ANALYSIS OF THE COMPETITION AND MARKET POWER IN THE COLOMBIAN WHOLESALE ELECTRICITY MARKET USING AN AGENT-BASED MODEL

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Abstract

Restructured electricity markets hinge on competition and market power mitigation strategies in order to ensure efficiency and constant innovation in wholesale electricity markets. This kind of markets convey information through the electricity spot prices which reflect inefficiencies due to market imperfections, explained in part by lack of competition and/or possible exercise of market power. This is a challenge in current wholesale electricity markets because prices above competitive levels can be transmitted to consumers of electricity, which is not a desired outcome. In particular, the policy makers in Colombia have raised concerns about market power and lack of competition in the electricity market measured as a detriment of consumer's welfare and lost in industry's competitiveness. This paper presents a methodology to calculate the extent of market power by a Power Generator Agent (PGA) in the formation of the electricity spot price in the day-ahead auction at the wholesale market. This paper goes from structural metrics (participation indices), that measures market power in a general fashion, to individual (PGA-based) analysis which measures an agent mark-up: the difference between prices above competitive levels due to unilateral actions by a PGA. The methodology of this paper proposes a novel approach in relation to the literature in two aspects: i) it takes into account real characteristics for each PGA in the market using the ex-post bids in the day-ahead auction, individual forward/hedge positions and considers real constraints that reflects the opportunity cost of electricity, in the case of hydroelectric units (major technology of energy in Colombia). And, ii) based on a principal-agent interaction for market power, this paper proposes a novel optimization method solved by a Genetic Algorithm that simulates the behavior of a PGA in the Colombian wholesale electricity market. In contrast to the related literature, these two approaches allow specific simulations that reflects the real behavior of a PGA in the Colombian electricity market and also builds the foundations for further counterfactual analysis. The results of the paper indicate the existence of some degree of market power exercised by the largest four (4) PGAs during certain times in Colombia. Given that Colombia only has participation indices to mitigate market power, the results from this paper play an important role in the policy-making process in order to propose mechanisms to mitigate potential market power in the Colombian electricity market. Also, the method in this paper can help in the current debate in Colombia to promote new policies to incentivize the participation of clean technologies in accordance with the national emissions commitment at COP21 in Paris. The conclusions of this paper are of importance for other electricity markets in the evaluation of competition and market power analysis.

Introduction

During the last decade of the twentieth century (1990-2000), the electricity industry around the world changed their organization towards a market-based structure [10-11]. The policy makers backed this restructuration in the aim to bring more participants (public and private investors) to the electricity industry in order to promote competition and more efficiency in the operation of the electricity. This restructuration brought a change of roles in the sense that governments turned to act more as a regulator and planner, than as a usual investor role. This reorganization carried also new paradigms on how the electricity activities were going to be considered onwards [7-8]. The generation of electricity (production) and the retailing activities were considered under economic competition rules, given that sellers and buyers of electricity were subject to participate in a market-based mechanism. In modern electricity systems, buyers and sellers of electricity are usually connected to the grid (transmission and distribution of electricity). Thus, the grid after the restructuring process were considered as a common-good activity, in which any buyer and/or seller could access to it in equal conditions to transact electricity.

The main role of the governmental agencies (including Colombia) after the restructuring process is to ensure, through economic regulation, the existence of enough resources to meet the electricity demand, even during critical weather conditions like drought seasons. Given that the majority of the installed capacity in energy generation is hydroelectricity (see Figure 1), the Colombian power sector poses risks of supply during drought seasons, like El Niño phenomena. According to international and national weather agencies[1], El Niño occurs approximately every 5 years, and it is reflected in Colombia as low flows of the rivers. The hydroelectricity generated during El Niño period could be around 55% (15% less than a normal period) and the difference (45%) must be produced through any other sources (see Figure 3), including thermal power plants (fossil fuels), in cases with zero blackouts. The types of fossil fuel are described in Figure 2.

The electricity demand is considered inelastic in the short run, which is problematic in the sense that only suppliers (mostly private rent-seekers) react to the market conditions and the impossibility for demand to react makes easier to exercise market power. In this sense, market power in the new restructured electricity markets has been a concern by governments, not only because some markets have fallen in crisis after restructuration, but also because spot prices in the wholesale sometimes do not reflect signs of competition. In this sense, the literature has

[1] Source: The National Oceanic and Atmospheric Administration
http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

analyzed this problem comparing the mark-ups (Lerner Index) based on a perfect competition in the generation of electricity and any other kind of equilibrium (Cournot or Bertrand) to reveal possible behavior of the market out of perfect competition. Also, structural or participation indexes can be used to explain the extent concentration within a market [2-4].

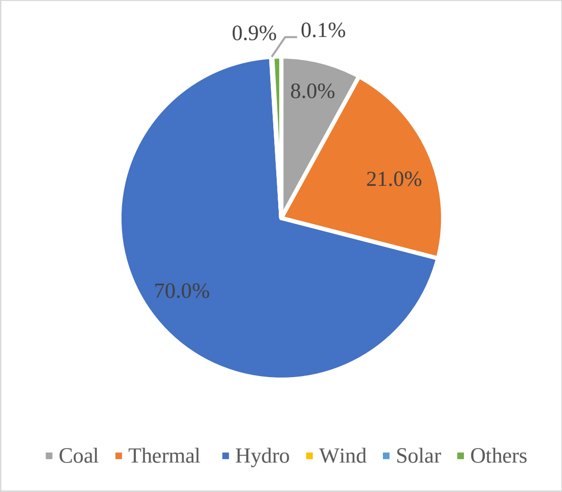


Figure 1. The current electricity generation mix in Colombia. Source XM[2]

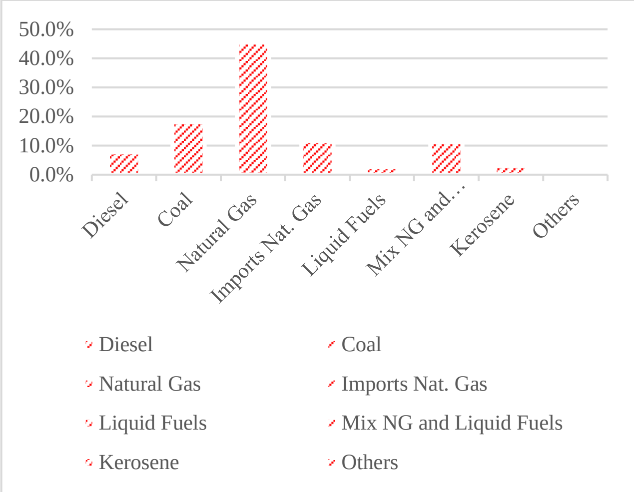


Figure 2. Types of fossil fuel electricity-generation in Colombia. Source: Independent System Operator, XM.

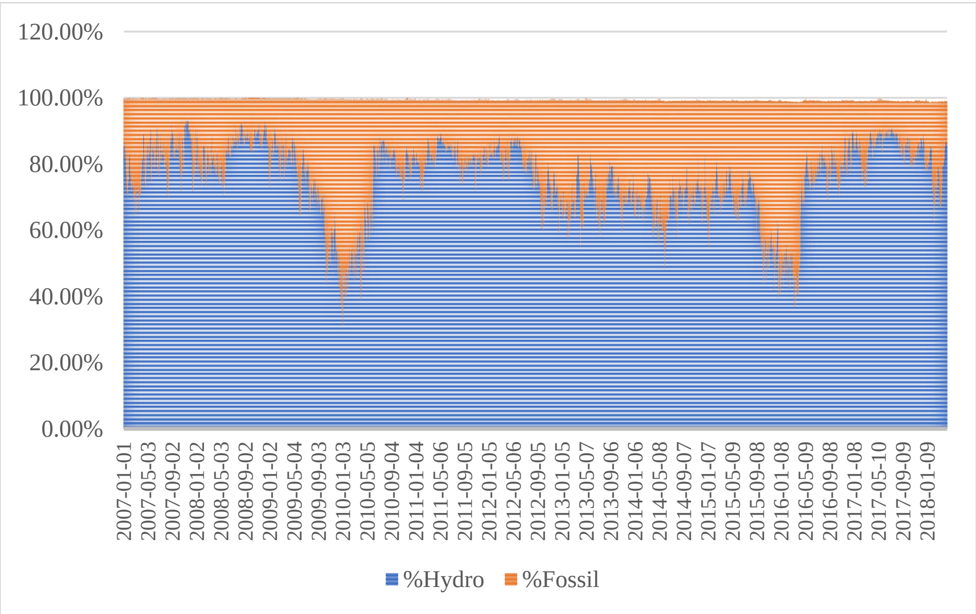


Figure 3. Share of the Generation of Electricity by technology. Source: Authors' calculation from the Colombian Independent System Operator.

This paper proposes a different approach from the usual participation-based analysis. This methodology is more accurate in relation to the current behavior of the Colombian

[2] XM is the independent electricity-system operator of Colombia

electricity markets in two different ways: i) This paper presents a discussion from the economic theory and includes real restrictions in a price setting model in the application of the Colombian wholesale market. This allows to consider the realities and/or actions PGAs have in order to influence prices. This paper uses the current bids (offers) of the generators as the benchmark scenario. ii) it is proposed a novel optimization method that describes a similar behavior of a PGA in the real electricity market process interacting with other participants in the supply of the aggregated energy demand. It is used a Genetic Algorithm to determine a pareto solution in which a power generator maximize profits subject to the behavior of the other participants and technical constraints faced by a generator.

The results indicate the existence of some degree of market power exercised by agents during certain times in Colombia. Energy policy regulations are proposed to mitigate potential market power in the Colombian electricity markets. The results of this paper are important also in the current debate to migrate to another market architecture in order to incentivize the participation of clean technologies in accordance with the national emissions commitment at COP21 in Paris.

The Colombian Electricity Market

The Colombian wholesale electricity market is a combination of three markets, in which each of them interact with the other. These three markets are: The Reliability Charge (similar as a capacity market [5-6]), the bilateral forward-contract market and the spot market.

Figure 4 shows the hourly arithmetic average for each day of the electricity spot price. Also, Figure 4 shows the Scarcity Price for every month. When spot price is higher than the scarcity price, all power generators that are part of the Reliability Charge must produce a committed amount of energy in order to avoid a blackout. The floor price of the spot price (the minimum) constitutes the price which remunerates the firm energy mechanism for Reliability Charge. The spot price has not a cap price, so it can go even above the Scarcity Price levels. However, when the spot prices are above the SP, the electricity demand is only charged until the SP, no matters if spot price is far away, like in 2016 (See Figure 4). When this situation occurs, all generators which participated in the Reliability Charge has to generate their firm energy. If there are any imbalances between real generation and firm energy, the imbalance is penalized under the spot price (which in scarcity period is higher than the SP). Thus, the interest of this paper is on spot prices manipulation for any power plant, no matters if there’s normal situation or scarcity period. This document only explores the dynamics of the spot price and how power plants exercise power in any of those conditions.

Note: gray blocs represent El Nino Phenomena periods, which indicates a drought season and also scarcity period for the hydro-electricity system.

Figure 4. Average the hourly spot prices and monthly scarcity prices in Colombia (Colombian pesos $March18 prices)

The Spot Market and Market Power

The electricity market in Colombia, as in many parts of the world, the spot price is the clear price of an ascending auction in which all suppliers aggregates in ascending price order the bids of their energy. The electricity demand for the short run is inelastic, and according to the Colombian rules, the demand does not participate in the bid process.

The special characteristics of the electricity can be also seen as close conditions for market power [12-13]. Given the high upfront costs of the generation of electricity, it is common to have oligopolies in the supply of electricity given that the rate of entry and exit in this kind of markets can be low in relation to other industries. In the Colombian case, five companies of electricity control the 74% of the total installed capacity with 60% of the total power plants (36/61) (See next table). The rest of the participants in the Colombian market represent nearly 26% of the total installed capacity with 25 power plants.

Also, the Herfindahl-Hirschman index (HHI) suggest some degree of market power. In particular, the HHI of hydro units suggest that the supply of electricity is moderately concentrated[3]. This can be true if one imagines the conditions of drought periods and the relation with high prices of electricity at the same time frame (see Figure 5).

Company name - Power Generator Agent (PGA)	%Share	# of power plants owned
Endg	21.4	13
Epmg	18.8	6
Isgg	18.6	9
Epsg	8.9	7
Chvg	6.3	1
Sub Total	**74**	**36**
Minor companies	26	25
Total	**100**	**61**

Another characteristic of the modern industry of electricity is that sellers (Power generator companies) and buyers (retailers) are interconnected with a whole system called the grid [8], which is composed by the transmission and distribution networks. The grid is considered neutral and open access to buyers and sellers which are under economic-competition rules. However, there's still vertically integrated power companies which has assets in the production and in the transportation system. Despite the fact the Colombian regulation is not allowing vertically integrated companies in the electricity sector, those companies vertically integrated before the restructuring process in 1994 could remain their position.

As a final characteristic of electricity as a commonality is that the demand in the short run has a low participation in the formation of spot prices [12-13]. For this reason, it is usual to consider it inelastic. This lack of reaction of the demand side due to changes in the aggregated supply curve can provoke faster changes in the formation of the electricity prices (e.g. high volatility). This feature can be exacerbated if it is considered that the electricity cannot store as much as operators shall desire in real time. That is, once the electricity is produced must be consumed in real time. High volatility in the spot prices of electricity, due to these characteristics, may imply that financial tools (e.g. bilateral forward contracts) could be an option to mitigate possible spikes in the electricity spot markets.

A section bellow in this paper evaluates the market power dimension in a broad way.

[3] The department of justice defines a moderately concentrated market if HHI is between 1500 and 2500. https://www.justice.gov/atr/herfindahl-hirschman-index

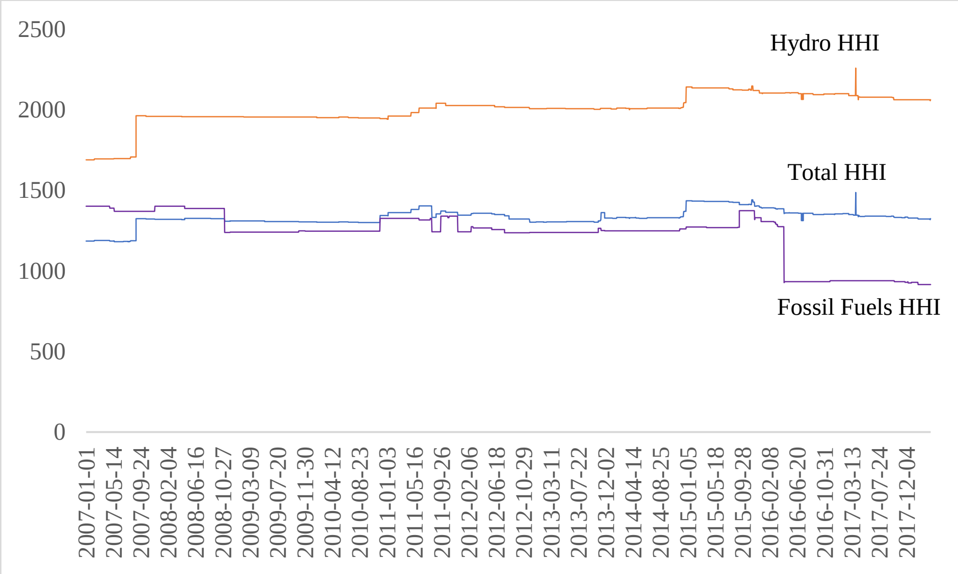


Figure 5. HHI index by technology measured by the shares of installed capacities.

Bilateral forward contract market

Due to the volatility in electricity spot markets, hedging process between buyers and sellers (PGAs) is a frequent situation and is allowed by the regulator [2], [12]. In Colombia, the regulator grants the liberty for buyers and sellers in the electricity market to sign bilateral forward contracts under private agreement conditions. The buyers in the Colombian electricity market are the retailers that represent the consumers of electricity, which can be private and/or public companies that buys the electricity for end-users in the wholesale market. The end-users of electricity can be small loads of energy, like households, small industrials and small commercial businesses.

In case any party (PGA and/or a retailer) do not comply with the bilateral contract agreement, the electricity is settled at the spot price that applies for a specific moment.

Figures 6 to 8 show the bilateral contract history of the three of largest four PGAs (EPM, Chivor, and Emgesa) in Colombia. Daily data from January 1-2007 until March 31-2018 is analysed in an index. The data set is based on sales, purchases and real power generation for all these PGAs within the mentioned time frame. The amount of sales of bilateral contracts is all the energy in MWh that a PGA report in the Colombian ISO as a bilateral contract for a day. The amount of sales in energy through bilateral contracts is the hedge that a PGA offered in any specific time for a retailer or another PGA. The amount of purchases of bilateral contracts is all the energy in MWh that a PGA had to buy as a bilateral contract in order to honour some obligations in the wholesale electricity market. For example, if a PGA has a commitment to deliver an amount of energy in a specific time due to a previous agreement with another player in the market, and the same PGA cannot comply this commitment, this PGA can subscribe (purchase) another forward contract with another PGA, so as to find a hedge position if he perceives spot prices' spikes in the delivery date, according to the initial contract. The third variable is the real power generation in MW of a PGA in this time frame.

Furthermore, the hedging position of a PGA is given for the following formula:

$$Hedge - Index_{i,t} = \frac{FCSales_{i,t} - FCPurchases_{i,t}}{RealGeneration_{i,t}} \qquad (1)$$

Where, $Hedge\text{-}Index_{i,t}$ is the hedge position of a PGA *i* and a day *t*. $FCSales_{i,t}$ is the sales in MWh of forward contracts reported by *i* in *t*. $FCPurchases_{i,t}$ is the amount of energy in MWh that a PGA *i* had to buy in forward contracts. Finally, $RealGeneration_{i,t}$ is the real power generation that *i* injected into the system in MWh.

If $Hedge\text{-}Index_{i,t}$ is greater to one (1), this means that the PGA *i* is offering more contracts to the market that in fact is capable to deliver physically with their power plants. That is, in (1) the numerator is greater than the denominator. A high frequency of this index above one could represent a warning sign for regulation.

A $Hedge\text{-}Index_{i,t}$ close to zero indicates that a PGA is not supplying entirely the maximum capability of hedge position to the market. If a $Hedge\text{-}Index_{i,t}$ is near to one (1), this mean that the position of a PGA is entirely offering hedge to the market or at least is physically capable to comply with its generation the difference between sales and purchases in forward contracts.

Figures from 6 to 8 show the histograms of the $Hedge\text{-}Index_{i,t}$ for the three of the largest four PGAs in Colombia. Figures 6 and 8 show the histogram for two vertical-integrated PGAs and Figure 7 shows the histogram for a PGAs that are not vertically integrated.

These histograms show that the vertically companies are close to one. Also, EPM and Emgesa have their own retail company. This could explain that vertically integrated PGAs and retailers do not have incentive to buy and sell electricity from the spot market, but from the bilateral market in order to find better prices. It is not possible with the available data to tell that all energy contracted by a PGA went to its associated retailer, but their respective retailers are EPM-retailer and Codensa, two of the biggest retailers in Colombia.

Histograms at Figure 7 show a different scenario in relation to Figures 6 and 8. One of the largest PGA, which are not vertically integrated, have the most frequent *Hedge-Index* away from one (0.5 and 0.4, respectively). This means, that these two players in the supply of electricity in Colombia find more times benefits in the spot market than in the bilateral market than the vertically integrated PGAs. Intuitively, this result reflects the reality in the sense that the PGAs that are not vertically integrated only care to look for hedge positions during low spot prices[4], meanwhile vertically integrated PGA has to be worried about not only low prices, but also high prices because the retailer within the company.

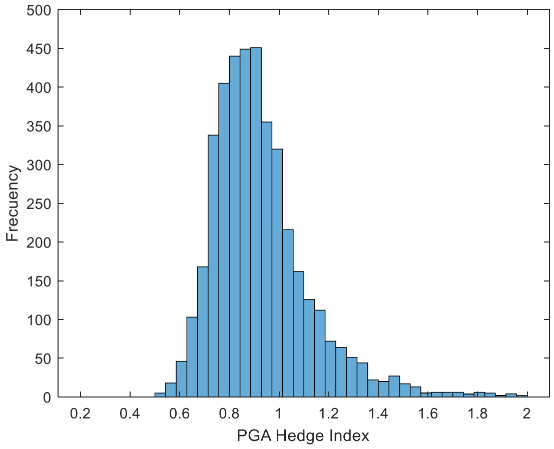


Figure 6. Hedge Index for EPM – vertical integrated PGA

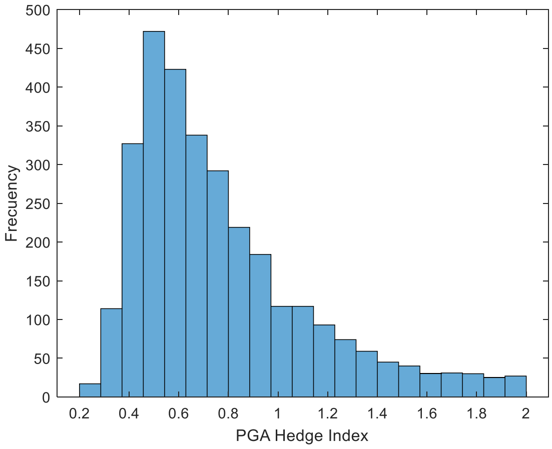


Figure 7. Hedge Index for Chivor – not a vertical-integrated PGA

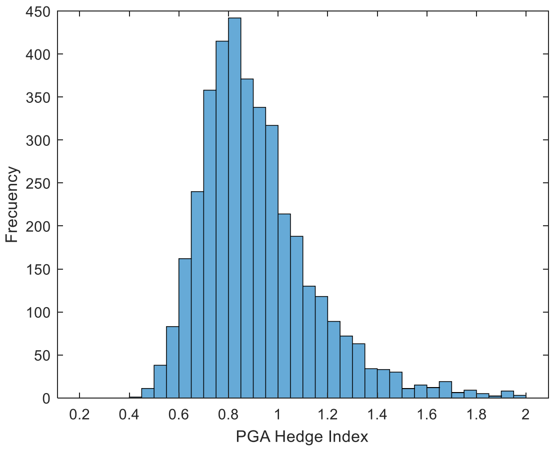


Figure 8. Hedge Index for Emgesa – vertical-integrated PGA

A PGA's Interaction-Model in the Wholesale Electricity Market

Having inelastic sections in the residual demand curve imposes extra challenges in the analysis of a PGA’s actions in the spot price formation. This is because there can be moments in which a PGA can take advantage of this knowledge and raise bid-prices without any reaction from its competitors (other PGAs), in this sense he could perceive more profits from its unilateral actions and raise prices above competitive levels. Also, having inelastic sections and

[4] A low-price scenario in the midterm could represent less profits than in a scenario in which a PGA fixes prices in order to obtain a better financial position.

discontinuities in the real residual demand trigger a second challenge in terms of the analysis of the price-sensitiveness that a PGA faces in the wholesale market. Differential calculus cannot be used in the determination of the elasticities of the residual demand in a specific section due to the functional form of this curve. This paper proposes a method in which enables the policy makers to determine spot-price impacts from any PGA, considering the nature of the functional form of the residual demand.

Despite the fact, participation indexes like the Herfindahl-Hirschman Index shows that the PGA market in Colombia exhibits a moderate oligopoly, the reality is that some moments in which prices can be distorted in favor of a particular PGA's action. Given that the parameters of the residual demand curve exhibit a prediction process to exercise distortions in the spot market, an ex-ante analysis imposes a challenge that is out of the scope of this document. The policy-making process is in fact interested in that the competitive forces keep the spot-prices in a competitive spectrum in order to ensure mitigation of possible market power and well-functioning of the operation of the wholesale electricity market. In other words, the regulator might be interested in the analysis of an ex-post spot-price formation in which the policy-maker could collect evidence and based on that take formal corrections.

This paper proposes the analysis of the impact of the spot-price formation considering real constraints in a hydro-dominated scenario like in Colombia, while keeping the functional form of the residual demand. In order to analyze the spectrum in which a PGA could influence the spot-prices, this paper proposes a lower-bound and an upper-bound considering a set of constraints that are as follows:

Upper-bound price impact

Driving the prices above competitive levels can be an incentive for a PGA (and in general for an agent) for two reasons principally:

a) Obtain more profits in the short-run and temporally exercise market power [1], [9].

b) Penalize the behavior of other competitors in cases in which other PGA is in needing for energy to comply a commitment in the spot market. For instance, if a PGA *i* sees that other PGA *j* cannot comply a bilateral forward contract and/or comply the firm energy in the Reliability Charge, PGA *i* can take advantage and increase prices in order to: i) obtain benefits from a replacement operation of *j's* position and/or ii) exercise market power to exclude competitors in the long run [1], [9].

The actions of the PGA *i* towards an increase in spot prices is preceded by a better-off position in the expectations of a PGA in the wholesale electricity market. This better-off position can be evaluated as the benefits that a PGA receives to participate in the three markets that composes the wholesale electricity market in Colombia. In other words, a PGA will sustain the spot prices above competitive levels during a time frame, if the PGA will be better-off in terms of profits.

The profit horizon at the Colombian wholesale electricity market is 24 hours (one day), due that the current bidding process only allows one price for an entire day. A PGA *i* is better-off through the result of the following optimization problem, which considers as best responses the actions of other PGAs denoted by *j*. A similar strategy is used in [1], [9] to capture interactions in a principal-agent interaction. In this case the firm (PGA) is the agent and the principal I sthe system (the rivals of PGA under analysis:

$$\varphi_i + \underset{p_k}{\mathrm{Max}}\{\pi_{i,d}(p_k)\} = \sum_{\substack{t=1 \\ k\in\Omega_i}}^{24} \left[\left(ResDem_{i,t}(p_k; p_{-k}{}^*) - FC_{k,t}\right) \cdot \; Pspot_t(p_k; p_{-k}{}^*)\right] \qquad (2)$$

s.t.

$$\sum_{\substack{t=1 \\ k\in\Omega_i}}^{24} ResDem_{i,t}\left(p_k; p_{-k}{}^*\right) + \sum_{\substack{t=1 \\ -k\in\Omega_j}}^{24} AGS_{-k,t}\left(p_{-k}{}^*; p_k\right) - \sum_{t=1}^{24} D_t = 0, \quad \forall\{j \neq i\}, \{-k \in \Omega_j\} \qquad (3)$$

$$\sum_{\substack{t=1 \\ kh\in\Omega_i}}^{24} AGS_{kh,t}\left(p_k; p_{-k}{}^*\right) = \sum_{\substack{t=1 \\ kh\in\Omega_i}}^{24} G\_ref_{kh,t} \qquad (4)$$

$$p_k \geq CEE \;\&\; p_k \geq Cost_{k,t} \qquad (5)$$

Where,

φ_i	Constant in the *i's* profit function that not depend on power plants' prices.
$k\epsilon\Omega_i$	All power plants (resources) owned by PGA *i*.
$-k\epsilon\Omega_j$	All power plants that are not owned by PGA *i*.
$kh\epsilon\Omega_i$	All hydroelectric power plants (resources) owned by PGA *i*.
p_k	Prices (bids) of all power plants associated with PGA *i*. This is the control variable.
$p_{-k}{}^*$	Prices (bids) of all power plants different than the PGA *i's* plants. These prices correspond to the real bid which PGAs *j* are considered best responses in the participation of the spot market.

$\pi_{i,d}(p_k)$	Profits of a PGA *i* during a day *d* which controls the price for each of its *k* power plants.
$ResDem_{i,t}$	Residual demand and generation of PGA *i* in MWh during time *t.*
$FC_{k,t}$	Bilateral energy contracts in MWh of all power plants owned by PGA *i.*
$Pspot_t$	Spot price in the electricity market in time *t* which depends on the prices of the *k* power plants and the other resources not associated to *i.* Units in $/kWh.
$Cost_{k,t}$	Cost of generating a power plant in $/kWh.
$AGS_{-k,t}$	Aggregate supply function by all power plants different than the PGA *i's* plants.
D_t	Aggregated electricity demand during time *t.*
$AGS_{kh,t}$	Aggregate supply function by all hydroelectric power plants owned by PGA *i.*
$G\_ref_{kh,t}$	Output in MWh of all hydroelectric power plants owned by PGA *i* under the real bidding conditions at *t*.

The objective function in (2) determines the profits of a PGA *i* that participates in the three markets in the Colombian wholesale electricity market. As this paper has explained, the only variable that *i* can control is the price for each of its power plants denoted by p_k, because every day the quantity submitted to the ISO has to be the maximum capacity in MWh. In other words, the PGA *i* is able every day to submit prices even above its costs ($p_k \geq Costs_{k,t}$), but *i* cannot withdraw quantity without a formal reason, all of this under current rules in the Colombian electricity system. Notice that this does not imply that the ISO would select the dispatch of one resource, because that depends on the auctioning prices and how competitive is the price of a recourse to be eligible to participate in a day of operation (see the example at the spot price market section).

The set of prices by the other plants not owned by *i*, denoted by p_{-k}*, are considered in this model as given and reflect the best response of the competitors of *i*, denoted by PGA *j.* The set of prices p_{-k}* are taken directly from the true prices submitted at the Colombian ISO (XM). Therefore, the optimization problem from (2) to (5) gives as a result the optimal set of prices that *i* could has submitted at the independent system operator (ISO) in order to be better-off in relation to the true prices submitted at the ISO.

The profits that *i* receives from the spot market is given by the product of the *i's* generation, that is the residual demand of *i*, and the spot price at time *t*. Thus, the spot market profits are denoted by the product $ResDem_{i,t}$ and $Pspot_t$.

The profits that *i* receives from the bilateral contracts is given by the difference between the income and the costs that *i* has in bilateral contract obligations. The income is given by the product of the bilateral contract $FC_{k,t}$ and the price of this contract in $/kWh. This income is considered in the constant value of φ_i because this term does not vary with the prices of *i's* resources p_k, so it can be evaluated outside of the optimization process. The cost of the contract is given by the product of the bilateral contract $FC_{k,t}$ and the spot price $Pspot_t$.

Notice that when $FC_{k,t}$ is equal to $ResDem_{i,t}$ the PGA *i* does not receive any incentive towards a bidding strategy because this has no impact on its profit-maximization function [3], [13]. When $ResDem_{i,t}$ is greater than $FC_{k,t}$ this can constitute an incentive to increase prices p_k in order to be better-off in terms of total profits. It is relevant here to highlight the results in the histograms from Figures 6 to 9 in which the largest PGAs participate more on the spot market than in the forward contract market. In other words, the history of the Colombian wholesale electricity market shows that PGAs may have incentives the majority of the times to set prices in a way to be in a better-off position.

The first constraint at (3) describes that in every moment the total amount of generation must be equal to the total aggregated demand D_t. The total power generated is denoted by the summation of the PGA *i* output in MW ($ResDem_{i,t}$) and the power by the rest of the other PGAs denoted by *j* given by $AGS_{-k,t}$. It is assumed in this model that the bids submitted to the auctioneer (the ISO) by the other PGAs *j* are best responses so this optimization process takes the true bids submitted by all the power plants different to those associated with PGA *i*. This is true in the sense that every PGA before a bid submission evaluates all the variables they have in order to maximize their profits.

The second constraint at (4) deals with a technical constraint in hydro-dominated electricity markets: the opportunity of cost of the water. A hydro electric power plant faces every day a question that involves the depletion or not of the water stored in its reservoir. This decision implies a balance not only the short run, but also the long run because commitments in the forward-bilateral market and in the Reliability Charge imposes obligations in the future. A PGA *i* with hydroelectric resources reflects this balance in its true prices that submit at the Colombian ISO for these kinds of power plants. Considering the true prices at the ISO, the hydroelectric generation of a PGA *i* denoted by *kh* is given by the term *G_ref*. This generation is the real generation of *i* with its hydropower plants considering the real prices that PGA *i* submitted at the ISO at day *d* during *t*. This generation is a reference which is contrasted with the hydrogeneration from this model denoted by $AGS_{kh,t}$.

The evaluation of the real cost of the water in the reservoir is out of the scope of this paper, because it requires more specific parameters and expectations in the forward-bilateral market and in the Reliability Charge for all PGAs which constitutes in essence another document in the future. However, the constraint at (4) compares G_ref and $AGS_{kh,t}$ and imposes a penalization for outcomes that imposes a imbalance between these two terms. The idea with this constraint is to have a more realistic behavior of a hydroelectric power plant and get a sense of the future expectations of a certain water reservoir that controls a PGA through its prices. This paper proposes a penalization in the objective function at (2) through a Lagrange multiplier which has the following the form at equation (6):

$$OB\_LaGrange_{5,d} = max\{p_{kh}\} \times \left(\sum_{t=1}^{24} AGS_{kh,t} - G\_ref_{kh,t}\right), \ \ \forall\{kh \in \Omega_i\} \tag{6}$$

Where, $max\{p_{kh}\}$ is the maximum true price that a hydro resource bid at the ISO among the all power plants of PGA *i*. This term captures the PGA *i*'s value of the water generated through a power plant and stored in a reservoir, so it can be used as a penalty for deviations at real power generated G_ref. The equation at (6) enters as a negative term in the objective function in equation (2). It is relevant to highlight that $AGS_{kh,t}$ is the aggregate generation of all PGA *i*'s hydro units, so it constitutes a fraction of the overall generation by *i* in $ResDem_{i,t}$.

The constraint at (5) imposes that all the options considered at p_k must be at least the production cost of the electricity for a specific power plant. Also, p_k must be higher than the equivalent cost of energy (CEE) for the Reliability Charge. Under the rules in the Colombian market it is not allowed prices below the CEE because this could compromise the reliability standard in this market.

The output of this model gives a set of optimal bid prices for all the resources owned by PGA *i* in which this agent maximizes its profits in the wholesale electricity market in Colombia (this also can be seen deriving the first order conditions like in [13]). Given that these set of prices contemplate technical and real market constraints that all PGAs faces in the Colombian regulation, the output of the model from equations (2) to (6) can be seen as the upper-bound in the possible impact that a certain PGA can cause over the time.

Lower-bound price impact

The lower-bound uses the same model from (2) to (6) but encouraging a more competitive outcome in terms of quantity and prices. That is, the lower-bound drives the method in a way in which the PGA *i* does not perceive an incentive to increase profits through prices and also participate more in the real operation of the spot market [2-3], [12-13]. This bound imposes another restriction in the sense that generation in the spot market should follow the forward-contracts, that is $ResDem_{i,t}$ near to $FC_{k,t}$. This is imposed through a second Lagrange multiplier, see equation (7) as follows:

$$OB\_LaGrange_{8,d} = max\{p_k\} \times \left(\sum_{\substack{t=1 \\ k \in \Omega_i}}^{24} FC_{k,t} - ResDem_{i,t} \right) \quad (7)$$

Where, $max\{p_k\}$ is the maximum true price among all PGA *i's* resources for a day of operation *d*. The equation at (7) enters as a negative term in the objective function in equation (2). In this way, the model penalizes a behavior when forward contracts in MWh are below the participation of PGA *i* in the spot market (like).

In total, the model for the lower-bound integrates the Lagrange multipliers (6) and (7) in (2) plus the restrictions (3) and (5).

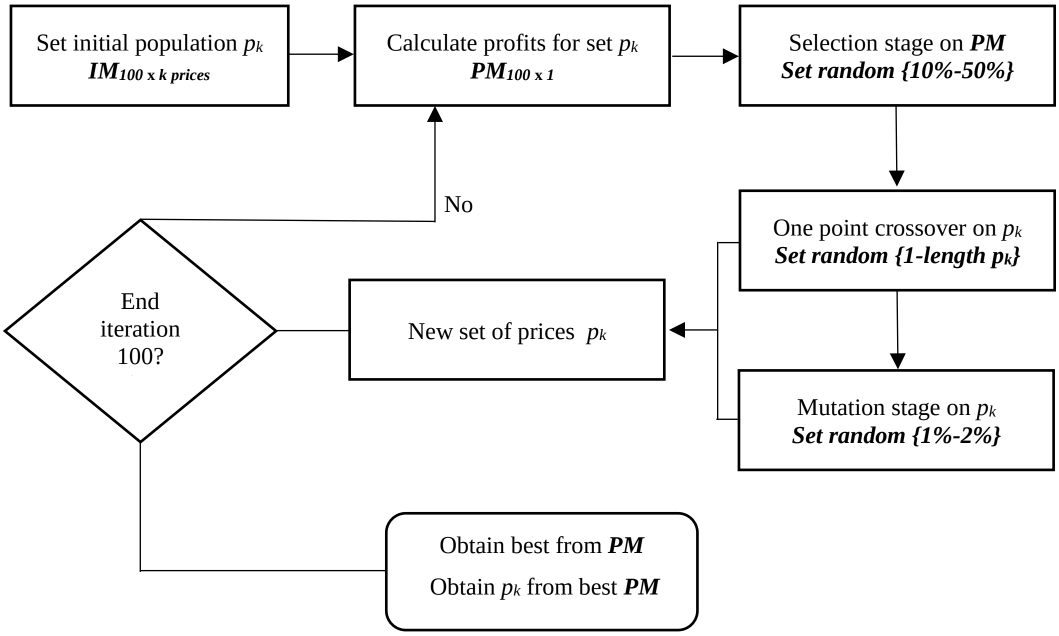
Solving the Optimization Method through a Genetic Algorithm

The solution of the optimization model from (2) to (5), including the Lagrange multipliers (6) in the case for the upper-bound and (6) and (7) in the case for the lower-bound is not an easy task because involves an optimization over a discontinuous function. The residual demand function of a PGA *i* $ResDem_{i,t}$ depicts discontinuities that makes irrelevant the use of optimization methods which deploys a routine based on derivative strategies, like the Newton Raphson techniques. Also, local search methods that involve a neighborhood search can be a useful alternative, but when there is a combinatorial explosion in the number of cases to be evaluated, these kinds of methods can easily fall in a local optimum. In these cases, computer science and operation research have analyzed metaheuristics which deals with large combinatorial problems with outcomes that overcome with possible local optimums.

One of well-known metaheuristics are the Genetic Algorithms which replicate the process of natural selection. Genetic Algorithms (GA) are basically an evolutionary algorithm that relies on mutation, crossover and selection operations in order to obtain outcomes in the direction of an optimization problem. The basic GA is composed by the description of four steps: initial population, selection crossover and mutation.

Description of the Genetic Algorithm

The stages form selection to mutation is repeated a number of times. This paper is proposing 100 iterations in order to avoid computational memory problems. To sum up, each day a PGA *i* is evaluated 10,000 times (100 options in the population times 100 repetitions) until obtain an optimal set of prices that satisfies optimization problems from (2) to (7), see the diagram above.



Results and Comments

The results for the four largest PGAs in Colombia are shown from Figures 9 to 12, the same PGAs analyzed above in the forward contract section. These figures show the result for simulations of the optimization method described for the upper and lower bound price. Also, these figures show the true spot price (legend as Real Spot Price) reached with the true bid prices that a PGA submitted for any day. In this sense, the lower-bound price shows a competitive level in which a PGA has no incentive to distort spot prices and meet all forward contracts in a day. Upper-bound price represents levels in which a PGA is better-off in terms of profits while real constraints are evaluated, like the opportunity cost for hydro units. Figures 9 to 12 show the results for a particular day. The PGA EPM displays the results for 2016/06/05 (Sunday), while the others show results for 2016/06/01 (Wednesday). Authors choose these days because represent normal conditions in the Colombian electricity market.

When the level of real spot price is near to the lower-bound price, this indicates that a PGA did not exercise the market power it has to distort spot prices. Also, this could indicate that due to the uncertainty in the bidding process before the day-ahead a PGA plays in a competitive way. For this reason, this paper proposes an ex-post analysis that considers not only a day, but also a longer time frame (e.g. a month) in order ensure repetition of market power exercise. Consider the first hours of the day, which represent low electricity demand conditions, for PGA EPM and Chivor. During this time of the day, these PGAs did not see incentives to distort the spot price above competitive levels. This finding is similar to the conclusions in [2].

When the level of real spot price is near to the upper-bound price, this indicates that a PGA did exercise the market power it has to distort spot prices, because is far from the competitive level. Consider the case for hours in which demand for electricity is the highest (hours 19 to 21). The PGA EPM sees profitable to increase prices for an hour. This result is similar to the findings for high-demand periods in [2] and [3].

There are some periods in which competitive levels are the same or close to the the upper-bound prices. This indicates that actually there's no space for manipulation in prices or no conditions in which a PGA finds profitable to increase prices above competitive levels. This situation corresponds to conditions in which the market is performing similar characteristics to a perfect competitive market despite the fact the existence of large market shares in the market for generation.

Figures 13 and 14 show the impact of contracts in the formation of electricity prices. When forward contracts are not taken into account, the upper-bound increases. This means that without contracts a PGA can have more incentives to distort market prices for its benefit. This result is similar to the findings in [4].

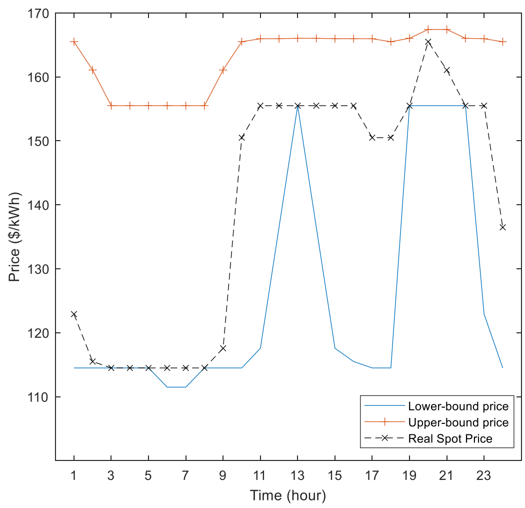


Figure 9. Spot price impacts for PGA EPM

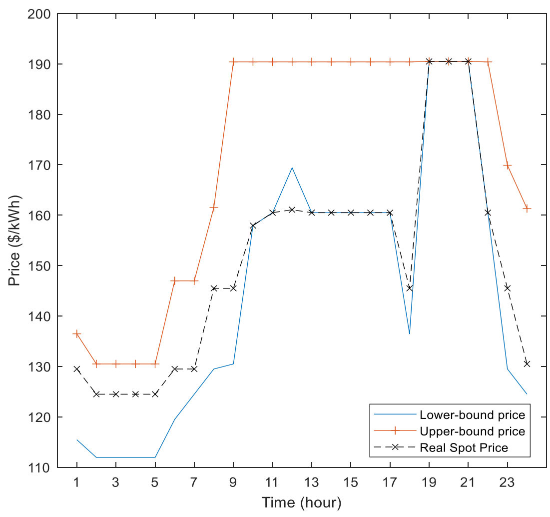


Figure 10. Spot price impacts for PGA Emgesa

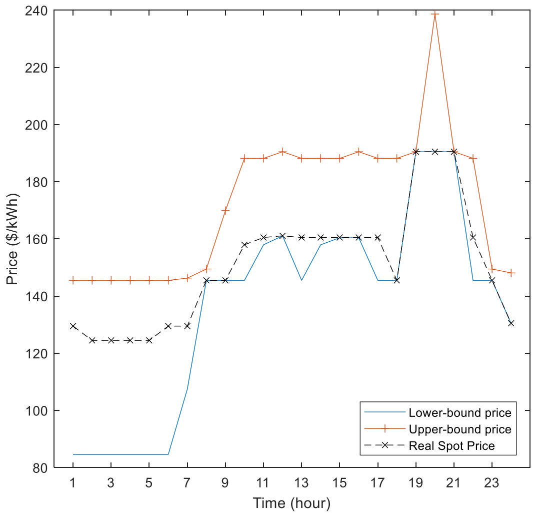


Figure 11. Spot price impacts for PGA Isagen

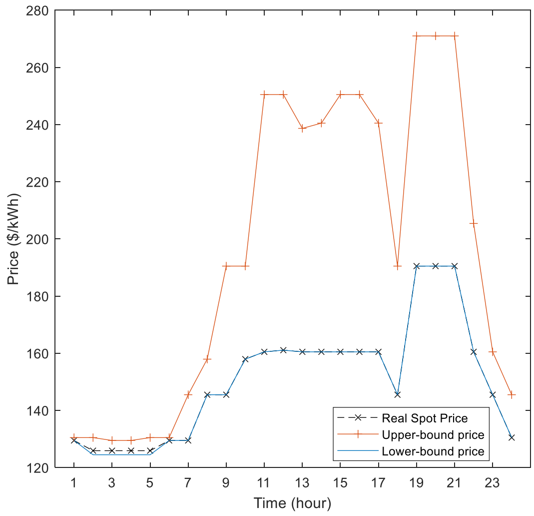


Figure 12. Spot price impacts for PGA Chivor

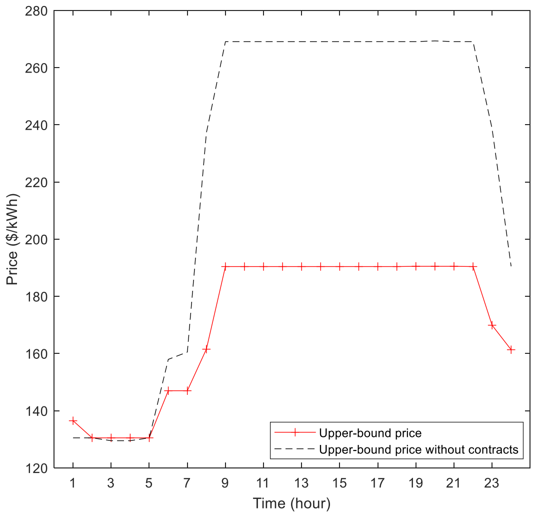


Figure 13. Influence of bilateral contracts on spot price for PGA Emgesa

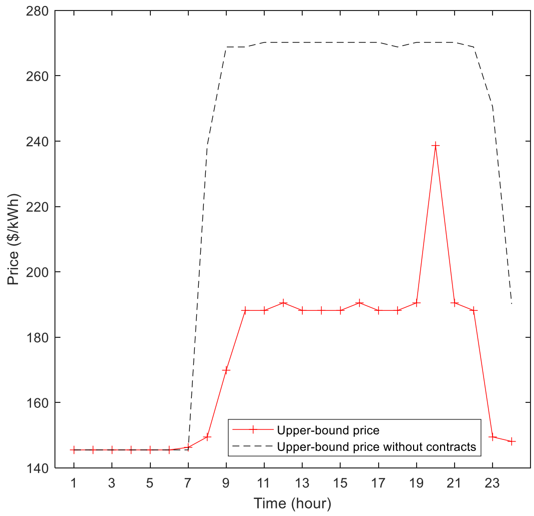


Figure 14. Influence of bilateral contracts on spot price for PGA Isagen

Discussion

a) This paper revises the traditional analysis on market power in electricity markets. This paper discuses that depending on the rules of each market and the organization of the electricity industry, the techniques to analyze competition and market power must be adapted to this condition in order to simulate real situations/constraints that happens in real interactions of wholesale electricity markets.

b) This paper evaluates upper and lower bounds in a different way than the tradition literature on this topic. This paper evaluates two kind of bounds which reveals the real scenario in which a generator in the Colombian electricity market is facing. Also, this paper discusses how a benchmark prices could differ form marginal costs.

c) This paper shows a novel methodology to estimate the behavior of a generator facing the residual demand. Despite other results found in the literature, this paper analyzes the real horizon of a generator in the spot market (a day). That is, analyzing only specific hours for market power analysis could not reveal the whole strategies in disposition of a generator during the day because the resources can be moved between the hours to gain profits.

d) The paper proposes two kinds of bounds. One to show the feasible range in which a generator has to exercise market power. And other, to show how large is the market power exercised. These two bounds are complementary in the sense that could alert policy makers of the amount of market power that a generator has in the market and also if that a PGA is really exercising that power.

e) The output of the model output gives a set of optimal bid prices in which a PGA maximizes its profits. In this sense, it is possible to do comparisons and measure the difference between the bids submitted for the auctioning process and the optimal bids. This gap can be named as the potential of market power an agent has in the electricity market.

f) The classical way to measure market power in electricity markets through the gap between prices and marginal costs cannot reflect entirely the process of anticompetitive behavior because bid prices usually contains future expectations that can be different to marginal costs.

g) The existence of oligopoly markets does not necessary implies conditions for market power. This paper shows that some hours the market could depict characteristics of competitive markets. Thus, evaluate a single day to determine market power is not a good approach. It is necessary to have a longer time frame to conclude repetition of dangerous behavior in the market. This method proposes ex-post evaluations to determine the magnitude of this repetition and how policy-makers could mitigate this situation.

h) Initial results show a potential market power by some agents during drought seasons which open a debate on how well the electricity markets are adopting measures to mitigate climate change and market power problems.

i) The forward contracts are a regulatory tool that helps to prevent market power. It is evident through simulations that an agent with less forward contracts give more opportunities for an agent to exercise market power.

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