frequently make losses.[6]

3 Numerical illustration

In this section, I investigate the market design implications of the model in Section 2 by comparing equilibrium outcomes of a simulated FTR auction to equilibrium outcomes of an alternative mechanism in which FTR capacity is sold path-by-path.

[6]For instance, data from the Midcontinent ISO FTR auction analyzed in O'Keefe (2024) indicates that roughly half of bids on FTR paths with only a single bidder are loss-making.

Figure 1: Six-Node Test Case



Wholesale Bids (Normal Scenario)

Node	Type	Supply	Demand
1	Gen	$10 + 0.05q$	–
2	Gen	$15 + 0.05q$	–
3	Load	–	$37.5 - 0.05q$
4	Gen	$42.5 + 0.025q$	–
5	Load	–	$75 - 0.1q$
6	Load	–	$80 - 0.1q$

I focus on the six-node test case analyzed in Chao et al. (2000) and Deng et al. (2010). Figure 1 presents a schematic depiction of the network along with node-level supply and demand bids. Nodes 1, 2, and 3 constitute a "North" region with excess generation capacity, while nodes 4, 5, and 6 constitute a "South" region with excess demand. The network diagram indicates the branch capacities (in MW) and admittances (per unit).[7] The supply and demand bids reflect exogenous supply and demand for power in the wholesale market.

Following Deng et al. (2010), I assume that the intercepts of the wholesale demand bids can be 25% higher or 25% lower with known probability, resulting in uncertainty over future congestion prices. Table 1 indicates the assumed probability of each demand scenario and resulting node-level locational marginal prices (LMPs), which determine FTR payoffs, along with the net congestion revenues earned by the market operator under each scenario. Expected congestion revenues are $9,048.86.

The main purpose of this exercise is to compare the FTR auction described in Section 2 with a benchmark mechanism in which the market operator holds simultaneous uniform price auctions for each distinct FTR path. To implement the latter, the market operator must first determine a quantity of FTRs to be sold on each path. To facilitate comparison,

[7] I do not impose the additional 340MW North-South flowgate constraint discussed in Chao et al. (2000). It appears that this constraint is imposed in Deng et al. (2010), at least for the "Normal" scenario, although this is not explicitly discussed in the text.

Table 1: Six-Node Test Case LMPs and Congestion Revenue

Scenario	Prob.	LMP-1	LMP-2	LMP-3	LMP-4	LMP-5	LMP-6	Revenue
Normal	0.6	23.03	33.55	28.29	46.71	41.45	51.97	$7368.42
Load +25%	0.2	22.92	35.42	36.04	48.96	57.08	65.83	$18203.12
Load −25%	0.2	21.20	28.25	24.73	37.07	33.54	40.59	$4935.90

I focus on the allocation in which the quantity of FTRs sold on each path coincides with the quantity allocated on that path in the equilibrium of the FTR auction game.[8]

Rights are purchased by symmetric, risk averse financial speculators with CARA preferences. Each speculator bids on one and only one FTR. In (2), I assume that the marginal valuation function is $v_{kj}(q) = E[\pi_k]q - \frac{\lambda}{2}q^2 Var(\pi_k)$ where π_k is the per-unit payoff of a path k FTR and $\lambda > 0$ is a risk preference parameter common to all bidders. π_k is defined the realized difference between the LMP at the sink node and the LMP at the source node.

Table 2 presents the market operator's revenues under both mechanisms when there are $J_k = 3$ distinct bidders on each FTR path.[9] The standard FTR auction recovers 95.7% of expected congestion revenues, while the path-wise uniform price benchmark recovers only 91.7%. The table decomposes the auction revenue shortfalls into risk premia demanded by the bidders and market power rents. Since bidders hold identical portfolios in either case, risk premia are the same for each mechanism. However, the FTR auction reduces market power rents by 96.9% as compared with the uniform price benchmark. In a larger and more realistic network, this effect would likely be even larger.

The striking difference in market power rents in Table 2 is a direct result of the cross-auction competitive linkages induced by the constraints in (1). In this network, there are 15 distinct FTR paths. All fifteen paths are strategically connected for the relevant range

[8] In practice a market operator seeking to implement path-wise uniform price auctions would need to select an allocation based on some other criteria. In this respect, the benchmark mechanism does not represent a realistic alternative to the FTR auction. Of particular interest are "revenue adequate" allocations, for which payoffs are weakly lower than congestion revenues in any state of the world (Hogan, 1992).

[9] This assumption simplifies comparison of the mechanisms. With quadratic preferences and common information, equilibria of the uniform price auction game only exist if there are three or more bidders (Rostek and Yoon, 2023). In contrast, equilibria of the FTR auction can exist with fewer bidders than three bidders on some paths, provided that Ψ_k is invertible in Proposition (1).

Table 2: Auction Results by Selling Mechanism

	Path-wise Unif. Auctions	Standard FTR Auction
Operator Revenue	8310.70	8643.44
expected value of FTRs	9048.86	9048.86
risk premia	369.08	369.08
market power rent	369.08	36.34
Operator Revenue / Expected Value	0.9184	0.9552

of parameters. The first two columns of Table 3 indicate that the price impact ψ_{kj} is uniformly lower across auction paths for bids in the FTR auction as compared with bids in the benchmark mechanism. To illustrate the significance of this difference, the third column indicates the number of bidders that would be required for the uniform price auction to deliver the same price impact as the FTR auction (relaxing the natural integer constraint on the number of bidders). This shows that, on average, bidders in the FTR auction bid as competitively as if they faced 11.8 directly competing bidders in a uniform price auction.

These results depend crucially on the convexity of bidders' valuations, which is determined by bidders' risk preference λ and the variance of each FTR $Var(\pi_k)$. In the limit as $\lambda \to 0$ or as $Var(\pi_k) \to 0$ for all k, bidders' marginal valuations converge towards the expected value of each FTR, and the difference in market power rents between the FTR auction and the benchmark mechanism collapses to zero. Conversely, when λ is larger or the variance of FTR payoffs is greater, bidders' demand greater risk premia, increasing the elasticity of the residual supply curves that bidders face. In response, bidders' behave more aggressively, and the difference in market power rents across mechanisms widens.

Higher levels of participation help to reduce shortfalls in the FTR auction, not only through decreased price impacts but also through reduced convexity costs. When there are more bidders, equilibrium position sizes shrink, reducing risk premia. As $J_k \to \infty$ for all k, bidders' marginal valuations converge towards the expected value of each FTR, and both risk premia and market power rents fall to zero. To compare these effects, Table 4

Table 3: Price Impacts by Path

FTR	Path-wise Unif. Auctions	Standard FTR Auction	Equivalent # Unif. Bidders
1-2	0.00155	0.00058	4.7
1-3	0.00573	0.00075	9.6
1-4	0.00607	0.00070	10.6
1-5	0.02662	0.00111	26.1
1-6	0.02826	0.00111	27.4
2-3	0.00261	0.00060	6.4
2-4	0.00159	0.00053	5.0
2-5	0.01715	0.00095	20.0
2-6	0.01739	0.00096	20.1
3-4	0.00404	0.00067	8.0
3-5	0.00785	0.00098	10.0
3-6	0.00978	0.00098	12.0
4-5	0.01365	0.00100	15.7
4-6	0.01184	0.00102	13.7
5-6	0.00097	0.00060	3.6

decomposes the average revenue impact of a marginal bidder when $J_k = 3$ on each path, separating the effects of changes in quantities from changes in bidders' strategies. In this example, increased revenue from the change in bidding strategies alone (via price impacts on k and k') contributes only 17.6% of the average increase in auction revenue. This suggests that policies that encourage greater auction participation may be beneficial even if bidding is currently close to competitive levels.

4 Conclusion

Persistent underpricing in FTR auctions raises important questions for the design of restructured electricity markets. In this paper, I investigate the contribution of unilateral market power to underpricing. I use a simple theoretical model to demonstrate that the market clearing mechanism used in FTR auctions can facilitate high levels of cross-path competition, which can significantly dampen bidders' incentives to exercise market power. The numerical model presented in Section 3 suggests that in an FTR auction, market power rents may contribute relatively little to auction revenue shortfalls in comparison to any sources of convexity in FTR bidders' valuations (such as risk premia or inventory costs).

Today, most ISOs directly allocate some FTRs to load serving entities (LSEs), while selling only "residual" FTRs in the FTR auction. Some observers have suggested eliminating the FTR auction and instead directly allocating 100% of FTR capacity to LSEs. Individual LSEs could then choose to sell their FTRs in a decentralized fashion. The analysis suggests that by breaking the strategic linkages across auctions, decentralization could significantly increase the scope for speculative buyers to extract market power rents. Anticipating this, LSEs would be incentivized to hold larger FTR portfolios, which could be inefficient.[10]

Another potential policy response to persistent auction revenue shortfalls is the elimination of bidding on FTR paths that are perceived to be vulnerable to strategic bidding. This approach was taken by the California ISO in 2018, which banned bidding on so-called "non-deliverable" FTR paths. The framework in this paper suggests that this policy could have exacerbated market power rents on the remaining paths, since bidders on non-deliverable FTR paths exert downwards pressure on price impacts elsewhere. However, the model presented here sets aside many other forces relevant to the CAISO intervention, such as endogenous entry. I leave the empirical evaluation of CAISO's reforms for future work.

Apart from these specific policies, the simulation results suggest that policy interventions to encourage greater participation can deliver significant improvements in auction revenue even if market power rents are currently modest. When more bidders participate, aggregate congestion revenue risk and inventory costs can be dispersed more widely, improving allocative efficiency and reducing costs. Potential policy interventions that could encourage greater participation include improved transparency and greater standardization across ISOs to reduce the cost of bidding. More controversially, ISOs could consider relaxing collateral requirements for FTR bidders.[11] ISO integration could also be beneficial.

[10] For example, if LSEs are more risk averse than speculators, it may be socially efficient for LSEs to sell risky FTRs to speculators at "low" prices that are reflective of speculators' disutility from risk.

[11] The potential benefits of such a policy would need to be weighted against the costs of increased counterparty risk for the ISO, which falls outside the model presented here.

Table 4: Marginal Bidder Revenue Impact

	Mean	SD
Δ Risk Premia	-7.65	5.07
Δ Market Power Rent	-1.63	0.71
from quantity re-allocation	0.01	0.38
from price impact adjustments	-1.63	0.77
Δ Operator Revenue	9.27	5.59

Finally, my findings highlight the importance of separating the specific issue of market power in FTR auctions from the general issue of whether congestion revenue management practices are socially optimal. Even if trading profits earned by financial speculators do not reflect the exercise of market power, the question of whether the benefits that LSEs derive from the sale of FTRs to speculators exceed shortfalls remains unanswered. Conversely, if these benefits are sufficiently large relative to shortfalls, even large market power rents could be acceptable to a benevolent social planner in a second-best world.

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A Model details and proofs

Proof of Lemma 1

The Lagrangian of the auctioneer's problem is:

$$L = \sum_{k\in K}\sum_{j\in J_k}\int_0^{q_{kj}} q_{kj}^{-1}(s)\,ds - \sum_{m\in M}\xi_m^U\left(K_m^U - \sum_{k\in K}\sum_{j\in J_k} z_{km}q_{kj}\right) - \sum_{m\in M}\xi_m^L\left(\sum_{k\in K}\sum_{j\in J_k} z_{km}q_{kj} - K_m^L\right)$$

In this expression, the first order condition with respect to q_{kj} is:

$$q_{kj}^{-1}(q_{kj}) - \sum_{m\in M} z_{km}\left(\xi_m^U - \xi_m^L\right) = 0$$

This implies that bidder kj is awarded all units for which she bids strictly greater than $\sum_{m\in M} z_{km}\left(\xi_m^U - \xi_m^L\right)$. Thus, $p_k = \sum_{m\in M} z_{km}\left(\xi_m^U - \xi_m^L\right)$ can be interpreted as the stop out price of a uniform price auction. Since all bids are smooth and strictly downward sloping, there is no rationing; p_k is the market clearing price.

Proof of Proposition 1

From Lemma 1, we know that:

$$p_k = \tilde{Z}_k'\tilde{\xi}$$

where $\tilde{\xi}$ the subvector of constraint shadow prices corresponding to $\tilde{M}$. Moreover, $\tilde{\xi}$ must be a solution to the system of equations defined by $\sum_\kappa\sum_j z_{km}q_{kj}\left(\tilde{Z}_k'\tilde{\xi}\right) = \tilde{P}_m$ where $\tilde{P}_m = P_m^U$ if $m \in \tilde{M}^U$ and $\tilde{P}_m = P_m^L$ if $m \in \tilde{M}^L$. In matrix form, the system of binding constraints is:

$$q_{kj}\tilde{Z}_k + \sum_{k'j'\neq kj} q_{k'j'}\left(\tilde{\xi}'\tilde{Z}_{k'}\right)\tilde{Z}_{k'} = \tilde{P}$$

If the FTR graph has multiple components, this system is separable across them. So we can focus on the subsystem associated with k:

$$q_{kj}D_k\tilde{Z}_k + \sum_{k'j'\neq kj\colon\, k'\in\mathcal{C}_k} q_{k'j'}\left(\tilde{\xi}'D_k'D_k\tilde{Z}_{k'}\right)D_k\tilde{Z}_{k'} = D_k\tilde{P}$$

Differentiating with respect to q_{kj} gives:

$$D_k\tilde{Z}_k + \sum_{k'j'\neq kj\colon\, k'\in\mathcal{C}_k} \frac{\partial q_{k'j'}\left(\tilde{\xi}'D_k'D_k\tilde{Z}_{k'}\right)}{\partial p_{k'}}\tilde{Z}_{k'}'D_k'\frac{\partial D_k\tilde{\xi}}{\partial q_{kj}}D_k\tilde{Z}_{k'} = 0$$

And therefore:

$$\left(\sum_{k'j'\neq kj\colon\, k'\in\mathcal{C}_k} \frac{\partial q_{k'j'}\left(\tilde{\xi}'D_k'D_k\tilde{Z}_{k'}\right)}{\partial p_{k'}}D_k\tilde{Z}_{k'}\tilde{Z}_{k'}'D_k'\right)\frac{\partial\tilde{\xi}}{\partial q_{kj}} = -D_k\tilde{Z}_k \tag{6}$$

By definition, $\psi_{kj} = \frac{\partial p_k}{\partial q_{kj}}$. Then clearly:

$$\psi_{kj} = \tilde{Z}_k'D_k'\frac{\partial D_k\tilde{\xi}}{\partial q_{kj}} \tag{7}$$

If (6) admits a solution, then substituting this solution into (7) gives:

$$\psi_{kj} = \tilde{Z}_k'D_k'\left(\Psi_k^{-1} + \frac{\partial q_{kj}\left(\tilde{\xi}'\tilde{Z}_k\right)}{\partial p_k}\tilde{Z}_k\tilde{Z}_k'\right)^{-1}D_k\tilde{Z}_k$$

where $\Psi_k^{-1} = -\sum_{k'j'\neq kj\colon\, k'\in\mathcal{C}_k}\frac{\partial q_{k'j'}\left(\tilde{\xi}'D_k'D_k\tilde{Z}_{k'}\right)}{\partial p_{k'}}D_k\tilde{Z}_{k'}\tilde{Z}_{k'}'D_k'$. From the optimality of bidding, the implicit function theorem implies:

$$q_{kj}'\left(p_k\right) = -\left\{c_{kj} + \psi_{kj}\right\}^{-1}$$

Therefore:

$$\psi_{kj} = \tilde{Z}_k' D_k' \left(\Psi_k^{-1} - \{c_{kj} + \psi_{kj}\}^{-1}\right)^{-1} D_k \tilde{Z}_k$$

By appealing to the Woodbury matrix identity, we can show:

$$\psi_{kj} = x_k - \left(-c_{kj} - \psi_{kj} + x_k\right)^{-1} x_k^2$$

Solving this equation for ψ_{kj} yields (4). (5) follows by symmetry.

Proof of Corollary 1

For 1., note that $x_k > 0$ by positive definiteness of Ψ_k. Then $c_{kj} > 0$ implies $\sqrt{c_{kj}^2 + 4x_k^2} \geq |-c_{kj} + 2x_k|$, and therefore $\psi_{kj} > 0$.

For 2., the case in which $k' \notin \mathcal{C}_k$ is immediate. For the case in which $k' \in \mathcal{C}_k$, monotonicity of ψ_{kj} in x_k implies that it will suffice to show that $x_k^1 < x_k^0$. To this end, define the function $F : \mathbb{S}_+^{|\tilde{M}^0|} \times \mathbb{Z}_+ \to \mathbb{S}_+^{|\tilde{M}^0|}$

$$F\left(\Psi; J_{k'}\right) = \Psi - g\left(\Psi; J_{k'}\right)$$

where $g : \mathbb{S}_+^{|\tilde{M}^0|} \times \mathbb{Z}_+ \to \mathbb{S}_+^{|\tilde{M}^0|}$ is given by:

$$g\left(\Psi; J_{k'}\right) = \frac{1}{2}\left(\sum_{k'' \in \mathcal{C}_k} \sum_{j'' \in J_{k''}} \left\{c_{k''j''} + 2\tilde{Z}_{k''}' \Psi \tilde{Z}_{k''} + \sqrt{c_{k''j''}^2 + 4\left(\tilde{Z}_{k''}' \Psi \tilde{Z}_{k''}\right)^2}\right\}^{-1} \tilde{Z}_{k''} \tilde{Z}_{k''}'\right)^{-1}$$

Inspection of g reveals two useful properties, summarized in the Lemma below.

Lemma 2. *[Monotonicity of g] g satisfies the following properties:*

1. $g\left(\Psi; J_{k'} + 1\right) < g\left(\Psi; J_{k'}\right)$ *in the positive semidefinite (psd) order*

2. $g\left(\Psi'; J_{k'}\right) < g\left(\Psi; J_{k'}\right)$ *in the psd order if* $\Psi' > \Psi$ *in the psd order*

By construction, $F\left(\Psi^0; J_{k'}^0\right) = 0$ and $F\left(\Psi^1; J_{k'}^1\right) = 0$. Observe that:

$$F\left(\Psi^1; J_{k'}^1\right) = \left\{F\left(\Psi^1, J_{k'}^1\right) - F\left(\Psi^1, J_{k'}^0\right)\right\} + \left\{F\left(\Psi^1, J_{k'}^0\right) - F\left(\Psi, J_{k'}^0\right)\right\} + F\left(\Psi, J_{k'}^0\right)$$

and therefore:

$$0 = \left\{F\left(\Psi^1, J_{k'}^1\right) - F\left(\Psi^1, J_{k'}^0\right)\right\} + \left\{F\left(\Psi^1, J_{k'}^0\right) - F\left(\Psi, J_{k'}^0\right)\right\}$$

The first property in Lemma 2 implies that $F\left(\Psi^1; J_{k'}^1\right) - F\left(\Psi^1; J_{k'}^0\right)$ is positive definite. But then $F\left(\Psi^1, J_{k'}^0\right) - F\left(\Psi^0, J_{k'}^0\right)$ must be negative definite. But the second property in Lemma 2 implies that $F\left(\Psi, J_{k'}\right)$ is strictly increasing in the psd order as Ψ increases in the psd order; hence, $\Psi^1 < \Psi^0$ in the psd order. It is easy to see that $x_k^1 < x_k^0$ if $\Psi^1 < \Psi^0$ in the psd order.

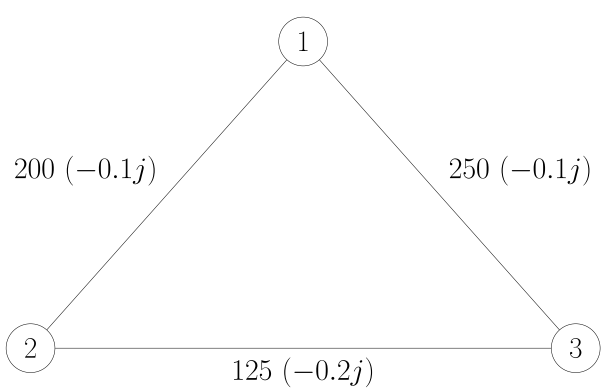
For 3., consider the example presented in Section B.1 below.

B Additional Examples

B.1 Numerical Exercise on Monotonicity

Figure 2 presents a simple three-node network derived from the example in Section 3. As in Section 3, suppose that the intercepts of the demand bids can be 25% higher or 25% lower, with the same probabilities as those given in Table 1. Suppose there are three FTR paths: one linking nodes 1 and 2, another linking nodes 1 and 3, and a third linking nodes 2 and 3. Figure 3 plots the price impacts on each path as a function of the number of bidders $J_{1\text{-}2}$, holding fixed the numbers of bidders $J_{1\text{-}3} = 2$. The blue solid and red dashed lines in each panel correspond to $J_{2\text{-}3} = 5$ and $J_{2\text{-}3} = 6$, respectively. In the unshaded regions, only the line between 1 and 2 binds in equilibrium. In the shaded regions, both of the lines between 1 and 2 and between 1 and 3 bind in equilibrium. The lines in the leftmost panel indicate that price impacts on 1-2 can increase when further entry on 1-2 induces a change in $\tilde{M}$; otherwise, price impacts are decreasing in entry. The lines in the center and right panels indicate that price impacts on paths 1-3 and 2-3 typically decrease but can also increase as a result of entry on path 1-2. The red dashed lines are strictly below the blue solid lines, indicating that a sixth bidder on path 2-3 reduces price impacts on all three paths.

Figure 2: Three-node network



Wholesale Bids (Normal Scenario)

Bus	Type	Supply	Demand
1	Gen	$15 + 0.05q$	–
2	Gen	$42.5 + 0.025q$	–
3	Load	–	$75 - 0.1q$

Figure 3: Price Impacts vs. FTR 1-3 Entry