

# Market Power in a Hydro-Dominated Wholesale Electricity Market

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## Abstract

Concerns about market power have led to regulatory constraints on the price-setting process in nearly all wholesale electricity markets around the world. We study the conditions that led to the exercise of market power in the Colombian wholesale electricity market between 2008 and 2016, focusing on the two most recent occurrences of the climatic phenomenon known as *El Niño*. During the 2015–16 event, the mean wholesale price was more than three times higher than in 2009–10, even though water levels, fuel prices, and the market structure were relatively unchanged. We show that the higher prices in 2015–16 can be attributed to a large increase in the ability of generation unit owners to exercise market power, resulting from a narrower gap between system demand and available system capacity.

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# 1 Introduction

For oligopoly industries, both regulatory and market forms of organization suffer from costly imperfections (Joskow 2010). Nonetheless, for most industries and most countries, the restructuring process over the past forty years has led to a consensus design based on a market mechanism and regulation where necessary. The major exception is the electricity industry. For many parts of the United States, the electricity industry is still organized as a vertically-integrated regulated monopoly. In other countries, even those which have ostensibly “deregulated” their electricity sectors, government regulators play an outsized role in production, pricing, and investment decisions.

The dominant role played by regulators in the electricity generation sector reflects the prominence of two types of market imperfection. First, there are externalities associated with electricity generation in the form of local and global air pollution. The unwillingness in most jurisdictions to rely solely on market mechanisms for the control of these externalities has led to regulatory interventions aimed at tilting production and investment decisions towards less-polluting types of generation. Second, peculiar features of electricity make it particularly susceptible to the exercise of market power, meaning prices that are set higher than those that would prevail in a perfectly competitive market (Griffin and Puller 2009). Concerns about market power have led to regulatory constraints on the price-setting process in nearly all wholesale electricity markets around the world.

In this paper we study the conditions that led to the exercise of market power in the Colombian wholesale electricity market between 2008 and 2016. Like the other electricity markets in South America, the majority of electricity generation capacity in Colombia is hydroelectric, and is vulnerable to periodic shortfalls in water inflows. However, Colombia is unique in having a bid-based wholesale market, in which prices are determined based on the price and quantity bids submitted by generation plant owners. Every other wholesale market in the region uses cost-based bids, in which the prices used to construct the market supply curve are set by a regulatory formula.

We focus in particular on the two most recent occurrences of the global climatic phenomenon known as *El Niño*—the warm phase of the El Niño Southern Oscillation. In Colombia, this event leads to lower inflows into hydro reservoirs, and greater reliance on thermal generation plants. During the 2009–10 El Niño, the mean wholesale price for electricity in Colombia was 185 Colombian pesos per kWh (US\$95 per MWh at the exchange rate at that time). However, during the 2015–16 El Niño, the mean wholesale price was more than three times higher in the local currency: 675 Colombian pesos per kWh (US\$217

per MWh).

We rule out several possible explanations for the remarkable difference in wholesale prices between the two El Niño events. There was little difference in the severity of the two climate events, which had similar rainfall patterns and hydro reservoir inflows. Input fuel costs for the thermal plants were similar in the two periods: although natural gas prices were higher, the price of liquid fuels used by the highest-marginal-cost thermal plants was lower. Traditional measures of market power based on market concentration indices changed little over the period we study. Finally, although there are frequent small changes to the market rules, the fundamental characteristics of the wholesale market design were the same in 2015–16 as in 2009–10. In particular, a capacity market which pays generation unit owners based on their minimum level of guaranteed generation capacity had been in place since December 2006.

Instead, we show that the much higher prices in 2015–16 can be attributed to a large increase in the ability of generation unit owners to exercise market power. We construct two alternative measures of the ability to exercise market power, both based on the residual demand faced by firms when setting their price and quantity bids for the wholesale market auction. The pivotal measure is an indicator for the firm facing a vertical inverse residual demand curve at some positive quantity, meaning that the firm is guaranteed to be assigned a positive generation quantity in the auction, regardless of the price that it sets. The inverse semi-elasticity measure summarizes the “steepness” of the residual demand curve—the ability of the firm to increase the market price by reducing its quantity offers.

Both of these measures show that all of the major firms in the market had a substantially greater ability to exercise market power in 2015–16 than in 2009–10. We show there is a strong positive correlation between the offer prices set by the firms each day and each of the measures of the ability to exercise market power. This relationship is also reflected in the wholesale market prices: these prices are higher on those hours and days in which market participants had greater ability to exercise market power.

What accounts for the greater ability of generation unit owners to exercise market power in the more recent El Niño period? We show that growth in electricity demand in Colombia has been higher than growth in available generation capacity. Between 2009 and 2015, peak electricity demand grew by 10 percent, while total generation capacity grew at a rate of 21 percent. However, 89 percent of the generation capacity additions were new hydroelectric plants, which remain vulnerable to a reduction in their inflows during an adverse hydrological event. As a result, the mean reported availability of generation capacity increased by only

7 percent between 2009 and 2015. This tightening of the gap between system demand and available system capacity led to many more hours in which the large generation firms were pivotal as well as reduced the elasticity of the residual demand that they faced.

Wholesale electricity markets provide a data-rich environment in which to study the behavior of firms in oligopoly industries. One particularly appealing feature of this institutional setting is the formalized process by which market prices and quantities are set. This makes it possible to calculate (at least ex-post) the exact residual demand that firms faced when setting their market bids. In most other industries, a much stronger set of assumptions is required in order to estimate the residual demand faced by firms and hence their ability to exercise market power. As a result, there is a substantial existing literature that studies the exercise of market power in this setting.<sup>1</sup>

We make several contributions to this literature. First, we study the effect of long-term changes in the ability to exercise market power. By comparing two market events six years apart, in which we can rule out many other possible explanations for differences in market outcomes, we can isolate the effect of under-investment in thermal generation capacity relative to demand growth. Many previous studies of market power in wholesale electricity markets focus on short-term changes in market structure or conditions.

This focus on long-term changes in generation capacity and market power is important because one of the primary motivations for electricity market restructuring is to improve the capital investment decision process. Regulated firms may have incentives to overinvest in capital, with the costs of excess capacity investment passed on to consumers. Since the electricity market in Colombia was restructured in the 1990s, capital investment has been lower than demand growth, even with the presence of a capacity payment mechanism. This paper highlights a fundamental tradeoff in industry restructuring: lower levels of capital investment tighten capacity margins and, in the short-term, may reduce market efficiency through an increased ability of firms to exercise market power.

This paper also studies the exercise of market power in a wholesale electricity that includes a capacity payment mechanism designed, in part, to reduce market power. Most earlier studies of market power focused on energy-only wholesale markets without a capacity mechanism. In the Colombian case, firms are paid for a minimum guaranteed level of generation capacity (determined by a regulatory formula), with the price they can receive for this generation capped at a “scarcity price” (also determined by a regulatory formula). However,

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<sup>1</sup>For example, Wolfram (1999) and Sweeting (2007) study the England and Wales market, Borenstein, Bushnell, and F. A. Wolak (2002), F. A. Wolak (2003) and Puller (2007) study the Californian market, and Hortacsu and Puller (2008) study the Texas market.

firms who can produce in excess of their minimum guaranteed level receive the market price for their additional generation, and so still may have an incentive to increase the wholesale market price.

Finally, this paper studies the interaction of generation investment and wholesale market outcomes in the particularly important setting of a middle-income country, where electricity demand growth is still relatively high and continued capacity additions are warranted. Most future global electricity demand growth will occur in low and middle-income countries (Gertler et al. 2016). Most existing studies of wholesale market power in electricity are in relatively mature markets with limited growth. Colombia is an ideal environment in which to study these issues given that it was a pioneer in industry restructuring and is still one of the few middle-income countries with a bid-based wholesale market.

The rest of the paper is as follows. Section 2 provides background on the Colombian electricity market and the data used for our analysis. Section 3 compares the market outcomes between the 2009–10 and 2015–16 El Niño events and rules out many possible explanations for the difference. Section 4 summarizes the price-setting process in wholesale electricity markets and the construction of our measures of ability to exercise market power. Section 5 contains our empirical analysis of the relationship between market outcomes and these market power measures. Section 6 concludes.

## 2 Institutional setting and data

Restructuring of the electricity industry in Colombia began in 1994. This process was motivated by a period of electricity rationing between March 1992 and March 1993, the result of an El Niño event that reduced inflows into hydro reservoirs.<sup>2</sup> The government lacked the financial capacity to invest in new thermal plants that could act as a backup for hydro generators in dry years (Dyner, Arango, and Larsen 2006). After the reforms, there was considerable private investment in thermal capacity during the late 1990s.

The market design for the industry restructuring in Colombia is different to that used in any other Latin American market (Rudnick and Montero 2002). It is based around a central pool in which prices are determined by daily price and quantity bids that generators submit to the system operator. Each generation unit may submit a single price for its output for the entire day. The quantity made available from each generation unit is allowed to vary

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<sup>2</sup>Fetzer, Pardo, and Shanghavi (2014) use satellite night lights to study the geographical variation in rationing during the 1992–93 blackouts. They show that the electricity shortages led to a short-term increase in fertility and a permanent increase in the number of children.

by hour. Beginning in 2009, generators were allowed to submit the startup costs associated with each unit, and the dispatch algorithm used by the system operator ensured that plants were only turned on if they would recover these costs.<sup>3</sup> By contrast to the Colombian market design, the other electricity markets in the region use a cost-based dispatch, in which the “price” of each unit is set based on a regulatory cost formula.

The market also includes a system of capacity payments that are made to generators even when they are not producing electricity. The amount of the capacity payment (in \$ per MW) is determined by auctions for long-term investment in new generation capacity, first held in May 2008 and December 2011.<sup>4</sup> Both existing and new generation plants receive the payments for their assigned capacity, known as the firm energy obligation. During periods when the wholesale price exceeds a regulated “scarcity price”, the generators who received these payments are required to pay the difference between the wholesale price and the scarcity price, multiplied by their firm energy. This creates a financial incentive for the generators to make their plants available during periods of system scarcity, in order to meet this financial obligation. In effect, the price that generators receive for their assigned capacity is capped at the scarcity price, although they still receive the wholesale price for any generation in excess of their firm energy. The scarcity price is recalculated each month based on changes in the price of an international fuel oil benchmark.

The three largest firms in the Colombian market are Empresas Públicas de Medellín (EPM), Emgesa, and Isagen, with a combined generation capacity of 60 percent of the total (Table 1). These firms are predominantly hydroelectric, although each has a small proportion of thermal generation. Three smaller firms have significant amounts of hydroelectric generation capacity: Celsia, AES Chivor, and Urrá. Ownership of thermal generation capacity is less concentrated, and there are several small firms that own or operate a single thermal plant.

The data for our analysis was provided by the Colombian market operator XM. We use hourly information on the operation of the market for the period January 2008 to June 2016. This hourly information includes the price and quantity offers for each generation unit, the system demand, the dispatched and actual generation output of each unit, and the market price. We supplement the hourly data with information on hydrological inflows and storage

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<sup>3</sup>Riascos et al. (2016) study the effect of including startup costs in the generation bids in the Colombian market. They find that it led to a reduction in production costs but this was not passed through to lower wholesale prices. Reguant (2014) studies the use of these complex bids in the Spanish wholesale electricity market.

<sup>4</sup>Harbord and Pagnozzi (2012) review the design, outcome and performance of these auctions.

levels, as well as information on fossil fuel usage and prices.

### 3 Comparison of El Niño events

Electricity generation in Colombia is predominantly hydroelectric. Total generation increased from 41.28 terawatt-hours (TWh) in 2000 to 66.55 TWh in 2015, an average annual growth rate of 3.2 percent. Between 2000 and 2009, most of this growth in electricity demand was met by increases in hydro generation (Figure 1). However, this changed after 2010, with demand growth mostly met by increasing thermal generation. Hydro generation peaked at 48.71 TWh in 2011 and has been lower in every subsequent year. Between 2000 and 2005, hydro comprised 78.7 percent of total generation. This fell to 71.7 percent of the total between 2012 and 2015.

The most striking pattern of the composition of electricity generation in Colombia is the periodic reduction in hydroelectric energy associated with the climatic phenomenon known as *El Niño*. This event is characterized by an increase in water temperatures in the central Pacific Ocean. One effect of this for Colombia is a reduction in rainfall (and hence inflows into hydro reservoirs) in some of the major hydro-producing regions of the country. This reduction in inflows associated with El Niño occurred in 2009–10 and again in 2015–16. As seen on Figure 1, these periods were associated with a large drop in hydroelectric generation and a large increase in thermal generation.

During the 2009–10 El Niño, the mean wholesale price for electricity in Colombia was 185 Colombian pesos per kWh (US\$95 per MWh at the exchange rate at that time). However, during the 2015–16 El Niño, the mean wholesale price was more than three times higher in the local currency: 675 Colombian pesos per kWh (US\$217 per MWh). The average price during October 2015 spiked at more than 1000 Colombian pesos per kWh (bottom panel of Figure 2). The wholesale price was much higher in the more recent El Niño in spite of utilization of thermal generation capacity being very similar between the two events (top panel of Figure 2).

We rule out several possible explanations for the higher prices in 2015–16. First, there is little evidence that hydrological conditions were more severe in the recent event. Hydro inflows in 2009 were comparable to hydro inflows in 2015 (Figure 3). One difference is that the 2015–16 event had been preceded by a sustained period of low annual inflows, with inflows in 2013 and 2014 similar to those in the critical years of 2009 and 2015.

Hydro reservoir levels are distinct from hydro inflows, in that they depend not only on

weather conditions, but also on the offer behavior of all generation unit owners. Daily average reservoir levels in 2013 were the lowest in our sample period, as shown in Figure 4. The unusually high inflows during 2011 were reflected in record high reservoir levels in 2011 and 2012. This figure illustrates that 2015–16 El Niño Event was not significantly different from 2009–10 event in terms of water inflows and water levels during the event period, although one difference was that the 2015–16 event was preceded by several years of low water inflows and low water levels.

Another reason why wholesale electricity might have been higher in 2015–16 than in 2009–10 is higher input fuel prices for thermal generators. Figure 5 plots the price of diesel fuel at Barrancabermeja (a major Colombian refining center and pipeline hub) and the US Gulf Coast over this same time period in Colombia Pesos (COP) per million British Thermal Units (MMBTU). Figure 6 plots the natural gas prices at Henry Hub and the Guajira and Cusiana locations in Colombia in COP/MMBTU over our sample period. The vertical black line marks the date that natural gas price regulation in Colombia ended. For both diesel prices and natural gas prices, the Peso per MMBTU prices throughout the mid-2012 to mid-2015 period were the same as or at most only slightly higher than they were during the 2009–10 El Niño period.

Although natural gas prices in Colombia rose significantly in late 2015, there are a number of reasons to believe these input fossil fuel price increases alone are insufficient to explain the extraordinary increase in wholesale prices in late 2015 shown in Figure 2. First the price of diesel fuel in Colombia was significantly higher than the price of natural gas and it was falling during much of this time period. Second, as shown in Figure 7, diesel and fuel oil were being used to produce some electricity throughout the mid-2012 to mid-2015 time period. This means that the marginal generation unit setting the wholesale market price would have been a diesel or fuel oil unit in both the 2009–10 and 2015–16 El Niño events. Lower diesel prices in 2015–16 mean that changes in fuel prices cannot explain the increase in the wholesale electricity price.

Similarly, traditional measures of market concentration cannot explain the higher prices in the 2015–16 El Niño event. Figure 8 presents the Herfindahl-Hirschman Index (HHI) of concentration from 2008 to the present time using the capacity shares of each market participant. There has been very little change in market concentration and structure over the period of interest. The HHI is presented separately for thermal generation capacity, hydroelectric generation capacity, and all generation capacity. Hydroelectric capacity is concentrated in the three largest firms which explains why the HHI for hydroelectric capacity

is significantly higher throughout the time period than it is for thermal capacity and all generation capacity. The higher HHI for hydroelectric capacity provide suggestive evidence that when water availability is low (as during the El Niño events) there is less competition to supply electricity and the large generation unit owners have a greater ability to raise the wholesale price by exercising unilateral market power. In the next section we describe two measures of the ability of a generation unit owner to raise the wholesale market price.

## 4 Measurement of market power in electricity markets

This section introduces two measures of the ability of a supplier in a bid-based wholesale electricity market to exercise unilateral market power. These measures depend on the hourly willingness-to-supply curves of all producers and the level of hourly demand.

A market participant is said to possess the ability to exercise market power if it can take unilateral actions to influence the market price and to profit from the resulting price change. The demand side of most electricity markets is composed of many small buyers and the supply side is typically composed of a small number of large sellers. It is also relatively straightforward for a large supplier to withhold output from the short-term market, whereas it is extremely difficult, if not impossible, for a large demander to do this unless it curtails the consumption of the retail customers that it serves. Consequently, the primary market power concern in wholesale electricity markets is from suppliers taking actions to influence market prices.

It is important to emphasize that a supplier exercising all available unilateral market power subject to obeying the market rules is equivalent to that supplier taking all legal actions to maximize the profits it earns from participating in the wholesale market. Moreover, a firm's management has a fiduciary responsibility to its shareholders to take all legal actions to maximize the profits it earns from participating in the wholesale market. Consequently, a firm is only serving its fiduciary responsibility to its shareholders when it exercises all available unilateral market power subject to obeying the wholesale market rules.

A supplier to an auction-based wholesale electricity market submits a willingness-to-supply or offer curve which is composed of a series of offer steps for each pricing period. The length of the step specifies an incremental quantity of energy to be supplied and the height of the step is the price at which the supplier is willing to sell that quantity of energy. The Colombian market has 24 hourly pricing periods each day. Suppliers are restricted to submit a single price step for the entire day for each generation unit, but they are allowed

different hourly quantity steps for each unit. Figure 9 shows the final offer curve submitted by Firm 1 for a peak hour in September 2015. For the lowest-priced offer step, Firm 1 is willing to supply 45 MW at a price of zero. If the market price increases to 129 pesos/kWh, it is willing to supply an additional 194 MW, and so on. As the offer price increases, the supplier's cumulative willingness to sell electricity increases along with the offer price, from 37 MW at 0 pesos/kWh to 239 MW at 129 pesos/kWh and 1479 MW at 250 pesos/kWh. This increasing relationship between the offer price and the supplier's cumulative willingness to sell yields the upward sloping offer curves for the supplier shown in Figure 9. Let  $S_k(p)$  denote the offer curve of supplier  $k$ . At each price  $p$ , this function gives the total quantity of energy that supplier  $k$  is willing to sell.

Summing over the offer curves of all suppliers in the market yields the aggregate offer curve  $S(p)$  given in Figure 10. This is equal to  $S_1(p) + S_2(p) + \dots + S_K(p)$ , where  $K$  is the total number of suppliers in Colombia. Let  $QD$  equal the aggregate market demand for this hour. The wholesale price in the market is computed by taking the aggregate willingness-to-supply curve and solving for the price where this curve intersects the total demand. The wholesale price is the solution in  $p$  to the equation  $S(p) = QD$ . An example of this process is shown in Figure 10. In this hour, the total market demand in Colombia was 9,319 MW. Based on the aggregate offer curve for all the suppliers, the market price had to be at least 322 pesos/kWh for there to be enough supply offers to meet this demand.

This description of the price-setting process allows a graphical description of how suppliers exercise unilateral market power in a bid-based wholesale market, which motivates our two measures of the ability of a supplier to exercise unilateral market power. To analyze the offer behavior of an individual supplier using this graphical framework, the above mechanism can be reformulated in terms of the supplier's own offer curve, the sum of the offers of other suppliers, and the total market demand. Specifically, the price setting equation  $S(p) = QD$  can be re-written as:  $S_1(p) + S_2(p) + \dots + S_K(p) = QD$ .

Suppose that we are interested in measuring the ability of supplier  $j$  to exercise unilateral market power. This price-setting equation can be re-written as:

$$S_j(p) = QD - (S_1(p) + S_2(p) + \dots + S_{j-1}(p) + S_{j+1}(p) + \dots + S_K(p)) = QD - SO_j(p),$$

where  $SO_j(p)$  is the aggregate willingness-to-supply curve of all firms besides supplier  $j$ . Define  $DR_j(p) = QD - SO_j(p)$  as the residual demand curve facing supplier  $j$ . The residual demand of supplier  $j$  at price  $p$  is defined as the market demand remaining to be served by supplier  $j$  after the willingness to supply curves of all other firms besides supplier  $j$  have

been subtracted from the market demand.

Figure 11 provides a graphical version of the above calculation of the residual demand for Firm 1 in the same hour. The total market demand is 9,319 MW and the total quantity offered by all suppliers other than Firm 1 is 5,172 MW at 250 pesos/kWh and 3,637 MW at 125 pesos/kWh. Therefore, Firm 1’s residual demand at 250 pesos/kWh is 4,147 MW (the market demand of 9,319 MW minus 5,172 MW of supply by other generators at that price). Its residual demand at 125 pesos/kWh is 5,682 MW (the market demand of 9,319 MW minus 3,637 MW of supply by other generators at that price).

Figure 12 shows the residual demand curve  $DR_1$  resulting from performing this calculation for all possible prices for Firm 1 in this hour. It also includes Firm 1’s offer curve  $S_1(p)$  from Figure 9. The quantity at the point where these two curves intersect defines Firm 1’s generation in that hour. The price at the point of intersection defines the market-clearing price for the system.

The residual demand curve that a supplier faces summarizes its ability to impact the market price through changes in its offer behavior, holding the offer behavior of other suppliers constant. A firm can choose to produce any price and generation quantity pair along its residual demand curve. Firms in imperfectly competitive markets often speak of “pricing to take what competition gives them” or “pricing at what the market will bear”. These statements can be interpreted as the firm choosing the price/quantity pair along its residual demand curve that maximizes its profits. In this sense, a supplier’s residual demand curve shows the trade-off between a higher system price and lower generation quantity for the supplier because of supply responses of its competitors.

We can use this residual demand to define two measures of the ability of a supplier to exercise unilateral market power (S. D. McRae and F. A. Wolak 2014). The first is called the inverse semi-elasticity of the residual demand curve. Define  $\eta_j$  for firm  $j$  as;

$$\eta_{hj} = - \frac{1}{100} \frac{DR_{hj}(p_h)}{DR'_{hj}(p_h)}$$

where  $DR_{hj}(p_h)$  is the value of firm  $j$ ’s residual demand curve hour  $h$  evaluated at the market-clearing price for hour  $h$  and  $DR'_{hj}(p_h)$  is the slope of firm  $j$ ’s residual demand curve during hour  $h$  evaluated at the market-clearing price for hour  $h$ .  $\eta_{hj}$  is equal to the \$/MWh increase in the market clearing price that would result from supplier  $j$  reducing the amount of energy it sells in the short-term market during hour  $h$  by one percent. A higher value of  $\eta_{hj}$  implies a greater ability of a supplier to exercise unilateral market power. Graphically,

the steeper the residual demand curve that supplier  $j$  faces during hour  $h$ , the greater is supplier  $j$ 's unilateral ability to raise the wholesale price by withholding output from the market and the larger is  $\eta_{hj}$ .

The second measure is the frequency that supplier  $j$  is pivotal. Supplier  $j$  is pivotal is the value of  $DR_j(\infty)$ , its residual demand at an infinite price, is greater than zero. In words, this means that the value of supplier  $j$ 's residual demand is positive for all possible prices. Alternatively, given the offers its competitors, supplier  $j$  must produce a positive amount of energy regardless of the market-clearing price or system demand will not be met. One measure of the ability of a supplier to exercise unilateral market power is the fraction of hours in some time period when the supplier is pivotal. The higher the frequency that a supplier is pivotal, the greater is the supplier's ability to exercise unilateral market power.

To provide a graphical illustration of the change in a supplier's expected profit-maximizing offer curve when its ability to exercise unilateral market power changes, Figure 13 plots the residual demand curve faced by Colombian Firm 1 and its offer curve at 6 pm on September 18, 2015. Note the very flat residual demand curve faced by Firm 1 on September 18 and the flat offer curve it submitted. Figure 14 plots these same two curves exactly two weeks later, for 6 pm on October 2, 2015. The residual demand curve during this hour is much steeper than the one at 6 pm on September 18, reflecting a significantly greater ability to exercise unilateral market power. Firm 1's offer curve is steeper during this hour, implying that the firm took this knowledge into account in formulating its offer curve for the day. The resulting wholesale price is much higher than it had been on September 18.

Note that residual demand curve for Firm 1 in Figure 14 becomes vertical at a quantity greater than zero on October 2, 2015, but it intersects the vertical axis at a finite price on September 18. Therefore, consistent with our definition of a pivotal supplier, Firm 1 is pivotal at 6 pm on October 2, 2015, but not at 6 pm on the earlier day.

## 5 Empirical analysis of market power

This section uses the two measures of the ability of supplier to exercise unilateral market power to explain the far more extreme market outcomes during the 2015–16 El Niño event versus the 2009–10 event. Specifically, we find that both measures of the ability to exercise unilateral market power show a massive increase in the ability of the large suppliers in Colombia to exercise unilateral market power starting in October 2015 and lasting through the Spring of 2016. This substantially greater ability to exercise unilateral market power is

reflected in the much higher market clearing prices during this time period.

The top panel of figure 15 plots the average weekly value of  $\eta_{hj}$  for Firm 1 from January 2008 to June 2016. The middle panel plots the fraction of hours in each week that Firm 1 is pivotal. The bottom panel plots the average weekly value of the highest accepted hourly offer price for Firm 1. The highest accepted hourly offer price is the highest offer price that has a positive value for Ideal Generation during that hour. Although there is a very small frequency that Firm 1 is pivotal during the 2009–10 El Niño period, there is very little evidence that Firm 1 had much of an ability to exercise unilateral market power during this time period. Consistent with this evidence, Firm 1’s maximum accepted offer prices only increase slightly during the 2009–10 El Niño period.

During the 2015–16 El Niño period there is a large increase in the average weekly values of  $\eta_{hj}$  and an equally large increase in the fraction of hours in the week that Firm 1 is pivotal to almost 60 percent of hours starting in October 2015. This is accompanied by an enormous increase in the maximum accepted offer prices submitted by Firm 1 starting at the same time. The results for Firm 2 in Figure 16 and Firm 3 in Figure 17 are quantitatively similar to the results for Firm 1, except that the differences between the unilateral ability measures for the 2009–10 and 2015–16 event are more stark. Both Firm 2 and Firm 3 are rarely pivotal and have very small values of  $\eta_{hj}$  during the 2009–10 El Niño Event, and both experience substantial increases in the values of  $\eta_{hj}$  starting in October 2015. Again, the maximum accepted offer prices for these suppliers during the 2009–10 period only increase slightly, whereas they more than quadruple starting in October 2015. A similar pattern is observed for smaller firms in the market.

Table 2 provides a quantitative analysis of the relationship between market prices and our measures of the ability of firms to exercise market power. The table shows the result of regressing the wholesale price each hour on the mean of the  $\eta_{hj}$  across the six major firms, the mean pivotal indicator across the six firms, or the mean pivotal quantity across the six firms. All of the regressions also include very flexible controls for the system load and the month of the sample. These controls account for changes in fuel prices, system demand, and hydrological conditions over our sample period. The first three columns show results for regressions in which the three market power ability measures are included separately. The final column shows the results for a regression that includes all three measures. All of the ability measures have a very precisely estimated positive relationship with the market price, with the exception of the mean pivotal indicator when this is included with the other two measures.

These results are supported by the analysis in Table 3. This table shows separate regressions for each of the six major firms. The dependent variable in these regressions is the offer price for the firm each hour, defined as the highest offer price for a unit owned by that supplier with non-zero ideal generation. This is regressed on the firm  $\eta_{hj}$  and the firm pivotal indicator. The  $\eta_{hj}$  have a very precisely estimated positive relationship with the offer price of each firm, as do the pivotal indicators in four of the six regressions. All of these results provide strong systematic evidence that our measures of market power are capturing the ability of suppliers to raise market prices.

The results above provide strong evidence in favor of the view that the remarkable increase in market prices during the 2015–16 El Niño event period relative to the 2009–10 period was the result of a tremendous increase in the ability of suppliers to exercise unilateral market power during the 2015–16 period that was not present during the 2009–10 period.

What explains this increase in unilateral market power? Electricity generation has continued to grow steadily from 2000 to 2016. However, a larger fraction of total generation is provided by thermal units, particularly for the post-2010 time period (Figure 1). This has occurred even though virtually all generation capacity additions since 2010 have been hydroelectric units. Compared to the existing hydroelectric plants, the new hydroelectric generation has relatively limited storage capacity. This makes it especially susceptible to declines in water inflows due to climatic events such as El Niño. The continued increase in electricity demand and the increased reliance on thermal plants has reduced the “buffer” in the system and its ability to meet demand in years with adverse weather conditions.

This reduction in the availability of generation relative to system demand is illustrated in Figure 18. The black line at the top of the graph is the nameplate capacity of generation units in Colombia from 2006 to the present time. The brown line below it is the total availability of generation capacity in Colombia during the highest demand hour of the week. This is the sum of offer quantities at any offer price during the highest demand hour of that week. The yellow line below the brown line is the total availability during the highest demand hour of the week minus the availability in that hour of the supplier with the largest total availability during that hour. Note that the supplier whose total availability is subtracted from the system-wide availability is not always the same supplier each hour, because different suppliers have the maximum total availability during the different hours of the sample. The blue line that lies below the yellow line before 2014, except for a short time during the 2009–2010 El Niño period, is total system generation during this maximum demand hour of the week. Finally, the red line at the bottom is the positive difference between the blue line and

the yellow line. Anytime this event occurs, the supplier with the larger total availability that hour of the week must supply some energy from the generation capacity it makes available or system demand will not be met. Such a supplier is pivotal. As Figure 18 demonstrates, starting in 2014, the yellow “Availability N-1” line frequently falls below the blue “Max Demand” line, indicating that the supplier with the largest total availability during that hour has substantial ability to exercise unilateral market power.

One rationale for the new capacity payment mechanism set up in 2006 was to provide financial support for new and existing thermal generators, in order to keep them available as backup for El Niño years. However, as illustrated by the market outcomes during the 2015–16 El Niño event, the mechanism has not been completely successful at achieving this goal (S. McRae and F. Wolak 2016). Several new thermal generation plants that were assigned firm energy in the auctions were never built or were completed far behind schedule. Some existing thermal plants failed to procure sufficient fuel in order to operate at capacity during the scarcity period. In one case, a thermal plant walked away from its firm energy obligations and refused to produce electricity, in spite of having received the firm energy payment during the previous nine years. For hydroelectric generations, the mechanism placed regulatory restrictions on the management of reservoirs, which limited the ability of these firms to optimally manage their water resources.

A second rationale for the capacity payment mechanism was to limit the incentive of generation firms to exercise market power during scarcity periods. The firm energy obligation had a similar effect to a forward contract: during scarcity conditions, generation firms receive the fixed scarcity price for output up to their firm energy obligation. Output in excess of the firm energy obligation received the wholesale market price. However, unlike an ordinary forward contract, generation firms have control over the occurrence of a scarcity condition, because their market power gives them the ability to set the wholesale price (recall that scarcity conditions are defined as the wholesale price exceeding the regulated scarcity price). Furthermore, during scarcity conditions, the settlement price for existing forward contracts held by generation firms is capped at the scarcity price. This means that for wholesale market prices above the scarcity price, the forward contract quantity no longer reduces the incentive of firms to increase the market price. As a result, the capacity mechanism creates a complex set of incentives for firms to exercise market power by either increasing or reducing the market price, depending on whether the firms are short or long relative to both their firm energy obligation and their forward contract position.

The capacity mechanism did limit the extent to which final end users were affected by

the exercise of market power during the 2015–16 El Niño event. The maximum price that unregulated customers had to pay for electricity was capped at the scarcity price. However, the high wholesale market prices still had important financial implications for generation firms. The generators with a long position relative to their firm energy obligations earned high profits during this period, at the expense of those generators with a short position relative to their firm energy obligations. In addition, the lack of price signals to electricity users created additional inefficiencies in the market. Consumers had no reason to adjust their consumption in response to the scarcity conditions.<sup>5</sup>

## 6 Conclusion

Electricity industries that rely on renewable sources such as hydroelectricity are particularly susceptible to shortfalls in generation capacity during adverse climate events. Such events may become more frequent and more severe in the future as the result of climate change. The design of electricity markets with large shares of renewable capacity should respond to this challenge. In particular, they require incentives for generation firms to keep sufficient thermal generation capacity available to be able to meet system demand during worst-case climate events, while limiting the ability and incentive of firms to exercise market power during these events.

We have shown in this paper that the current design of the Colombian wholesale electricity market has not met these objectives. During the 2015–16 El Niño event, the large generation firms in the market had a high level of market power, as measured by either their pivotal frequency or the semi-elasticity of their residual demand curves. The firms exploited this market power by raising their generation offer prices, leading to very large increases in the wholesale market price. Market outcomes were very different to the 2009–10 El Niño event, reflecting the much greater market power that firms had during the more recent event. We ruled out other possible explanations for the differences between the two events, such as differences in hydrological conditions or fuel prices. The principal cause of the increase in market power was a shortfall in generation investment relative to demand growth, particularly investment in thermal generation that can be used in dry years. The existing market design, especially the capacity payment mechanism, has contributed to both the short-run exercise of market power and the long-run underinvestment in appropriate

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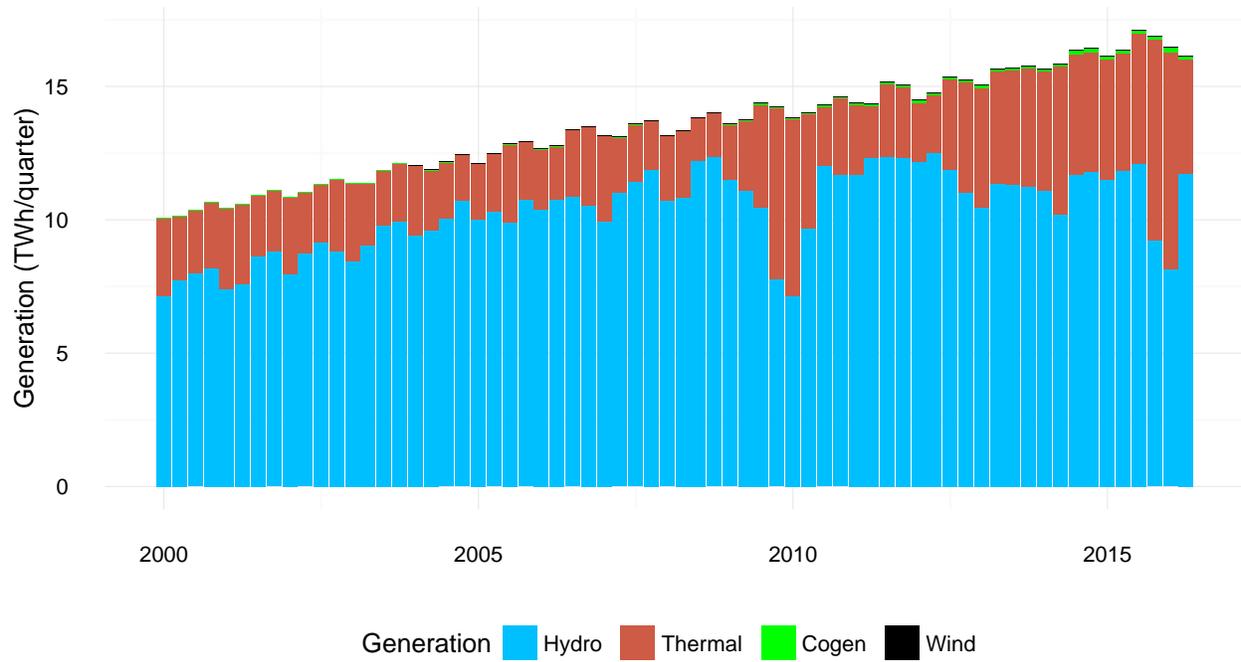
<sup>5</sup>In early 2016, the government introduced an ad hoc rebate system to provide an incentive for regulated users to reduce their electricity consumption.

generation capacity.

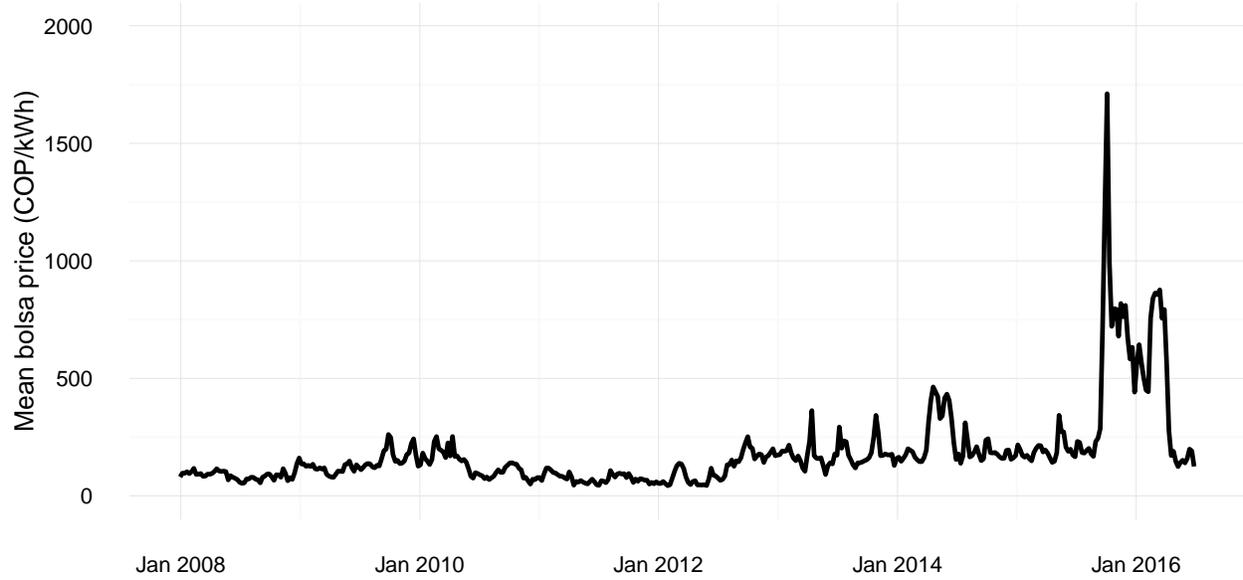
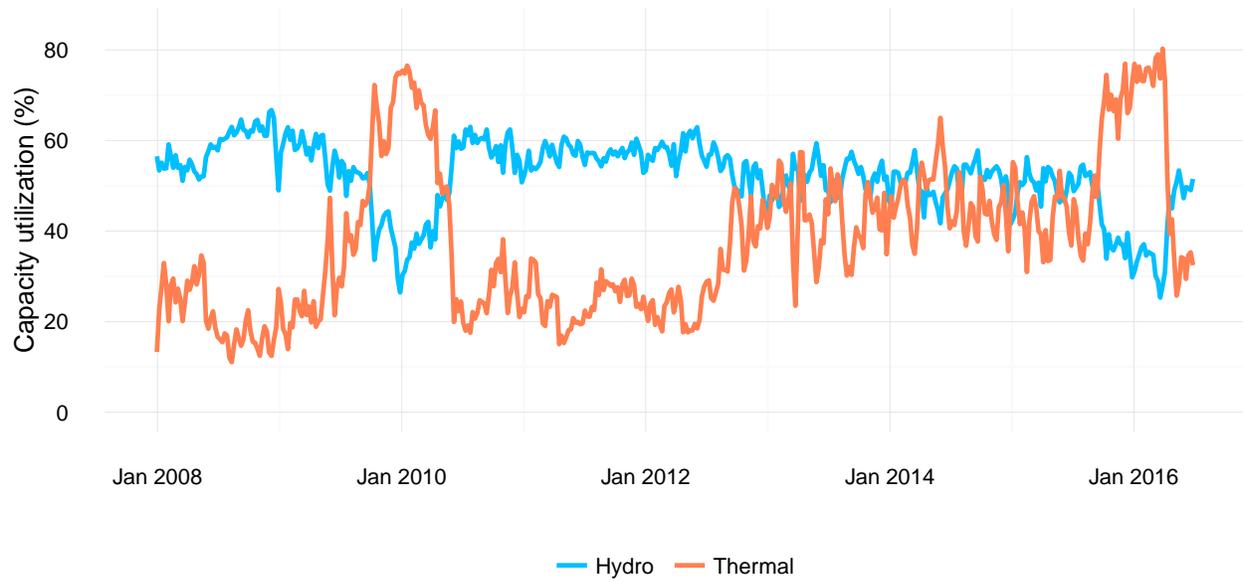
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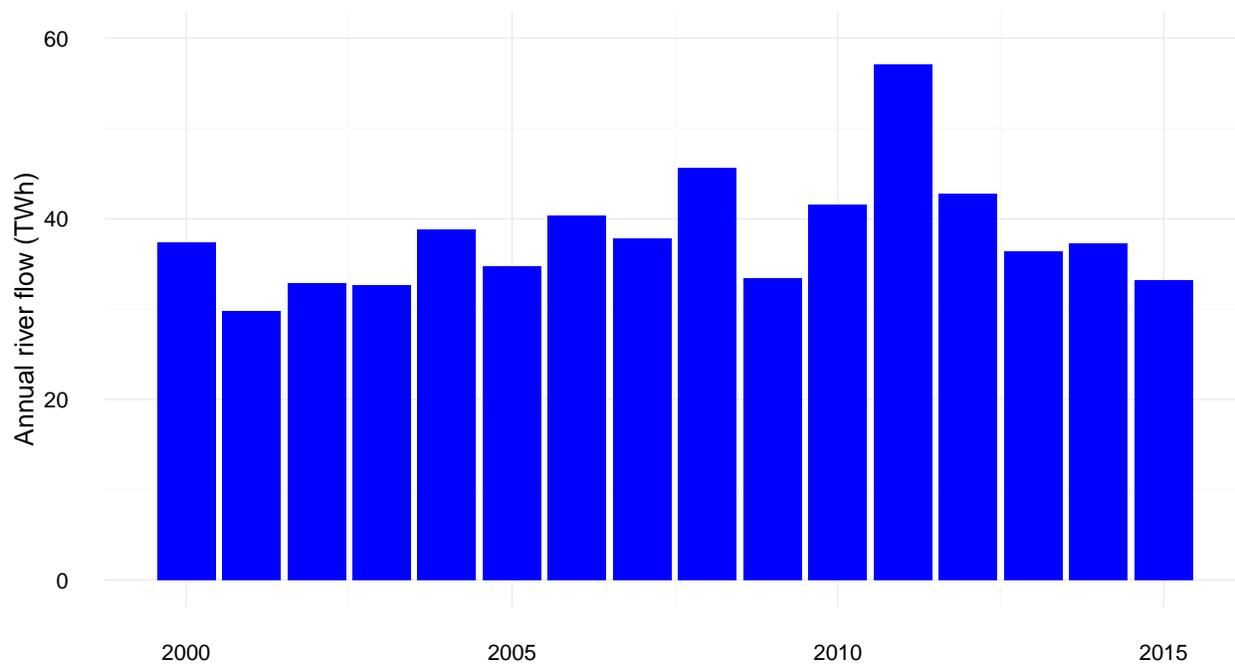
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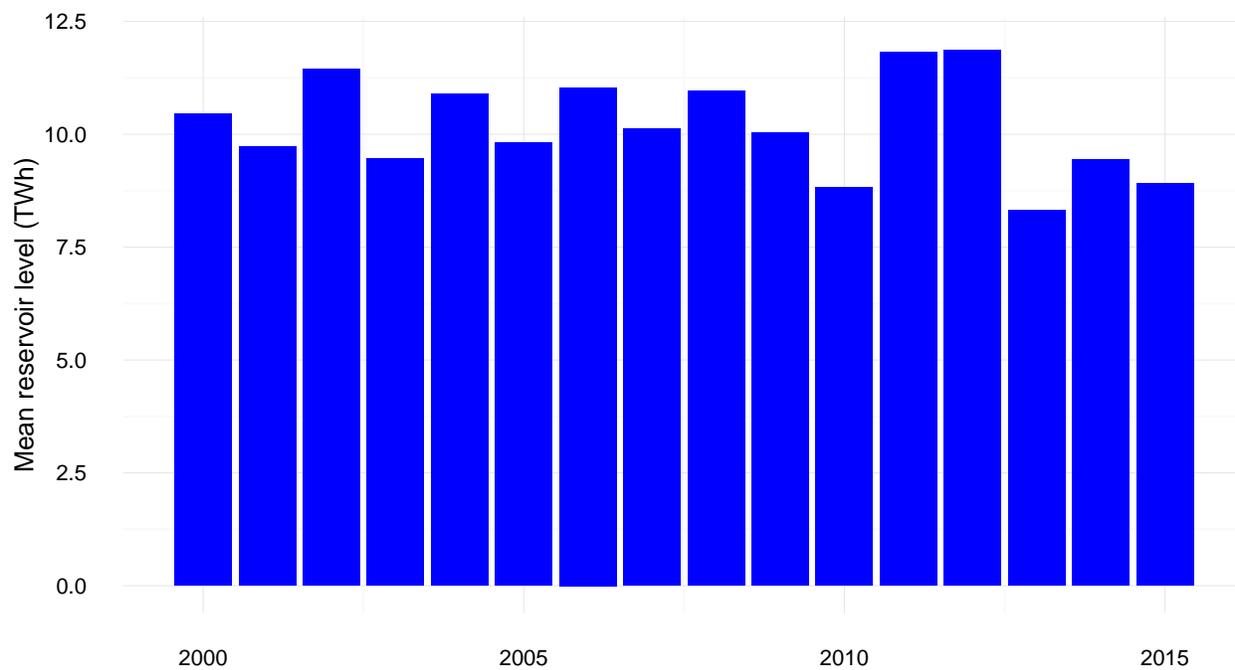
**Figure 1:** Quarterly actual electricity generation in TWh, by type of generator



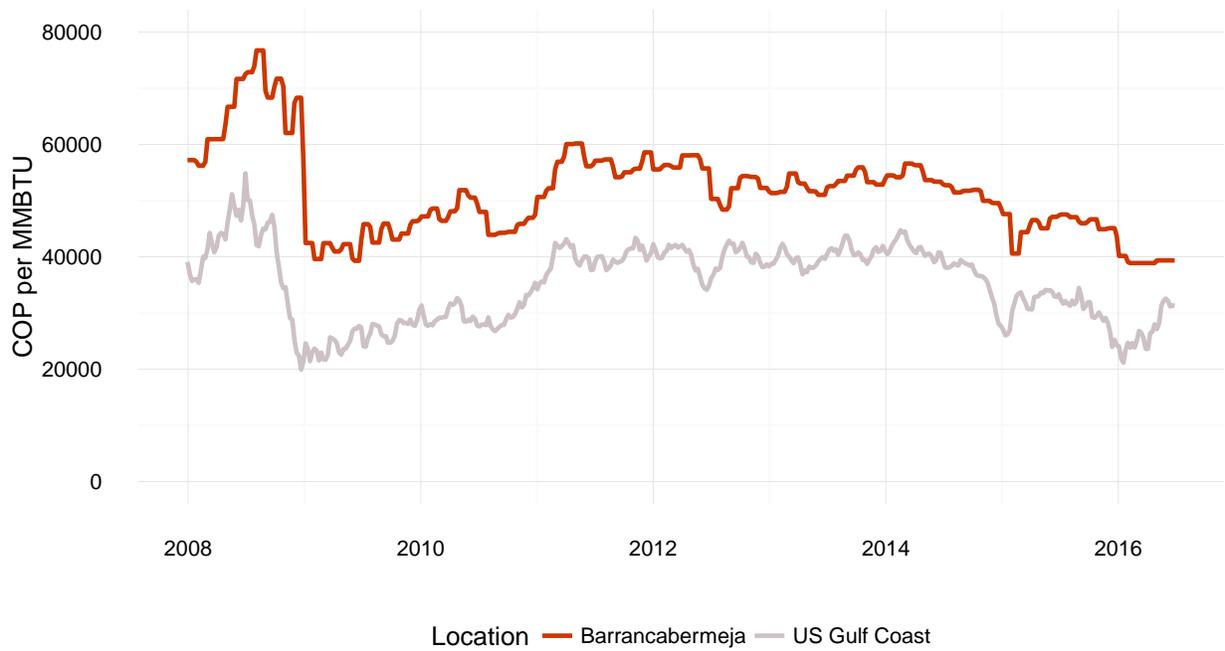
**Figure 2:** Weekly capacity utilization by technology and average bolsa price



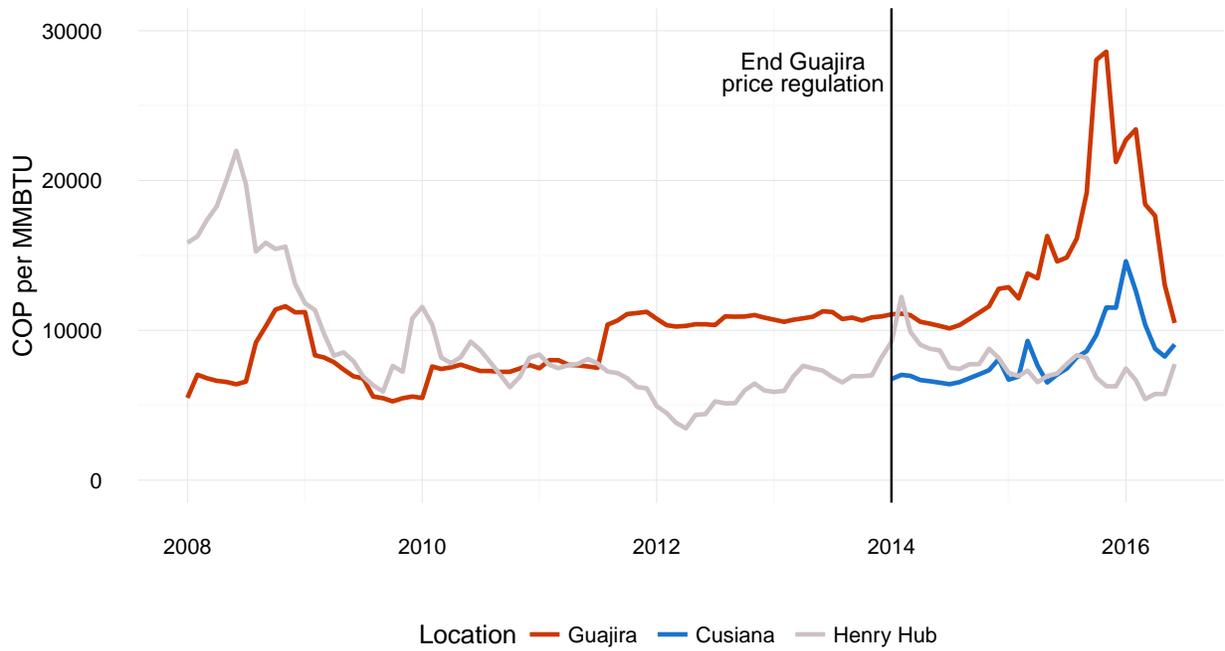
**Figure 3:** Annual river flow, in TWh equivalent, 2000–2015



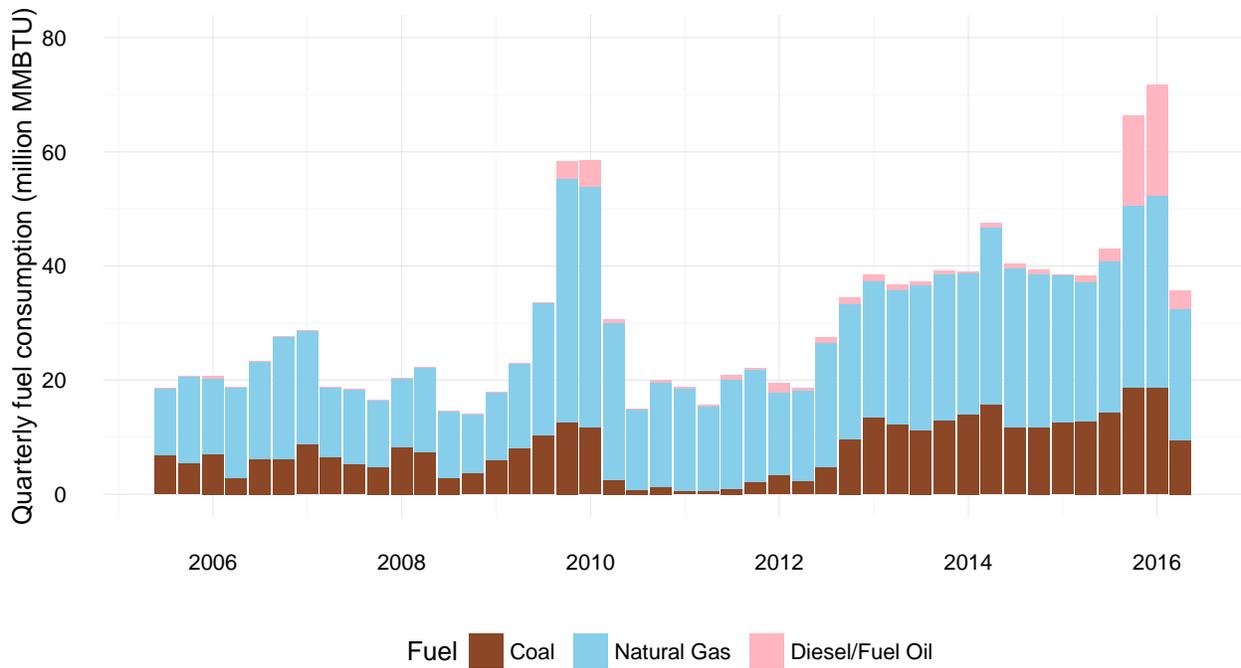
**Figure 4:** Annual mean hydro reservoir levels, 2000–2015



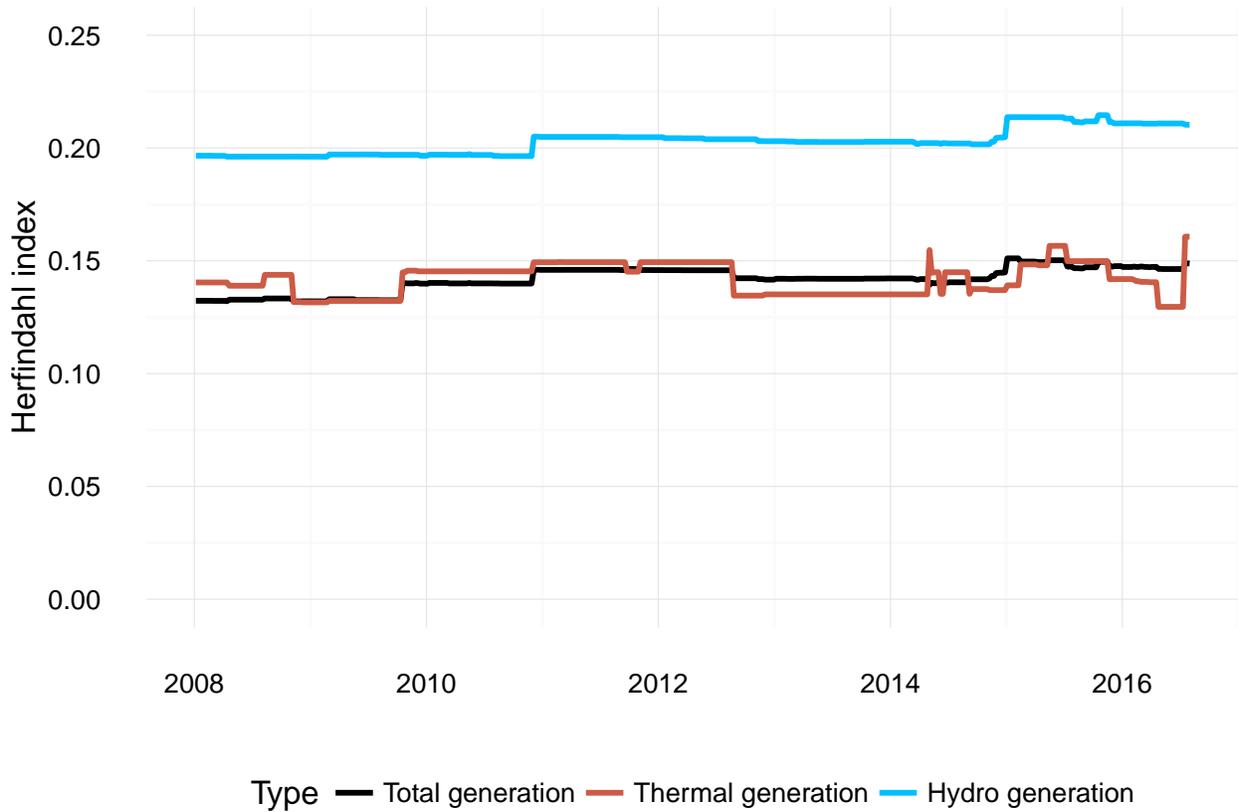
**Figure 5:** Diesel price at Barrancabermeja and US Gulf Coast, 2008–2016



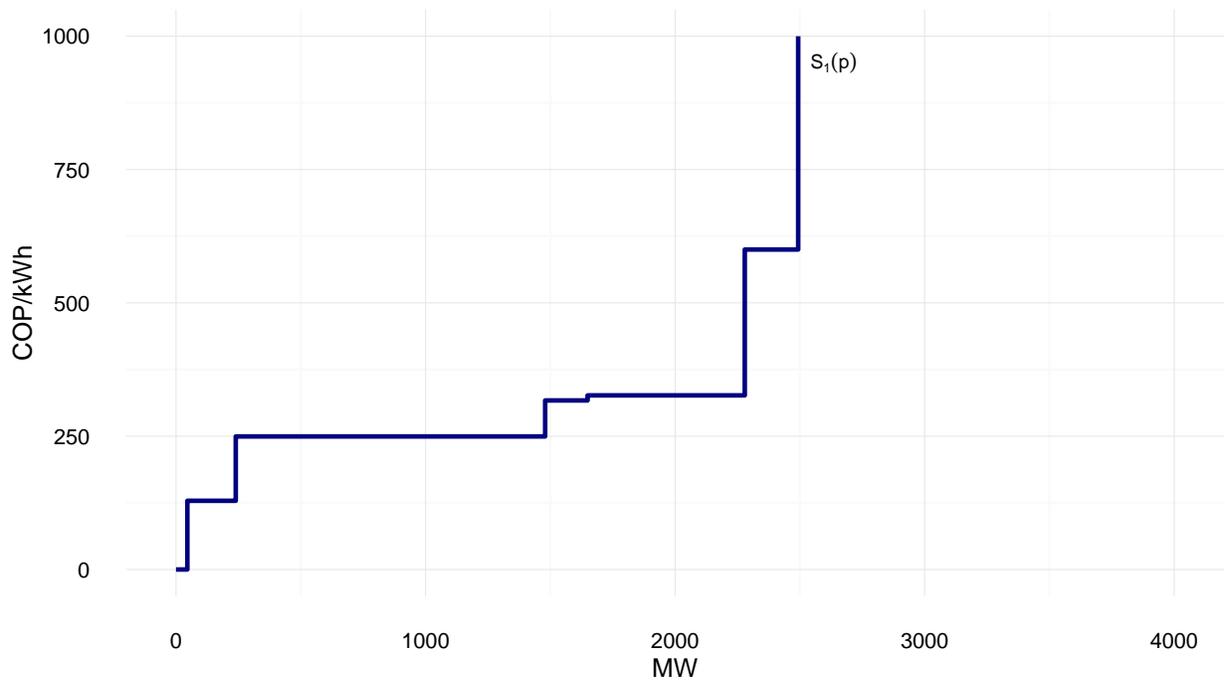
**Figure 6:** Natural gas prices at Henry Hub and major Colombia price points, 2008–2016



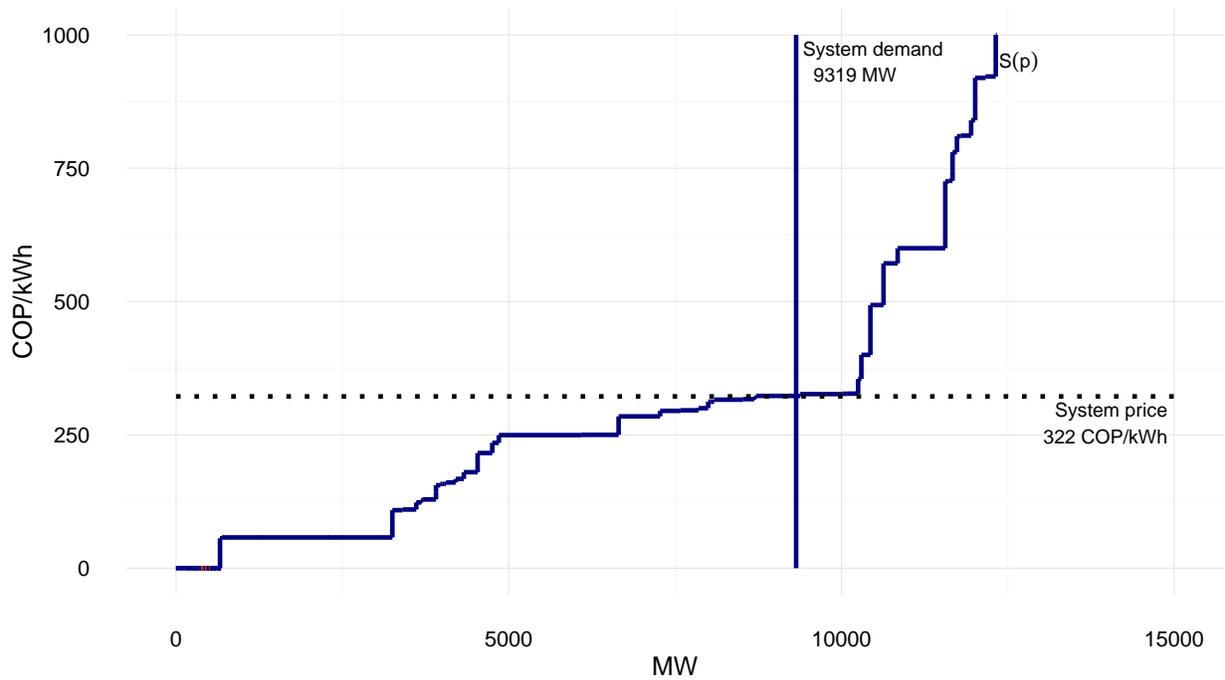
**Figure 7:** Quarterly fuel consumption by thermal generators, 2005–2016



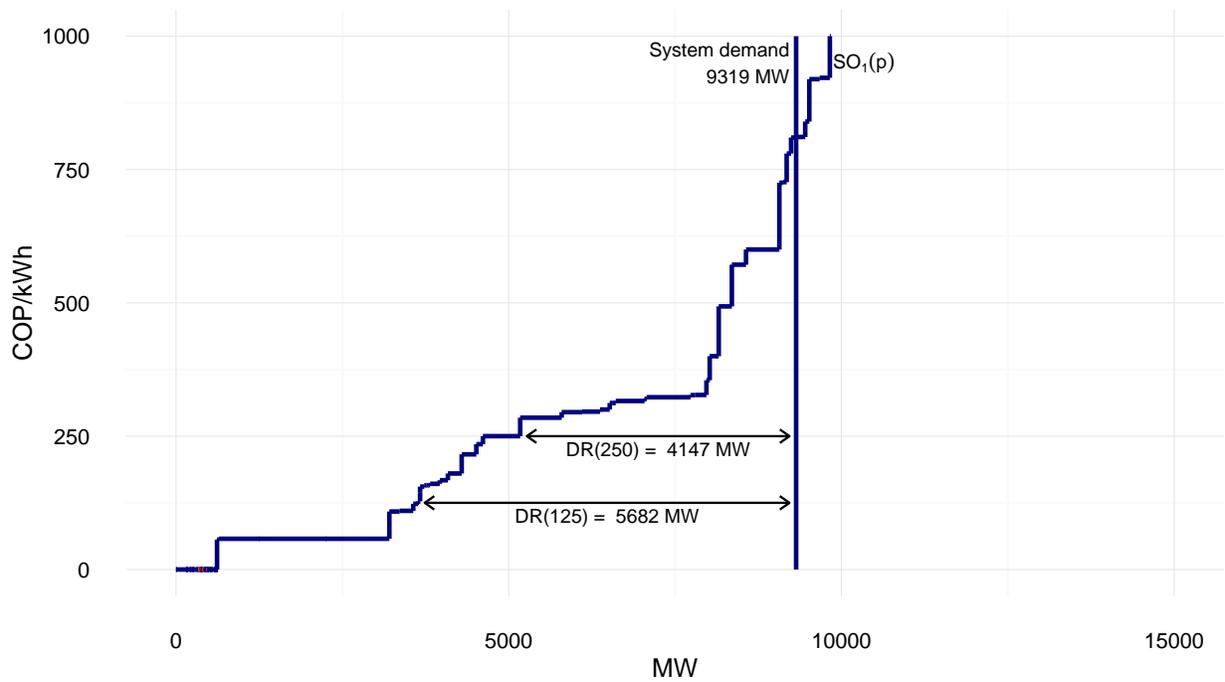
**Figure 8:** Herfindahl-Hirschman index for generation capacity, 2008–2016



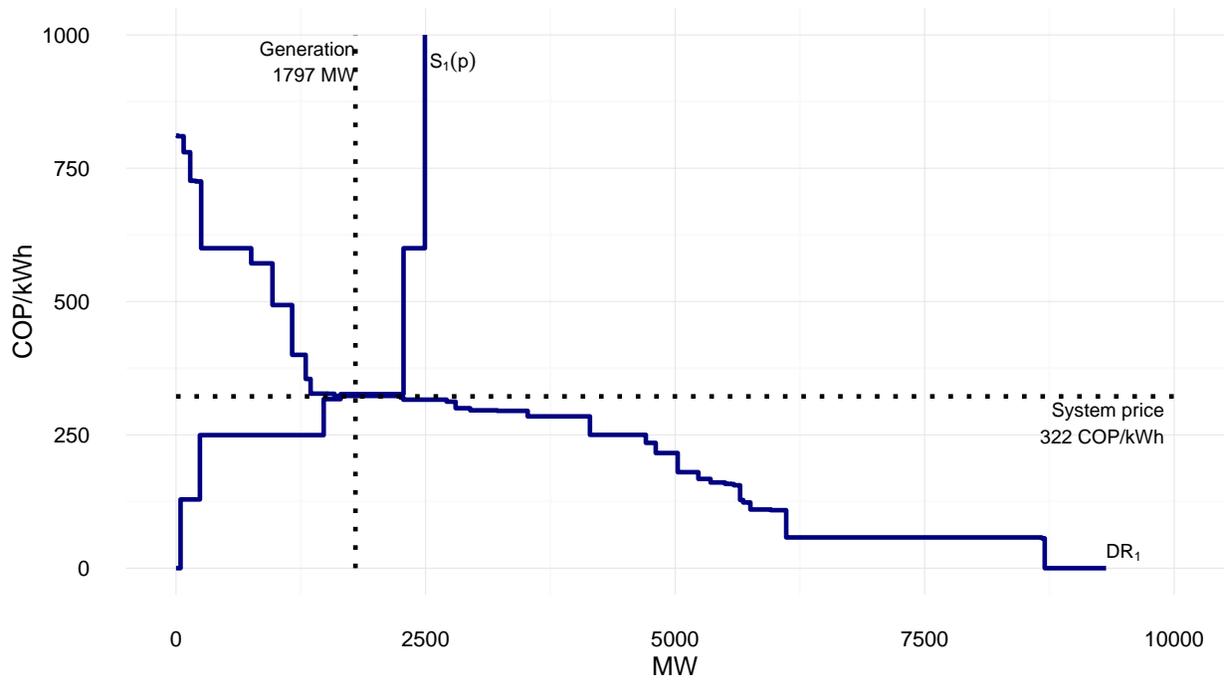
**Figure 9:** Offer curve for Firm 1 for a peak period in September 2015



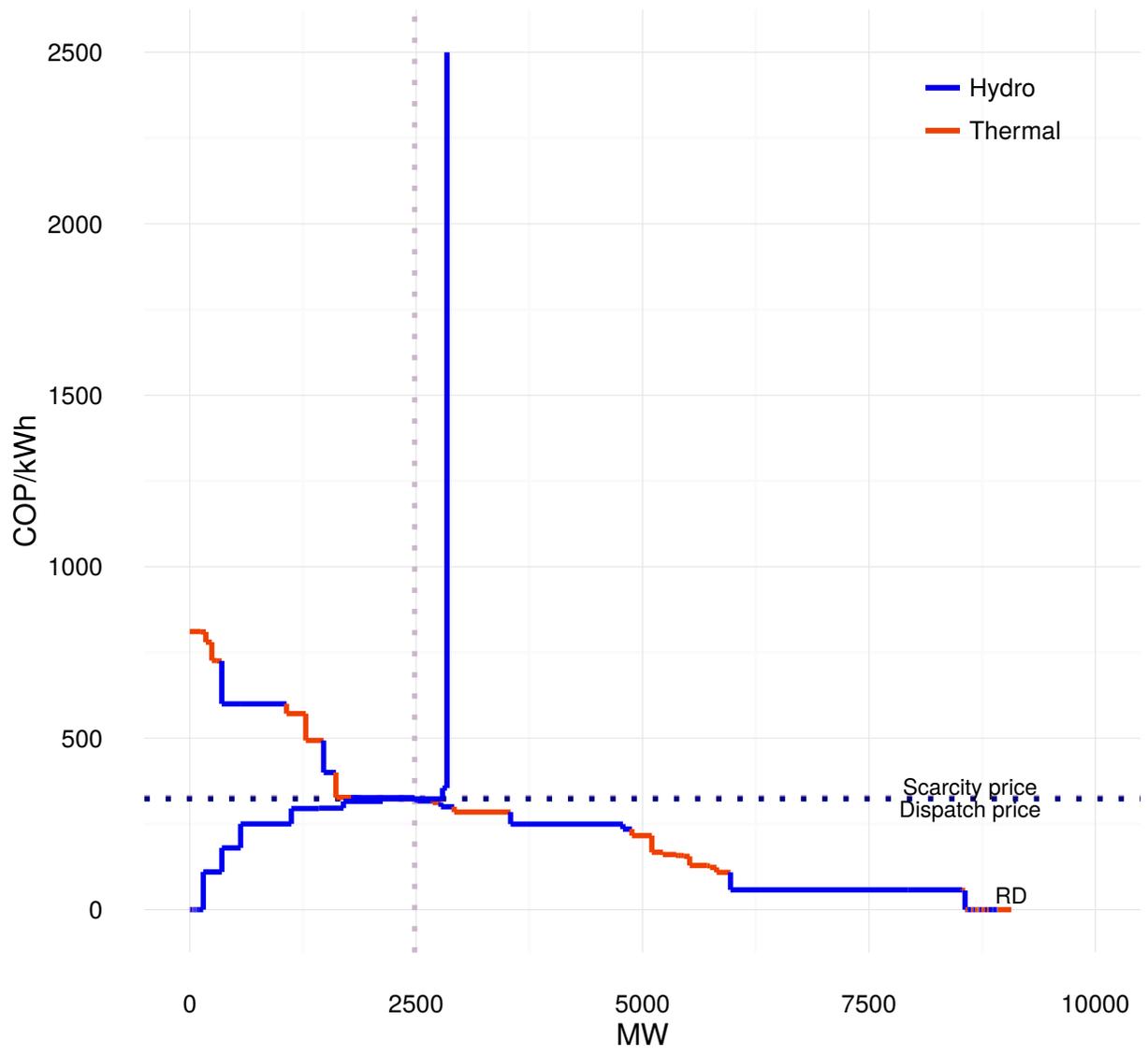
**Figure 10:** Aggregate offer curve for all generators and calculation of the system price



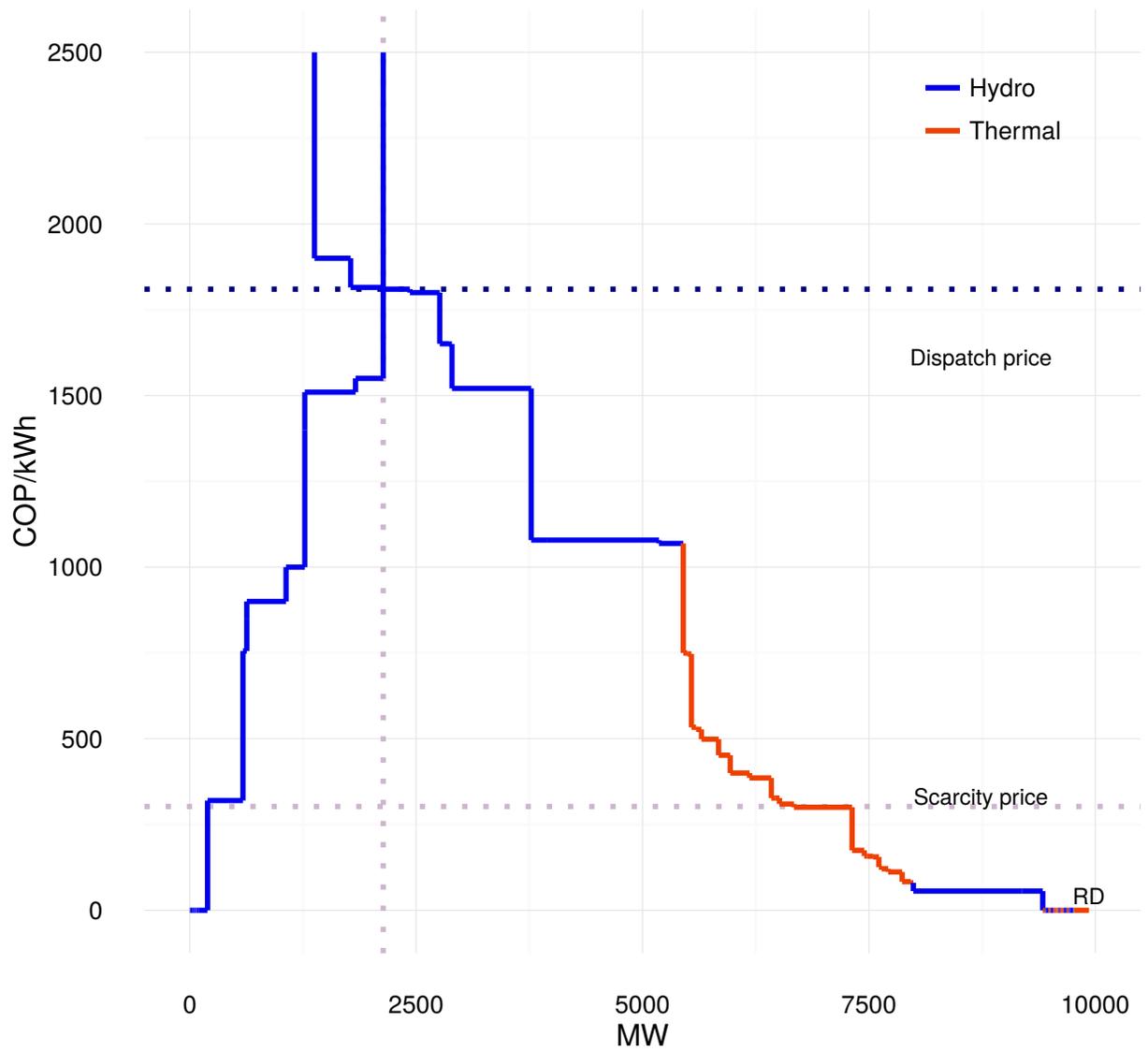
**Figure 11:** Calculation of residual demand for Firm 1



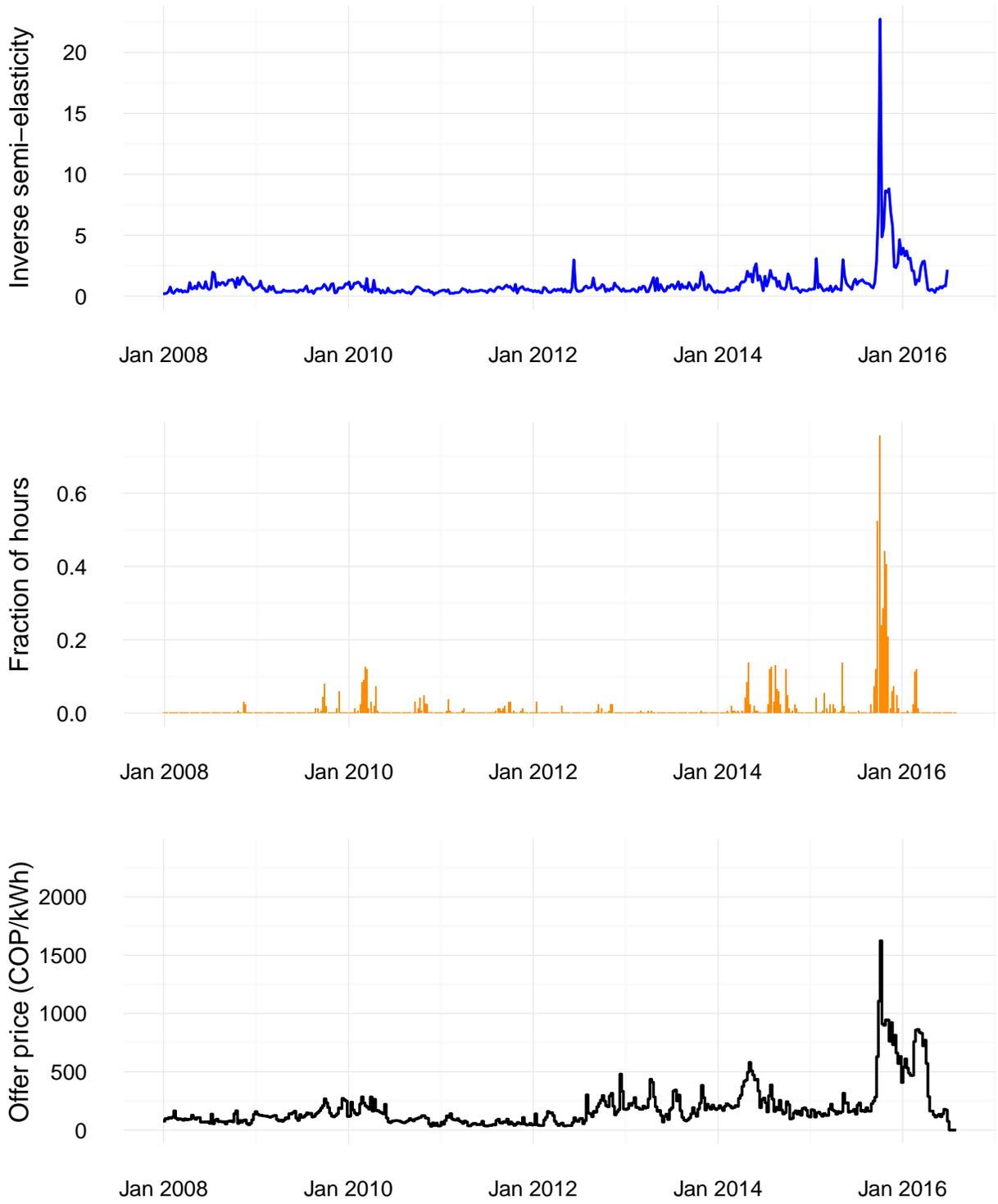
**Figure 12:** Residual demand and offer curve for Firm 1



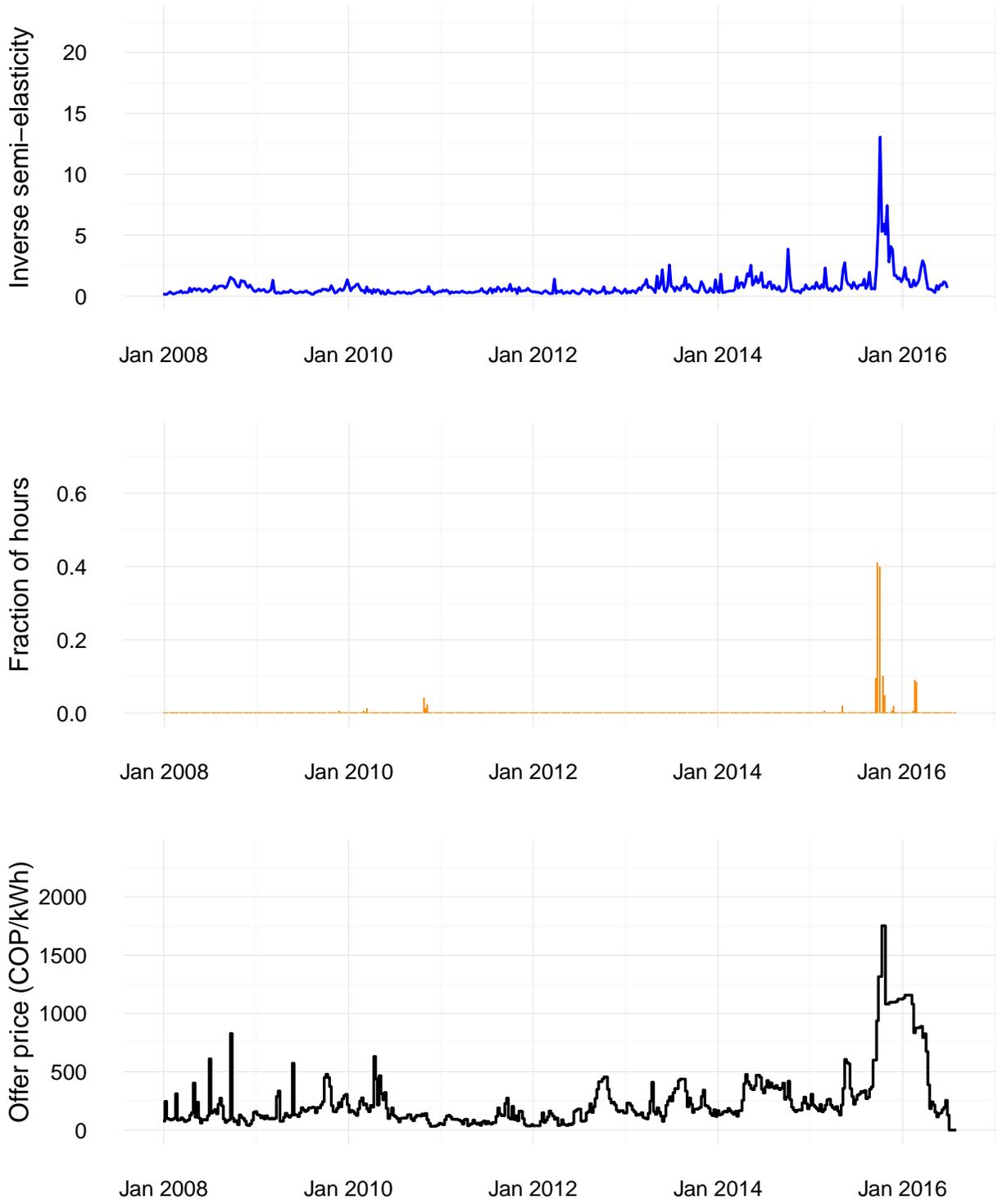
**Figure 13:** Offer curve and residual demand at 6:00PM on September 18, 2015—Firm 1



**Figure 14:** Offer curve and residual demand at 6:00PM on October 2, 2015—Firm 1



**Figure 15:** Offer prices and market power measures—Firm 1



**Figure 16:** Offer prices and market power measures—Firm 2

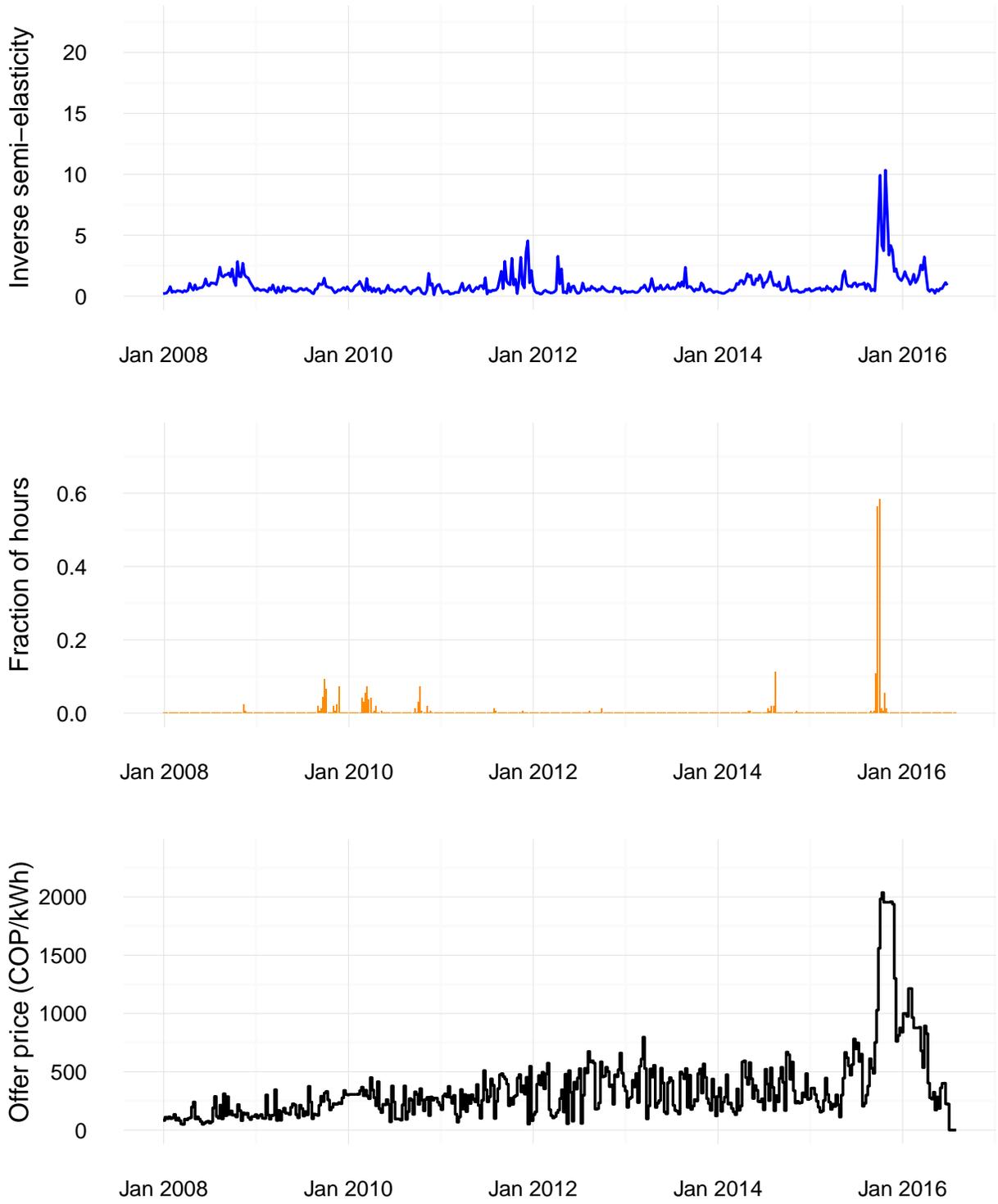
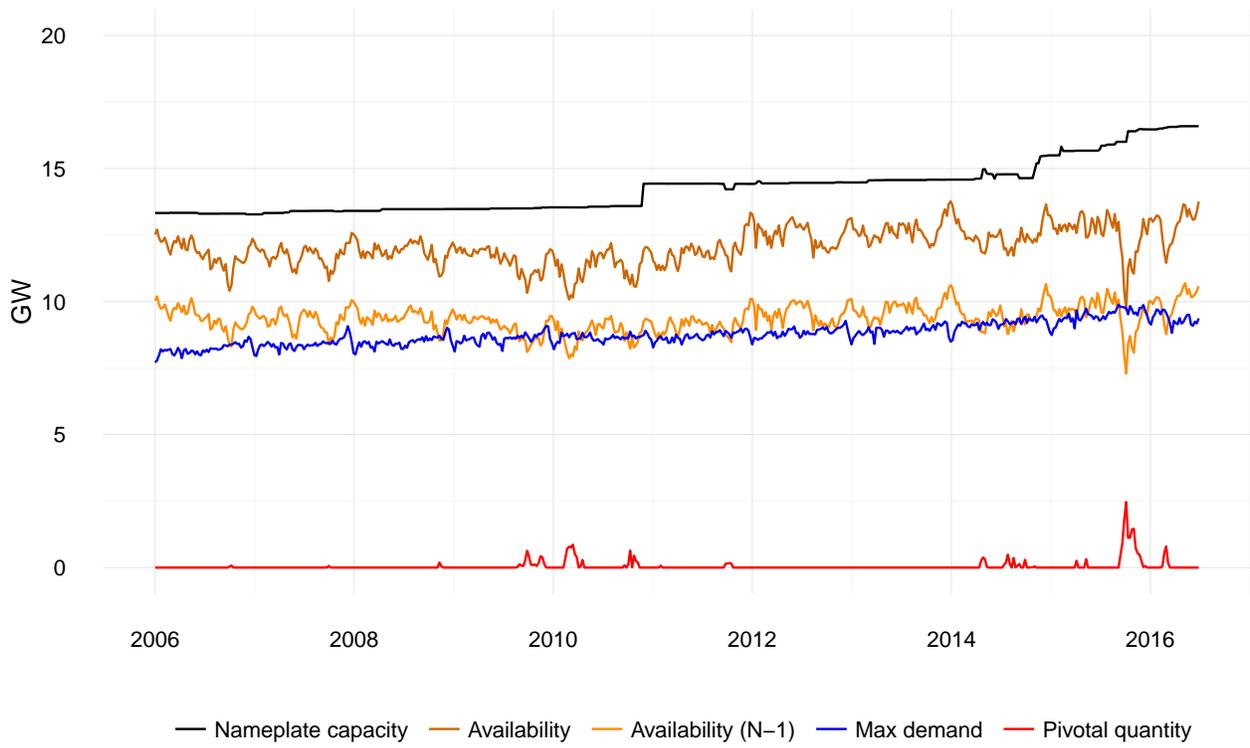


Figure 17: Offer prices and market power measures—Firm 3



**Figure 18:** Generation availability on highest demand hour of each week, 2006–16

**Table 1:** Ownership or control of generation capacity in GW, as of 30 June 2016

Firm	Hydro	Thermal	Cogen	Wind	Total	Percent
EPM	2.99	0.54	0.01	0.02	3.56	21.48
Emgesa	3.02	0.41	0.01	0.00	3.44	20.73
Isagen	2.73	0.26	0.00	0.00	2.99	18.02
Celsia	1.08	0.78	0.05	0.00	1.90	11.47
SCLEA consortia	0.00	1.22	0.00	0.00	1.22	7.34
AES Chivor	1.00	0.00	0.00	0.00	1.00	6.03
Gecelca	0.00	0.46	0.00	0.00	0.46	2.80
Urra	0.34	0.00	0.00	0.00	0.34	2.04
Colgener	0.00	0.33	0.00	0.00	0.33	1.98
Gensa	0.00	0.32	0.00	0.00	0.32	1.93
Termocandelaria	0.00	0.32	0.00	0.00	0.32	1.90
ContourGlobal	0.00	0.21	0.00	0.00	0.21	1.28
Other	0.33	0.11	0.06	0.00	0.50	3.01
<b>Total</b>	<b>11.48</b>	<b>4.97</b>	<b>0.13</b>	<b>0.02</b>	<b>16.59</b>	<b>100.00</b>

**Table 2:** Wholesale price and measures of ability to exercise market power

	Bolsa price (COP/kWh)			
	(1)	(2)	(3)	(4)
Mean $\eta$	18.15*** (6.16)			11.90*** (3.44)
Mean pivotal indicator		858.22*** (246.13)		200.12 (138.19)
Mean pivotal quantity (MW)			1.70*** (0.21)	1.26*** (0.18)
Hour $\times$ year	Y	Y	Y	Y
Month-of-sample	Y	Y	Y	Y
Gen bin $\times$ year	Y	Y	Y	Y
Observations	73,742	73,742	73,742	73,742
Adjusted R <sup>2</sup>	0.84	0.86	0.86	0.87

*Notes:* The dependent variable in each regression is the wholesale price in one hour. The three explanatory variables are the hourly mean of  $\eta$ , an indicator for being pivotal, and the pivotal quantity, across the six largest firms. All regressions include interaction terms for hour-by-year, binned-generation-by-year, and month-of-sample. The generation bins are 50 indicators for the level of aggregate generation.

**Table 3:** Offer price and measures of ability to exercise market power

	Offer price at dispatch quantity (COP/kWh)					
	(1)	(2)	(3)	(4)	(5)	(6)
$\eta$	8.81** (3.84)	14.18*** (5.44)	3.18* (1.79)	6.59*** (1.92)	5.19*** (1.57)	6.55*** (2.21)
Pivotal (0/1)	442.72*** (23.07)	337.58*** (99.58)	58.51 (73.09)	129.20*** (44.95)	123.19*** (18.34)	-28.29 (115.87)
Hour $\times$ year	Y	Y	Y	Y	Y	Y
Month-of-sample	Y	Y	Y	Y	Y	Y
Gen bin $\times$ year	Y	Y	Y	Y	Y	Y
Observations	58,894	46,765	73,407	73,649	51,948	73,188
Adjusted R <sup>2</sup>	0.63	0.75	0.70	0.76	0.44	0.72

*Notes:* Each column shows a separate regression for each generation firm. The dependent variable is the highest accepted offer price for the generation firm in that hour (the offer at a plant with non-zero ideal generation). All regressions include interaction terms for hour-by-year, binned-generation-by-year, and month-of-sample.