Competition and Merit Order Effect in the Colombian Electricity Market

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ABSTRACT

In this paper, we study the relationship between the merit order effect and the ownership structure of renewable resources in electricity markets. We use daily frequency data from the Colombian electricity market in 2012-2019 and designed a strategy to estimate the spot price's dependence on renewable energy. We study how the participation of multi-technology firms in renewable energy alters the spot price. Our main results show a merit order effect for the Colombian electricity market, but this weakens in the presence of greater participation of multi-technology firms in the total availability of renewable energy for the day.

Keywords: Merit Order Effect, Renewable Energy, Electricity Spot Markets, Imperfect Competition
JEL Classifications: D43, Q49, L11, L12, L94.

1. INTRODUCTION

Global trends in the inclusion of renewable energy in electricity markets show notable growth in generation with these technologies (IRENA, 2019). This growth responds to the notable cheapening of these technologies and countries' political support for the world's energy transition (Fu et al., 2017). These trends mean that markets, whether dominated by conventional technologies such as thermal generation, must prepare for a growing penetration of renewable energy. This penetration affects the formation of electricity prices and carbon emissions in the countries, regardless of how green their energy matrices are the inclusion of renewable energy in spot electricity markets and its effect on relevant variables such as prices and greenhouse gas (GHG) emissions has motivated a variety of studies in recent years.

The addition of renewable energy in spot electricity markets and its effect on relevant variables such as prices and greenhouse gas

(GHG) emissions has motivated various studies in recent years[1]. These works argue that a larger share of renewable energy in spot electricity markets leads to lower GHG emissions and cheaper electricity. On the price side, these investigations have revealed a phenomenon known as the merit order effect (MoE) in the literature on energy markets. MoE is present because renewable energy has negligible marginal costs, which reduces the equilibrium spot prices of electricity.

Since the work of Acemoglu et al. (2017), interest in studying how the ownership structure of renewable energy resources by the

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1   Evidence for the Spanish market is found by Gil et al. (2012), Ketterer (2014) in Germany, and Cutler et al. (2011) in Australia. For the United States markets, the works of Woo et al. (2011) for Texas, Gil and Lin (2013) for PJM, and Woo et al. (2016) for California are highlighted. In the Colombian case the work of Perez and García-Rendón (2021) is highlighted. Works focused on reducing GHG emissions from the inclusion of renewable generation in electricity markets are Cullen (2013), Kaffine et al. (2013) and Novan (2015).

generating firms can affect the magnitude of the MoE has increased. The authors develop a model of oligopolistic competition a la Cournot where they show the existence of MoE[2]. Additionally, they show that when firms with a diversified production portfolio (thermal and renewable technologies) have a higher proportion of available renewable energy, MoE partially neutralizes. In extreme cases where multi-technology firms own all the renewable energy supply, and the cost function is linear, the MoE disappears. This last result implies that higher energy supplies with renewable sources have no impact on electricity's equilibrium prices. The authors show that these results are robust to the inclusion of forward contracts and imperfect information by multi-technology firms on renewable generation availability in the market.

In our paper, we design an empirical strategy applied to the Colombian market to test the hypotheses of Acemoglu et al. (2017). We only know of one work related to testing these hypotheses, which is Genc and Reynolds (2019), focuses on Ontario (Canada) energy market. The authors investigate the implications of the ownership of a new technology of low production costs in the market. Their theoretical framework measures the impact of renewable energy introduction in the Ontario electricity market and examines how renewable capacity ownership changes the market's outputs (prices, production, emissions). Given that policymakers currently have decision-making power over new renewable energy plants' ownership structure, the research provides valuable information for public policy. The authors show how and why ownership of renewable capacity is relevant when there is market power.

Using a model with asymmetric Cournot firms and a competitive strip, they find that when a firm with market power has new renewable capacity, production and welfare are lower than when competitive marginal firms have the same amount of new renewable capacity. The effect of renewable energy ownership on emissions is ambiguous, depending on the distribution of emission rates among power plants. The results confirm the theoretical predictions. Both, the simulation analysis based on the structural model and the estimation of equations in reduced form show that the magnitude of the fall in prices in the face of a wind expansion is less when a firm with market power owns the new capacity.

In this paper, we show evidence of these theoretical predictions for the Colombian electricity market. This is an electricity market dominated by hydroelectric and thermal generation, in addition to being exposed to strong variations in the hydrological resource. On the other hand, Ontario is a market dominated by nuclear and hydroelectric power plants, and this region is little exposed to abrupt changes in the hydrological resource. The model of Acemoglu et al. (2017) studies how the possibility of substituting between energy sources with zero and non-zero marginal cost leads to less efficient prices. The case of Ontario, dominated by technologies with zero marginal cost, does not have the attractiveness of the Colombian market, dominated by a technology with zero marginal cost, and another with non-zero marginal costs. In our paper, we design an empirical strategy that

contrasts how multi-technology firms' participation in renewable energy availability is related to electricity's spot price. We also study an additional prediction of Acemoglu et al. (2017) related to the volatility of prices and renewable energies' ownership structure. Our results show evidence of the merit order effect: an increase in renewable energies' availability tends to reduce the spot prices of electricity. Additionally, we find that a higher concentration of ownership of renewable resources by multi-technology firms decreases the magnitude of the merit order effect. On the other hand, we do not find evidence of a relationship between price volatility and renewable resources ownership.

Our paper has five sections. This section, the first, introduces. In the second section, we describe the Colombian electricity market. The third section presents Acemoglu et al. (2017) model's main predictions, the data, and our empirical strategy. The fourth section presents the results, and the fifth section, some policy implications.

2. COLOMBIAN ELECTRICITY MARKET

This section closely follows the description of Colombia's electricity spot market in Perez and García-Rendón (2021). In general, the electricity market in Colombia has two levels, each characterized by its own institutional rules: (1) The Wholesale Market and (2) the Retail Market. Generating firms interact with retail firms in the Wholesale Market. Both types of agents interact, mainly, in the Energy Exchange or Spot Market (Day-Ahead Market) and Bilateral Contracts or Contracts market. In the Spot Market, all generating firm's electricity trades daily, yielding the electricity spot price. Since our interest lies in studying the relationship between the spot price and the ownership structure of renewable resources, we will focus on the Spot Market description.

In the Spot Market, an algorithm allocates the generation required to cover the official forecast of the total demand of the system for each hour of the following day. The allocation prioritizes low-cost generators. The algorithm minimizes the generating cost of electricity for end-users. To do this, the market operator carries out a dispatch taking into account technological and institutional restrictions in electricity generation. Generators and retailers participate in this market. Generators participate for the right to have their generation plants dispatched. There are centrally dispatched generating plants and others that are not. The centrally dispatched generating plants are those with a net effective capacity greater than 20 MW. The firms that own these plants must compete for the right to generate in the centralized dispatch with them. Generating plants with a net effective capacity less than 20 MW to not need to compete for the right of generate in the spot market, they just inform if they wish to generate in the next day. In this market, supply and demand interact to determine the spot price and the electricity produced by each generating plant. The market mechanism that operates in the Spot Market is the auction mechanism of the last bid price.

The auction format consists of auctioning the right to generate in the market based on a bid made by the firms for each of their plants for each hour of the day. This bid consists of a price in COP/kWh and a declared generation availability in kWh for each hour of the

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2   Works that use the Cournot approach in electricity markets are Borenstein and Bushnell (1999) for California, and recently Ribó-Pérez et al. (2019) for Spain. An application for Colombia is in Duarte and García (2015).

day for each plant of the firm. The main objective of the auction is to obtain the spot price of electricity per kWh based on a production program of the generating plants that guarantees low costs to the end-users. This market mechanism has been subject to various institutional changes. From 1995 to 2001, the bids corresponded to a price-quantity pair for each hour of the day. CREG Resolution 026 of 2001 established that the bids made by the firms must report for each of their plants a single price that will be the same for all 24 h of the day, but the generation availability is by the hour. CREG Resolution 051 of 2009 added a component to the bid made by the firms, the start-up and shutdown costs of thermal plants, which are declared quarterly. This component seeks to guarantee that the thermal generators dispatched are compensated for their losses due to starting and stopping at the spot price. In 2014, CREG Resolution 026 of 2014 modified the compensation calculation for thermal plants that register losses. Plants with less than 20 MW of installed capacity that participate in the market only send their availability and do not declare a bid price.

When the market operator has received all bids, it uses a cost minimization algorithm subject to different technical and economic restrictions to define the dispatch quantities for each plant in the system and the spot price for each hour of the day. In economic terms, the operator constructs an aggregate supply curve and an aggregate demand curve for each hour of the day. Since some smaller generating plants may elect to be dispatched without bidding a price, the aggregate hourly supply curve formed by the bids does not start from the origin. Also, this curve must have a stepped and non-decreasing shape. The height of each step corresponds to the bid price of the plants used by a firm, and the length of the step is the additional amount of electricity that the plants contribute to the system. The closing price of the auction is the one that equals aggregate supply and demand and is called the marginal price of the system. The spot price is the marginal price plus the incremental delta, which is a charge to compensate for the thermal plants dispatched with operating losses. The value of the incremental delta is greater than zero only when there is at least one dispatched thermal plant in which the operating income is not enough to cover the operating losses at the marginal price. In this way, when added to the marginal price, the incremental delta ensures that each kWh of electricity generated in the system, regardless of the type of generation it comes from, covers the total losses of the thermal plants dispatched.

The Colombian Spot Market is competitive, but there may be episodes where firms use their market power to control prices. Figure 1 shows the HHI index on the declared generation availabilities of the plants owned by the firms. The HHI index takes values between 0 and 1, with values between 0.1 and 0.25 associated with a relatively competitive market and above 0.25 with a highly concentrated market. For the Colombian market, this value tends to oscillate between 0.12 and 0.18, which shows a medium concentration level in the declared generation availabilities. Additionally, to prevent episodes where firms exercise market power, CREG Resolution 060 of 2007 establishes that generating firms cannot have participation greater than 25% in the generation of electricity for the day, or the HHI exceeds the value of 0.18.

The generation of electricity is different from the declared generation availability. The generation of electricity is a result of the auction, where the operator assigns the quantities to generate. On the other hand, the declared generation availabilities are prior to the dispatch. The CREG Resolution 060 applies to the generation of electricity, not on the declared generation availabilities. When a firm owns more than 25% of the generation, it must assign part of its right to generate to another firm until its participation is less than 25%. This regulation prevents the market from tending to be highly concentrated in generation.

The generation matrix of the Colombian market has renewable (hydroelectric, wind, and solar plants) and thermal (plants that use fossil fuels such as gas, coal, and other liquids) energy sources. In Figure 2, we present the time series of the share of renewable and thermal energies in the total generation availability of the day. The participation of renewable sources tends to oscillate around 70%, while thermal sources account for 30%; this shows that Colombia has a fairly renewable energy matrix, the primary renewable source of generation being hydroelectric plants.
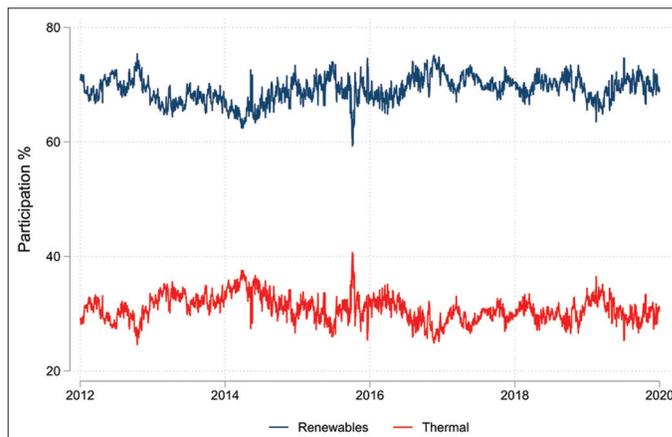
Based on the previous description of the market, Perez and García-Rendón (2021) developed a theoretical model to study the

Figure 1: HHI index on generation availability
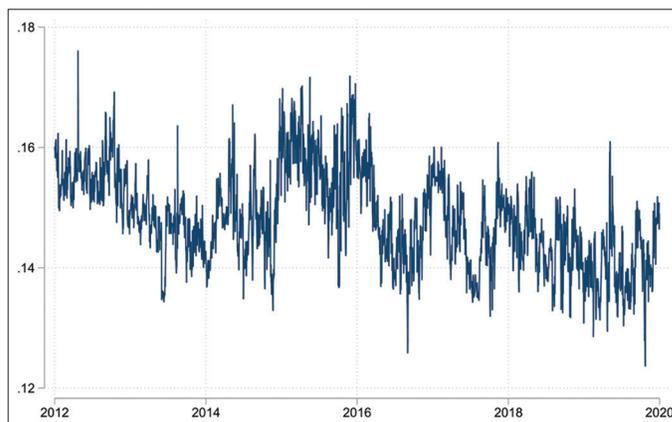
Source: Author's elaboration

Figure 2: Participation of renewables and thermal in generation availability

Source: Author's elaboration

response of the spot price to the inclusion of renewable energy with unconventional sources in Colombia. One of the predictions from their results is that the bid prices are a function of the plants' marginal costs. The plants' marginal costs depend on their fuel: water for hydroelectric plants and fossil fuels for thermal plants. Since solar and wind plants are less than 20 MW, they do not usually bid a price in the Spot Market; therefore, their marginal costs do not account for the spot price formation. In this paper, we propose an empirical strategy to study the relationship between the concentration in ownership of renewable energy sources and the merit order effect on spot prices, considering that price formation depends on the fundamentals associated with the marginal costs of generating plants.
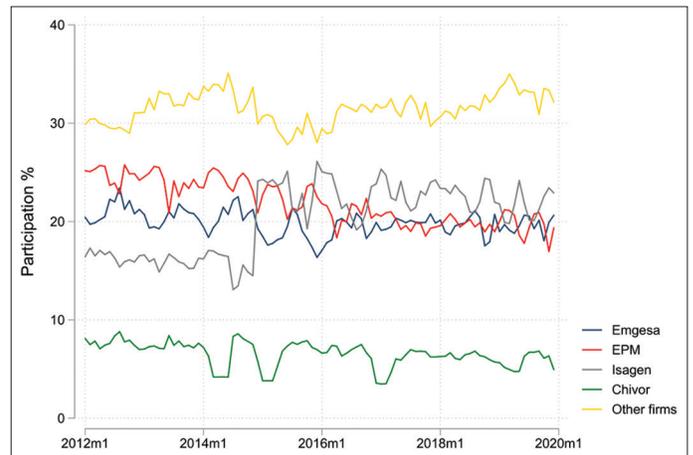
2.1. Market Ownership Structure

Electricity generating firms in Colombia constitute an influential stakeholder in the Colombian electricity market. The landscape resulted from the enactment of the Energy Reform Bill in 1994, whose main purpose was to create a functioning electricity market by allowing the participation of private firms in the generation, transmission, and commercialization of energy. At the same time, the electricity dispatch model turned to a bid model, where the generator with the most competitive price is the first to serve the market.

The largest generators as of July 2021 are EPM, EMGESA, ISAGEN, AES (Chivor), and URRA; with a market share in excess of 69%. The largest is EPM (Empresas Públicas de Medellín), an integrated utility company owned by the City of Medellin, the 2nd city in Colombia. EMGESA is a private company, jointly owned by Enel, a Chilean Energy company and GEB (Grupo de Energía de Bogotá), a Colombian listed company, whose majority owner is the City of Bogotá. Enel has the operational control of EMGESA since 1997, when the Major's city at that time solved a severe financial crisis at EEB, currently GEB, by selling 50% percent of the company to foreign investors. ISAGEN is now a private company, rescinded from ISA in 1995. ISA, an energy company owned by the Country of Colombia, participated in the generation and transmission markets. Since that time, ISAGEN owns the largest hydro-dam in Colombia. In 2006 the firm was listed in the Colombian Exchange due to a privatization effort by the Colombian government, who sold 20% of its ownership to minority investors. In 2017, the government sold its remaining shares to a Canadian energy firm, who delisted ISAGEN from the local exchange. AES owns Chivor, a 1000 MW hydro-dam, it is a subsidiary of AES Gener, a Chilean company. AES Gener

is, in turn, a filial of AES Corporation, an American company. Table 1 shows the details of each company:

In Figure 3 we present the monthly share of the 4 largest firms in declared generation availability, and in Figure 4 we show this share but only among the declared availabilities of plants that they operate with renewable energies. It should be noted that the other firms in the Spot Market tend to maintain a share of declared availabilities of more than 30%. However, when the participation in the declared availabilities from renewable sources is observed, its participation falls to levels of around 10%. This shows that, although there is not a high concentration on the part of these 4 large firms in the total

Figure 3: Participation of firms in availability

Source: Author's elaboration

Figure 4: Participation of firms in renewable availability
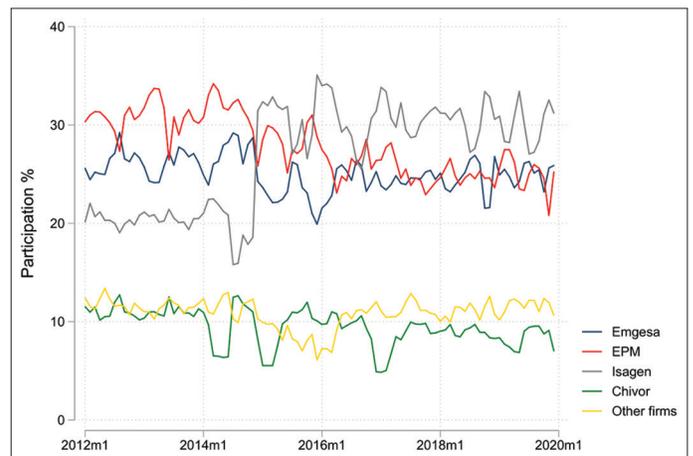
Source: Author's elaboration

Table 1: Ownership structure of the largest firms

| Firm | Owner | Country | Type | Last change in ownership | Capacity MW | | | % | Cumulative |
					Renewables	Thermal	Total		
EPM	City of Medellin	Colombia	Public	None	3101.4	582.4	3683.8	21.23	21.23
EMGESA	GEB-Enel	Chile-Colombia	Private	1997	3143.6	444.5	3588.1	20.68	41.92
ISAGEN	Brookfield	Canada	Private	2017	2732	300	3032	17.48	59.39
AES	AES Corporation	Chile-USA	Private	1996	1000	0	1000	5.76	65.16
URRA	Country of Colombia	Colombia	Public	None	676	0	676	3.90	69.05
Others					1220.8	4148.3	5369.1	30.95	100.00

Source: Author's elaboration

market, there is a high concentration in relation to the ownership of renewable energy sources. This last aspect is related to one of the objectives that arises with the entry of new renewable plants to the country. In this paper we show that, in terms of more efficient prices, it should be ensured that the inclusion of new renewable plants is through the entry of new firms to the market, and not those that are already established. Since these firms have a high concentration of renewable energy availability in the market.

3. THEORETICAL FRAMEWORK AND METHODOLOGY

In this section, we present the model developed by Acemoglu et al. (2017) along with its main theoretical predictions, which we seek to contrast with data from the Colombian electricity market. The authors develop a quantity competition model for an electricity market with an oligopoly structure. There are n firms that participate in the market and have a portfolio of technologies to produce electricity: thermal or conventional, and renewable energy sources. The production of a quantity of electricity q by the firm i with conventional sources implies a cost $C(q_i)$, where C is a convex and differentiable function. Additionally, the firms have at their disposal a fraction δ/n of the total amount of renewable energy that the economy owns, being $0 \leq \delta \leq 1$. The assumption is that all firms with conventional technologies have an equal share of renewable energy, but there is a quantity of renewable energy that is not appropriate by any of them. $Q = \sum_{i=1}^{n} q_i$ represents the total amount of electricity produced with conventional technologies. The inverse demand function that determines the market price is $P(Q+R)$, with P being a differentiable, decreasing, and concave function. Firms compete by choosing their level of q_i maintaining given their availability in renewable energy $\delta R/n$ to maximize their profits facing the following problem

$$\max_{\{q_i\}} \Pi_i = \left(q_i + \frac{\delta R}{n} \right) P(Q+R) - C\left(q_i \right) \qquad (1)$$

The assumption that the cost function does not depend on the amount of renewable energy implies that they have marginal cost equal to zero. Acemoglu et al. (2017) solves this game to obtain a Nash-Cournot equilibrium whose properties that we seek to contrast in this work are summarized in the following theorem.

Theorem 1: There is a unique equilibrium such that:

- The equilibrium price p^* is a non-decreasing function of the renewable energy supply R, that is, $\frac{\partial p^*}{\partial R} \leq 0$. This is known as the merit order effect or MoE

- The equilibrium price is strictly increasing in δ, that is, $\frac{\partial p^*}{\partial \delta}$ In equilibrium, the firms' profit margin grows as the firms' diversification extends, partially neutralizing the MoE.

- The MoE is fully neutralized if and only if producers are fully diversified and the cost function is linear. That is, $\frac{\partial p^*}{\partial R} = 0$ if and only if $\delta=1$ is linear.

Proof: Acemoglu et al. (2017).

The theorem establishes the merit order effect: a greater supply of renewable energy reduces the market price. A greater supply of renewable energy, which has zero marginal cost, has dispatch priority in the supply of demand and, therefore, translates into less residual demand that thermal generators must meet. The result implies that the supply curve shifts to the right, a phenomenon called the merit order curve. This shift in the supply curve implies that, in equilibrium, market prices for a given demand decrease. Additionally, the theorem shows that the merit order effect weakens as producers diversify and control a greater proportion of renewable energy. As the degree of diversification increases, firms have an incentive to reduce their production with thermal energy since they can internalize the losses of this strategy with a larger production with renewable energies. The firms' lower production with thermal energy implies that the market price decreases to a lesser extent due to increases in the supply of renewable energy in the economy. Finally, there is a complete nullification of the MoE when multi-technology firms own all renewable resources ($\delta=1$) and the production cost function for conventional sources (thermal) is linear

The results in Theorem 1 hold when the model expands to account for contracts and incomplete information from firms on renewable energy owned by their rivals. When considering incomplete information Acemoglu et al. (2017) find an additional relationship summarized in the following proposition.

Proposition 1: Given the correlation structure between the amount of renewable energy that firms have, the volatility of the equilibrium price decreases when the energy portfolio of the companies diversifies more, that is, $\frac{\partial Var(p^*)}{\partial \delta} < 0$.

Proof: Acemoglu et al. (2017).

This result is intuitive considering that the source of price volatility is the uncertainty that firms face regarding the amount of renewable energy in the economy and how much is owned by its rivals. When the proportion of renewable energy owned by firms with thermal technology increases, then the uncertainty that firms face decreases because they can know more about who has renewable energy in their portfolio and can infer how they behave based on their best response functions. This reduction in uncertainty implies that prices exhibit lower volatility than in the former case. The argument for reducing uncertainty also shows that as the correlation between renewable energy available to firms increases, the volatility of spot prices decreases. Given that there is more certainty about the energy availability of rival firms, the firms face less uncertainty, and thus the formation of prices is less volatile.

3.1. Data
We use data on the Colombian Spot Market from XM (2020) between January 1 of 2012 and December 31 of 2019. This data set includes information on generation availability declared in kWh by the firms for each of their plants, the type of technology used by the plants, hourly demand forecasts in kWh, water inflows levels in m^3/sec and converted in kWh, and observed spot prices for each hour of the day in COP/kWh. With the information on firms' declared availability, we estimated the Herfindahl-Hirschman

Index (HHI) to measure market power. We do not use generation to calculate the HHI because this measure is ex-post to the market auction; therefore, it is endogenous to the price. Instead, we use declared generation availabilities that are ex-ante to the auction; therefore, it is more reasonable to assume that they are exogenous at the spot price. For a proxy of the opportunity cost of thermal generation, we gather data on international prices of fuels (gas in USD/m^3, coal in USD/Ton, and fuel oil in USD/bar) from Investing website and the COP/USD exchange rate. We aggregate forecasted demand data daily, while the daily spot price is an hourly average. In this way, the frequency of our data is daily.

Additionally, following Sierra and Castaño (2010) we use the quotient between demand (kWh) and water inflows (kWh) as one of the determinants of the spot price. According to the authors, and as we will see in the results section, this variable collects a good part of the dynamics that the spot price of electricity follows. This variable is relevant given that it captures the stochastic process that the demand follows and how the availability of renewables allows to satisfy the demand. Episodes with a high level of water inflows in the rivers imply that generation to cope with the demand comes mainly from renewable energies; on the other hand, periods of drought with low water inflows imply that the demand is mainly coped with thermal generation. This attribute of the water inflows to respond to adverse weather conditions such as droughts and rainy seasons is attractive. It allows controlling for aspects related to the presence of El Niño or La Niña. Unlike water reservoir levels, water inflows are exogenous to the stochastic process of price. The water reservoir levels explain the price, but it also depends on it. Therefore, there is a problem of bi-directional causality between both variables. When controlling for the water inflows of the rivers that feed the reservoirs, we are using a variable correlated with the water reservoir levels, but that does not depend on the prices formed in the market. This exogeneity with prices, and its correlation with the water reservoir levels, makes the water inflows levels desirable to fit a correct model for determining spot prices. Table 2 describes all the variables we use.

To obtain a measure of the ownership structure of renewable resources, we use data on the declared availability of plants. We identify those firms that are multi-technology (renewable and thermal) and add their generation availability with renewables, which we divide by the total generation availability in renewables[3]. In this way, we quantify the used proportion of declared availability by multi-technology firms as an approximation of the ownership structure of renewable resources. In Figure 5, we show the time series of the multi-technology firms' participation in the availability of renewable energy of the day. The series undergoes several level changes. These level changes are what we can exploit to test one of the predictions of Acemoglu et al. (2017). The participation of multi-technology firms tends to vary between 75% and 95% for a large part of the sample.

3.2. Empirical Strategy

To contrast the predictions established by Theorem 1 of Acemoglu et al. (2017) we propose the following econometric specification for

Table 2: Dictionary of variables

Variable	Units	Description
Spot Price	COP/kWh	Average daily spot price of electricity. The spot price is hourly, therefore, we average for 24 h a day
Demand	kWh	Forecast Daily Electricity Demand
Flows	kWh	River flows that feed the National Interconnected System generating plants, added per day, and converted from m3/s to kWh
delta	[0,1]	Participation of multi-technology firms (renewable and thermal) in the total availability of renewable energies of the day
HHI	[0,1]	Herfindahl-Hirschman index on the declared generation availabilities of the firms' plants on the Spot Market, for a given day
Gas	US/m^3	International price of natural gas
Coal	US/ton	International price of coal
Brent	US/bar	International price of oil (Brent)
EXR	COP/US	Colombian peso to US dollar exchange rate

Source: Author's elaboration

Figure 5: Participation of multi-technology firms in renewables
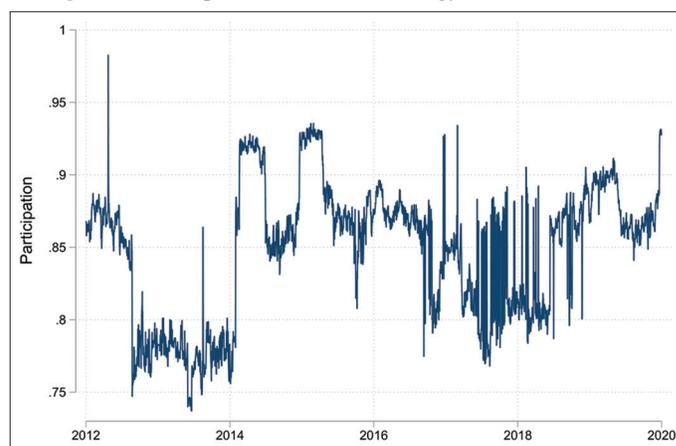
Source: Author's elaboration

the spot price P on day t, that is a non-linear function of spot price on fundamental variables of marginal costs of generating plants:

$$P_t = \beta_0 + \beta_1 D_t + \beta_2 \delta_t + \beta_3 \delta_t \times D_t + x_t' \gamma + \int_t \qquad (2)$$

P is the spot price in time t and D is the quotient between demand and water inflows in time t. δ is the participation of multi-technology firms in the total availability of renewable energy on the day t, x includes controls such as market power (HHI), fuel prices (gas, coal, and liquids), exchange rate COP/USD (EXR), and interactions between fuel prices and EXR with D that allow non-linear relationships affecting the spot price[4].

The interactions between D and fuel prices play an important

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3   For the total availability of renewable energy, we take into account the existence of plans that operate with wind and solar energy. However, its share in the system's installed capacity is less than 1%.

4   We only use the aggregate level of water inflows as a measure of the quantity of renewable energy. We do not include energy that comes from wind and solar sources since these are an irrelevant proportion in the Colombian market (less than 0.6% in capacity installed to year 2019).

role in the proposed functional form. When the level of the water inflows is low, or demand is high, then the determination of the spot price will be mainly with fuels; on the other hand, when the water inflows are high, or demand is low, then the fuels will determine to a lesser extent the spot price. The proposed functional form allows us to capture how fossil fuel prices interact and the impact of water availability (hydroelectric fuel) in determining the spot price. The effect that D has on P allows us to capture the MoE. Given that we have a non-linear form, we use the marginal effect of D on P to estimate whether or not there is evidence of the MoE. A positive marginal effect of D on P implies that either an increase in water inflows or a fall in demand tends to reduce spot prices (evidence of MoE). The reason is that a higher level of water inflows implies that the bid prices by the hydroelectric plants will tend to determine the spot price. Likewise, lower demand implies that there will be less space for thermal technologies to compete with renewables, which tend to be cheaper; therefore, the spot price will tend to be determined to a greater extent with the bid prices for renewable energy.

On the other hand, a positive marginal effect of δ indicates that greater participation by multi-technology firms in the availability of renewable energy implies a higher value of the spot price. For this to happen, it is sufficient that $\beta_2, \beta_3 > 0$. We expect that $\beta_2 > 0$, since this is what the hypothesis of the Acemoglu et al. (2017) theorem predicts, but we expect that $\beta_3 < 0$. β_3 is the coefficient of the interaction between δ and D, implying that $\beta_3 \times \delta$ is a component of the marginal effect of D on P. By the working hypothesis of Acemoglu et al. (2017), we expect that δ will tend to weaken the marginal effect of D, that is, increases in δ tend to reduce MoE. Therefore, the net effect of δ on P will depend on the relation between β_2 and $\beta_3 \times \delta$. The marginal effect of δ on P would be positive if $\beta_2 > \beta_3 \times \delta$.

Finally, we include a dummy variable that takes the value of 1 between September 2015 and April 2016 and zero otherwise. We include this variable to control for the energy crisis that affected Colombia in these months. During that time, the market faced the strongest and most prolonged El Niño phenomenon in many years. To respond to the scarcity of water resources that this causes, Colombia designed the mechanism of firm energy obligations ("obligaciones de energía en firme"). This mechanism ensures that, in adverse weather conditions, there is the energy available to supply the system's demand by paying some plants for the commitment to stay in good condition so that, if necessary, they supply a quantity of energy agreed to the system. Unfortunately, some thermoelectric plants could not generate the amount of electricity they had committed; thus, the system faced a supply crisis during this period, causing the electricity spot prices to rise to historic levels. This increase in prices was due to a combination of the presence of El Niño with the exit of operations of some relevant thermoelectric plants; consequently, the increase does not follow the process of determining spot prices under normal conditions. We account for this circumstance with a dummy variable that captures the high average levels of spot prices.

3.2.1. Dynamic model
The expression in equation 2 establishes the long-term relationship between the spot price and the fundamental variables. The adjustment in the short term is also of interest; thus, we also estimate the previous model, including the pot price lags. We test the following specification:

$$\ln p_t = X_t' \beta + \sum_{j=1}^{H} \alpha_j I_j \ln p_{t-j} + \int_t \tag{3}$$

X is a matrix containing all observations of independent variables in equation 2. On the other hand, H represents the maximum number of lags to include in the equation and I_J is an indicator variable that takes the value of 1 when the lag j is actually included in the model. The determination of the set of lags corresponds to the minimum AIC information criterion. We recursively estimate the equation of interest, each time including one more lag, until the estimated model produces non-autocorrelated residuals. Since this procedure involves an overidentified model, and many of the H lags are not significant, based on genetic algorithms, we find the combination of these that minimize the model AIC[5]. That is, the optimization with the genetic algorithm determines in which of the H lags I_j=1 or I_j=0. Once we exclude the redundant lags, the model continues to generate non-autocorrelated residuals. This model allows estimating the dynamic adjustment of spot prices, in the face of a shock in the amount of renewable energy measured by water inflows, for various levels of the variable δ.

3.2.2. Variability of spot prices
The second working hypothesis of Acemoglu et al. (2017) we test is the relationship between the variability of prices and the level of concentration in the supply of renewable energies by multi-technology firms. To study this relationship, we calculate the variability of daily spot prices by monthly standard deviation. Additionally, since at a monthly level there are few observations for the period 2012-2019 (96 obs.), we calculate the variability at a biweekly level to obtain more observations. We did not calculate the variability of the data at a weekly level since it would imply calculating these measures of variability from only seven observations. Later, we define the following econometric specification.

$$P_m^{sd} = \alpha_0 + \alpha \delta_m + \alpha_2 \mu_m + w_m' \lambda + u_m \tag{4}$$

P_m^{sd} is the standard deviation in month or biweek m of daily spot price. δ_m is the share of renewable energy availability for month or biweek m of multi-technology firms in total generation availability. We expect that $\alpha_1 < 0$, that is, a greater concentration of renewable energies by multi-technology firms reduces the variability of the spot price. The controls in w are the standard deviations of month or biweek m of D and dummy variable for the period of crisis in 2015-2016. We do not include the variability of fuel prices or the exchange rate because the source of uncertainty in the market is the availability of renewable resources, not thermal resources. For this reason, we only include the variability of D as an explanatory variable for the variability of the spot price, which is a measure of the variability in the availability of renewables to satisfy market demand.

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5   Here differential evolution is used, a method specific within the set of genetic algorithms.

On the other hand, μ_m is a one-dimensional measure associated with the structure of correlations between the amount of renewable energy firms have. To do this, we use a measure derived from the Bonacich centrality in network theory. This measures the degree of centrality of a set of nodes joined by weighted graphs with weights determined by a correlation matrix Σ (Ballester et al., 2006; Acemoglu et al., 2012). We define Σ as a correlation matrix between the water inflows of the generating plants in a month or biweek. $b=(I+\Sigma)^{-1} 1$ is the Bonacich centrality, 1 being a vector whose elements are 1. Allowing Σ to represent the matrix of correlations between the water inflows from each hydroelectric plant, the degree to which the water inflows from each plant co-vary is

$$\mu=b' \Sigma b \qquad (5)$$

In a weighted graph, where the nodes represent the plants and the weights are given by the entries in the array Σ, b is the vector of Bonacich centrality. This vector contains a measure of the relative importance of each node in the network, that is, a metric that reflects to what extent each node is interrelated with the others (how much the water inflows of a plant correlate with water inflows in another plant). An increase in indicates a decrease in the correlation of water inflows. As we mentioned in Section 3, the model of Acemoglu et al. (2017) predicts that an increase in μ is associated with an increase in price variability ($\alpha_2>0$). When there is a lower correlation between the water inflows of the plants (increase in μ), then there is greater uncertainty about the generation availabilities that the firms will declare; therefore, the firms will tend to bid poorly correlated prices. Consequently, the resulting spot price may inherit part of this uncertainty, increasing its variability over a period of time. On the other hand, there will be less uncertainty, and the spot price is less variable when the water inflows are highly correlated.

4. RESULTS

In Figure 6, we present the time series of the spot price and our fundamental variables. To present the figure of the spot price, we discard the observations of the days between 2015 and 2016 in which the price rose to more than 1000 COP/kWh; these values affect only the graph scale. Fundamental variables are the quotient between demand and water inflows (D), HHI, fuel prices, and the COP/USD exchange rate. As expected by Sierra and Castaño (2010), demand/water inflows adjust the dynamics of the spot price in some periods. A close look at the figure shows the tendency of the quotient to take an inverted U shape, which inherits the spot price in some periods. On the other hand, the movements of international fuel prices and the exchange rate show dynamics that the spot price tends to follow at some time. To corroborate these insights, we performed unit root and cointegration tests between the series.

Figure 6: Spot price and fundamental variables
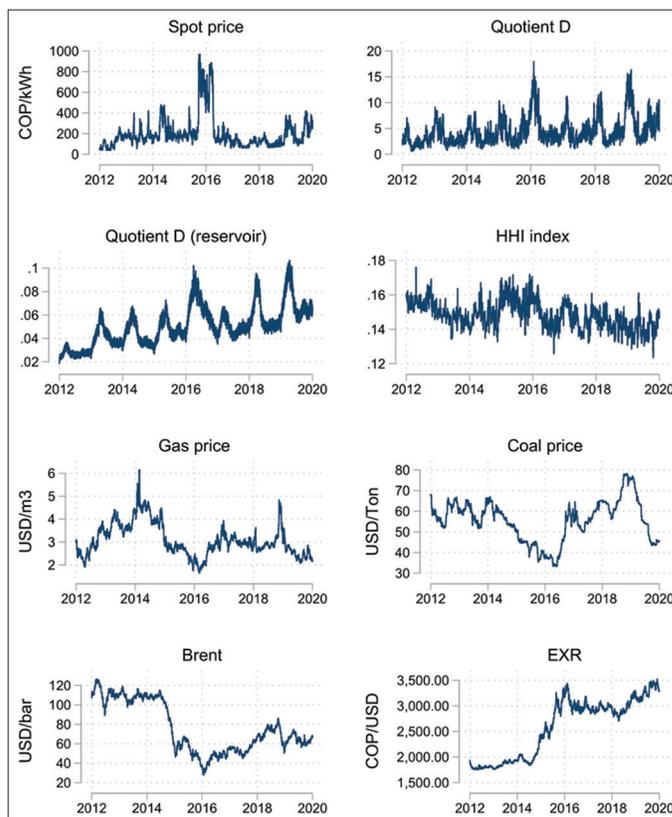
Source: Author's elaboration

Table 3: Unit-root tests

	Variable in levels			Variable in first differences		
	PP	**KPSS**	**BVR**	**PP**	**KPSS**	**BVR**
Spot price	−5.043****	0.584***	0.006***	−48.909****	0.016	3.7426e−06****
D	−11.273****	1.623***	0.012*	−89.905****	0.012	7.8514e−07****
delta	−9.201****	1.186****	0.009**	−126.994****	0.050	2.025e−06****
HHI	−14.322****	0.4502****	0.0028249**	−90.284****	0.0167	9.8576e−07****
Gas	−2.517	1.878****	0.017	−56.798****	0.052	1.502e−05****
Coal	−1.773	1.215****	0.011*	−50.935****	0.120	6.537e−05****
Brent	−1.503	5.365****	0.050	−58.009****	0.142	4.723e−05****
EXR	−0.725	9.153****	0.087	−51.800****	0.107	4.063e−05****
D*delta	−10.901****	1.697****	0.013****	−90.446****	0.012	7.6072e−07****
D*Coal	−9.755****	1.808****	0.014**	−88.988****	0.014	1.0019e−06****
D*Gas	−11.869****	0.660****	0.005****	−88.577****	0.014	9.679e−07****
D*Brent	−12.991****	0.490****	0.003****	−90.117****	0.009	6.5584e−07****
D*EXR	−8.642****	3.361****	0.027	−89.361****	0.013	8.8402e−07****

Source: Author's elaboration. Note: The optimal number of lags are chosen with the AIC criterion under PP, and Schwartz criterion under KPSS and BVR. The tests are done without including trend. ****P<0.01, ***P<0.025, **P<0.05, *P<0.1

In Table 3 we show the results of the Phillips-Perron (PP), KPSS and Breitung's Variance Ratio (BVR) tests for the series of the variables and interactions with D, HHI and our measure of the participation of multi-technology firm δ. or all variables, we performed the tests without including a trend term. Additionally, we carried out the tests for the first differences series to confirm that they are integrated of order 1. Both PP and BVR tests have the null hypothesis that the variable contains a unit-root, and the alternative is that a stationary process generated the variable. PP uses the Newey-West standard errors to account for serial correlation, making the test robust to the presence of heteroskedasticity and autocorrelation. BVR is a test with nonparametric statistic. KPSS test has the null hypothesis that the variable is stationary, and the alternative is that the variable has a unit root. According to PP and BVR, there is unit-root evidence for the series of fuel prices, exchange rate, and interaction between exchange rate and D. KPSS shows evidence of the presence of unit root for all series, including interactions and δ. The results of the tests for the first differences show that the series are integrated of order 1. The KPSS test is the only test with the existence of unit root as an alternative hypothesis. In statistical terms, it is the only unit root test; the others are tests of stationarity. These results agree with the theoretical model of Perez and García-Rendón (2021), given that the determination of spot prices comes essentially from marginal costs, which in turn depend on fundamental variables (demand, water inflows, fuel prices, and the others). Since the latter have a unit root, necessarily the spot price as well.

Based on the unit root tests, we conclude that the variables of interest have a unit root and are integrated of order 1. Therefore, to rule out the problem of spurious correlations, we test the cointegration hypothesis by evaluating whether the error in equation 2 is stationary. Table 4 reports the results of the tests. The ADF, PP, KPSS, and BVR tests conclude that the residuals are stationary. However, these tests do not consider that the residuals result from an estimation process; therefore, they are biased. Such bias increases the probability of finding cointegration. To solve the bias, we modify the p-value of the ADF test using the MacKinnon distribution. The result is robust to the change; thus, the estimated errors are stationary, and there is evidence that our series are cointegrated. From a theoretical point of view, the spot price follows the fundamental variables; that is, it is the spot price that searches for the common trend that it shares with the fundamental variables. Therefore, in this work, we propose that the spot price is a function of the fundamental variables.

4.1. Merit Order Effect

As evidenced previously, there is a cointegration relationship between the spot price of electricity and its fundamental determinants associated with the marginal costs of generating plants. The result implies that the estimation of equation 2 produces valid results from a theoretical and statistical point of view, allowing us to evaluate the hypotheses of the model of Acemoglu et al. (2017) on the existence of the MoE and the relationship between it and the participation of multi-technology firms in the ownership of renewable energies. In Table 5, we show the results of estimating equation 2 using OLS. In column 1, we only include as explanatory variables D and El Niño. In column 2, we add our measure of participation of multi-technology firms δ and interaction with D. Column 3 includes the controls associated with market power, fuel prices, exchange rate, and interactions. In Column 4, we present the marginal effects calculated for the regression of Column 3 on the average values of the explanatory variables. Table 4, presented above, contains the unit root test of the residuals of the model estimated in Column 3.

The results in columns 1 and 2, without including controls, show that there is a positive relationship between spot prices

Table 4: Tests for cointegration: Stationarity of residuals

	ADF	PP	KPSS	BVR	ADF corrected
Residuals	−7.239****	−10.405****	0.075	0.000****	−7.238****

Source: Author's elaboration. Note: The optimal number of lags are chosen with the AIC criterion under PP, and Schwartz criterion under ADF, KPSS and BVR. The tests are done excluding trend. ****P < 0.01, ***P < 0.025, **P < 0.05, *P < 0.1

Table 5: Regressions: Spot price, renewable energy and multi-technology firms

	(1) Spot Price	(2) Spot Price	(3) Spot Price	(4) Marginal Effects
D	10.02*** (0.871)	37.76** (18.67)	23.85 (24.20)	11.004*** (1.093)
delta		290.5*** (98.76)	343.9*** (103.4)	151.05*** (53.115)
Dxdelta		−32.84 (21.54)	−43.06* (22.52)	
Nino	470.3*** (8.308)	469.4*** (8.317)	480.5*** (10.54)	
HHI			456.2 (340.4)	456.05 (340.39)
Gas			111.2*** (8.026)	40.297*** (4.208)
DxGas			−15.82*** (1.763)	
Coal			−6.559*** (0.616)	−3.858*** (0.341)
DxCoal			0.603*** (0.0940)	
Brent			0.670 (0.494)	2.011*** (0.222)
DxBrent			0.299*** (0.0913)	
EXR			0.0326 (0.0225)	0.060*** (0.010)
DxEXR			0.00622 (0.00405)	
Constant	121.9*** (4.292)	−122.8 (84.30)	−356.8*** (127.8)	
Observations	2,922	2,922	2,922	2,922
R-squared	0.597	0.599	0.649	

Source: Author's elaboration. Note: Standard errors in parentheses. Marginal effects are calculated for the average value of variables. ***P<0.01, **P<0.05, *P<0.1

and D. Additionally, δ has a positive sign and a negative sign for its interaction with the flow levels. When we include controls, because we have non-linear relationships between the spot price and the variables of interest, we calculate the marginal effects of the variables on their average values and show the results in column 4. We highlight that, on average, D has a positive and significant marginal effect on the spot price, providing evidence of MoE in the Colombian market. When water inflows increase D decreases; therefore, a fall in D implies a fall in the spot prices.

Additionally, there is a positive marginal effect of; greater participation of multi-technology firms in the availability of renewable energy tends to increase spot prices, on average. This is evidence in favor of the hypothesis of Acemoglu et al. (2017). Concerning market power, there is a positive relationship between the spot price and the HHI, but this is not significant. For fuel prices, we find positive marginal effects for gas and Brent prices and the exchange rate, but we find a negative marginal effect for coal. The direction of the marginal effect of the coal price may reflect the substitution of this by another fossil fuel such as gas.

In Figure 7 we show how the marginal effect of on the spot price varies for different levels of δ. For $\delta \in [0,1]$ there is evidence of MoE. When water inflows decrease, D increases; thus, an increase in D implies an increase in the spot prices. Moreover, as the participation of multi-technology firms in the availability of renewables increases, the MoE becomes smaller, and we found evidence that it becomes statistically zero with a confidence interval of 95% in $\delta=1$. We posit that this result is evidence in favor of the hypothesis of Acemoglu et al. (2017) related to the total nullification of the MoE for $\delta=1$. The confidence intervals are small for the values of 0.8 and 0.9 since these are the values that tend to take δ, those are values for which we can better estimate the interaction between the MoE and δ. For other values, the confidence intervals are larger since we do not have observations in which takes these values, resulting in less precision in the estimators.

4.2. Estimation of Dynamic Model

This section shows the results associated with the short-term dynamic adjustment of changes in the fundamental variables on the spot price of electricity. To do this, we estimate equation 3, which establishes the serial dependence of the spot price. This exercise allows us to assess whether there are differences in the adjustment of spot prices to changes in the availability of renewable energies, depending on the ownership of multi-technology firms. We evaluate for a maximum of 150 lags. We estimate equation 3 with 60 lags (2 months); this specification minimizes the AIC information criteria. In addition, this model produces non-autocorrelated residuals. Using genetic algorithms, we select a subset of the 60 lags that minimizes the AIC.

This final model elaborates the impulse response functions (IRF) of the spot price by a shock in the amount of renewable energy. This is reflected as a fall in D when the water inflows increase and approach the level of the day's demand or when the day's demand decreases, and the water inflows are constant. In Figure 8, we present the impulse response functions of spot price by a drop of 1 in D for various levels of δ. Given that all IRFs take negative values, we show that, for the dynamic model, the MoE exists.

A fall in, explained as an increase in water inflows, tends to lower spot electricity prices. Additionally, the magnitude (in absolute value) of IRF tends to decrease as increases, which is evidence that the dynamic adjustment of spot prices by changes in available renewable energy weakens when multi-technology firms have greater participation in the renewable energy ownership. On the other hand, for the adjustment of the dynamic model, we do not find evidence of the complete nullification of the MoE when $\delta=1$.

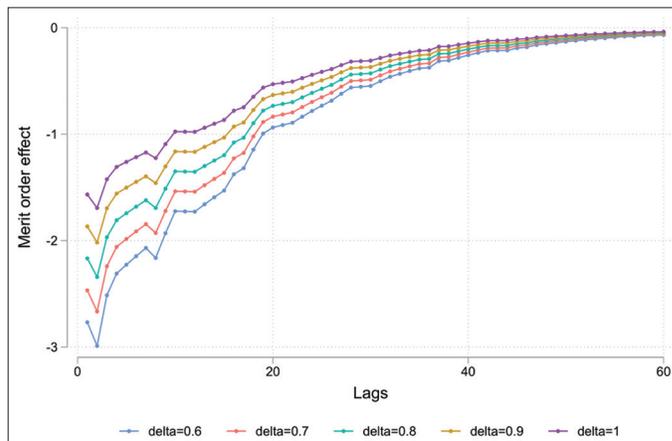## 4.3. Variability of Spot Price

In Figure 9, we show the monthly and biweekly variability of the electricity spot price. The spot price has high variability in the years 2014, 2015, and 2016. In these years, the generation availability from renewable sources was relatively lower than in other years, producing higher variability in the spot prices. Additionally, Figure 10 shows the time series of the centrality measure of Bonacich for water inflows in the SIN. This measure has a very uneven behavior; the degree to which the water inflows correlate with each other does not seem to have a relatively constant behavior over time. Table 6 shows the results of estimating equation 4 using OLS for monthly and biweekly data. Columns 1-2 are monthly data, and columns 3-4 are biweekly data. In columns 1 and 3, we

Figure 7: Average marginal effects of demand/water inflows (MoE) with 95% Cis
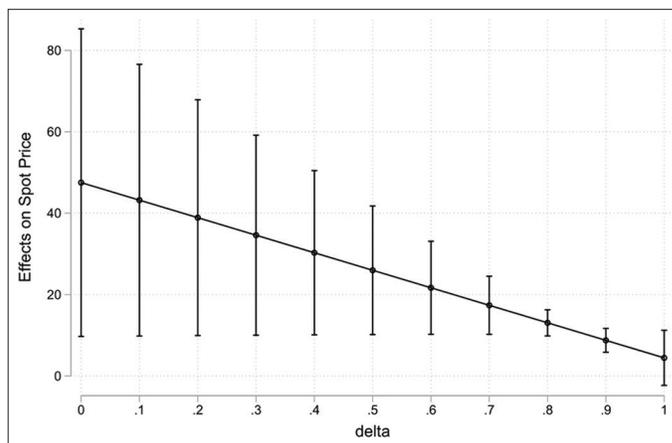
Source: Author's elaboration

Figure 8: Impulse response functions of spot prices for water inflows at different levels of δ
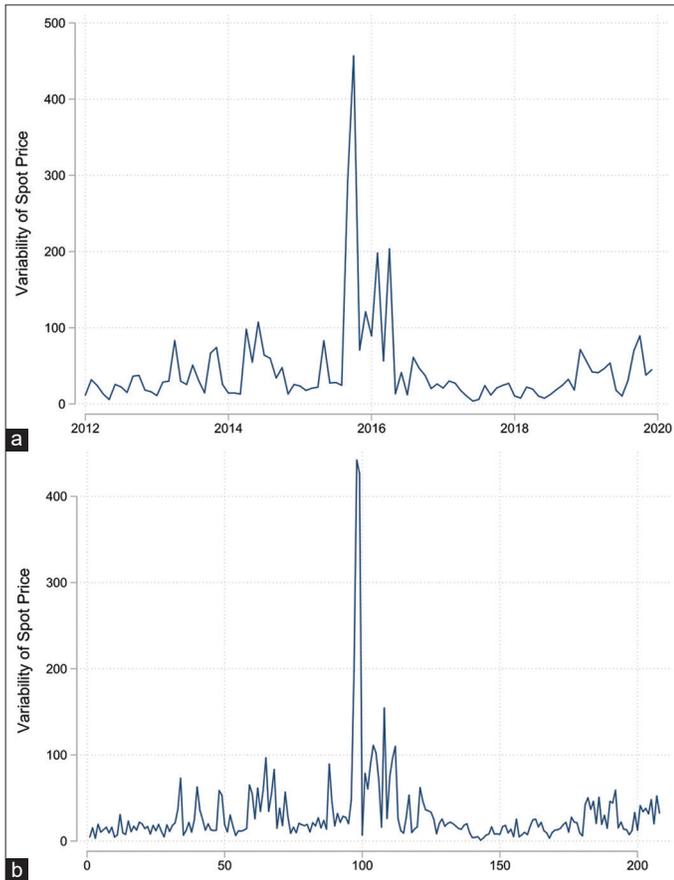

Source: Author's elaboration

Table 6: Regressions: Variability of spot price

	(1) Monthly	(2) Monthly	(1) Biweekly	(2) Biweekly
Delta	−28.83 (102.6)	−57.58 (100.4)	20.53 (63.48)	29.56 (63.61)
Nino	154.7*** (15.94)	155.8*** (15.67)	82.02*** (9.459)	81.46*** (9.400)
Cor Flows		−6.914 (10.29)		−8.769 (5.794)
Var D		168.2*** (62.39)		64.87* (38.54)
Constant	56.56 (88.13)	50.38 (88.65)	5.355 (54.16)	4.552 (55.71)
Observations	96	96	208	206
R-squared	0.504	0.541	0.273	0.297

Source: Author's elaboration. Note: Standard errors in parentheses. The dependent variable is the standard deviation of daily spot price. All variables are standard deviation of daily series excepts Nino, Cor Flows and delta. ***P<0.01, **P<0.05, *P<0.1

Figure 9: Variability of the spot price. (a) Monthly. (b) Biweekly

Source: Author's elaboration

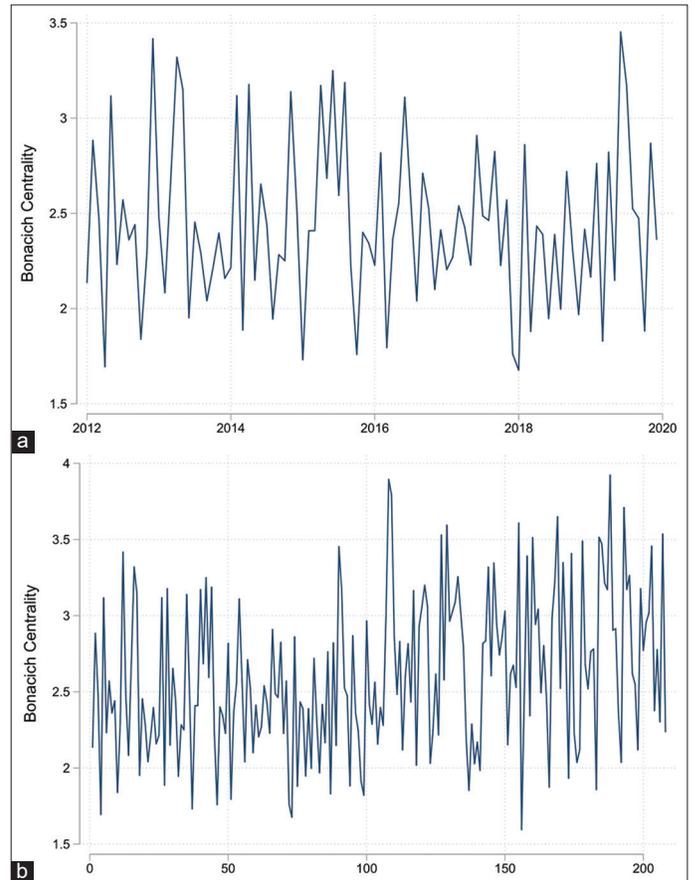**Figure 10:** μ for water inflows of plants. (a) Monthly. (b) Biweekly

Source: Author's elaboration

estimate the model only with δ and El NIño. In columns 2 and 4 we include as controls μ and the variability of .

Our results show that there is a direct relationship between the variability of D and the variability of the spot price, which is robust to the frequency in which we measure the variability. This relationship makes theoretical sense, given that greater variability in the availability of renewable energy relative to demand implies greater uncertainty in the formation of spot prices. The participation of multi-technology firms in the availability of renewable energy does not have a relationship with the variability of spot prices. Finally, there is a negative relationship between ⌷ and variability of spot prices, but this is not significant. These results do not favor the hypotheses of Acemoglu et al. (2017) on the determinants of the variability of spot prices, both for the relationship with the participation of multi-technology firms and for the correlation

between the renewable energies of firms. Therefore, there is no evidence of a relationship between the variability of spot prices and the participation of multi-technology firms in the ownership of renewable energies.

5. CONCLUSIONS

This paper explores the relationship between the electricity spot prices and the ownership structure of renewable energy for the Colombian electricity market. The theoretical foundation of this relationship comes from Acemoglu et al. (2017). Additionally, the authors derive predictions about the relationship between the spot prices volatility and the ownership structure of renewable energy. We propose an empirical strategy to contrast theoretical predictions with data from the Colombian market. Our main results show a

merit order effect in the Colombian electricity market, but this is weaker when the availability of renewable energies of the day concentrates in multi-technology firms. Our results stand even after controlling for firms' market power measured by the HHI index on declared availabilities of generation. In other words, even keeping the potential exercise of market power by firms constant, there is a negative effect on MoE derived from the high concentration of renewable energies owned by multi-technology firms.

This result has policy implications on the energy auctions that Colombia regularly carries out to satisfy electricity demand. These auctions aim for the country to have a cleaner energy matrix for the coming years. Consequently, auctions are held for new plants with renewable technologies to enter the spot market. Based on our results, there is a benefit of the entry of new firms that operate these generation plants. In terms of price formation, it is not efficient that firms already established in the market and that operate multiple generation technologies are the ones that carry out the creation of new generation plants. Our results make sense to the observed dynamics in monopolistic or oligopolistic markets; new and independent entrants tend to reduce the incumbents' rents.

Regarding the variability of spot prices, we approximate it based on the monthly or biweekly standard deviation of the spot price. The hypotheses of Acemoglu et al. (2017) indicate that there is a negative relationship between variability of spot prices and the participation of multi-technology firms in the ownership of renewable energies. This relationship can be a benefit of greater concentration in the availability of renewable energies. While higher concentration implies higher spot prices, it also implies less price variability. However, our evidence indicates no relationship between price variability and the participation of multi-technology firms. In short, there is no evidence in favor of the potential benefit of a greater concentration in the availability of renewable energies. Taken together, our results make a solid case to devise regulations that favor the entry of new firms that operate with renewable energies in the Colombian market. A structural model of our empirical approach will surely produce more insights regarding policy implications about the entrant's regulation in the spot market. That is the next stage of our research.

6. ACKNOWLEDGMENT

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