

Dynamic competition and arbitrage in electricity markets: The role of financial players

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November 30, 2018

Abstract

I study the role of purely financial players in electricity markets, where they trade alongside physical buyers and sellers. In this context, physical sellers intertemporally price discriminate, leading to price differences that financial traders arbitrage, thus restricting producers' market power. Using detailed individual data, I examine physical and financial firms' response to regulation that exogenously increased financial trading. I show that the effect of financial traders on generators' market power depends on whether firms are in a static Nash equilibrium or not. I then develop a structural test of static Nash equilibrium and show the null of static Nash does not hold during the period of reduced financial trading. To implement the test, I present a new method to study the competitive structure of electricity markets using machine learning tools to define markets. I find that increased financial trading reduced generators' market power and increased consumer surplus.

1 Introduction

The role of financial traders in commodity markets is controversial. Although they are expected to facilitate risk sharing and increase informational efficiency, distrust of financial traders is so widespread that some politicians have proposed restrictions and bans on their activity. In this paper, I employ a unique dataset to study the role of speculators as competitors of physical producers in the Midwest electricity market.

^{*}I am especially indebted to Ali Hortaçsu and Michael Greenstone for invaluable advice and guidance. I am also grateful to John Birge and Brent Hickman for their comments and support. Further, I would like to thank Ignacio Cuesta, Gunnar Heins, Akshaya Jha, Ashley Langer, Derek Neal, Mar Reguant, Ryan Sutton, and Frank Wolak for detailed comments, and to the participants of seminars at the Berkeley Energy Camp, the Heartland Workshop, the UChicago IO lunch, the UChicago Applications of Economics workshop, the University of Washington, Rice University, the University of Wisconsin-Madison, Carnegie Mellon Heinz, NYU Stern, Columbia SIPA, MIT, MIT Sloan, Georgetown McDonough, Johns Hopkins Carey, UChicago Harris, University of California Santa Barbara, Carlos III in Madrid, BI Norwegian School of Business, EIEF, University of Florida, Berkeley EEE, IIOC 2016, NBER Meeting Economics of Commodity Markets 2016, and NBER SI 2018 for helpful comments and suggestions. All errors are my own.

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Typically, it is hard to identify the effect of speculation on a commodity market because only aggregate market outcomes are observed and the physical good is not traded together with its derivatives. Electricity markets provide an excellent setting to study the effects of financial trading since all transactions involving both physical producers and financial players occur in a single market. This paper focuses specifically on the Midwest electricity market (MISO¹), which has two additional advantages. First, a regulatory change in 2011 that exogenously attracted more financial traders, which allows me to identify the effect these traders had on the market. Second, I observe individual-level behavior and can separately analyze how buyers, producers, and financial traders reacted to the regulatory change. Exploiting these unique features, this paper shows that financial trading decreases physical producers' market power and increases consumer welfare.

In electricity markets, financial trading takes place in sequential markets where physical energy is traded. There is first a forward market that schedules production a day in advance, and then a spot market that balances demand and supply immediately before operation. In such markets, generators have incentives to engage in intertemporal price discrimination. Instead of fully scheduling their intended production in the forward market and using the spot market for unexpected shocks, producers withhold part of their generation in the forward market in order to increase the forward price (Ito and Reguant, 2016). This results in a forward premium that has been documented in several wholesale electricity markets.²

Because a forward premium distorts planning decisions and therefore results in inefficiencies, wholesale electricity markets have introduced financial traders to arbitrage these price differences. These traders sell (buy) in the forward market, and their transaction is then reversed in the spot market, such that their profits are the (negative) forward premium times the quantity traded. In the Midwest electricity market the forward premium persisted despite the presence of financial traders because high transaction costs made arbitrage unprofitable (Birge et al., 2018). A regulatory change lowered these costs significantly in April 2011, after which financial trading increased and the forward premium became smaller.

¹Midwest Independent System Operator until 2013, then Midcontinent ISO.

²Bowden et al. (2009) and Birge et al. (2018) find it in the Midwest, Saravia (2003) in New York, Jha and Wolak (2018); Borenstein et al. (2008) in California, Ito and Reguant (2016) in the Iberian market, among others.

I show that generators' withholding in the forward market, measured as the difference between spot and forward sales, also decreased, as would be expected when there is price discrimination and arbitrage becomes cheaper. Interestingly, generators did not only react to the regulatory change by exerting less market power in the forward market, but they did it months before it was implemented. This response is not consistent with the static Nash equilibrium that we typically assume in structural estimation of auctions, since in a static setting firms are not expected to respond to the sole threat of competition. Moreover, if firms are in a static Nash equilibrium, we would conclude that there is no effect of financial players on competition because generators' behavior is the same right before and right after the regulatory change. If firms were in a dynamic equilibrium, on the other hand, and their behavior was an anticipated response to future competition, financial traders would have an important role in reducing generators' market power.

In order to understand the generators' reaction, I use individual bid data to estimate a static model of optimal generator behavior and test the hypothesis of static Nash equilibrium. Following the approach of Wolak (2000) and Hortacsu and Puller (2008),³ I build a static model of a generator that decides how much to bid in the forward and spot markets. In MISO, these markets are organized as sequential auctions in which firms bid step functions specifying how much they are willing to sell or buy at each price, so I extend Hortacsu and Puller (2008)'s model of optimal bidding in the spot market to the case of a sequential market.

In my model, a firm's optimal bid depends on its contract position⁴ and on the elasticity of its residual demand, *i.e.* total demand minus the quantity sold by competitors. Consequently, the model rationalizes the observed change in behavior as a reaction to changes in current market conditions, *i.e.* residual demand or contract positions, which are not coming from increased financial trading. The richness of my dataset allows me to observe or estimate every element of the model's optimality condition, and then to

³There are a number of papers following this approach in electricity markets. Wolak (2007) uses the optimality conditions obtained from static profit maximization to estimate firm's marginal costs. He tests the hypothesis of profit maximization and finds no evidence against it. Hortacsu and Puller (2008), on the other hand, find that while it describes big firms' behavior well, small firms are far less sophisticated. Reguant (2014) studies an auction in which firms' bids can include complementarities across production hours, which she uses to estimate startup costs. Ryan (2014) estimates marginal costs from bids in the Indian market, taking into account transmission constraints to estimate the consequences of transmission investment

⁴Wolak (2000) shows that the forward contract position affects a firm's incentives to exert market power.

empirically test the null static Nash equilibrium by examining whether this condition holds in the data.

If firms behavior is not accurately represented by a static Nash equilibrium, firms are potentially in a dynamic equilibrium in which they respond to the threat of competition even before it effectively arrives. I analyze the way in which firms deviate from static Nash equilibrium to consider two alternative equilibrium hypotheses, *i.e.* two mechanisms that could explain why firms changed their conduct before market conditions changed.⁵ The first is a cooperative equilibrium in a repeated game, which is sustained as long as a player's benefits from continued cooperation outweigh the gains from deviating and stealing the market today. In the context of this paper, increased arbitrage in the future eliminates the benefits from future cooperation, because speculators will arbitrage away any resulting price gap. Given that the same firms interact with each other every day, and have good information about demand and each others' costs, a cooperative equilibrium is in principle possible.⁶

The second mechanism is entry deterrence. If generators expected financial, or "virtual", traders to enter the market and arbitrage the forward premium, they might have tried to make the market less attractive by lowering the forward premium. Entry deterrence does not seem to be sustainable in equilibrium, as there is no link between periods that could make today's competition affect the entrant's profits in the future.⁷ Nonetheless, I include this mechanism for the sake of completeness, since the generators' pricing changes might have been a failed attempt to deter the entry of financial traders.

The test I use to evaluate generators' conduct is based on a simple intuition. In a repeated game cooperative equilibrium, firms do not play best response, but behave as if the market were *less* competitive than it is. Under entry deterrence, generators do not play best response either, but they act as if the market were *more* competitive than it is. Therefore, if I reject the null of static Nash and find that firms' markup is higher than what would be statically optimal, their behavior would be in principle consistent

⁵As I only test a static model, I can only present suggestive evidence of a dynamic equilibrium in case the null of static Nash is rejected.

⁶Evidence of tacit collusion in electricity markets has been found by Fabra and Toro (2005) in the Spanish electricity market. They observe price wars together with periods of price stability.

⁷Like dynamic demand, for instance, as in Goolsbee and Syverson (2008). In this context, increasing capacity as in Dixit (1980) would not make a firm's threat more credible. Obtaining reputation as a fighter could justify lowering today's profits to deter future entry (Milgrom and Roberts, 1982), but in this case the market became more competitive before entry.

with a cooperative equilibrium. If, on the other hand, the observed markup is lower than statically optimal, their behavior would be consistent with entry deterrence. Although these hypotheses do not exhaust the space of alternatives, they can be taken as examples of two different ways in which the null hypothesis of static best response can be rejected, *i.e.* behaving *more* or *less* competitively than what would be optimal under static best response.⁸

The implementation of the test of static Nash equilibrium requires to compute the residual demand faced by each firm, which in principle can be done by adding up the demand bids and subtracting the supply bids of the generator's competitors. However, this exercise is complicated by the fact that the Midwest electricity market is a nodal market, *i.e.* there may be a different clearing price in each location or node where electricity is traded. This price represents the marginal cost of supplying energy at that node, which varies significantly because nodes are connected by transmission lines with limited capacity. When the lines reach maximum capacity, demand cannot necessarily be satisfied by the lowest cost generator and is instead satisfied by the lowest cost feasible generator.

To deal with nodal pricing, I assume the MISO market is split into several independent markets. I define these markets empirically by using machine learning techniques that cluster nodes together based on the correlation of their prices. Unlike most applications of these clustering techniques, I build a measure of fit that allows me to choose the market definition that better fits the data. To do this, I simulate prices that would clear under each alternative market definition and compare them with those observed in the data. I show that the clusters fit the data fairly well, since simulated prices are close to observed prices. To the best of my knowledge, this paper is the first to use a structural model to study a nodal market, which is made possible by these market definitions.

My findings indicate that, prior to learning of the impending regulatory change, firms acted as if they had more market power than they did according to the static model, therefore rejecting the null hypothesis of static Nash equilibrium. After learning about the future fall in transaction costs for financial traders, the market moved closer to a static

⁸Puller (2007) studies the competitiveness of the electricity market in California. Using a Cournot model for the spot market, he simulates the price that would have resulted under perfect competition, Cournot-Nash, and tacit collusion, concluding that the market is well described by the static Nash equilibrium. My approach is similar but I have the advantage of observing all bids. Additionally, I am mainly interested in the effect of financial trading on competition, instead of assessing the overall competitiveness of the market.

Nash equilibrium. Moreover, I find that this effect comes mainly from firms located in the West area of the market; for generators in the rest of the market I cannot reject the null of static Nash equilibrium.

While financial traders reduce generators' market power in the forward market, they do not eliminate their market power altogether since generators could exert more market power in the spot market once they are not able to intertemporally price discriminate. I estimate the firms' markups in the spot market and find that they remain roughly at the same level during the whole period of analysis, as opposed to what Ito and Reguant (2016) find by running a counterfactual in which they introduce financial traders into a sequential market that does not have them. There are two reasons behind the differences. First, in this paper firms move from a dynamic to a static equilibrium instead of going from price discrimination to uniform pricing in a static setting. Second, the market operator closely monitors production withholding in the spot market but not in the forward market, reducing firms' ability to exert market power in the spot market.

As firms exert less market power in the forward market and there are no big changes in the spot market, financial trading has a positive effect on welfare. Consumers are better off because they pay less for energy, saving roughly \$1,800,000 per day on average; producers are worse off because they cannot price discriminate. Nonetheless, the total effect is not just a transfer from producers to consumers because production costs go down. Less underscheduling in the forward market results in better planning, which allows cheaper generating units to be scheduled and decreases production costs. Though I do not quantify it, this effect is likely to be sizable since 98 to 99 percent of production is scheduled in the forward market.

This paper makes two main methodological contributions. First, it presents a data driven method to define markets that does not require to impose a particular form of competition between firms. Further, I propose a measure of fit that allows to select the market definition that better describes the data, which is not typically possible with clustering tools from machine learning. This methodology is what makes possible to analyze a nodal market following a structural approach.

Second, this paper presents a case in which the standard assumption of static Nash equilibrium does not hold. This assumption would need to hold not only for a structural estimation to be able to identify structural parameters, but also for any analysis that

compares variables of interest before and after the policy change and attributes the differences to the respective policy. Though in most markets it is not possible to obtain a dataset rich enough to implement the test of static Nash equilibrium proposed in this paper,⁹ the fact that in this case firms are in a dynamic equilibrium suggests a careful consideration of how results would change under alternative equilibria is important for robust analysis.

The rest of this paper is organized as follows: The next section describes the Midwest electricity market. Section 3 then describes the market's reaction to lower transaction costs for financial traders. Section 4 presents the model, and Section 5, the data. The empirical strategy is described in Section 6, and results are presented in Section 7. Section 8 concludes.

2 The MISO energy market

The Midcontinent Independent System Operator (MISO) serves 42 million people in the American and Canadian Midwest, and collects US\$20 billion in gross charges per year. Its energy market is organized as an auction in which participants submit bids to buy or sell energy in particular nodes or locations; MISO then clears the market at the lowest prices for each location given the capacity of the transmission network. This is known as nodal pricing and results in prices that typically vary across nodes because transmission constraints do not always allow demand to be covered by the cheapest generator.

Like many deregulated electricity markets, the MISO energy market is structured as a sequential auction. There is first a day-ahead or forward market that schedules production for the 24 hours of the next day. It takes place once a day and clears simultaneously for each hour of the next day. Then, there is a real-time or spot market, which takes place thirty minutes before operation and balances demand and supply to accommodate last minute shocks.

The forward market is purely financial in the sense that no energy is traded. Firms are paid for the quantity sold in the forward market regardless of how much they actually produce, but the difference between the forward schedule and the actual production is

⁹In structural analysis, optimality conditions are usually imposed on the data and used to obtain an estimate of primitive parameters from the model. Instead, the richness of my data allows me to compute every component of the optimality condition for the forward market.

settled at the spot price. For instance, if a generator schedules 100MWh in the forward market, but then clears 80MWh in the spot market, she receives the forward price for 100MWh but has to pay the spot price for 20MWh, as if she were buying.

The rationale behind a sequential market is that generation is cheaper when it is planned, so scheduling forecasted demand in advance decreases production costs. Generators with lower marginal costs generally have high startup costs and cannot adjust the level of production easily. On the other hand, generators that can start and vary production quickly, called peakers, often have high marginal costs. By scheduling production in the forward market, it is easier to satisfy expected demand with cheaper generators and only unanticipated shocks with peakers. Additionally, scheduling the 24 hours of the next day in the forward market increases efficiency by taking into account complementarities across hours, which come from the startup costs faced by some generating units.¹⁰ The existence of the forward market also allows market participants to face less risk, as price is more volatile in the real-time than in the day-ahead market.¹¹

2.1 Price discrimination and arbitrage

In a perfectly competitive market, firms would schedule their intended generation in the forward market and sell in the spot market only when they face unexpected shocks. However, market power is a concern in electricity markets even with concentration levels that would be considered competitive in other industries (Borenstein et al., 2002; Ito and Reguant, 2016; Ryan, 2014; Fabra and Toro, 2005). When generators have market power, they have incentives to withhold sales in the forward market in order to increase the forward price, which results in a forward premium (Ito and Reguant, 2016). This forward premium has been observed in several deregulated wholesale electricity markets (Saravia, 2003; Ito and Reguant, 2016; Saravia, 2003; Jha and Wolak, 2018), including MISO (Bowden et al., 2009; Birge et al., 2018).¹²

Financial or virtual traders have been introduced into several wholesale electricity markets to arbitrage this forward premium. These bidders profit from the differences

¹⁰See Reguant (2014) for an analysis of the welfare consequences of allowing complementarities in bids.

¹¹Additionally, Allaz and Vila (1993) show that sequential markets enhance competition among firms when they compete à la Cournot.

¹²Generators are able to price discriminate between the forward and the spot market because demand is not responsive. Appendix B discusses potential reasons behind this, as well as demand's response to the regulatory change.

between the forward and the spot price. For instance, selling 1 MWh in the forward market yields profits equal to $P^{forward} - P^{spot}$ because it implicitly requires the purchase of 1MWh in the spot market. In the presence of a forward premium, financial participants have incentives to sell in the forward market, neutralizing generators' underbidding and leading to price convergence.

The introduction of financial traders to wholesale electricity markets has been controversial. On the one hand, the forward premium decreased after arbitrageurs were allowed (Jha and Wolak, 2018; Saravia, 2003), leading to a reduction in production costs and emissions (Jha and Wolak, 2018). On the other hand, Birge et al. (2018) find that while arbitrage was limited by institutional constraints on financial bidding, financial bids were used to unlawfully manipulate the price of a related financial instrument used to hedge congestion in the MISO market.

In MISO, the forward premium persisted even in the presence of financial traders, because financial bids were subject to high transaction charges that made arbitrage unprofitable (Birge et al., 2018). These charges are Revenue Sufficiency Guarantee (RSG) charges, which are imposed on deviations from forward schedules that result in higher spot market demand (less available generation or more demand than scheduled). These deviations require plants to ramp up production or to start inactive plants. Because the clearing price does not cover ramping or startup costs, but only marginal cost, firms that buy in the spot market are subject to these deviation charges. The revenue collected is then distributed among participants who incurred ramping or startup costs.

Virtual bidders do not sell any physical energy, so a virtual forward sale entails an equal spot purchase and was therefore subject to RSG charges in full. In 2010 the average forward premium was \$0.9 and RSG charges were \$1.8 per MWh on average, making arbitrage unprofitable. On April 2011, the Federal Energy Regulatory Commission (FERC) approved MISO's proposal to modify the way RSG were calculated, so that charges were significantly lowered from \$1.8 per MWh to \$0.3 per MWh on average.¹³ In this paper, I use this exogenous change in virtual trading to study the effect of arbitrageurs on the competitiveness of the market.

The change in RSG charges did not come as a surprise to market participants, but instead occurred after a long debate about how to compute RSG charges and who should

¹³See Appendix A for computation details.

be subject to them. After the proposal to alter RSG charges was submitted to FERC, the market started preparing for implementation of the changes, which were expected to occur in March 2011. For instance, MISO began training sessions in January 2011, so firms affected by the change were expected to be aware of it before the proposal was approved and implemented.¹⁴

3 Reaction to the regulatory change

3.1 Financial players

When RSG charges dropped, hedging became cheaper and profitable arbitrage opportunities appeared (Birge et al., 2018), so the volume traded by financial players increased. This can be observed in the top panel of Figure 1, which shows the monthly average of the daily volume traded by virtual bidders. The dashed vertical line indicates the announcement on December 1, 2010 that the proposal to redesign RSG charges had been submitted to FERC. The solid vertical line on April 1, 2011 indicates the date on which the new RSG proposal was actually approved and implemented. The green line is the monthly virtual trade volume.

In order to confirm that there was a change in virtual activity, I look for a structural break in the time series of daily traded virtual volume.¹⁵ The standard test for structural break at a known date is the Chow test, which estimates the parameters before and after the break separately, and then tests for equality using an F statistic. As the date of the break is unknown in this case, I compute the F statistic for all dates in the sample. The maximum value is known as Quandt statistic (Hansen, 2001; Quandt, 1960). I use the critical values provided by Andrews (1993) and largely reject the null hypothesis of stable parameter values across the sample.

I follow Bai and Perron (1998) to find the break dates in the time series. The bottom

¹⁴In MISO, proposals to change market rules are discussed in groups of stakeholders. The change in RSG charges was reviewed by the Revenue Sufficiency Guarantee Task Force, a group specially created for this purpose. The minute from their meeting in December 2010 states that training sessions for all market participants were going to be held in January, while the minute from January 2011 states they expected the proposal to become effective in March, 2011. These are all available in the MISO website.

¹⁵These tests have been used in the applied micro literature before by Greenstone and Hanna (2014); Fabra and Toro (2003). Similar to the spirit of this paper, Fabra and Toro (2003) examine the British electricity market's response to a regulatory change and use breakpoint test to determine whether the response is anticipated, and thus consistent with collusion.

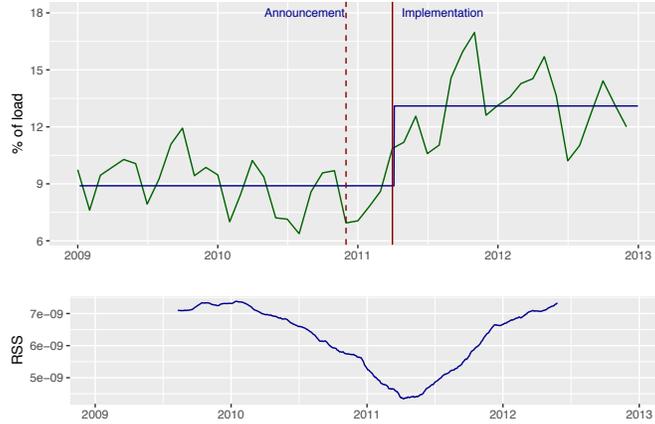


Figure 1: **Virtual trading over time** The green line indicates the monthly average of the daily volume traded by virtual bidders. The first dashed red line is December 1, 2010, when the proposal to redesign RSG charges was submitted to FERC. The solid red line on April 1, 2011 indicates the moment in which the RSG change was implemented. The bottom plot shows the residual sum of squares (RSS) for a model that assumes a structural break in each of the dates in the x-axis. The minimum is where the break occurs.

panel of Figure 1 plots the residual sum of squares for each potential break date. The minimum is reached on April 9, 2011, with the confidence interval between April 6, 2011 and April 12, 2011 (Bai and Perron, 1998). This break point in the daily time series confirms that virtual bidders changed their behavior after RSG costs were reduced. The blue line in Figure 1 shows the mean traded volume before and after the breakpoint, which increased around 40 percent. This shows that the reduction in RSG charges indeed attracted more financial trading.

3.2 Generators

If generators price discriminate between the forward and the spot markets, their average spot sales will be positive, i.e. they will, on average, use the spot market to increase their sales. This is precisely what we observe in Figure 2, which shows in green the average daily spot sales for each month.

Figure 2 also shows that spot sales became smaller when RSG charges were reduced. This is also in line with expectations if generators are exerting market power. Once transaction costs are lower, virtual traders will arbitrage the gap between the forward and spot prices, making underbidding by generators less attractive.

Lastly, in Figure 2 it seems that generators reacted after the announcement of the

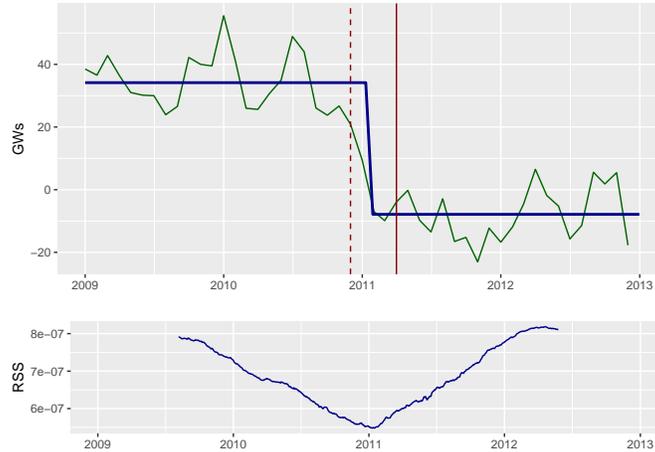


Figure 2: **Generators' underbidding over time** The green line indicates the monthly average of the daily difference between the quantity cleared in the forward and spot markets, which is a measure of generators' underbidding in the forward market. The first dashed red line is December 1, 2010, when the proposal to redesign RSG charges was submitted to FERC. The solid red line on April 1, 2011 indicates the moment in which the RSG change was actually implemented. The bottom plot shows the residual sum of squares (RSS) for a model that assumes a structural break in each of the dates in the x-axis. The minimum is where the break occurs. The structural break occurred on January 10, with a confidence interval between January 5 and January 15.

regulatory change (dashed line), but before its implementation (solid line). In fact, using the same tools described in the previous section, I find that there was a structural break on January 10, 2011, with a confidence interval between January 5 and January 15. I do not find other breaks that are robust to changing the sample periods.¹⁶

The generators' early reaction to the regulatory change is surprising, since future financial arbitrage did not restrict generators' market power in advance. Moreover, it implies it is not possible to identify the effect of financial players on competition without knowing what kind of game firms are playing. If firms are in a static Nash equilibrium, as we often assume in empirical work, they only respond to changes in current competitive conditions. In this case, increased financial trading would have no effect on competition since the generators' strategy change would be due to other factors that made the market more competitive. On the other hand, if firms were in a dynamic equilibrium in which they respond to future competition, financial players were effective in restricting producers'

¹⁶Appendix B shows that physical buyers also changed their behavior before financial trading increased, but after generators stopped price discriminating. Figure I.2 shows the evolution of the forward premium over time, though the effect is not as clear since the premium is very volatile. Figure I.3 show the evolution of the forward and spot prices.

market power.

The next section presents a model of generator behavior from which I will develop an empirical test of static Nash equilibrium that will allow me to distinguish between these two interpretations. An additional advantage of using a structural test of static Nash equilibrium is that it should capture changes in competitive conditions unobserved to the econometrician as long as they alter the residual demand faced by each firm.

To the best of my knowledge, there were no important changes in the market clearing algorithm or the market structure around these dates. Wind power became subject to RSG charges in August 2010, and intermittent power sources like wind became dispatchable -*i.e.* able to be turned on or off by the market operator according to demand- in July 2011, but it is not clear how this could affect quantities cleared in the forward and spot market in the observed manner. Regarding the change in RSG charges itself, though it affects firms' incentives to schedule more in the forward market than what they produce, there is no reason why firms' behavior would change before the change is implemented.

4 Model

4.1 Static Model

In this section I consider the decision of a generator that sells its production in a sequential auction. I assume firms decide simultaneously how much to produce and how to split sales between the forward and spot markets.

My model modifies that of Hortacsu and Puller (2008) by introducing sequential markets instead of focusing on the spot market. Additionally, I account for the limited capacity of electrical transmission lines by assuming that both the forward and spot markets are segmented into M independent markets. This is a simplifying assumption, since in practice any node can potentially affect any other at a given moment, depending on the level of congestion and the characteristics of the transmission network. I make this assumption for two reasons. First, it makes the model tractable by allowing each market to clear independently. Second, it matches the empirical strategy that I follow to deal with congestion and nodal pricing, which in turn matches the observed data fairly well (see Section 6.1).

Empirical papers on wholesale electricity markets have avoided this problem by study-

ing markets in which congestion is adjusted for in a separate market (Ito and Reguant, 2016; Reguant, 2014), looked at hours without congestion (Hortacsu and Puller, 2008), or studied zonal markets for which congestion data are available (Ryan, 2014). Jha and Wolak (2018) study the effect of financial traders in California, where prices are nodal as well, but do not fit a structural model because CAISO does not publish bid data. To the best of my knowledge, this is the first paper in the economics literature to use a structural model to analyze a nodal market.

Demand

Demand for each market has the same structure in the forward and spot markets. I assume demand in each market m and period t is given by $D_{m,t}(p) = d_{m,t}(p) + \epsilon_{m,t}$, where $d_{m,t}(p)$ is a non-stochastic component and ϵ is a demand shock. I will omit the period subindexes t because I am using a static model, and therefore all equations are the same for every period and there are no connections between periods.

For the spot market, this is a natural assumption since demand comes from households, who mostly pay a fixed rate per MWh and are thus price insensitive. In fact, there are no demand-side bids in the spot market, as enough generation is cleared to cover MISO's short-term load forecast for each hour. For the forward market, this equation is a simplification, since demand is expressed by bids and can be strategic. Appendix F shows that optimality conditions for generators do not change in a model with strategic demand.¹⁷

Generators' schedules

Generators decide how much to produce, and how to split sales between the forward and spot markets. Each generator i submits a schedule $Q_i(p^F)$ to the forward market auction, and a schedule $S_i(p^S)$ to the spot market auction. These schedules specify how much a generator is willing to sell at each price. In this section, the quantity cleared in the spot market when the clearing price is \tilde{p}^S , $S_i(\tilde{p}^S)$, is the total quantity produced by generator i , *not* the difference between total production and the quantity scheduled in the forward market. Note that this is a different definition than the one used in previous

¹⁷The residual demand they face will change, but not the condition for the optimality of the generator's bid.

sections, where I used “spot quantity” to refer to the quantity in excess of that sales in the forward market.¹⁸

Each generator’s strategies $Q_i(p^F, x^F)$ and $S_i(p^S, x^S)$ depend on the firm’s positions x^F and x^S in financial contracts used to hedge risk. These contracts specify a certain quantity x and a price h . If the market clearing price \tilde{p} is greater (lower) than the contract price, the firm has to pay (is paid) $(\tilde{p} - h)x$ to (by) the buyer of the contract (Green, 1999; Wolak, 2000, 2003a). They are settled in terms of the differences between the prices because these contracts are purely financial and do not require physical delivery of energy. It is important to account for forward price hedging contracts in the analysis of generators’ decisions, because a firm’s financial position determines whether it has incentives to increase or decrease the forward price.^{19 20}

Each generator i has a cost function $C_i(q)$, where q is the quantity cleared in the spot market, *i.e.* the quantity actually produced. I assume generators know each others’ cost functions. This is not a strong assumption since the same firms interact with each other over long periods, and the only information required to compute costs are the technical characteristics of the plant, which do not change over time, and fuel prices, which are easy to observe. Forward hedging positions, on the other hand, are harder to observe because they change over time for each firm, which is why I assume that the hedging positions are private information.

Market clearing

In the forward market, the market clearing price \bar{p} in market m is determined by the forward market clearing condition $\sum_{j \in m} Q_j(\bar{p}) = d_m(\bar{p}) + \epsilon_m$. Market clearing in the spot market is the same; the clearing price is determined by balancing demand and supply: $\sum S(\bar{p}^S) = d(\bar{p}^S) + \epsilon$.

¹⁸In practice, the spot market is cleared for total production, as in this section. Generators are paid the spot price only for the difference between the quantity scheduled in the forward market and sold in the spot market. This is the sense in which the forward market is financial.

¹⁹ See Wolak (2000) for the importance of contracts on incentives to exert market power.

²⁰ Often generators hold physical contracts in addition to financial ones. These specify a price and a quantity as well, but in this case energy is delivered to the buyer, who pays the price specified in the contract. These contracts can be treated as sunk costs because they are negotiated in advance and therefore do not affect the generator’s decision about how to split sales between the forward and the spot market. Physical contracts affect costs if production costs are not linear, but even in such cases we can simply assume that $C(0)$ in the model is equal to the cost of producing the quantity specified in the physical contract. For this reason, physical contracts are not explicitly included in the model.

Generator's uncertainty

Each generator i faces uncertainty over the clearing prices \tilde{p}^F and \tilde{p}^S , because she does not know what clearing price will result from submitting different schedules. This uncertainty comes from two sources, which combine into uncertainty over the residual demand.²¹ First, the demand function has a stochastic component that shifts its level unpredictably. Second, a generator does not know other generators' bids because she does not know their financial contract positions.

Bidder i 's uncertainty is represented by $F(x_{-i}, \epsilon | x_i)$, the joint distribution of other firms' contract positions and the demand shock. It is conditional on i 's own position because i 's position may contain information about others' contracts.²²

Following Hortacsu and Puller (2008), I define a probability measure over the realizations of the forward clearing price from the perspective of firm i , conditional on i 's private information about its contract position x_i^F , i 's submission of a schedule $\hat{Q}_i(p, x_i^F)$, and her competitors playing their equilibrium strategies $\{Q_j(p, x_j^F), j \neq i\}$. $H(p, \hat{Q}_i(p); x_i^F) \equiv \Pr(\tilde{p}^F \leq p \mid x_i^F, \hat{Q}_i)$ represents the uncertainty over the forward market clearing price faced by firm i . It is the probability, given i 's contract position, that generator i will be paid a price p when she sells a quantity $\hat{Q}_i(p)$ and all other generators submit the equilibrium offer functions. The event $\tilde{p}^F \leq p$ is equivalent to the event of excess supply at price p . Equivalently, generator i 's uncertainty over the clearing price in the spot market can be represented by the probability measure $G(p, \hat{S}_i(p); x_i^S) \equiv \Pr(\tilde{p}^S \leq p \mid x_i^S, \hat{S}_i)$.

The generator's problem

At clearing prices \tilde{p}^F and \tilde{p}^S in the forward and spot market, respectively, the ex-post profits for generator i are given by²³

$$\Pi_i(\tilde{Q}, \tilde{S}) = \tilde{p}^F \tilde{Q} + \tilde{p}^S [S - Q] - C(\tilde{S}) - [\tilde{p}^F - h^F]x^F - [\tilde{p}^S - h^S]x^S \quad (1)$$

where \tilde{Q} is $Q(\tilde{p}^F, x^F)$ and \tilde{S} is $S(\tilde{p}^S, x^S)$ (the arguments are omitted for clarity). The last two terms come from the financial position held by the generator in the forward and spot

²¹*i.e.* the market demand minus the schedules submitted by all other generators in the market.

²²Correlation between the demand shock and the contract positions of the competitors is allowed, but note that this remains a private value setting since i 's profits do not depend on its competitors' contracts (Hortacsu and Puller, 2008).

²³Subindexes i are omitted from now on unless necessary to avoid ambiguities.

markets.

A firm chooses schedules $Q_i(p^F, x_i^F)$ for the forward market and $S_i(p^S, x_i^S)$ for the spot market so as to maximize its expected profits, where the expectation is with respect to H and G . If bids are additively separable in price and contract positions, as in Hortacsu and Puller (2008), the optimality conditions for the generator's problem can be written as follows:²⁴

$$p^F - p^S = -[Q^*(p^F) - x^F] \frac{1}{R'(p^F)} \quad (2)$$

$$p^S - c' = -[S^*(p^S) - Q^*(p^F) - x^S] \frac{1}{R'(p^S)} \quad (3)$$

These conditions are similar to an oligopolist's first order condition. In the forward market, the markup is with respect to the spot price instead of the marginal cost, since this is the opportunity cost of selling in the forward market. Whether the generator wants to have a positive or negative markup will depend on her hedging contract position, i.e. on whether she is a net seller or a net buyer in the forward market. This is weighted by a function of the elasticity of the residual demand faced by the firm, $R(p)$, which determines the generator's market power. This condition can be rewritten as $\frac{p^F - p^S}{p^F} = -\frac{Q - x^F}{Q} \frac{1}{\eta}$, where Q and η are functions of p^F .

A similar trade-off is present in the spot market. The optimal markup for a generator depends on whether she is a net seller or buyer in the spot market, which depends on both her contract position in the spot market and her forward sales. Additionally, the importance of this position is weighted by the firm's ability to affect prices with bids.

5 Data

The empirical work in this paper uses an hourly panel that is publicly available on MISO's website. It contains each participant's bid, as well as the corresponding cleared quantity and price for each hour between 2010 and 2011. The panel has around 100 millions observations, 20 millions from generators' bids, and 80 millions from demand and financial participants' bids.

²⁴See Appendix C for a detailed presentation of the model and derivation of Euler-Lagrange conditions. See Appendix D for a discussion of the additive separability assumption and evidence suggesting that it holds in this particular market.

Generators may submit price-taker or price-sensitive bids, and they also have the option of submitting an increasing piecewise linear function instead of a step function. In my sample, 70 percent of generator bids and 82 percent of the megawatts hour cleared by generators correspond to piecewise linear bids. I discretize these bids as step functions in intervals of 0.1 MWh in my analysis. Supply bids also include information about the technological restrictions of each plant, such as the minimum/maximum number of hours it needs to operate, ramping times and costs, and startup costs, but I do not observe these variables. MISO only publishes the bid, cleared price and quantity, maximum and minimum production levels under normal and emergency conditions, and the amount a generator sells as a price taker.

The data identify buyers who place bids at multiple nodes, and sellers who own multiple units, but it is not possible to know which participants are vertically integrated utilities, nor whether a generator is also using virtual bids to hedge or arbitrage. While around 90 percent of physical demand bids are cleared in the forward, only around 10 percent of virtual bids and 50 percent of physical supply bids are cleared. Summary statistics on bids are presented in appendix tables I.4, I.1 and I.2.

Additionally, MISO posts the clearing prices at each pricing node in the market, information I use to match bids, which are not reported by node, to the corresponding nodes. In my data, a node is just an identifier number and a name where one or more participants submit bids. Each node's geographical location is not disclosed.

I use data on prices and volumes of traded Intercontinental Exchange (ICE) futures for the Indiana hub during peak hours. These data are available on the EIA website. Data on oil, coal, and natural gas prices were obtained from the Federal Reserve Bank of St. Louis. They correspond to daily crude oil prices (West Texas Intermediate - Cushing, Oklahoma), the Henry Hub natural gas spot price, and coal prices in two coal regions (Illinois Basin and Powder River Basin).

6 Testing static Nash equilibrium

The observed change in firms behavior in January 2011 admits two interpretations, depending on the kind equilibrium that firms were playing. If firms were in a static Nash equilibrium, they responded to a change in current competitive conditions that is unrelated

to financial trading, since generators did not lose market power until transaction costs were effectively lower. If firms were not in a static Nash equilibrium, the observed reaction is consistent with an anticipated response to future competition from financial participants.

To test the null hypothesis of static Nash equilibrium, I test the empirical analogue of Equation 2, which implicitly defines the static best response function for generators. For this, I define the Best Response Deviation (BRD) as the difference between the two sides of this equation.

$$BRD \equiv p^F - p^S + [Q(p^F) - x^F] \frac{1}{R'(p^F)} \quad (4)$$

where the second line results from rearranging the terms.

If the static model is a good representation of the firms' behavior, $BRD = 0$. This is the null hypothesis, under which financial traders have no effect on market competitiveness. Under the null, generators' response is rationalized by changes in contract positions or the elasticity of the residual demand. If $BRD \neq 0$, firms are not in a static Nash equilibrium and generators' change in behavior is in principle consistent with an anticipated response to increased financial trading in the future.

Though rejecting the null hypothesis of static Nash does not imply firms are into any specific equilibrium, I will consider two alternative hypotheses that are consistent with specific deviations from the best response. If $BRD > 0$, the observed markup is higher than what would be optimal if firms were in a static equilibrium, given the competitive conditions they face at the moment. This is consistent with any equilibrium in which firms exert more market power than what would be statically optimal, and in particular with a repeated game in which a cooperative equilibrium is sustained as long as future benefits exceed the profits from deviating. Once firms learn that the equilibrium will not be sustained in the future, when financial traders' arbitrage is cheaper, the equilibrium unravels.

If firms were in a cooperative equilibrium that broke with the announcement of increased competition in the future, the BRD would be initially positive, and then move toward zero after the announcement of the regulatory change. How close to zero it ends up depends on financial bidders' effectiveness in arbitraging the forward premium. The speed of the adjustment depends on the pace at which the collusive equilibrium breaks. The adjustment could happen all at once when the market learns about the future change, or

gradually, beginning at the time of the announcement and finishing when financial trading increases.

A tacit collusive equilibrium does not need to be an explicit agreement in which firms sit around a table and agree upon each group member's bid. The equilibrium could take the form of a simple rule of thumb for bids in the forward and spot markets. Firms do, however, have some contact, since the large ones are often MISO stakeholders. These stakeholder firms meet periodically to discuss market design and draft joint proposals for market reform. The likelihood that large firms follow similar strategies is also increased because many of these large firms hire outside firms to do their trading. Furthermore, any collusion between these large firms could have a significant impact on prices, since production is fairly concentrated, with 20 percent of firms controlling 80 percent of generation capacity.

If $BRD < 0$, firms are exerting less market power than what would be optimal in a static setting, i.e. they choose a smaller markup than what is optimal given the elasticity of the residual demand they face. This is consistent, for instance, with generators attempting to deter financial traders' entry by making the market less attractive at the time of the regulatory change. Under entry deterrence, the BRD is expected to start at zero before the announcement, become negative when the market learns about future competition, and increase towards zero when generators feel safe from the threat of entry. It is not clear when this last step would happen, as financial participants can increase their trading as soon as generators open the gap enough to make virtual trading profitable.

Following a structural strategy has the advantage of capturing changes in firm behavior that are unobserved to the econometrician. To the best of my knowledge, there were not other changes in the market around the time in which generators' underbidding went down, had there been they should be captured by changes in either firms' contract positions or the residual demand they face.

The richness of the dataset allows me to compute the BRD for each firm in each hour and market in which it is active. For this, I will use observed forward prices and quantities, back out contract positions following Hortacsu and Puller (2008), and estimate spot price expectations and residual demands. Each of these components can potentially introduce bias to the BRD. The test is robust to these biases as long as they do not change systematically over time in a way that is not captured by the controls, as will be discussed in the next sections. The next sections describe how the different components of the BRD

are estimated.

6.1 Residual demand and its elasticity

In principle, the residual demand for each generator could be computed directly from the data by just adding up the demand bids and subtracting the supply bids. However, this is not always a close approximation in a market with nodal pricing. When transmission lines are at capacity, the set of generators and physical buyers that enter a given generator's residual demand is a subset of the MISO market. Determining that subset is therefore crucial to correct computation of the residual demand.

Market definition

The MISO energy market has over 2000 pricing nodes and often becomes congested (transmission lines reach capacity), so in practice there is significant price dispersion among the nodes and prices can substantially differ geographically and over time. The presence of congestion is relevant for the empirical analysis of this market because when lines are at capacity demand cannot always be served by the cheapest generator. As a consequence, congestion segments the market, creating local markets in which firms have more market power than they would otherwise. This poses a challenge for the empirical analysis of nodal markets, because the degree of market power enjoyed by a firm depends directly on the degree of congestion and its transmission structure. I address this problem by using prices to define independent markets within the MISO market with a machine learning algorithm called hierarchical clustering. This method allows to compute the competitive structure without imposing a model of firm behavior and using only data on prices and bids, as MISO typically do not publish node locations and transmission lines location and available capacities.²⁵

Clustering techniques group elements of a set into groups or clusters, based on a predefined notion of similarity. In hierarchical clustering, each element is initially its own cluster.²⁶ The first step is to merge the two most similar objects into one cluster, according

²⁵Even if data on the location and capacity of the grid were available, using them to determine the exact residual demand faced by each firm would require solving a very complex problem.

²⁶This is the agglomerative algorithm. In the divisive algorithm, all elements start together in one single cluster, and each step splits the most different elements.

to the similarity measure. In each of the following steps, the two most similar elements or clusters are joined into one cluster.

I use the price correlation between nodes as the similarity measure for the clustering algorithm, since we would expect prices to move together if the nodes belong to the same market (Stigler and Sherwin, 1985). Although in principle it is possible that two nodes that are geographically far from each other have correlated prices, this would only happen if both the congestion and line loss components coincide.

The main source of uncertainty in this problem are physical contracts among market participants, which do not affect market clearing prices or quantities, but alter the available capacity of the transmission network. For this reason, I define markets separately for each month, year, and hour of the day, a period in which firms' contractual obligations are likely to remain constant.²⁷ For instance, I take the prices for all nodes during hour 5 of April 2011 and compute the correlation matrix. I then use these correlation data to define markets for the hour between 5 a.m. and 6 a.m. of April 2011.²⁸ The details of the application of the algorithm are described in Appendix E.

The hierarchical clustering algorithm returns a set of potential market definitions, one for each number of clusters. For instance, if there are 5 nodes there are 5 potential market definitions: There could be only one market $\{1,2,3,4,5\}$, or three markets $\{1\},\{2\},\{3,4,5\}$, etc. Typically the number of clusters is determined arbitrarily, as there is no appropriate measure of fit for the clusters. To remedy this uncertainty, I use bid data to define a measure of fit and test the ex-post fit of alternative market definitions. To do this, I take a market definition (e.g. 3 markets) and clear each of the market clusters by adding up the demand and supply bids submitted at the nodes belonging to each cluster. For instance, to evaluate the market definition with three clusters, I clear market 1 by crossing aggregate demand and supply bids at node 1. To clear market 3 I add up demand and supply bids from nodes 3, 4, and 5 to obtain aggregate supply and demand, and then clear the market. This process results in a simulated clearing price and quantity for each market under each market definition, which can be compared to the clearing prices and quantities observed

²⁷While imposing a constant market definition over time has the advantage of being able to examine a particular market during different periods, this may introduce bias in the estimates if the competitive structure changes over time. For this reason, I take the more conservative approach of allowing market definitions to vary.

²⁸I also tried accounting for day of the week effects, caused by contracts to deliver electricity during weekdays, but this did not improve the fit.

in the data. Because the inelasticity of demand makes quantities much less variable than prices, I use only price deviations when selecting market definitions. The mean difference in prices is below 10 percent for all hours, and below 5 percent for the majority of them.

The difference between the observed and simulated clearing prices for each market definition is then regressed on a constant to test the null hypothesis that this difference is zero. This is done with both an OLS and a quantile regression for the median, and all market definitions for which the null is not rejected in either of the regressions are kept. When there are several market definitions for one month-hour, I first drop the definitions with higher deviations in absolute value, and then select the market definition that is most common for that hour across all months. (See Appendix E for details.) For some hours and months, the difference between the observed and simulated cleared prices is statistically different from zero for all market definitions. When this is the case, I exclude that hour from the sample. This happens with for at least one month in hours 1, 3, 4, 8, 12, 20, 22, and 23.

This method to define markets is an approximation, because in reality all nodes in the MISO market can affect each other's price. Moreover, the residual demand faced by a firm may have discontinuities, coming from the capacity of the surrounding transmission lines, that will not be captured assuming markets are independent. Though these concerns are potentially serious, the fact that the simulated clearing price is, on average, not far from the observed one indicates that the ex-post fit of these definitions is good. As long as market conditions remain constant within the month, these definitions can also be used ex-ante to represent generators' rational beliefs about the residual demand they will face.

Using the generators' physical locations to group nodes into markets may appear to be a simpler way to define markets. However, MISO does not disclose generators' locations. Even with this information it is not possible to infer which firms compete with each other without having observing the transmission network's capacity. Neighbor nodes may have very different prices and thus, belong to different markets (see Appendix Figure I.1 for a heatmap of prices.). Moreover, transmission data is not enough to determine the competitive conditions faced by a firm in a nodal market. For instance, Borenstein et al. (2000) use a two node example to show that the flow of electricity on a line may not be informative about the effect of the line on competition, since the threat of competition brought by the line may be enough. Finally, even if I had all of the relevant data, I would

need to solve a complex optimization problem multiple times for each generator in order to estimate residual demand. This process would be computationally demanding, and most likely far from what firms actually do when they make bidding decisions. The clustering method presented in this paper is a simplification, but it seems to reasonably capture the competitive structure of the market given that the difference between simulated and observed prices is on average small.

Zheng (2016) also uses clustering tools to define markets in her estimation of an entry game between discount retailers. She splits the market into independent submarkets to lower the computational burden and make the estimation of the model possible. In my case, the richness of the electricity dataset allows me to define markets and a measure of fit that do not depend on the model of firm behavior.

Residual demand and its elasticity

I construct the residual demand faced by each firm in each market simply by adding up demand bids and subtracting the competitors' supply bids. A residual demand is defined for each firm in each market, which is assumed to be the information that each firm uses to make decisions.²⁹

Seventy-five percent of the bids and 82 percent of the megawatts cleared by generators are piecewise linear bids, while the rest are step functions. I convert these piecewise linear bids into step functions by splitting them into 0.1 MW increments. As a consequence, residual demand is expressed in step functions with very small steps. To compute the elasticity, I fit a cubic spline to the resulting residual demand, and take the derivative at the market clearing price. This provides an estimate of the $R'(p^F)$ component of equation 4 for each firm in each market during each hour.

6.2 Expected spot price

My model assumes that firms take the decision of how to split sales between the forward and the spot market simultaneously. In this case, the optimality condition in Equation 2 is pointwise optimal. Nonetheless, in reality the spot market takes place once the forward

²⁹This assumes that decisions are taken independently by a same company in different markets. Although it seems a strong assumption, given that markets are independent there would not be any gain from making the decisions jointly.

market has cleared. For this reason, I use an estimate of the expected spot price by each firm to compute the best response deviation. For this, I assume rational expectations: generators are forward-looking and use all available information to predict the spot price. For each node, I run the following regression with data from the prior month

$$p^S = \alpha + \beta_1 f_p^S + \beta_2 f_q^S + \beta_3 p_{lag}^S + \beta_4 p_{lag}^F + \varepsilon \quad (5)$$

where f_p^S is the price and f_q^S the traded volume of the futures for the Indiana hub in peak hours traded in the Intercontinental Exchange (ICE). These are spot price futures traded one day before the underlying production date, so their prices are almost identical to the forward price. p_{lag}^S and p_{lag}^F indicate the lags of the spot and forward price, respectively. The lags used are one, two, and three days before for the same hour and the previous one, plus the price in the previous 12 hours. The same lags are used for the forward and spot prices. I estimate the coefficients of Equation 5 using data for the month preceding t , the day for which I want to predict the price. Then I predict the spot price for day t using data on day $t - 2$, as bids are submitted on day $t - 1$, while markets for that day are still clearing. After having the predictions at the node level, I compute each generator's belief as the quantity-weighted mean of the forecast separately for each market in which the generator is ever active. Mean deviations from the observed spot price for the firm specific expected spot price are 8 cents in 2010 and 20 cents in 2011, and the median .

Table 1 describes the difference between rational expectations and the observed spot price. Although the predictions are not unbiased, the magnitude of the bias is small.³⁰ Predictions can alternatively be computed by running predictive regressions for each generator, including firm-specific variables like whether the bid sets the price or the bid price is close to the clearing price. This approach resulted in much worse predictions, so I used only price lags in the regressions. If these estimates do not accurately represent firms' expectations over spot prices, the BRD will be biased. Unless for some reason the bias varies systematically over time, this should affect the estimated BRD level, but should not result in consistent changes in level across periods.

³⁰Note, also, that the estimated expected spot prices are much closer to the spot price than the forward price.

Table 1: **Expected spot prices**

	2010	2011
$E[P^S]_{RE} - P^S$	0.036 (0.006)	0.163 (0.007)
$P^F - P^S$	1.142 (0.005)	0.500 (0.006)
Spot price	31.101 (0.006)	30.310 (0.007)
Observations	16,920,576	16,350,480

6.3 Hedging contracts

I back out the hedging contract position held by each generator from the optimality condition in Equation 2, as in Hortacsu and Puller (2008). Recall the optimality condition is: $p^F - p^S = [Q(p^F) - x^F] \frac{1}{|R'(p^F)|}$. The optimal schedule for the forward market is such that when the forward and spot prices are the same, the total quantity offered by each generator in the forward market equals its forward contract quantity, *i.e.* $Q(p^S) = x^F$. From this equation, I obtain the contract position for each generator in each market.

The forward hedging contract position can be correctly backed out when the optimality condition holds, *i.e.* under the null hypothesis of static Nash equilibrium. The test is valid because the hedging positions are correct under the null, but when the null is rejected the interpretation of the results must be done carefully. If the BRD is positive, contract positions will be biased downwards, which in turn biases the BRD upwards. The opposite happens if the BRD is negative; the bias leads to underestimating its value. (See Appendix H for a detailed argument). Therefore, when the null of static Nash is rejected, the estimated BRD should be interpreted as an upper bound, in absolute value, of the true value.

A second potential source of bias is the estimate of the expected spot price. There is in principle no reason to think that this bias will change over time. Therefore, systematic deviations from firm's price expectations would cause the contracts and the BRD to be biased, but should not change its pattern over time.

6.4 Best response deviation (BRD)

The previous sections have shown how to compute each of the components of the BRD: the forward hedging position, the derivative of the residual demand, and the expected spot price. Each of these elements is obtained separately for each hour, market, and firm. As there are many nodes in each market, each with a potentially different clearing price, I define the market price as the quantity-weighted average. With all these elements, I can build a panel in which I observe the BRD for each firm in each hour of each day and market in which she was active (BRD_{imt}).

To analyze the evolution of the BRD over time, I define three time periods according to market events related to the change in RSG charges. These periods are the following:

Before : The four months prior to December 1, 2010. On that date, MISO announced that it submitted a proposal to FERC for the redesign of RSG charge and the market began to prepare for the expected implementation of the proposal. The before period therefore provides data about baseline market conditions.³¹

Transition : the four months between December 1, 2010 and April 1, 2011, the date on which the change was implemented. During this period, the market knew the regulatory change was likely to occur, but it had not yet been implemented.

After : the four months between April 1, 2011 and July 31, 2011. This period represents the first four months after the RSG charges were lowered. There were two major events in July 2011: (1) renewable plants became dispatchable, meaning they could be started and stopped by the market operator according to demand like any other plant, and (2) a large producer firm left MISO to join the PJM Interconnection, which serves a market adjacent to MISO's. The latter event changed the market structure because the firm's transmission lines were transferred to PJM as well. Additionally, the summer of 2011 was particularly hot. For these reasons, I add a dummy for July 2011 to the regressions.

Seasonality is important in electricity markets because demand is higher when hot or very cold days, and wind production is typically higher in shoulder months. Nonetheless, I

³¹Training sessions to explain market participants how these costs were going to be computed started in January. A group of market participants was in charge of the redesign proposal. In January, they wrote they expected it to be implemented on March, 2011.

cannot add monthly fixed effects because given that the sample covers only one year, they are not identified if I also include the time period dummies. For this reason, I compute the mean BRD for each hour and month using data on 2010 and 2011, and subtract it from the BRD. The average of these monthly and hourly means is then added back to preserve the level.

I examine the evolution over time of the estimated best response deviation running the following regression of the BRD on the time periods defined above:

$$BRD_t = \alpha_0 \text{before} + \alpha_1 \text{interim} + \alpha_2 \text{after} + \text{July 2011} + \varepsilon_t \quad (6)$$

where BRD_t is the mean BRD for each hour and market, weighted by the size of the firm, defined as the maximum quantity sold during that month.

The sample exclude peakers, which are fast responding generators typically used to cover last minute increases in demand. Therefore, they are very likely to produce when demand in the spot market exceeds production scheduled in the forward market. Including them in the analysis may add effects coming from technical characteristics instead of from firm behavior. Furthermore, the BRD estimation produce a few extreme values that have a disproportionate effect on the results. For this reason, I remove the top and bottom 1 percent of my observations.

Equation 6 describes the baseline specification. Additionally, I run the regression using a 9 months sample that goes from September 2010 to June 2011, excluding the market changes of July 2011. In this specification, the time period dummies cover only 3 months, with the interim period going from January 2011, when there was a structural break in the generators' behavior, to March 2011.

A third specification controls for the number of generators in a market and the HHI (Herfindahl-Hirschman Index) to understand how the BRD is affected by market structure. This specification is also more robust to potential biases in the market definitions that lead to more or less concentrated markets during some particular months.

Finally, the sample is split geographically between the west and the rest of the market and the regression in Equation 6 is run separately for each subsample. This partition came from running Equation 6 for each individual firm and finding that results seem to be driven by a smaller group of firms located mostly in the West. This is discussed in more

detail in Section 7.

6.5 Market power in the spot market

Although financial participants decrease generators' market power in the forward market, because they cannot intertemporally price discriminate, they do not eliminate it altogether. Rather, firms retain the ability to withhold production in the spot market in order to drive up the spot price. This is analogous to an instance where increased arbitrage forces a monopolist to stop price discriminating between two sets of consumers. Just as the monopolist's new uniform price will be higher than the original price in the low-demand market, electricity generators will use their market power to raise spot prices after arbitrage decreases the forward premium.

I examine the effect of increased arbitrage on market power looking at firms' spot-price markups. I back out the spot markup for each firm from the optimality condition in Equation 3. I assume that firms' hedging position in the spot market is 0, because firms generally hedge with respect to the forward market, since that is where they sell the bulk of their production. For expositional clarity, I rewrite Equation 3 here for the case without hedging

$$\text{markup} = p^S - c' = -[S^*(p^S) - Q^*(p^F)] \frac{1}{R'(p^S)}$$

I estimate the markup in the spot market from the right hand side of this equation. I observe the cleared quantities in the forward and spot markets, and estimate the residual demand as I do for the forward market. For consistency, I use the same market definitions as in the forward market.³² I then run a regression of the quantity weighted average markup for each market and hour on the same time period dummies used in the BRD analysis. The next section describes the results.

Notice that the output from this estimation is the markup with respect to the firm's opportunity, which is not necessarily equal to actual production cost. Therefore, I cannot quantify the change in production costs using this mechanism. Nevertheless, this equation is sufficient to determine firms' market power, since the firms use marginal opportunity

³²Competitive conditions should be similar in the forward and spot market, though not necessarily the exact same because of unforeseen shocks and because the models used to clear the two markets make different simplifications.

Table 2: **Markets summary statistics**

Statistic	Mean	St. Dev.	Min	Median	Max
# mkts	31.6	12.9	3	35	49
# of f traders	9.0	8.7	0.0	6.8	56.7
# of buyers	5.1	16.2	0.0	0.0	104.5
# of sellers	6.9	16.9	1.0	2.0	110.3
HHI sellers	0.4	0.4	0.0	0.1	1.0
MWh sold	3,027	10,675	0	110	87,747

cost, rather than physical cost, to make their bidding decisions.

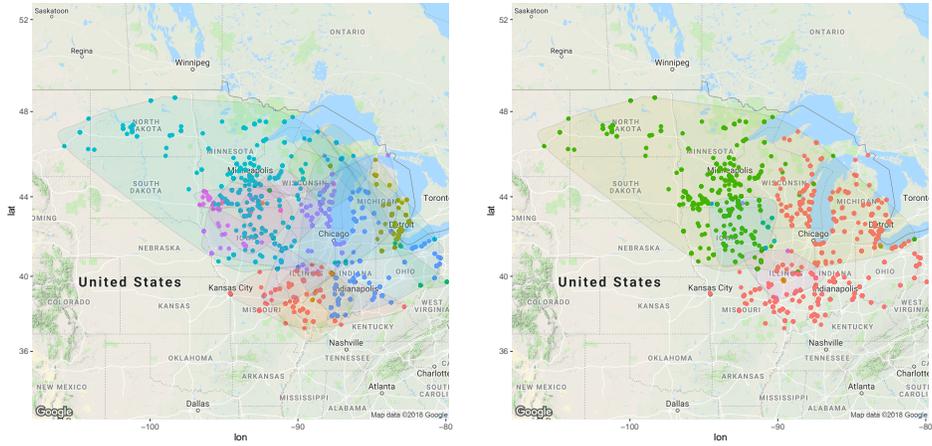
7 Results

7.1 Market definitions

Table 2 presents summary statistics from the markets defined using hierarchical clustering and selected by matching clearing prices. MISO is split into several markets, typically with one large market and many smaller ones, which explains the low mean and the high maximum number of firms and MWhs sold, as well the large number of markets. Concentration is not too low and there are even some monopolies, a much less competitive market structure than what would result from analyzing MISO as a single market.

Though I do not observe the pricing nodes' location, I know to which load balancing authority (LBA) they belong. LBAs are areas that were typically served by a single utility, which also used to be of balancing demand and supply there. For this reason, they are more likely to have enough transmission to move energy within the area and therefore to belong to the same market. With my market definitions, 88% of load balancing authorities are in a single market for a given hour in a month and year. Those that are split are the larger LBAs, i.e. those that include more nodes.

I have recently been able to match about 60% of generators to a location using EIA data and the information contained in the node's name. Figure 3 shows an example of how my market definitions look on the map, suggesting that the algorithm is not perfect but generally manages to put together nodes that are spatially close.



(a) March 2011, hour 18

(b) June 2010, hour 2

Figure 3: Market definitions on the map

7.2 Best response deviation (BRD)

Results from the BRD regressions are presented in Table 3 and are similar across the three first specifications: main specification, 9 months sample, and controlling for HHI and number of producers. The BRD was positive in the initial *before* period, rejecting the null hypothesis of static Nash. It then went down in the *interim* period, and stayed low after financial trading increased. This implies that firms initially exerted more market power than they had in a static Nash sense, and moved closer to a behavior consistent with static Nash after the announcement of the policy change that reduced transaction costs for financial traders. Moreover, I cannot reject the null hypothesis that the *between* and *after* coefficients are the same, which implies that the full adjustment took place between the announcement and the implementation.

I take advantage of the fact that I can estimate the BRD for each firm to identify a small group of firms that seem to be driving the results. For this, I run individual regressions for each firm and I find that generators for which the BRD went down in the interim and after period have a few features in common. They are medium or large in size, and together they own 72 percent of the total capacity of the west area of the market and 86 percent of total wind capacity. Most importantly, they are concentrated in the west area of the market. Though I cannot observe the location of the different pricing nodes, the names

Table 3: Best response deviation analysis

	Main	9 months	Controls	West	No west
Interim	-0.385*** (0.144)	-0.550*** (0.147)	-0.378*** (0.144)	-0.531*** (0.166)	0.013 (0.181)
After	-0.620*** (0.165)	-0.683*** (0.162)	-0.563*** (0.166)	-0.747*** (0.189)	-0.104 (0.203)
hhi			-1.092 (0.916)	2.822** (1.336)	-2.699** (1.246)
Market size			-0.132*** (0.029)	-0.156*** (0.030)	0.106** (0.053)
July 2011	1.681*** (0.255)		1.694*** (0.255)	1.937*** (0.275)	1.898*** (0.383)
Market size×hhi			0.203 (0.140)	-0.576*** (0.208)	0.697*** (0.183)
Constant	0.885*** (0.110)	0.883*** (0.105)	1.784*** (0.277)	1.979*** (0.299)	-0.586 (0.525)
interim = after	Y	Y	Y	Y	Y
before = after	N	Y	N	N	Y
Observations	36,686	31,887	36,686	29,421	19,309
R ²	0.001	0.001	0.002	0.004	0.005

Note: *p<0.1; **p<0.05; ***p<0.01

Results from regressing the BRD on time period dummies using data between August 2010 and July 2011 (October 2010 to June 2011 for the 9 months sample). The top and bottom 1 percent of the sample are removed to avoid extreme values. Then, the BRD is computed as the mean for each hour and market, weighted by the size of the firm. To deal with seasonality, I then remove monthly and hourly means computed using data for 2010 and 2011, since with the sample used in the regression it is not possible to separately identify time period dummies and monthly fixed effects. Robust standard errors reported.

of the nodes indicate the load balancing authority (LBA) to which they belong.³³ These firms belong to LBAs in the west area of the market.

Using this information, I split the sample between the west and the rest of the sample and run the same regression as above. Results are in the last two columns of Table 3, and indicate that the changes in BRD come from firms in the west. These generators were exerting more market power than they had in a static Nash sense in the initial period, and moved to a behavior consistent with a static Nash equilibrium after the announcement of increased financial activity in the future. In contrast, firms in the rest of the market did not change their behavior during this period. When Figure 2 is plotted excluding firms in the west I also find no change in underbidding.

³³Using LBAs to define markets does not result in clearing prices close to the observed ones.

Table 4: Residual demand elasticity and forward contract positions

	<i>Dependent variable:</i>					
	Residual demand elasticity			Contract position		
	All	West	No west	All	West	No west
Interim	-18.32*** (2.33)	-9.32*** (3.25)	-17.96*** (5.59)	15.75* (8.46)	3.11 (10.61)	-136.18*** (14.23)
After	-12.64*** (2.582)	-6.60* (3.38)	-15.84*** (6.106)	-52.03*** (9.252)	-14.43 (11.326)	-174.68*** (16.205)
Constant	-26.07*** (3.388)	-40.031*** (4.14)	-30.452*** (9.33)	92.65*** (14.35)	132.37*** (17.40)	45.90* (27.17)
Constant	-158.17*** (1.86)	-192.99*** (2.52)	-306.58*** (4.561)	703.61*** (6.41)	696.90*** (7.57)	1,208.82*** (11.49)
Observations	32,537	26,380	17,361	79,164	60,237	33,383
R ²				0.001	0.001	0.004

Note:

*p<0.1; **p<0.05; ***p<0.01

Regression of the quantity weighted residual demand elasticity and forward contract position on time period dummies and hour fixed effects between August 2010 and July 2011. The derivative of the residual demand is computed using a spline. The top and bottom 1 percent of the sample are removed to avoid extreme values. Then, the dependent variable is computed as the mean for each hour and market, weighted by the size of the firm. To deal with seasonality, I then remove monthly and hourly means using data for 2010 and 2011, since with the one year sample used in the regression it is not possible to separately identify time period dummies and monthly fixed effects. Robust regressions are used for the elasticity because there are still extreme values that affect the results. Robust standard errors reported.

Even though the west is less concentrated than the rest of the market, with an average HHI of 0.1 as opposed to 0.19 in the rest of the market, most medium or large firms are in the west. In fact, when I split the market into large and small firms and plot underbidding over time as in Figure 2, I only find a change in behavior for the large firms. These firms are more often isolated from the rest of the market because the most observed congestion pattern in MISO is west-to east- congestion.

Table 4 shows the evolution of the residual demand elasticities and backed-out contract positions over time. For the elasticity, I use a robust regression that weights observations with large errors less since errors are not distributed symmetrical and results are biased. Elasticity went down, though less for firms in the west than in the rest of the market. Contract positions changed differently for the two sectors in the market. In the west, firms increased their forward position in the interim period, but went back to the initial position afterwards. Firms in the rest of the market, on the other hand, lowered their

Table 5: **Forward premium over time**

	All	West	No west
Interim	-0.27** (0.12)	-0.57*** (0.13)	0.49*** (0.14)
After	-0.24* (0.13)	-0.48*** (0.15)	0.24 (0.17)
July 2011	0.89*** (0.18)	0.93*** (0.20)	1.11*** (0.26)
Constant	3.08*** (0.09)	3.43*** (0.10)	2.58*** (0.11)
interim = after	Y	Y	Y
Observations	36,878	29,936	19,549

Note: *p<0.1; **p<0.05; ***p<0.01

Regression of the quantity weighted forward premium on time period dummies and hour fixed effects between August 2010 and July 2011. The top and bottom 1 percent of the sample are removed to avoid extreme values. Then, the dependent variable is computed as the mean for each hour and market, weighted by the size of the firm. To deal with seasonality, I then remove monthly and hourly means using data for 2010 and 2011, since with the one year sample used in the regression it is not possible to separately identify time period dummies and monthly fixed effects. Robust regressions are used because there are still extreme values that affect the results. Robust standard errors reported.

forward contract positions over time.

As expected, the forward premium decreased after the announcement as well, as shown in Table 5. As for the BRD, the effect seems to come from firms active in the west area of the market. Though the coefficient for the *after* period is smaller than the one for the *interim* period, they are statistically the same.

Discussion There are two main conclusions to be drawn from the results presented in Table 3. The first is that before the announcement of the regulatory change firms were not in a static Nash equilibrium, they exerted more market power than what would be statically optimal. The discussion in the previous sections show that testing the level of the BRD can be affected by measurement error in any of its components. However, in that case I would expect the bias to be present in the whole market and not only in the West area, which is also where the BRD decreased significantly after the announcement of the policy change. Outside the west, on the other hand, the null of static Nash is not

rejected in any period.

The second conclusion is that firms initially exerted more market power than statically optimal, and moved towards static Nash after the announcement but before the implementation of the regulatory change. Though not conclusive, this is consistent with a tacit collusive agreement that breaks as soon as firms learn they will not be able to sustain it in the future. Although biases in any of the components of the BRD could bias these results, the observed variation in the BRD over time and geography makes it more plausible that findings come from firms' strategies and not from measurement error.

I take this second conclusion as supporting the rejection of static Nash more than standing on its own. The presented evidence does not prove that there is tacit collusion, it rather suggests that a cooperative model may rationalize the observed behavior better than a static Nash model, the workhorse model in many empirical applications. In this sense, it underscores the importance of research aimed at understanding the determinants of the equilibria reached by different markets, as well as at developing empirical tools that allow us to understand markets without necessarily assuming static Nash equilibrium.

7.3 Spot market markups

Table 6 presents the results from the spot markups analysis, showing that spot markups stayed roughly at the same level during the whole sample period, since the coefficients are economically small even if they are significant. Though we would have expected markups to increase in response to increased financial trading, there are a few reasons why firms would not exert more market power. First, this is not exactly a case in which firms go from price discrimination to uniform pricing, but rather from dynamic to static competition. For this reason, firms do not necessarily have incentives to exert more market power in the spot market. Secondly, MISO carefully monitors firms' behavior in this market and can find out if firms are withholding since the plants' capacity is public knowledge. On the other hand, in the forward market the focus of the market operator is on avoiding situations in which there is more demand than scheduled generation, not on intertemporal price discrimination. For this reason, generators' market power is likely to be much more restricted in the spot than in the forward market. Lastly, the spot market is much more volatile and there are fewer bids used in the computation of the residual demand, as only generators submit bids, which can undermine statistical power.

Table 6: **Spot market markups**

	Markup		Markup over spot price	
	Spline	Slope	Spline	Slope
	(1)	(2)	(3)	(4)
Interim	-0.08*** (0.03)	-0.12** (0.06)	-0.002* (0.001)	-0.003 (0.002)
After	-0.18*** (0.03)	-0.18*** (0.07)	-0.01*** (0.001)	-0.004 (0.003)
July 2011	0.11** (0.05)	0.09 (0.10)	0.003* (0.002)	0.002 (0.004)
Constant	0.29*** (0.02)	0.22*** (0.04)	0.01*** (0.001)	0.01*** (0.002)
Observations	36,097	41,514	36,307	37,224
R ²	0.001	0.0002	0.001	0.0001

Note: *p<0.1; **p<0.05; ***p<0.01
 Regression of the markup in the spot market on time period dummies between August 2010 and July 2011. The derivative of the residual demand is computed using a spline and as the ratio of differences using two points (slope). The top and bottom 1 percent of the sample were removed to avoid extreme values. I remove month and hour averages by defining the dependent variable as the residual from a regression of the forward premium on monthly and hourly dummies using 2 years of data, then I add the mean fitted value. Robust standard errors reported.

8 Welfare

Financial trading made consumers better off, since the reduction of the forward premium means that they pay less and total quantity does not change because final demand is perfectly inelastic. Producers, as a group, are worse off because they lose market power.

Additionally, costs are likely to go down because production underscheduling in the forward market lead to productive inefficiencies that then disappeared. First, because more expensive producers will be scheduled in the forward market to cover demand. Second, because some units will need to be dispatched in the spot market, and the units that can react on short notice often have higher marginal costs. Jha and Wolak (2018) compare production costs and carbon emissions before and after the introduction of financial traders into the California market, and find that both decreased. Given that 98 percent of the energy sales happen in the forward market, i.e. that most production

is scheduled in advance, total costs are likely to decrease when generators cannot engage in price discrimination. A precise quantification of this effect requires cost data and is therefore left for future research.

Consumers are unambiguously better off, since they pay less for their electricity purchases. To quantify this, I look at changes in total expenditure per MWh over time. After controlling for fuel prices and the forecasted demand level, total expenditure decreased in the period between announcement and implementation of the regulatory change and stayed below the initial level after implementation, as Table 7 shows. The coefficients indicate that total expenditure was between 3 and 9 percent higher before the announcement than after implementation. Given that total demand is 1,500,000 MWh a day on average, and the price is around \$30 per MWh, this means that consumers save at least \$1,350,000 per day on average. Note, however, that it is important to control for demand and fuel prices. Simply looking at changes in total expenditure, without controls, would indicate that, relative to the period after implementation, total expenditure was 10 percent lower in the “before” period, and 10 percent higher in the “interim” period.

Consumer savings come from two sources. The first is the direct effect of financial traders on generators’ ability to engage in price discrimination in the forward market. The second mechanism is the change in the dynamic equilibrium. The evolution of the best response deviation over time indicates that firms’ initial conduct was consistent with more market power than they had, and that after the change, increased arbitrage pushed their conduct closer to the static Nash equilibrium. This effect can be roughly quantified by multiplying the change in the BRD, which is measured in dollars, by the average daily load. Using the lowest estimate for the change in the BRD in the after period, this calculation yields an average savings of about \$750,000 a day (\$0.5 times 1,500,000 MWh). This indicates that at about half of the reduction in consumer cost is attributable to firms reverting to a static Nash equilibrium. This can be taken as an upper bound, since when the null of static Nash is rejected, the contract positions are biased and this leads to overestimating the BRD.

Table 7: **Total expenditure**

	(1)	(2)	(3)
before	0.270*** (0.068)	0.093*** (0.024)	-0.117*** (0.018)
interim	0.073* (0.042)	-0.029** (0.014)	0.041*** (0.015)
log(real-time load)	3.480*** (0.030)	3.476*** (0.029)	
Trend	0.000 (0.000)		
Fuel price controls	Y	Y	N
Observations	7,100	7,100	7,100
R ²	0.917	0.917	0.017
Adjusted R ²	0.917	0.917	0.016

Note: *p<0.1; **p<0.05; ***p<0.01
Total expenditure was computed as total purchases in each market, times the average clearing price at demand node. The total is the sum of the purchases in the forward and spot market. Specifications (1) and (2) includes hour and month fixed effects were used. Data is hourly. Fuel prices and their 24 and 48 hours lags are included as controls. The sample goes from August 2010 to July 2011. HAC standard errors reported.

9 Conclusion

This paper studies competition and the role of financial players in electricity markets. I examine a regulatory change that exogenously increased virtual trading. I test and reject the null hypothesis of static Nash equilibrium, a standard assumption in both structural industrial organization and event studies. Evidence suggest firms were rather in a cooperative equilibrium that broke as soon as firms learnt about increased competition in the future. My findings highlight the importance of considering potential dynamic incentives in empirical analysis. In this case, assuming static Nash would have lead to conclude that financial traders have no effect on market competitiveness, while I show that they restricted generators' market power and resulted in increased consumer welfare.

References

- Blaise Allaz. Oligopoly, uncertainty and strategic forward transactions. *International Journal of Industrial Organization*, 10(2):297–308, 1992.
- Blaise Allaz and Jean-Luc Vila. Cournot competition, forward markets and efficiency. *Journal of Economic Theory*, 59(1):1–16, 1993.
- Hunt Allcott. Real time pricing and electricity markets. 2013.
- Donald Andrews. Tests for parameter instability and structural change with unknown change point. *Econometrica*, pages 821–856, 1993.
- Jushan Bai and Pierre Perron. Estimating and testing linear models with multiple structural changes. *Econometrica*, pages 47–78, 1998.
- Jushan Bai and Pierre Perron. Computation and analysis of multiple structural change models. *Journal of Applied Econometrics*, 18(1):1–22, 2003.
- John Birge, Ali Hortaçsu, Ignacia Mercadal, and Michael Pavlin. The role of financial players in electricity markets: An empirical analysis of MISO. *Energy Economics*, forthcoming, 2018.
- Severin Borenstein and James Bushnell. An empirical analysis of the potential for market power in california’s electricity industry. *The Journal of Industrial Economics*, 47(3): 285–323, 1999.
- Severin Borenstein, James Bushnell, and Steven Stoft. The competitive effects of transmission capacity in a deregulated electricity industry. *The RAND Journal of Economics*, pages 294–325, 2000.
- Severin Borenstein, James Bushnell, and Frank Wolak. Measuring market inefficiencies in california ’s restructured wholesale electricity market. *American Economic Review*, 92 (5):1376–1405, 2002.
- Severin Borenstein, James Bushnell, Christopher R Knittel, and Catherine Wolfram. Inefficiencies and market power in financial arbitrage: a study of california s electricity markets. *The Journal of Industrial Economics*, 56(2):347–378, 2008.
- N. Bowden, S. Hu, and J. Payne. Day-ahead premiums on the midwest ISO. *The Electricity Journal*, 22(2):64–73, 2009.
- James Bushnell. Oligopoly equilibria in electricity contract markets. *Journal of Regulatory Economics*, 32(3):225–245, 2007.
- Meghan Busse. Firm financial condition and airline price wars. *RAND Journal of Economics*, pages 298–318, 2002.
- Ronald H Coase. Durability and monopoly. *Journal of Law and Economics*, 15:143, 1972.
- Joseph Cullen. Measuring the environmental benefits of wind-generated electricity. *American Economic Journal: Economic Policy*, 5(4):107–133, 2013.
- Avinash Dixit. The role of investment in entry-deterrence. *The economic journal*, 90(357): 95–106, 1980.

- Natalia Fabra and Juan Toro. The fall in British electricity prices: market rules, market structure, or both? 2003.
- Natalia Fabra and Juan Toro. Price wars and collusion in the Spanish electricity market. *International Journal of Industrial Organization*, 23(3-4):155–181, 2005.
- Bassam Fattouh, Lutz Kilian, and Lavan Mahadeva. The role of speculation in oil markets: What have we learned so far? *The Energy Journal*, pages 7–33, 2013.
- Austan Goolsbee and Chad Syverson. How do incumbents respond to the threat of entry? evidence from the major airlines. *Quarterly Journal of Economics*, 2008.
- Richard Green. The electricity contract market in England and Wales. *The Journal of Industrial Economics*, 47(1):107–124, 1999.
- Michael Greenstone and Rema Hanna. Environmental regulations, air and water pollution, and infant mortality in India. *American Economic Review*, 104(10):3038–72, 2014.
- Bruce E Hansen. The new econometrics of structural change: Dating breaks in us labor productivity. *Journal of Economic Perspectives*, pages 117–128, 2001.
- Ali Hortacısu and David McAdams. Mechanism choice and strategic bidding in divisible good auctions: An empirical analysis of the Turkish treasury auction market. *The Journal of Political Economy*, 118(5):833–865, 2010.
- Ali Hortacsu and Steven L Puller. Understanding strategic bidding in multi-unit auctions: a case study of the Texas electricity spot market. *The RAND Journal of Economics*, 39(1):86–114, 2008.
- Koichiro Ito and Mar Reguant. Sequential markets, market power, and arbitrage. *American Economic Review*, 106(7):1921–57, July 2016.
- Akshaya Jha and Frank A Wolak. Testing for price convergence with transaction costs: An application to financial trading in California’s wholesale electricity market. 2018.
- Paul L Joskow and Jean Tirole. Transmission rights and market power on electric power networks. *The RAND Journal of Economics*, pages 450–487, 2000.
- Luciana Juvenal and Ivan Petrella. Speculation in the oil market. *Journal of Applied Econometrics*, 2014.
- Lutz Kilian and Daniel P Murphy. The role of inventories and speculative trading in the global market for crude oil. *Journal of Applied Econometrics*, 29(3):454–478, 2014.
- Christopher R Knittel and Robert S Pindyck. The simple economics of commodity price speculation. *American Economic Journal: Macroeconomics*, 8(2):85–110, 2016.
- Erin T Mansur. Measuring welfare in restructured electricity markets. *The Review of Economics and Statistics*, 90(2):369–386, 2008.
- Paul Milgrom and John Roberts. Predation, reputation, and entry deterrence. *Journal of economic theory*, 27(2):280–312, 1982.
- David M Newbery. Competition, contracts, and entry in the electricity spot market. *The RAND Journal of Economics*, page 726–749, 1998.
- John E Parsons, Cathleen Colbert, Jeremy Larriau, Taylor Martin, and Erin Mastrangelo. Financial arbitrage and efficient dispatch in wholesale electricity markets. *MIT Center for Energy and Environmental Policy Research*, (15-002), 2015.
- Steven L Puller. Pricing and firm conduct in California’s deregulated electricity market. *The Review of Economics and Statistics*, 89(1):75–87, 2007.
- Richard E Quandt. Tests of the hypothesis that a linear regression system obeys two

- separate regimes. *Journal of the American Statistical Association*, 55(290):324–330, 1960.
- Mar Reguant. Complementary bidding mechanisms and startup costs in electricity markets. *The Review of Economic Studies*, 81(4):1708–1742, 2014.
- Nicholas Ryan. The competitive effects of transmission infrastructure in the indian electricity market. Technical report, 2014.
- Celeste Saravia. Speculative trading and market performance: the effect of arbitrageurs on efficiency and market power in the New York electricity market. *Center for the Study of Energy Markets*, 2003.
- George J Stigler and Robert A Sherwin. The extent of the market. *The Journal of Law and Economics*, 28(3):555–585, 1985.
- Frank A. Wolak. Identification and estimation of cost functions using observed bid data: an application to electricity markets. In Mathias Dewatripont, Lars Peter Hansen, and Stephen J Turnovsky, editors, *Advances in economics and econometrics: theory and applications, Eighth World Congress*.
- Frank A Wolak. An empirical analysis of the impact of hedge contracts on bidding behavior in a competitive electricity market. *International Economic Journal*, 14(2):139, 2000.
- Frank A Wolak. Identification and estimation of cost functions using observed bid data. In *Advances in Economics and Econometrics: Theory and Applications, Eighth World Congress*, volume 2, page 133. Cambridge University Press, 2003a.
- Frank A Wolak. Measuring unilateral market power in wholesale electricity markets: the California market, 1998-2000. *American Economic Review*, pages 425–430, 2003b.
- Frank A Wolak. Quantifying the supply side benefits from forward contracting in wholesale electricity markets. *Journal of Applied Econometrics*, 22(7):11791209, 2007.
- Frank A Wolak. Measuring the benefits of greater spatial granularity in short-term pricing in wholesale electricity markets. *American Economic Review*, 101(3):247, 2011.
- Catherine D Wolfram. Measuring duopoly power in the British electricity spot market. *American Economic Review*, pages 805–826, 1999.
- Fanyin Zheng. Spatial competition and preemptive entry in the discount retail industry. Technical report, 2016.

Online appendix - For online publication

A Revenue Sufficiency Guarantee (RSG) charges

In the MISO market, some eligible generators are guaranteed the full recovery of their production cost when MISO commits them to produce a quantity that differs from their day-ahead schedule. The production cost has three components: the start-up cost, incurred when the generating units start running, the no-load cost, which is the cost of operating and producing zero MWs, and the marginal cost. Only the latter is covered by the market clearing price (LMP), so the eligible generators need to be compensated for their incurred start-up and no-load costs. This is funded by imposing Revenue Sufficiency Guarantee (RSG) charges on deviations from the day-ahead schedule, *i.e.* on differences between the MWs that a market participant cleared in the day-ahead market and what she produces in the real-time market. As virtual participants do not physically buy or sell energy, the total virtual MWs are considered a deviation and are subject to RSG charges.

MISO's treatment of virtual bidders with respect to the RSG has varied over time in a way that affects incentives. When the market was opened to financial participants in April 2005, virtual transactions were not subject to RSG charges. In April 2006, the FERC issued an order according to which virtual offers had to pay RSG charges retroactively until 2005. This was reversed in October of the same year. After a long discussion between MISO, market participants, and the FERC, in November 2008 the latter determined that virtual supply had to pay RSG charges. This applied to future trades as well as retroactively until April 2006. The discussion about what trades should be subject to the charges and how these should be computed continued until April 2011. During this period, charges were constant across nodes, computed as $RSG_i = MW_i^S \cdot RSG_RATE$, where i is a bid and MWS are MWs of virtual supply. This means that if a virtual bidder was buying 1 MW at a node, her payoff was just the real-time price minus the day-ahead one. For a virtual participant selling 1 MW in the day-ahead market, the payoff was $p^F - p^S - RSG_RATE$. Charges during this period were on average larger than the day-ahead premium (see Tables 1 and 3). On March 2011 the FERC accepted MISO's proposal for a change in the computation of the RSG charges. Since April 1st, 2011, both virtual supply and virtual demand are subject to these charges and their calculation has changed. In addition to a component that is common across nodes, the Day-Ahead

Deviation & Headroom Charge or DDC, there is a component that depends on congestion at each specific node called the Constraint Management Charge or CMC. As shown in the formula below, the CMC depends on the sum of deviations weighted by a congestion factor called the Constraint Contribution Factor or CCF which is between -1 and 1. When it is positive, the constraint is relaxed by more demand or less supply, so charges are imposed only on supply; when the factor is negative, only demand has to pay deviation charges. The calculation of the charges for each participant is as follows:

$$\begin{aligned} \text{RT_RSG_DIST}_h &= \text{CMC_DIST}_h + \text{DDC_DIST}_h \\ \text{CMC_DIST}_h &= \sum_n \max \{ (MW_n^S - MW_n^D) \cdot \text{CCF}_{h,n}, 0 \} \cdot \text{CMC_RATE}_{h,n} \\ \text{DDC_DIST}_h &= \sum_n \max \{ (MW_n^S - MW_n^D), 0 \} \cdot \text{DDC_RATE}_{h,n} \end{aligned}$$

where h is an hour, MW_n^S and MW_n^D are the virtual supply and demand, respectively, cleared by the participant at node n for hour h .

B Physical's demand response to the regulatory change

Generators are able to increase the forward price only if demand does not respond shifting purchases to the spot market. Figure B.1 shows spot purchases in the MISO energy market, which are on average positive before the regulatory change. Although this is consistent with market power on the demand side, it is also what a price-taker buyer facing a forward premium would do to minimize its purchasing cost. A price-taker buyer wants to buy as little as possible in the forward market because the price is lower in the spot market. A buyer with market power restricts its demand in the forward market in order to lower the price. Therefore, in the presence of a forward premium, purchases in the spot market are expected to be positive.

As Figure B.1 shows, buyers were initially withholding purchases in the forward market, and spot purchases decreased after RSG charges were reduced. I find a structural break in the net purchases time series on January 26, 2011.³⁴ This indicates that demand

³⁴ The confidence interval for the break date is between January 20 and February 2.

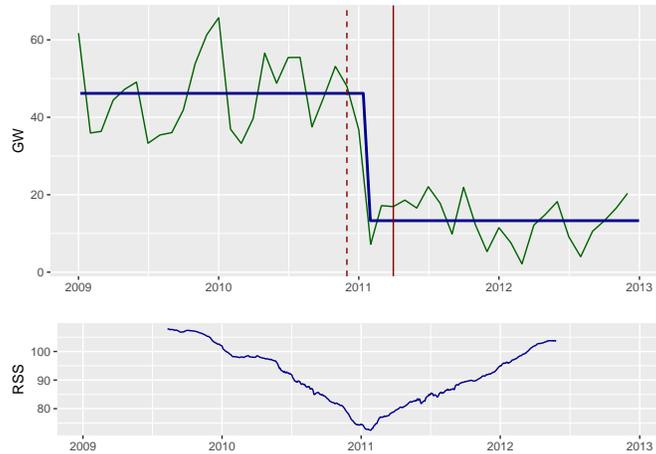


Figure B.1: **Load cleared in the spot market** The green line shows the monthly average of the daily difference between the quantity cleared in the forward and spot markets. The dashed red line on December 1, 2010 indicates the announcement of the regulatory change; the solid red line on April 1, 2011, its implementation. The structural break occurred on January 26, with a confidence interval between January 20 and February.

reacted before the change in RSG charges was actually implemented, but after generators did, suggesting demand responded to the generators' reaction and not directly to the regulatory change.

Purchasers' late response, as well as the fact that the forward premium was positive both before and after the regulatory change, which is advantageous for sellers, indicates that the premium was being driven by generators rather than purchasers. This may seem surprising because utilities are large companies and are generally expected to have considerable market power. There are a few reasons why demand may not have reacted as much as would be expected. First, many utilities can pass increased costs directly to final consumers, which makes them price insensitive. Second, MISO and the market monitor pay special attention to demand underscheduling. If utilities exerted too much market power by declining to purchase electricity in the overpriced forward market, they could be sanctioned by the authorities. Third, spot purchases are subject to RSG charges, which makes spot sales expensive for buyers. Lastly, demand may be hedged as there are financial instruments available to hedge the risk of spot price volatility, particularly because hedging costs are generally among the costs that regulated utilities are allowed to recover.

C Derivation of the Euler-Lagrange conditions for the generator's problem

The generator chooses bids in the forward and spot market to maximize expected profits. The generator's problem is the following:

$$\max_{Q_i, S_i} \int_{\underline{p}}^{\bar{p}} \int_{\underline{p}}^{\bar{p}} U(\Pi_i(Q_i, S_i)) dH(p^F, Q(p^F); x_i^F) dG(p^S, S_i(p^S); x_i^S) \quad (7)$$

where $Q_i = Q_i(p^F, x_i^F)$ and $S_i = S(p^S, x_i^S)$. G and H are the distributions of the clearing price defined in Section 4.

We can rewrite $dH(p^F, Q(p^F); x^F)$ and $dG(p, \hat{S}(p); x^S)$ as:

$$\begin{aligned} dH(p^F, Q(p^F); x^F) &= \frac{dH}{dp^F} dp^F = (H_Q Q' + H_P) dp^F \\ dG(p^S, S(p^S); x^S) &= \frac{dG}{dp^S} dp^S = (G_S S' + G_P) dp^S \end{aligned} \quad (8)$$

Replacing the above and defining the integrand as $J(Q, Q', p^F, S, S', p^S)$, the integrand now becomes

$$J(Q, Q', p^F, S, S', p^S) \equiv U[H_Q Q' + H_P][G_S S' + G_P]$$

where $U = U(p^F Q(p^F) + p^S [S(p^S) - Q(p^F)] - C(S(p^S)) - [p^F - h^F]x^F - [p^S - h^S]x^S)$. The argument is omitted from now on. The Euler-Lagrange equations are:

$$\begin{aligned} J_Q &= \frac{\partial}{\partial p^F} J_{Q'} \\ J_S &= \frac{\partial}{\partial p^S} J_{S'} \end{aligned} \quad (9)$$

Taking derivatives:

$$\begin{aligned} J_Q &= U'[p^F - p^S][H_Q Q' G_S S' + H_Q Q' G_P + H_P G_S S' + H_P G_P] + \\ &\quad U[H_{QQ} Q' G_S S' + H_{QQ} Q' G_P + H_{PQ} G_S S' + H_{PQ} G_P] \\ J_S &= U'[p^S - c'][H_Q Q' G_S S' + H_Q Q' G_P + H_P G_S S' + H_P G_P] + \\ &\quad U[H_{QS} Q' G_S S' + H_{QS} Q' G_P + H_{PS} G_S S' + H_{PS} G_P] \\ J_{Q'} &= U[H_Q G_S S' + H_Q G_P] \\ J_{S'} &= U[H_Q Q' G_S + H_P G_S] \end{aligned}$$

$$\begin{aligned}
\frac{\partial}{\partial p^F} J_{Q'} &= U'[Q + p^F Q' - p^S Q' - x^F][H_Q G_S S' + H_Q G_P] + \\
&\quad U[H_{QQ} Q' G_S S' + H_{QP} G_S S' + H_{QQ} G_P Q' + H_{QP} G_P] \\
\frac{\partial}{\partial p^S} J_{S'} &= U'[p^S S' + S - Q - c' S' - x^S][H_Q Q' G_S + H_P G_Q] + \\
&\quad U[H_Q Q' G_{SS} S' + H_Q Q' G_{SP} + H_P G_{SS} S' + H_P G_{SP}]
\end{aligned}$$

After substituting and canceling terms, the Euler-Lagrange conditions are:

$$p^F - p^S = [Q(p^F) - x^F] \frac{H_S}{H_P} \quad (10)$$

$$p^S - c' = [S(p^S) - Q(p^F) - x^S] \frac{G_S}{G_P} \quad (11)$$

where $H_Q = \frac{dH}{dQ}$, $H_p = \frac{dH}{dp}$, $G_S = \frac{dG}{dS}$, and $G_p = \frac{dG}{dp}$. H_p is the density of the clearing price in the forward market when all firms submit optimal schedules. H_Q is the change in the price distribution caused by a change in the bid submitted by i , which can be interpreted as a measure of i 's market power. G_S and G_p have equivalent interpretations in the spot market.

Because the forward market is purely financial, generators' sales there have no physical cost. Nonetheless, the spot price is the opportunity cost faced by a generator willing to sell in the forward market, since each unit can be sold in either the spot or the forward market. This becomes clear in Equation 10, which is similar to an oligopolist's first order condition in which the spot price replaces the marginal cost. The forward premium is then a markup with respect to this opportunity cost. Whether the generator wants to have a positive or negative markup will depend on her hedging contract position, because this determines whether the generator is a net seller or a net buyer in the forward market.

A similar trade-off is present in the spot market. The optimal markup for a generator depends on whether she is a net seller or buyer in the spot market, which depends on both her contract position in the spot market and her forward sales. Additionally, the importance of this position is weighted by the firm's ability to affect prices with bids, G_S .

Hortacsu and Puller (2008) present a separability condition that allows the optimality conditions to be simplified. Intuitively, the condition is that financial contracts shift the optimal bid, but do not change its slope. Formally, it requires schedules to be additively separable in the two sources of uncertainty, which holds when they can be written as $Q_i(p^F, x_i^F) = \alpha_i(p^F) + \beta_i(x_i^F)$. Appendix D presents some empirical evidence backing up this assumption.

If bids are additively separable, the optimality conditions can be written as directly as a function of the residual demand faced by each firm (see Appendix D for a proof):

$$p^F - p^S = -[Q^*(p^F) - x^F] \frac{1}{R'(p^F)} \quad (12)$$

$$p^S - c' = -[S^*(p^S) - Q^*(p^F) - x^S] \frac{1}{R'(p^S)} \quad (13)$$

Using the separability assumption to write the optimality conditions in terms of the residual demand makes it much easier to obtain its empirical counterpart. The residual demand within a market can be constructed from the bids, while the distribution of prices is harder to compute.

D Additive Separability

The empirical strategy in this paper relies on the assumption of additive separability of the optimal bid in the hedging contract position and the price. If schedules are additively separable in the contract position and the price, then the event of excess supply can be written

$$D^F(p^F) - Q_i - \sum \alpha_j(p^F) < \sum \beta_j(x_j^F) - \epsilon^F \quad (14)$$

Define $\theta \equiv \sum \beta_j(x_j^F) - \epsilon^F$, a random variable with distribution $\Gamma(\cdot)$. This variable θ contains the uncertain components determining the clearing price. Using the definition of θ , H can be rewritten as follows

$$\begin{aligned} H(p, \hat{Q}(p); x_i^F) &= \Pr\left(\sum_{j \neq i} Q_j(p, x_j^F) + \hat{Q}_i \geq D^F(p) | x_i^F, \hat{Q}\right) \\ &= \Pr\left(D^F(p^F) - Q_i - \sum \alpha_j(p^F) < \sum \beta_j(x_j^F) - \epsilon^F\right) \\ &= 1 - \Gamma\left(D^F(p^F) - Q_i - \sum \alpha_j(p^F)\right) \end{aligned}$$

and an equivalent expression holds for G . Taking derivatives of this expression and simplifying,

$$\frac{H_S}{H_p} = \frac{1}{D'(p) - \sum \alpha'(p)} \quad (15)$$

Notice that the denominator of the right hand side of equation 15 is the derivative of

the ex-post residual demand faced by generator i . For a given realization of ϵ and x_{-i} , the residual demand faced by i is

$$R(p) = D(p) + \epsilon - \sum_{j \neq i} \alpha_j(p) - \sum_{j \neq i} \beta(x_j) \quad (16)$$

therefore its derivative is $D'(p) - \sum \alpha'(p)$. Replacing this in the optimality conditions, they become

$$\begin{aligned} p^F - p^S &= -[Q^*(p^F) - x^F] \frac{1}{R'(p^F)} \\ p^S - c' &= -[S^*(p^S) - Q^*(p^F) - x^S] \frac{1}{R'(p^S)} \end{aligned}$$

If this assumption holds, changes in the contract position will shift the bid without affecting the slope. I follow Hortacsu and Puller (2008) and use the data to test the assumption. The test evaluates whether the slope of the bids changes with variations in the contract position. Under additive separability, contracts should only cause parallel shifts in the bids, with no effect on the slope.

I fit a linear function to the submitted bids to obtain their slope,;the fit is around 68 percent, a decent approximation. I then regress the slope of the bid on the hedging contract position obtained as explained in Section 6.3. The first column of Table D.1 present the results of this regression, using firm-market fixed effects. The correlation between the slope of a firm's bid and its contract position is not statistically significant, which supports the additive separability assumption.

Because the optimal bid submitted depends on the other players' strategy, I add the slope of the residual demand faced by each firm as a control. I also control for the spot price, since it is the opportunity cost of bidding in the forward market. After controlling for these factors, the forward position is still not significantly correlated with the slope of the bids, as the last three columns of Table D.1 show.

Table D.1: **Test of additive separability** Results from regressing the slope of the bids submitted by producers on their forward contract position. Includes owner-market, month and hour fixed effects. The fact that the correlation between the slope and the contract position is not significant supports the additive separability assumption.

	(1)	(2)
Residual demand's slope		-0.000 (0.00000)
Expected spot price		0.055 (0.035)
Contract position	-0.003 (0.002)	-0.002 (0.002)
Observations	800,597	798,301
R ²	0.0001	0.001
Adjusted R ²	-0.014	-0.014
<i>Note:</i>	*p<0.1; **p<0.05; ***p<0.01	

E Market definitions construction

1. Define markets using hierarchical clustering Clusters are defined using hierarchical clustering. This algorithm requires to specify the linkage, or how to compute the distance between clusters. I chose to use centroid centroid, but results do not change significantly when using complete linkage, single linkage, Ward, or average. Centroid fits as well as the other methods or better. To compute the clusters, I use the function *hclust* from the base R package stats. It requires two parameters: distance measure and method to compute distance between clusters. The distance is the matrix with price correlations and the method is centroid. The correlation matrix is built using the price for all nodes during one hour of one month of the sample, i.e. January 2011 between 6am and 7am. The output is over 2,000 alternative market definitions, so I restrict the output to up to 50 clusters. Initially I allowed more markets but those definitions did not have a good fit.

2. Market clearing as measure of fit For each candidate market definition, I take all bids submitted by physical and financial participants and clear the market. This exercise results in a clearing price and quantity for each market in each candidate market definition. This clearing price is from now referred of as simulated price. When a candidate market does not clear, the simulated price is 0.

3. Price deviation This step computes the difference between the simulated price and the observed price. The observed price is the mean price at the nodes included in the candidate market, weighted by the quantity cleared by physical generators. The difference between the simulated and observed price is then divided by the observed price. This implies that when a market does not clear, the price is set to 0 and thus the deviation is 1. Notice that the fit, measured as the price deviation described above, does not necessarily get better as the number of markets increase, because the market may not clear. In fact, assuming each node is a market will result in most markets not clearing.

4. Selection: first step For each hour of each month and year, the price deviation is regressed on a dummy for the market definition using both standard OLS and a quantile regression for the median. The number of observations for each regression is the number of days in the months times the number of markets in each market definition. All market definitions for which the coefficient is not significant at 5% under either OLS or the quantile regression are kept, the rest are discarded. For hours 1, 3, 4, 8, 12, 20, and 22, the null hypothesis of zero difference between the simulated and observed price was always rejected at 5%. For this reason, these hours were excluded from the sample.

5. Selection: second step The previous step may result in several market definitions for which the simulated prices are statistically similar to the observed prices. When this happens, I take the market definitions for which the absolute value of the deviation is lower than 0.25, 0.35, or 0.55 in successive order. After this step, there are 4 cases for which the deviation is higher than 0.25 (though statistically zero): hour 2 in September 2011, hour 5 in September 2011, hour 6 in May 2010, and hour 13 in December 2010. Only the latter is part of the main period of analysis.

6. Selection: last step As the previous steps still leave more than one market definition for some hours, in this final step I take for each month the market definition that is more common for that hour. For instance, if in hour 0 of January 2011 the market can be split into between 6 and 17 clusters, I look at what market definitions describe the market well in hour 0 during other months. Splitting the market into 12 separate markets is a suitable market definition for 8 other months, while the other market definitions are suitable during

fewer months. I then take the 12 clusters market definition for January 2011 during hour 0. This results in one market definition for each hour of every month and year.

F Model with strategic demand and supply

This appendix extends the model presented in section 4.1 to include strategic demand. Instead of taking demand given, I model buyers strategically choosing how to distribute their purchases between the spot and the forward markets. Because in wholesale electricity markets most purchases come from utilities serving downstream consumers, I will refer to buyers as utilities. Additionally, I will assume that firms do not hold hedging contracts for the spot price, i.e. $x^S = 0$. The market subindexes are omitted in this section, but the analysis is always done under the assumption of independent separate markets.

Demand Unlike generators, utilities' only decision is how to split purchases between the forward and the spot markets. They do not choose how much electricity to buy in the spot market, because final demand is given by households' electricity consumption. Therefore, the spot market is cleared such that there is enough generation to cover the load forecast L , which has a deterministic component l and a random component ϵ . In the forward market, each buyer submits a schedule $D(p^F)$ indicating how much she is willing to buy at each price. The difference between the quantity cleared in the forward market and L has to be purchased in the spot market.

Like generators, buyers may have financial contracts that affect their position in the forward market. I denote the contract terms as above: a firm holds a contract for a quantity x at a price h . Profits from the hedging contract are computed differently from generators though, because utilities are on the other side of the contract. If the clearing price is larger than h , the buyer gets paid the difference; if the clearing price is smaller than h , the buyer pays the difference to the other side (a generator).

Market clearing The market clearing prices \bar{p}^F and \bar{p}^S are determined by the market clearing conditions below

$$\sum_{j \in \text{Sellers}} Q_j(\bar{p}^F) = \sum_{b \in \text{Buyers}} D_b(\bar{p}^F) \quad (17)$$

$$\sum_{j \in \text{Sellers}} S_j(\bar{p}^S) = l + \epsilon \quad (18)$$

Generators' uncertainty As before, each generator i faces uncertainty over the clearing prices \tilde{p}^F and \tilde{p}^S , because she does not know what clearing price will result from submitting different schedules. In the spot market, uncertainty comes from the random component of demand, as in the section without strategic demand. In the forward market, it comes from the unknown hedging positions of other firms, which are private information and therefore make the clearing price uncertain. In other words, the generator is uncertain about the residual demand she faces, because residual demand depends on other firms' bidding behavior.

Bidder i 's uncertainty in the forward market is represented by $F_x(x_{-i}|x_i)$, the distribution of other firms' contract positions. It is conditional on i 's own position because i 's position may contain information about others' contracts. Note that this remains a private value setting since i 's profits do not depend on its competitors' hedging positions. In the spot market, uncertainty comes from ϵ , which has distribution $F_\epsilon(\epsilon)$.

As above, I define a probability measure over the realizations of the forward clearing price from the perspective of firm i , conditional on i 's private information about its contract position x_i^F , i 's submission of a schedule $\hat{Q}_i(p, x_i^F)$, and her competitors playing their equilibrium strategies $\{Q_j(p, x_j^F), j \neq i\}$.

$$H(p, \hat{Q}_i(p); x_i^F) \equiv \Pr(\tilde{p}^F \leq p \mid x_i^F, \hat{Q}_i) \quad (19)$$

$H(p, \hat{Q}_i(p); x_i^F)$ represents the uncertainty over the forward market clearing price faced by firm i . It is the probability, given i 's contract position, that generator i will be paid a price p when she sells a quantity $\hat{Q}_i(p)$ and all other generators submit the equilibrium offer functions. The event $\tilde{p}^F \leq p$ is equivalent to the event of excess supply at price p . Using the market clearing condition in Equation 18, H can be written as

$$\begin{aligned}
H(p, \hat{Q}(p); x_i^F) &= \Pr\left(\sum_{j \neq i} Q_j(p, x_i^F) + \hat{Q}_i(p) \geq \sum_{d \in \text{Buyers}} D_d^F(p, x_d^F) | x_i^F, \hat{Q}\right) \\
&= \int_{x_{-i}^F} 1 \left\{ \sum_{j \neq i} Q_j(p, x_i^F) + \hat{Q}_i(p) \geq \sum_{d \in \text{Buyers}} D_d^F(p, x_d^F) \right\} dF^F(x_{-i}^F | x_i^F)
\end{aligned} \tag{20}$$

The generator's problem The problem of the firm is to choose forward and spot bids that maximize its expected profits. As in the case without strategic demand, the generator's expected profits are given by:

$$\max_{Q(p^F), S(p^S)} \int_{\underline{p}}^{\bar{p}} \int_{\underline{p}}^{\bar{p}} U\left(\Pi(Q(p^F, x^F), S(p^S))\right) dH(p^F, Q(p^F); x^F) dG(p^S, S(p^S); x^S)$$

The Euler-Lagrange conditions for the bids that maximize the generator's profits are (proof analogous to the one in Appendix C)

$$p^F - p^S = [Q(p^F) - x^F] \frac{H_S}{H_P} \tag{21}$$

$$p^S - c' = [S(p^S) - Q(p^F) - x^S] \frac{G_S}{G_P} \tag{22}$$

Additive separability

If the schedules submitted by both buyers and sellers satisfy additive separability, the optimality conditions can be written in terms of the residual demand or supply. To see this, assume that demand and supply schedules are additively separable and therefore can be written as $D(p) = a(p) + b(x)$ and $Q(p) = \alpha(p) + \beta(x)$. The event of excess supply at price p can then be written

$$\begin{aligned} \sum_{i \in I^S} \alpha_i(p) + \sum_{i \in I^S} \beta_i(x) &\geq \sum_{i \in I^D} a_i(p) + \sum_{i \in I^D} b_i(x) \\ \sum_{i \in I^S} \alpha_i(p) - \sum_{i \in I^D} a_i(p) &\geq \sum_{i \in I^D} b_i(x) - \sum_{i \in I^S} \beta_i(x) \end{aligned}$$

Defining $\theta \equiv \sum_{i \in I^D} b_i(x) - \sum_{i \in I^S} \beta_i(x)$, a random variable with distribution Γ . Then, the expectation of excess supply from the perspective of a generator is

$$\begin{aligned} H(p, \hat{Q}(p); x_i^F) &= \Pr\left(\sum_{j \neq i} Q_j(p, x_j^F) + \hat{Q}_i \geq D^F(p) | x_i^F, \hat{Q}\right) \\ &= \Pr\left(\sum_{j \in I^D} a_j(p) - Q_i - \sum_{j \in I^S} \alpha_j(p^F) \geq \sum_{j \in I^D} \beta_j(x_j^F) - \sum_{j \in I^D} b_j(x)\right) \\ &= \Gamma\left(\sum_{j \in I^D} a_j(p) - Q_i - \sum_{j \in I^S} \alpha_j(p^F)\right) \end{aligned}$$

And equivalently for demand. Taking derivatives and simplifying, the optimality conditions can be rewritten as Equations 12 and 13 for sellers and an equivalent one for buyers.

G Market-clearing algorithm

In the MISO market, generators submitted schedules consist of more information than the 10 steps of the bid. They additionally indicate the maximum and minimum quantity that they can produce economically, and under an emergency, as well as whether they act as price-takers. Additionally, they may indicate that the unit is already working, so it must run during that hour but they do not need to pay the start costs. They also provide technical information about the plant like the maximum and minimum temperatures, ramping times and costs, and the number of hours in a row a unit needs to run. The effect of these cost complementarities has been studied by Reguant (2014)

MISO only publishes some of the information provided by the generators at each moment. The main part missing are the complementarities between hours that the market authority must consider when clearing the market. As a simplification, I do not consider this when I clear the markets either, but this does not seem to cause great divergence

between my simulated market clearing quantities and prices, and those observed in the data.

I include the step function submitted by each bidder, as well as whether they are price-takers. Additionally, I adjust some bids to reflect other parameters. For instance, a good number of run-of-river and wind units submit offers for 999MW in the second step, even though their capacity, as represented by the economic and emergency maxima, is below this (usually around 10MW).³⁵ As keeping this would alter the market clearing results, I modify the bids to reflect the unit's capacity. I generally restrict every step to be below the specified economic maximum. Additionally, when a bid specifies a quantity in the first step, but no prices, I assume they are willing to pay any price for that quantity.

H Bias in the contract position

The estimate of the contract position described in Section 6.3 is only valid under the null hypothesis of static Nash equilibrium. This appendix shows that when the null does not hold, the resulting bias in the contract positions leads to underestimating the BRD. To see this, consider the case in which $BRD = \alpha > 0$. Then

$$BRD = p^F - p^S - \frac{Q(p^F) - x^F}{|R'(p^F)|} = \alpha > 0$$

When $p^F = p^S$,

$$\begin{aligned} x^F - Q(p^S) &= \alpha |R'(p^S)| \\ x^F &= Q(p^S) + \alpha |R'(p^S)| \end{aligned}$$

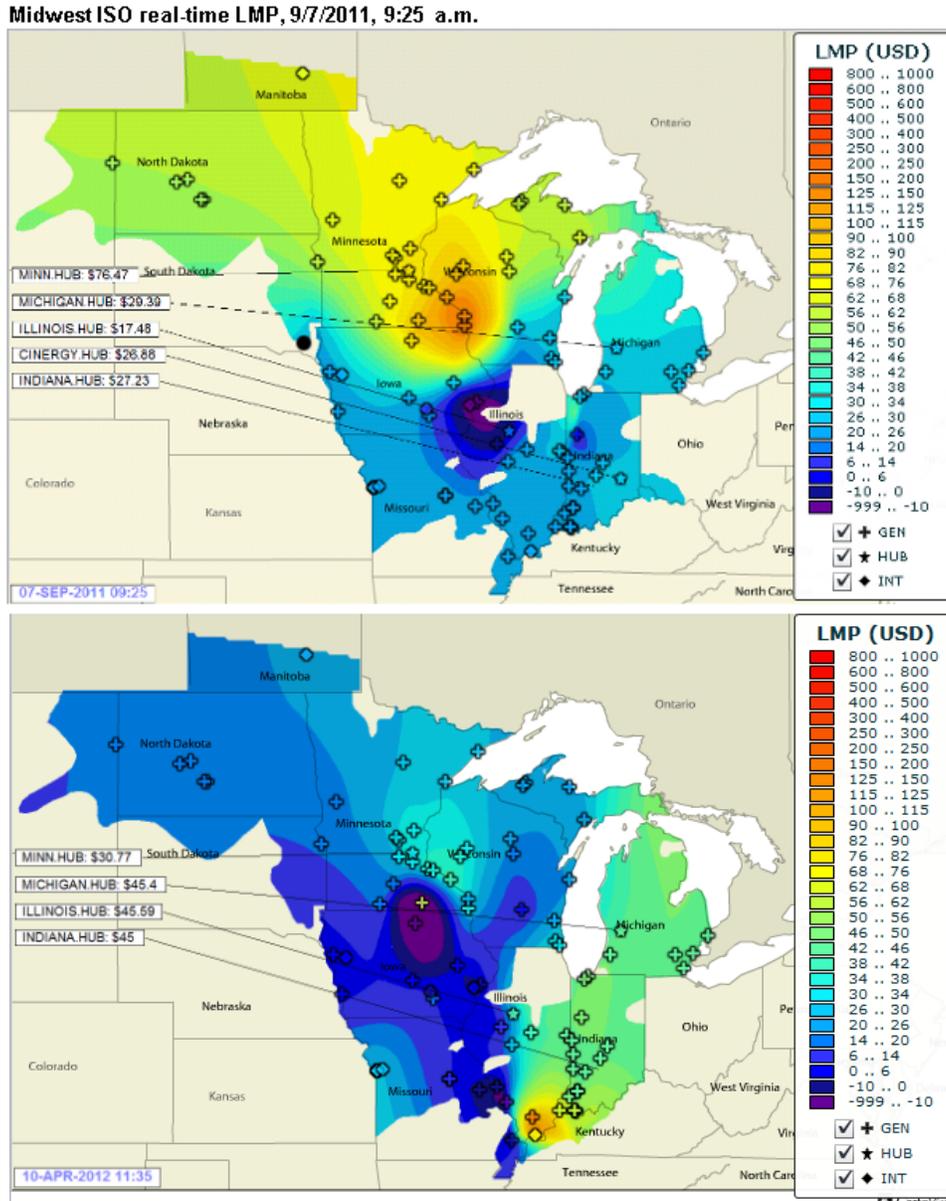
Consequently, estimating the hedging position as $\hat{x}^F = Q(p^S)$ will result in a negative bias, since $\alpha |R'(p^F)| > 0$. This downward bias will result in an upward bias in the BRD, since $\frac{\partial BRD}{\partial x^F} > 0$. An analogous argument shows that when $BRD < 0$, the bias in the forward contract position will lead to underestimating it.

It is not clear that this bias can be corrected, even though the components are observed. For the case of $BRD > 0$, the exercise would lead to moving between overestimating the

³⁵The economic minimum and maximum are part of the bids submitted by generators, and indicate the minimum and maximum quantity that it is profitable to produce. They may be willing to produce more under emergency conditions.

BRD and underestimating it, with no guarantee of convergence. Nonetheless, it is possible to establish bounds.

I Additional figures and tables



Apr. 10, 2012 - Interval 11:35 EST

Figure I.1: **Price dispersion** Heat map of prices across the MISO market on September 7, 2011 and April 10, 2012. Prices may differ significantly in a given moment, and over time. Source: MISO

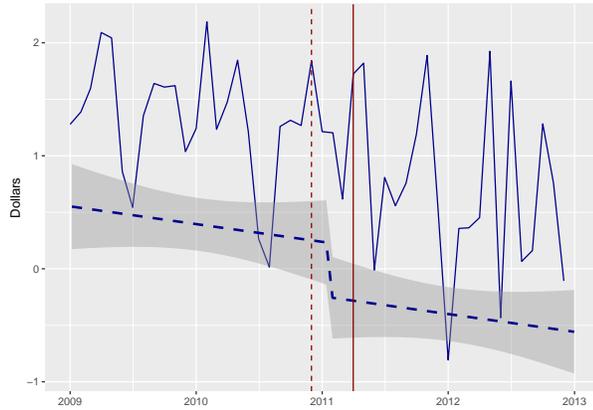
Table I.1: **Supply bids in the forward market** Each variable is computed daily. For instance, the number of bids is the total number of bids submitted each day. The sample goes from January 2010 to December 2011.

Statistic	N	Mean	St. Dev.	Min	Max
# bids	730	20,717	1,036	18,861	21,886
# nodes	730	927	28.2	883	957
# units	730	1,147	41.172	1,079	1,197
# firms	730	126	4.78	120	132
Percentage of bids cleared	730	0.361	0.035	0.288	0.511
Cleared MW	730	1,214,775	162,234	849,110	1,672,726
Price taker MWs	730	163,606	24,390	101,316	212,362
Percent piecewise linear	730	0.75	0.012	0.72	0.77
MW piecewise linear	730	0.82	0.013	0.78	0.86

Table I.2: **Supply bids in the spot market** Each variable is computed daily. For instance, the number of bids is the total number of bids submitted each day. The sample goes from January 2010 to December 2011.

Statistic	N	Mean	St. Dev.	Min	Max
# bids	730	13,037	1,031	10,607	17,071
# nodes	730	525.2	53.4	432	776
# units	730	603.9	65.1	493	914
# firms	730	100.3	6.24	88	118
Percentage of bids cleared	730	0.72	0.027	0.62	0.79
Cleared MW	730	1,447,665	189,301	1,075,636	1,977,326.000
Price taker MWs	730	123,147	27,014	63,248	196,913
Percentage bids piecewise linear	73	0.62	0.03	0.53	0.71
Percentage MW piecewise linear	730	0.81	0.02	0.74	0.86

(a) OLS



(b) Robust regression

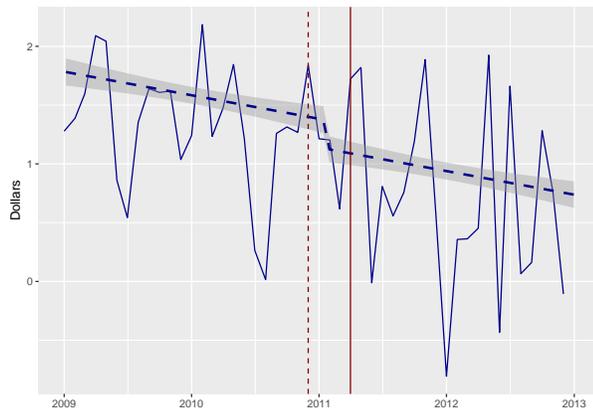


Figure I.2: **Forward premium over time.** The solid line shows the monthly average of the daily forward premium. Since the premium is so volatile, the plotted premium is a residual of a regression of the forward premium on monthly fixed effects, wind production, and actual demand. The dashed solid lines shows a regression line that includes a trend and a dummy for the two periods. The dashed vertical line on December 1, 2010 indicates the announcement of the regulatory change; the solid vertical line on January 16, 2011 shows the data in which there is a structural break for generators' behavior.

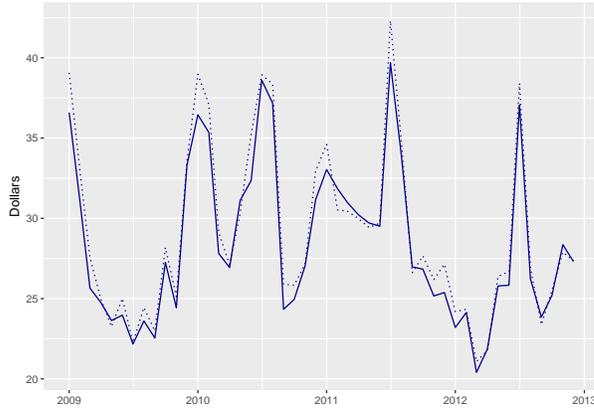


Figure I.3: **Forward and spot prices.** The dashed line shows the monthly average of the forward price over time, the solid line shows the same for the spot price.

Table I.3: **Summary statistics for demand bids** Each variable is computed daily. For instance, the number of bids is the total number of bids submitted each day. The sample goes from January 2010 to December 2011.

Statistic	N	Mean	St. Dev.	Min	Max
Price takers					
# bids	730	5,762	297.8	5,156	6,299
# nodes	730	228.6	15.7	197	246
# bidders	730	96.2	2.4	90	100
Percentage of bids cleared	730	1.000	0.000	1	1
Cleared MW	730	1,478,659	191,083	1,082,308	2,043,150
Price sensitive					
# bids	730	1,015	63.5	792	1,152
# nodes	730	42.3	2.7	33	48
# bidders	730	25.2	2.16	18	31
Percentage of bids cleared	730	0.9	0.031	0.78	0.99
Cleared MW	730	30,992	5,846	17,030	52,089

Table I.4: **Virtual bids summary stats** Each variable is computed daily. For instance, the number of bids is the total number of bids submitted each day. The sample goes from January 2010 to December 2011.

Statistic	N	Mean	St. Dev.	Min	Max
Virtual Demand					
# bids	730	53,556	18,873	15,240	97,824
# nodes	730	874	274.9	318	1,280
# bidders	730	56.4	6.71	31	77
Percentage of bids cleared	730	0.102	0.038	0.028	0.228
Cleared MW	730	86,263	22,058	39,909	161,463
Virtual Supply					
# bids	730	62,313	22,024	16,080	117,384
# nodes	730	993.6	309.4	351	1,378
# bidders	730	50.9	6.34	32	69
Percentage of bids cleared	730	0.095	0.032	0.034	0.197
Cleared MW	730	60,983	19,354	23,825	128,022