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Research article

Market power and adverse weather events in a market dominated by hydroelectric energy

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Abstract

We studied the effect of adverse weather events on retail electricity prices, focusing on the Colombian case given that this market is dominated by hydroelectric energy and exposed to El Niño weather pattern. This condition is associated with a reduction in the country's hydrological resources. We apply a structural model to understand the formation of retail prices and how these respond to extreme weather events. Our results show that, under normal conditions, retail firms have control over the pass-through of wholesale cost shocks in retail prices. However, we did not find evidence that the pass-through differs when El Niño occurs. Thus, its effect on retail prices runs exclusively through its effect on wholesale costs. Furthermore, we found that retail prices increase in the presence of El Niño due to the increase in spot prices in the wholesale electricity market. However, the increase in retail prices is less than proportional to the increase in spot prices due to the market power of retail firms.

Keywords: electricity markets; retail prices; wholesale prices; El Niño weather pattern.

Poder de mercado y eventos climáticos adversos en un mercado predominantemente hidroeléctrico

Resumen

Estudiamos el efecto de los eventos climáticos adversos en los precios minoristas de la electricidad centrándonos en el caso colombiano, dado que este mercado es dominado por la energía hidroeléctrica y está expuesto al fenómeno de El Niño, el cual se asocia con una reducción de los recursos hidrológicos del país. Aplicamos un modelo estructural para comprender la formación de los precios minoristas y cómo responden a los fenómenos meteorológicos extremos. Nuestros resultados muestran que, en condiciones normales, las empresas minoristas tienen control sobre la transmisión de los shocks de costos mayoristas en los precios minoristas; sin embargo, no se encontró evidencia de que el traspaso difiera cuando ocurre el fenómeno de El Niño. Así, su efecto sobre los precios minoristas se produce exclusivamente a través del impacto en los costes mayoristas. Además, encontramos que los precios minoristas aumentan cuando ocurre El Niño debido al aumento de los precios al contado en el mercado mayorista de electricidad. Sin embargo, el aumento de los precios minoristas no es proporcional al aumento de los precios al contado debido al poder de mercado de las empresas minoristas.

Palabras clave: mercados eléctricos; precios minoristas; precios mayoristas; fenómeno de El Niño.

Poder de mercado e eventos climáticos adversos em um mercado de eletricidade dominado pela energia hidrelétrica

Resumo

Estudamos o efeito de eventos climáticos adversos sobre os preços de varejo da eletricidade, com foco no caso colombiano, dado que esse mercado é dominado pela energia hidrelétrica e exposto ao padrão climático do El Niño. Essa condição está associada a uma redução dos recursos hidrológicos do país. Aplicamos um modelo estrutural para compreender a formação dos preços de varejo e como os preços respondem a eventos climáticos extremos. Nossos resultados mostram que, em condições normais, as empresas varejistas têm controle sobre a transferência dos choques de custos do mercado atacadista para os preços no varejo. No entanto, não encontramos evidências de que a transferência seja diferente quando ocorre o El Niño. Assim, o efeito do padrão climático sobre os preços no varejo ocorre exclusivamente por meio de seu efeito sobre os custos no mercado atacadista. Além disso, descobrimos que os preços no varejo aumentam quando ocorre o El Niño devido ao aumento dos preços spot no mercado atacadista de eletricidade. No entanto, o aumento dos preços no varejo é menor do que proporcional ao aumento dos preços spot devido ao poder de mercado das empresas varejistas.

Palavras-chave: mercados de eletricidade; preços no varejo; preços no atacado; padrão climático El Niño.

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1. Introduction

Electricity prices in Colombia depend primarily on hydrological variables because hydroelectric power plants generate most of the country's electricity. Different studies about Colombia have investigated how the electricity spot price responds to variations in climatic conditions, particularly to El Niño-Southern Oscillation or ENSO (Villa-Loaiza et al., 2023; Sierra and Castaño, 2010; Gil and Maya, 2008; Villarreal, 2017; Botero et al., 2016; Perez et al., 2022a). This weather pattern is related to temperature increases in the eastern equatorial Pacific Ocean. It implies periods of drought that reduce water inflows to Colombian rivers, thereby affecting the country's electricity generation from its primary source (Morcillo et al., 2020; Pulgarín-Morales and Krueger, 2025). Evidence indicates that spot electricity prices increase and are highly volatile during strong El Niño events (Trespalacios et al., 2020; Perez and Garcia-Rendon, 2020; Perez et al., 2022a). However, its effects on energy markets outside Colombia show significant heterogeneity, some of them are affected and others benefit from it (Huang et al., 2025). Particularly, spot prices tend to increase with El Niño, which has implications for retail electricity prices and the final consumers pay for them. To the author's knowledge, there is no research on this matter; thus, we propose an analytical framework to explore how El Niño weather pattern affects retail electricity prices and how incorporating nonconventional renewable energies (NCREs; e.g., solar and wind) can support the electricity system during adverse weather events.

The relationship between electricity prices and hydroelectric power generation has been widely studied in Colombia. Sierra and Castaño (2010) found that the series of spot prices closely follow the dynamics of the quotient between demand and the aggregate level of water inflows in hydroelectric power plants in Colombia. El Niño weather pattern directly affects water inflows; therefore, it is the primary input to hydroelectric power plants, which affects the spot price. When the availability of water resources is high, prices tend to decrease and increase again when this resource is scarce. This relationship shows that, to know the effect of El Niño on spot prices, the behavior of water inflows must be modelled. Furthermore, Perez et al. (2022a) found that the relationship between electricity demand and water inflows cannot explain increases in spot prices during certain periods, such as the 2015-2016 El Niño weather pattern. The authors noted that much of the price increase during this period was due to the closure of two thermoelectric plants that could not meet their emergency generation obligations. Therefore, particular events can determine the spot price in each case of El Niño weather pattern.

There are few works that study the formation of retail electricity prices in Colombia. We highlight Correa-Giraldo et al. (2021), McRae and Wolak (2021), and Ramirez-Hassan and Lopez-Vera (2024). Correa-Giraldo et al. (2021) estimated the pass-through of wholesale costs to retail prices for regulated users. They proposed an econometric model for a reduced-form equation, following Duso and Szücs (2017), on the determinants of retail price. Their results showed that firms tend to transmit wholesale cost shocks more than proportionally to retail prices. Furthermore, they found evidence that firms with more market share tend to have greater pass-through than other firms. Similarly, they documented that the transfer has increased over the years. They relate this finding to the implicit cost of El Niño in 2015 and 2016, which raised spot prices to historical highs and caused the pass-through to increase over the years. Additionally, to the best of our knowledge, few studies have explored the effect of El Niño on retail electricity prices in Colombia. Thus, our work fills this literature gap.

McRae and Wolak (2021) explored how to reform the current retail electricity pricing policy to improve adoption of new clean technologies by residential users. They highlighted that current regulations do not favor the inclusion of clean technologies that can harm lower-income households due to increases in final prices, thus encouraging the use of fossil fuels. In our work, we study the effects of including more wind and solar energy on retail prices, thus contributing to this area of the literature. Finally, Ramirez-Hassan and Lopez-Vera (2024) studied how taxes on electricity consumption for regulated users affects the well-being of consumers. Their results showed that including this tax would imply a loss of well-being, for both low- and high-income households. In our study, we exclude the case of regulated residential users and thus do not follow the strategies of previous studies.

We apply a structural model to examine the response of retail prices to short-term extreme weather events. In the literature on estimating structural models applied to the electricity market, we highlight Wolfram (1999) and Bushnell et al. (2008). They explored how electricity spot prices are affected by the market power of generating firms. Among the recent applications, we highlight Lundin and Tangeras (2020) on the Nordic wholesale markets, Ribó-Pérez et al. (2019) on Spain, and Kiesel and Kusterman (2016) on France and Germany. Lundin and Tangeras (2020) identified that generating firms have market power and factors that can explain their existence. Ribó-Pérez et al. (2019) studied how the inclusion of self-generation with solar PV affects the formation of wholesale prices in the presence of market power of generating firms. Kiesel and Kusterman (2016) developed a structural model to evaluate the effect on electricity prices and the value of power plants of a potential coupling between the French and German markets. In Colombia, we highlight the work of Perez and Garcia-Rendon (2020) on the effect of including Non-Conventional Renewable Energies (NCRE) on spot prices, and Camelo et al. (2018) on the effect of transitioning to a system where firms commit to covering the start/stop costs of their plants and another where a centralized planner ensures that the market price covers these costs. We have not found any work proposing a structural model to study price formation in retail electricity markets.

We focus on examining the retail market for unregulated users in Colombia. The country constitutes a particularly relevant case study due to its hydro-dominated electricity system, where hydropower accounts for most of electric power generation. While this mix implies a high share of renewable energy, it also makes the power system highly dependent on hydrological conditions and therefore especially vulnerable to climate variability. In particular, extreme weather events associated with the El Niño–Southern Oscillation can generate substantial supply shocks, increase wholesale price volatility, and pose challenges for market stability. Since Colombia is located in the eastern equatorial Pacific—one of the regions most exposed to these phenomena—its electricity market provides a valuable setting to analyze how cost shocks and climate-related risks are transmitted along the electricity value chain.

Regarding users, unregulated ones can openly negotiate price generation and commercialization. Therefore, their retail price is largely subject to the law of supply and demand. Our monthly data for 2012-2019 include two El Niño periods: a long-term El Niño between 2015 and 2016, with relevant impacts on the market, and the short-term one at the beginning of 2019. We use a two-part strategy to analyze how extreme weather events affect retail prices. Short-term extreme weather events directly affect the wholesale level of the market; thus, spot price formation. We propose a reduced-form equation to study this direct effect. Subsequently, we applied a structural model for retail competition. We analyze how retail prices respond to changes in wholesale cost components, including the spot price.

We highlight two relevant results: one for the general retail market and the other for the effect of extreme weather events on prices. Regarding the retail market, we find evidence of a more than complete pass-through of wholesale cost shocks to prices for all markets studied. The average profit margins between retail firms' markets are approximately 14%. Additionally, we do not find evidence that the pass-through of wholesale cost shocks to retail prices differs between periods with normal weather conditions and El Niño, except for one of the 20 markets studied.

Regarding the effect of extreme weather events, we propose a scenario for evaluating how El Niño occurred in 2019 affected retail prices. The year 2019 experienced normal conditions, except for February and March, when El Niño was detected, but without substantial effects on the market. Our proposed scenario illustrates an extensive El Niño event similar to that occurred in 2015-2016. We found that strong El Niño would reduce the aggregate level of water inflows by 23%. Therefore, spot prices would increase by 19.2% on average. Regarding retail prices, we found an increase between 1% and 3.8%, depending on retail firms exposure to purchases in the spot market.

Based on results, two policy recommendations have arisen. First, there is no evidence to support differentiated regulation between normal conditions and the presence of El Niño, so policymakers should focus on preventing the marginal costs of generating power plants from increasing considerably. The second recommendation is to encourage greater inclusion of NCRE, as they help hydroelectric generation during drought. However, it should be accompanied by increased natural gas generation to ensure system stability due to the intermittency of NCREs. This relates to the adverse effects on final prices brought about by the inclusion of NCRE, as illustrated by the case of Germany (Botero et al., 2019). In this country, the massive integration of wind and solar generation sources led to substantial increases in final tariffs due to higher costs from constraints associated with the intermittency of these sources.

This paper is organized as follows: Section 1 presents the institutional details of the market and the data used; Section 2 presents the proposed model of competition between firms and discusses how firms transmit cost movements to final prices; Section 3 discusses empirical strategy; Section 4 presents the results and analysis of the scenarios, and Section 5 concludes.

2. Institutional aspects and data

2.1 Wholesale level

Colombia's electricity market is regulated by the Energy and Gas Regulation Commission (CREG by its Spanish acronym) both wholesale and retail. The spot price of electricity is formed in wholesale, which is the primary market signal. Then, bilateral contract prices are formed between generating and retail firms. These prices allow their signatories to hedge against the risk that implies substantial variations in the spot price. A market operator called XM is designated to set the spot price through a uniform price auction with a complex bid. The National Dispatch Centre (CND by its Spanish acronym) facilitates the bidding process to determine the price of each hour the next day. Then, generation programs of each plant are dispatched in the auction together with the bid. XM uses the next day's demand forecasts through an algorithm that minimizes the dispatch cost subject to economic and technological restrictions. This mechanism is based on the order of merit, where plants that bid lower prices are dispatched, and those that bid higher prices are not. The generating firms participating in the auction send bids for their respective generating plants, including the bid price and declared availability to generate. For thermal plants, start-up costs are included. In Colombia, the main types of plants are hydroelectric and thermoelectric. CND uses this information to perform the next day's auction and determine the hourly spot price.

To prevent generating firms from exercising their market power, CREG Resolution 060 of 2007 has been issued. It states that generating firms cannot participate more than 25% in the total daily generation. If, on a given day, the dispatch indicates a generating firm with participation greater than 25%, XM must assign the production of the firm's last dispatched plant to the next one in the order of merit of the auction.

Long-term bilateral contracts are commitments between generators and retailers for future electricity purchase/sale in a volume and maturity negotiated between both parties. These contracts are strictly financial obligations between contracting parties and do not imply that the generator must produce contracted electricity. Generation is determined in the spot market auction. The prices established in the contracts can be fixed by contract or equal to the spot price with maximum and minimum limits. Contract maturity varies from a few weeks to years, though long-term relationships can occur between agents for extended periods. CREG supervises these contracts to guarantee compliance with these obligations by both parties. It also ensures that agents have the physical and financial capacities to fulfil their commitments. Furthermore, there are vertical integration structures between generators and retailers. Thus, CREG has established that a retailer can purchase, in terms of contracts, from a generator with which it is vertically integrated no more than 60% of the total amount of energy they generate.

Lastly, we present wholesale related to the scarcity price and Firm Energy Reliability Mechanism (FERM). Colombia is subject to severe periods of drought caused by El Niño. Thus, the reliability charge is created to avoid energy rationing and interruptions. FERM is a purchase option that allows the regulator to acquire the right to buy firm energy from the generators at an agreed price and for the duration of the option. Under normal conditions, generating plants with FERM receive a monthly remuneration for being able to generate at optimal conditions when required. FERM is activated when El Niño occurs and certain conditions are met. The scarcity pricing gives the option's exercise price. This price is the maximum price that generators can receive for their FERM delivery. The regulator calculates the scarcity price, which corresponds to the generation cost of the plant with the lowest technological efficiency that used fuel oil no. 6 as an alternative fuel (CREG, 2006). Under this contract, the regulator obtains the right to acquire firm energy for the contractor's reliability charge if the spot price exceeds the scarcity price. If the option is executed, the generator must generate the amount of energy assigned to it by CND. This assignment is also dictated by the dispatch determined in the auction. This mechanism guarantees no energy rationing during El Niño and inexpensive energy because the price users pay for the generated energy is the scarcity price and not the spot price.

2.2 Retail level

Regarding the retail level, retail firms and end users interact. Retail firms purchase electricity from generators through long-term contracts or the spot market. Then, they sell it to end users. They receive payments from the latter and subsequently pay the rest of the production chain for the services they provide. Retailers function in the sector is not complex and does not require large investments as generating firms do.

End users are divided into regulated and unregulated. For regulated users, the regulator sets the price of electricity they consume. For unregulated users, they can openly negotiate with retailers regarding the payment terms for the generation and commercialization components. Additionally, they can choose their retailer. Users can opt to be unregulated if their electricity demand exceeds 55 MWh/month; however, this qualification applies only to large electricity consumers. On average, the share of regulated and unregulated users in the total daily demand is 67% and 33%, respectively.

Regarding retail price formation, it is determined by Resolution 119 of 2007 (CREG, 2007b) and its pertinent modifications. This Resolution establishes that the retail price paid by end users for each kWh is determined every month and has six components: generation (G), transmission (T), distribution (D), commercialization (C), losses (P by its Spanish name), and restrictions (R). This Resolution is mandatory for regulated users, whereas unregulated users can negotiate for the G and C price components. The activities of T and D are associated with natural monopolies. Thus, they are regulated for both types of users due to the structure of decreasing average costs. The regulator determines the payment made for these components in Resolution 119 of 2007. R and P components are determined by the regulator because generating and retail firms have no control over them.

The tariff or retail price paid by users takes the following form:

$$\mathrm{p_{v,t,f,d} \equiv G_{t-1,f,d} + T_t + D_{v,t} + C_{t,f,d} + P_{v,t,f,d} + R_{t,f}}, \tag{1}$$

where *v* denotes the user's connection voltage level, *t* is the month, *f* denotes the retailer firm and *d* is the commercial market that depends on the department or region. Below, we briefly describe how each component is determined.

Transmission (T) and Distribution (D): Electricity is transported from the generating plants to end users through the national transmission system (STN), which is passed to the regional transmission system (STR). Then, it is brought to users through local distribution systems (SDL). CREG defines the STN as an interconnected electrical energy transmission system comprising a set of lines with corresponding connection modules that operate at voltages equal to or greater than 220 kV. STR comprises regional or interregional transmission networks including a set of lines and substations with associated equipment operating at voltages lower than 220 kV. SDL is made up of a set of lines and substations, with their associated equipment that operate at voltages lower than 220 kV. SDL lines and substations do not belong to the STR because they are dedicated to municipal, district or local distribution systems.

The monthly rate paid by the STN is unique nationally and is independent of the voltage level to which the user is connected. STR is divided into two areas: north and south[1]. STR rates depend on the transmission area and are established monthly as set by Resolution 011 of 2009 (CREG, 2009). The T component is calculated by comparing the monthly income of the energy transmission company with the electric energy demand of the Interconected National System (SIN). The distribution cost depends on the distribution areas (ADDs, whose monthly rate per voltage level is established by the legislation[2].

Restrictions (R) and Losses (P): CREG regulates the remuneration of the R and P components. R is allocated to system surcharges associated with the technical limits of the transmission network. This cost is assigned monthly to each retailer and is independent of the user type and voltage level. Losses (P) constitute technically and non-technically lost energy (energy theft) in the transformation and transportation of electricity. This cost is also assigned to each retailer per month and depends on the user type, location, and voltage.

Generation (G): Retail firms establish contracts with generators to meet the hourly demand of their users every day. These contracts define the amount of electricity per hour and the price paid. When the demand at one time of the day is higher than what the retailer has contracted, the retailer must buy the difference in the spot market. When this demand is lower, the retailer sells the difference in the spot market. The costs transferred per generation include these electricity purchases made by retailers in the spot market and bilateral contracts in the previous month. For regulated users, generation costs transferred to them are established by a formula for the cost per generation. For unregulated users, these generation costs are negotiated between them, as represented by the retailers, and the generators. However, the generation cost formation is similar for both types of users.

The generation cost is a weighted average between the spot and contract prices. For the spot market, firms take a monthly average of the price weighted by the quantities purchased in this market. When the spot price exceeds the scarcity price at a given hour, firms charge end users the scarcity price, not the spot price at which they purchase electricity. This mechanism protects end users from spot price increases due to weather changes associated with El Niño and water resource scarcity. Regarding contract prices, the firms establish prices with generators, and these are confidential. However, the market operator reports the average price of the firm's contracts for regulated and unregulated users. Component G is a weighted average between the average price of purchases in the spot market and the price of contracts, where the weight is the share of monthly purchases in each market.

Commercialization (C): For regulated users, the commercialization cost consists of a non-binding maximum cost scheme; retailers can charge a value equal to or lower than that defined according to the regulation's calculation. For unregulated users, this cost is freely negotiated between them and the retailers and does not have an upper or lower limit.

2.3 Data

We used three sources of information: Sinergox from XM (2021) for the wholesale market, Superservicios (2021) for the retail market, and NOAA (2022) to measure the presence of El Niño. Retail data included carefully disaggregated information. We exclusively used data for commercial and industrial unregulated users. Therefore, we examined the formation of retail prices for large electricity consumers; namely, commercial and industrial companies. We gathered information on the value paid on electricity bills in COP (including and excluding contributions and subsidies), end users' electricity consumption in kWh, and the number of users. These data have a monthly frequency from 2012-2019. We aggregated this information by department–retailer firm and measured the retail price as the quotient between the value paid in commercial invoices (excluding contributions) and the quantity consumed. Similarly, for each department, we calculated each retail firm's share in total consumption to measure their market share in each department. For 2012-2019, we collected data on 45 firms that serve unregulated users in 20 departments and defined markets. Twenty out of these 45 firms are vertically integrated between generation and commercialization, and only eight operate in a single market. Therefore, most of them are multimarket. The selected departments belong to the National Interconnected System, where data reporting is more consistent, reliable, and free from the measurement issues observed in non-interconnected regions. Departments with documented data inconsistencies were therefore excluded. We discarded data from the departments of Arauca, Caquetá, Casanare, La Guajira, Nariño, and Putumayo due to inconsistencies in the registry. These excluded departments represent less than 3% of the annual electricity consumption.

To measure wholesale costs, we used data from Sinergox, which provides hourly information on the spot price, quantities bought and sold in the spot market by retail firms, and monthly information on average contract prices. Information on the specific contract prices of each firm is not available due to confidentiality. We followed Perez et al. (2022b) to calculate the wholesale cost; we used the net quantities purchased in the spot market for each retail firm as a spot price weight and calculated the monthly average spot price for each retail firm. When the spot price of an hour is higher than the scarcity price, the latter is used to calculate the monthly average spot price as established by regulation. Subsequently, we added all the quantities purchased in the spot market in a month and calculated their share of the total demand of the retail firm reported in Superservicios. Thus,

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[1] The north STR covers the subnational entities or departments of La Guajira, Atlántico, Magdalena, Cesar, Sucre, Córdoba and Bolívar. South STR covers the remaining departments.

[2] Central: Santander, Norte de Santander, Caldas, Risaralda, Quindío and Antioquia. West: Cauca, Valle del Cauca and Nariño. East: Boyacá, Arauca, Huila, Cundinamarca and Bogotá D.C. South: Caquetá, Meta, Putumayo and Casanare. North: Atlántico, Bolívar, Cesar, Córdoba, La Guajira, Magdalena and Sucre. Tolima represents an Distribution Area (ADD).

we obtained the weight of the spot price, and the difference between the two is the weight of the contract prices. Finally, we obtained the wholesale cost as the weighted average between the monthly spot and contract prices.

To determine the presence of El Niño, we used the multidimensional ENSO index (MEI) of NOAA (2022). MEI is a multivariate measure given by principal component analysis of the six variables observed in the tropical Pacific Ocean. These data are available for the period 1979-2019. The values are normalized such that the high and low values represent the warm phase (El Niño; MEI ⩾ 0.5) and cold phase (La Niña; MEI ⩽ -0.5) of ENSO, respectively. In Colombia, El Niño is related to dry periods, and La Niña to rainy periods (Ramirez B. and Jaramillo R., 2009). When the MEI exceeds the value of 0.5, El Niño is in its weak stage but considered strong when the MEI exceeds 1. Other authors like Botero et al. (2016), Perez et al. (2022a), and Jimenez-Saenz et al. (2024) have used the MEI to evaluate the effects of El Niño in Colombia and study how it influences the variability of river flows in the country, which affect the generation of hydroelectric energy from four power plants relevant to the sector. There are other ENSO measures such as the Oceanic Niño Index (ONI) and the Southern Oscillation Index (SOI). Following Wolter and Timlin (2011), we use the MEI because it reflects multiple characteristics rather than just one, it is less sensitive to errors and better descriptor of the ENSO.

Figure 1 illustrates the role of the El Niño weather pattern in Colombia's electricity generation. The figure shows the share of electricity generated by hydroelectric and thermoelectric plants, with a monthly frequency between 2012 and 2019. The grey bars in the monthly frequency indicate the presence of El Niño. This weather pattern occurred in two periods: May 2015–May 2016 and February–March 2019. Moreover, we present the three main types of fuel employed in thermoelectric plants. Under normal conditions, hydroelectric and thermoelectric power generation constitute between 90% and 60% and between 10% and 30%, respectively. The main fossil fuel for energy generation is natural gas, followed by coal. In the presence of El Niño, hydroelectric generation is below 50%, and the shares of natural gas and liquid fuels increase. Of the two periods when El Niño was identified, only 2015-2016 affected hydroelectric generation.

Figure 2 shows the series of average retail prices and average wholesale costs, the areas that denote the distribution of variables between the 5th and 95th percentiles, and grey bars that indicate the presence of El Niño. This figure provides evidence of how average retail prices follow the dynamics of average wholesale costs. Therefore, our measurement strategy for the G component paid by unregulated users is reasonable. This measurement is similar to that of regulated users. On average, retail prices and wholesale costs maintained a 1:1 relationship, and no systematic changes were observed in the gap that separates retail prices from wholesale costs. This finding is consistent with the hypothesis of retail firms' competitive behavior. In this work, we focused on testing this hypothesis with data. We contrast whether firms tend to follow competitive behavior or show a relative degree of market power. Additionally, in the presence of El Niño, wholesale costs and retail prices tend to rise and the distribution of retail prices is more stable than that calculated for wholesale costs.

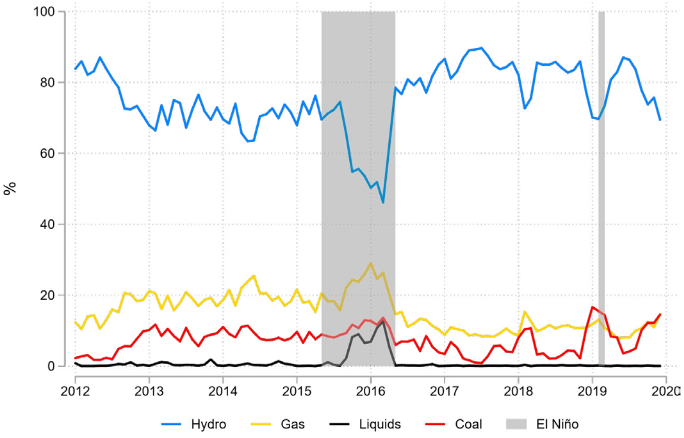

Figure 1. Participation per source in electricity generation.
Source: own elaboration based on XM.

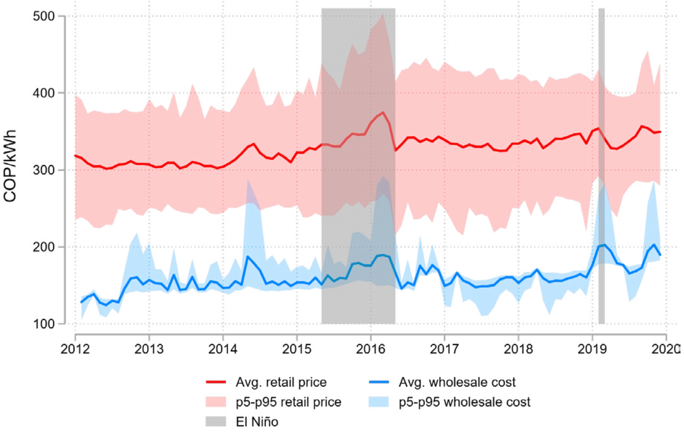

Figure 2. Retail prices and wholesale costs.
Source: own elaboration based on Superservicios and XM.

For the wholesale cost components, Figure 3 shows the series of monthly average spot prices, monthly average contract prices for unregulated users, and scarcity prices for 2012-2019. Contract prices for retail firms are not applied due to limited data. The average price of the contracts is almost a straight line compared with the spot price, which tends to fluctuate strongly. Figure 3 highlights that spot prices tend to respond substantially in the presence of El Niño, whereas contract prices do not exhibit a short-term response. Spot prices are below the scarcity price for the entire period, except during El Niño. When it occurs, the mechanism that protects end users is activated, and no increase in similar proportions is observed in the wholesale costs as seen in Figure 2.

Table 1 presents sample descriptions of the 20 markets used to estimate the structural model. In the second and third columns, we present the average number of firms and vertically integrated firms between generation and commercialization. The following columns present the average number of users served, HHI market concentration measure, average retail price, and wholesale cost weight that firms assign to the spot market depending on the presence of El Niño. The average number of firms per market ranges 5-18. Certain firms in each market are vertically integrated between generation and commercialization; Valle del Cauca has the greatest number of vertically integrated firms (eight). The Sucre market has the lowest average number of users, with 34, and those with the most average users are Antioquia and Valle del Cauca, with more than 1866. The 20 markets have a total of 5864 unregulated users. Bolívar and Valle del Cauca markets have the highest (HHI = 0.55) and lowest (HHI = 0.18) concentrations, respectively. Fifteen of the 20 markets have an HHI > 0.25, indicating high concentration.

Regarding differences between normal conditions and the presence of El Niño, retail prices and wholesale costs are higher when El Niño occurs, and firm's exposures to the spot market have no clear relationship with it. In certain markets, firms are more exposed in the presence of El Niño and are less exposed in other markets. Average retail prices are dispersed between markets with normal conditions, ranging between 286 and 363 COP/kWh; for wholesale costs, they are less dispersed, between 155 and 159 COP/kWh. Finally, we found that Antioquia is the market where firms tend to expose themselves to spot market purchases the most, with an average weight of 17%. Norte de Santander and Boyacá are the markets where firms tend to expose themselves the least, with 9%.

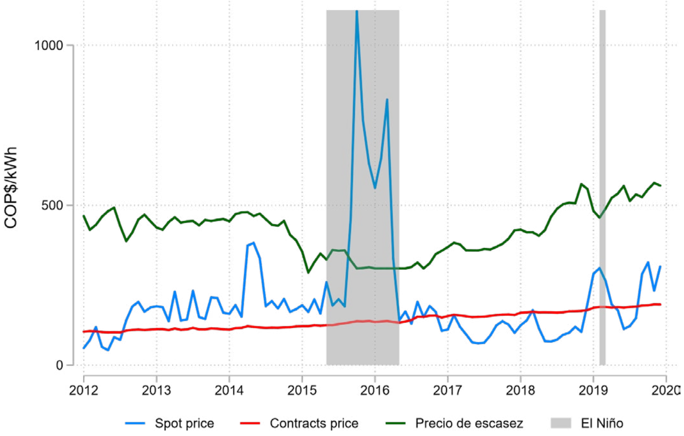

Figure 3. Spot prices, contract prices, and scarcity pricing.
Source: own elaboration based on Superservicios and XM.

3. Model

Following Bushnell et al. (2008) and Wolfram (1999), we developed a model to study retail price formation in a

Table 1. Descriptives per market.

					Normal conditions			El Niño		
	Number of firms	Vertically integrated	Number of users	HHI	Retail price COP/kWh	Wholesale cost COP/kWh	Weight of spot market purchases	Retail price COP/kWh	Wholesale cost COP/kWh	Weight of spot market purchases
Antioquia	15	6	768	0,52	331,45	157,09	17,4%	354,27	172,54	14,5%
Atlántico	12	4	423	0,42	321,88	158,87	12,9%	340,40	178,14	16,9%
Bogotá, D.C.	16	7	910	0,35	342,64	157,39	16,4%	362,56	173,67	14,6%
Bolívar	9	3	214	0,55	313,67	157,17	13,4%	335,67	175,89	15,8%
Boyacá	8	4	50	0,42	286,38	157,32	8,3%	305,31	164,54	7,0%
Caldas	8	4	98	0,46	332,51	156,90	14,5%	351,71	176,53	17,0%
Cauca	11	5	113	0,20	306,56	157,72	11,7%	332,14	174,26	14,5%
Cesar	7	4	50	0,35	304,29	156,92	14,1%	335,29	177,06	16,1%
Córdoba	9	2	81	0,38	311,80	157,01	11,8%	326,06	174,97	15,0%
Cundinamarca	17	7	391	0,31	335,31	157,81	16,9%	365,64	175,50	15,8%
Huila	8	4	94	0,36	325,20	158,89	16,4%	342,11	171,74	13,3%
Magdalena	8	3	101	0,34	306,43	156,13	12,0%	330,96	176,00	15,3%
Meta	10	6	108	0,36	336,06	158,75	14,7%	366,64	174,34	14,5%
Norte de Santander	7	3	91	0,44	336,14	156,74	9,0%	357,41	167,59	8,6%
Quindío	7	5	56	0,48	363,89	155,74	13,2%	382,86	171,54	12,7%
Risaralda	12	7	102	0,22	326,55	157,67	15,1%	336,16	179,64	18,8%
Santander	11	5	178	0,24	329,66	156,74	11,7%	352,18	170,71	11,5%
Sucre	5	2	34	0,45	307,34	156,31	14,7%	324,25	175,78	15,9%
Tolima	10	5	134	0,24	327,31	157,34	12,8%	342,62	170,00	11,4%
Valle del Cauca	16	7	1866	0,18	319,13	157,37	12,9%	331,80	179,03	17,4%

Source: own elaboration.

homogeneous good market when retail firms have market power. The market has *N* retail firms. Retail firm *i* has a linear cost function $C_i(q_i) = c_i$ where $c_i > 0\ qi$ is the (constant) marginal cost of firm *i* and q_i is the quantity. On the demand side, this function is described in aggregate as $D(P^r, x, \epsilon)$ where P^r is the retail price, *x* is a vector of observable factors that shift demand, and ϵ represents a disturbance term. We assume that *D* is twice differentiable, strictly decreasing and concave in P^r.

Retail firms face a simple problem: they must purchase electricity from generating firms to satisfy the demand of end users. Moreno and Ubeda (2006) and Kreps and Scheinkman (1983) demonstrated that a two-stage oligopolistic competition model, where firms select their installed capacity and then compete via prices, is equivalent to the Cournot quantity competition model[3]. This two-stage game approximates how the Colombian retail electricity market works. Retail firms compete to attract end users, who determine the amount of electricity firms must satisfy (their installed capacity) and subsequently set prices. Therefore, we propose that the retail firms' problem is a Cournot competition. The profit maximization problem of the retail firm *i* is:

$$\max_{\{q_i\}} \pi_i = \mathrm{Pr}\left(Q, x, e\right) q_i - C_i\left(q_i\right), \qquad (2)$$

Where $Q = \sum_{i=1}^{N} q_i$ is the total quantity in the market, and P^r is the inverse demand function.

The first-order condition of Equation (2) for retail firm *i* is[4]

$$\frac{\partial \pi}{\partial q_i} = P^r\left(Q, x, e\right) + \frac{\partial P^r}{\partial Q}\left(Q, x, e\right)\theta_i q_i - c_i = 0 \qquad (3)$$

$\theta_i = \frac{\partial Q}{\partial q_i} = 1 + \sum_{j \neq i}^{N} \frac{\partial q_j}{\partial q_i}$ is the retail firm's conjectural variation in the market's reaction to a change in its

strategic variable (Bresnahan, 1989). θ_i is a behavioral parameter that allows us to represent a wide range of possible market outcomes, including the standard model of symmetric oligopoly competition and perfect competition. When $\theta_i = 1$, the retail firm considers that its actions do not alter those of its rivals. Therefore, it acts as a monopolist against its residual market demand. This case demonstrates the Cournot-Nash equilibrium for a symmetric oligopoly. Furthermore, when $\theta_i = 0$, the retail firm has competitive behavior because its actions do not change the total quantity in the market. Assuming the joint profit maximization or collusion conjecture, we have $\theta_i = N$, where *N* retail firms produce the pure monopoly quantity, each setting the monopoly price. Negative values of θ_i are typical, for example among inferior products in Shaked and Sutton models (1982) on vertically differentiated products with price competition. This condition implies that firms gain an increased share of the producer surplus to the extent that large firms have an increased θ_i value. However, because we are modelling the price of electricity, which is a normal good, we did not consider this case for our analysis.

From the Equation (3), we obtain:

$$P^r = \frac{P^r \theta_i q_i}{\eta Q} + c_i \qquad (4)$$

where $\eta = -\frac{\partial Q}{\partial P^r}\frac{P^r}{Q}$ and $s_i = \frac{q_i}{Q}$.

Solving for P^r, we obtain Proposition 1 as follows:

Proposition 1: *In the game described above, the equilibrium prices are given by*

$$P^r = \left(\frac{\eta}{\eta - \theta_i s_i}\right) c_i \qquad (5)$$

Equation (5) establishes the pricing rules of retail firm *i*. When n > 1 and Si, $\theta_i \epsilon [0,1]$ we have that $\frac{\eta}{\eta - \theta_i s_i} > 1$ that is the retail firm imposes a markup on the marginal cost by setting price P^r (Bettendorf et al., 2003). The condition $\theta_i \epsilon [0,1]$ implies no collusive behavior in the market. When $\theta_i > 1$, the resulting profit margin can be negative because joint profit maximization internalizes the effect of a firm's decision on the conjecture $\frac{\partial q_j}{\partial q_i}$ from another firm. Equation (5) suggests that if a retail firm has market power, then it can control the pass-through of marginal costs to retail prices to obtain profits above the marginal cost.

Additionally, one of the sources of heterogeneity in the profit margin among firms is market share. Firms with more market share have lower profit margins than those with fewer.

The formalization of the role of θ as a behavioral parameter in symmetric imperfect competition models is due to Weyl and Fabinger (2013). When θ does not depend on market conditions, we have the standard interpretation discussed above, where θ allows us to contemplate behaviors between perfect competition and pure monopoly, such as the Cournot competition or monopolistic competition, up to the cartel behavior. Weyl and Fabinger (2013) showed how θ behaves when it depends on market conditions. For differentiated products and consumers' discrete choices, price competition implies that θ increases as prices increase and quantities decrease. Hence, the passthrough is higher than the case suggests since θ does not depend on market conditions. However, in our study, it is not reasonable to consider the electricity sold by retail firms as a differentiated good. Therefore, we use the traditional case in which θ does not vary with market conditions. Thus, we obtained the results presented above, which are standard in literature.

4. Estimation

This section describes the steps for estimating the model proposed in the previous section. First, we address

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[3] The assumption is that demand is twice differentiable, strictly decreasing and concave. Firms have access to the same technology with constant marginal costs. The model we developed meets these assumptions.

[4] The second-order conditions of the problem are satisfied given that P^r is twice differentiable, strictly decreasing and concave in *Q*.

the estimation of the first fundamental parameter, namely the elasticity of demand. Subsequently, we establish how to identify the parameters associated with the marginal costs. Then, we propose a reduced form to examine how spot prices depend on weather conditions. Finally, we discuss aspects related to the identification of the model.

4.1 Elasticity of demand

Each department in our data represents a market. Each retail firm is assumed to act independently in each market, that is, retail firms maximize profits in each department independently. The way local distribution is designed enables dividing departments into separate markets. Additionally, it is reasonable to assume that, for a retail firm, the marginal cost of serving a user in one market does not differ from that of serving a user in other markets. That is, its cost function is separable across markets; therefore, it can operate independently in each market. We assume that fundamental demand parameters are similar for all consumers throughout the country as they do not vary between markets. To identify the coefficients θ, the elasticity of demand n must be estimated. Following Wolfram (1999), we estimate a log-linear version of the demand equation as follows:

$$\ln \mathrm{Q}_{\mathrm{dt}} = \beta \ln \mathrm{P}^{\mathrm{r}}_{\mathrm{dt}} + \boldsymbol{x}'_{\mathrm{dt}}\boldsymbol{\alpha} + \epsilon_{\mathrm{dt}} \qquad (6)$$

where Q is the average consumption per user in market d in period t, $P^r$is the average retail price in market d and period t and x includes variables that determine unregulated industrial and commercial users' aggregate demand. Among the controls, we include the economic activity index as a measure of the economic activity level, which varies monthly and is aggregated at the national level[5]. We include the average price of natural gas (COP/m^3) for industrial and commercial users in each department with a monthly frequency, reported by Superservicios (2021). Natural gas serves as a substitute good for electricity for large industrial and commercial consumers to satisfy their energy needs[6]. Regarding temperature measures, we include the monthly average maximum temperature as a measure of the temperature during the day, and monthly average minimum temperature as a measure of the temperature during the night. Both variables are obtained from Copernicus. The climate data has information on a grid level of 30 kilometers. Data is available from 2012-2019, with daily input. From Colombia's shape-file documents, the climate data at a department level can be added. We converted the minimum and maximum temperature data to Celsius (°C). The European Center for Medium-Range Weather Forecasts (ECMWF) shares this data publicly.

There is a potential bidirectional causality problem between ln$Q$ and lnP^r. Thus, we instrumented the retail price with the level of water inflows (in logarithms) to hydroelectric power plants. A high availability of the hydrological resource reduces retail prices for end users, whereas a shortage implies high retail prices. Furthermore, the water inflow level does not correlate with the users' electricity demand. To estimate Equation (6), we recover the underlying (constant) elasticity of demand as follows:

$$\hat{\eta} = -\frac{\partial \ln \mathrm{Q}}{\partial \ln \mathrm{P}^{\mathrm{r}}} = -\hat{\beta}$$

4.2 Marginal costs of retail firms

To identify the marginal costs in data, we used spot prices, average contract prices, and retail firms' electricity purchases as reported in the spot market and each firm's total quantity demand. Let P^w, P^c, and P^r be the spot, contract and retail electricity prices, respectively. Considering how the spot market operates, only vertically integrated firms between generation and commercialization could influence the formation of the spot price, a component of the cost at which they acquire electricity. Riascos et al. (2016) and Balat et al. (2022) found generating firms' market power can systematically influence spot prices. However, the spot price formation is relatively efficient as it significantly reflects aspects related to the marginal costs of the plants and less significantly reflects aspects related to generating firms' strategic behaviors. Under this evidence, for simplicity, we assume that spot prices are exogenous for retail firms, both integrated and non-integrated. Additionally, when the spot price exceeds the scarcity price, end users effectively pay the scarcity price completely to the firms. For contract prices, retailers negotiate the terms of the contracts with the generating firms, though we did not observe these contracts or the prices they establish. Because of this limitation, we can only assume that retail firms take contract prices as given when deciding the retail price of electricity.

From these observations and assumptions, we assume that marginal costs take the following form:

$$\mathrm{c}_{\mathrm{idt}} = \varphi_{\mathrm{it}}\mathrm{P}^{\mathrm{w}}_{\mathrm{t}} + (1 - \varphi_{\mathrm{it}})\mathrm{P}^{\mathrm{c}}_{\mathrm{t}} + \tau_{\mathrm{dt}} + \nu_{\mathrm{it}} + \varepsilon_{\mathrm{idt}}$$

where ϕ_{it} represents the weight of spot purchases in the total demand of retail firm i in period t. τ_{dt} represents the distribution, τ_{dt} transmission and other charges set by regulation, applied in market d in period t. An additional feature is the inclusion of ν_{id}, which captures different heterogeneity sources in retail firms' costs across markets. Unobserved heterogeneity is the price of firm-level contracts, which tend to be long-term relationships between unregulated users and retail firms and can be largely controlled by ν_{id}. ε_{idt} is an error term. The previous expression establishes that the purchasing cost for 1 kWh of electricity for the retail firm is equal to the weighted average between the spot price and contract price, and other charges.

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[5] Measures of economic activity are not available with monthly frequencies that vary between departments.

[6] Industrial and commercial natural gas prices are regulated by CREG. It does not regulate natural gas for electricity generation in the spot market, and its price depends on international gas prices and the dollar exchange rate.

Summarizing the expressions of marginal costs and having an estimated value of demand elasticity, we define the empirical version of Equation (5), which varies between markets:

$$\mathrm{P^r} = \left(\frac{-\hat{\beta}}{-\hat{\beta}-\theta_{dt}s_{idt}}\right)\left[\varphi_{it}\mathrm{P}_t^w + \left(1-\varphi_{it}\right)\mathrm{P}_t^c + \nu_{id} + \tau_{dt} + \tilde{\varepsilon}_{idt}\right] \quad (7)$$

Equation (7) is defined for each market *d*. Due to data confidentiality from contracts with unregulated users, only the average wholesale cost of retail firms can be observed $(\varphi_{it}\mathrm{P}_t^w + (1-\varphi_{it})\mathrm{P}_t^c)$. A limitation of our work is that we do not model a retail firm's ϕ_{it} choice. This aspect may introduce bias in the θ. We propose using instrumental variables to control this potential problem. Among the instruments we used, there is the aggregate level of water inflows, which is correlated with the spot price that motivates the decision to choose ϕ_{it}. The second instrument is the average retail price in other markets in the same zone as the STR (north or south)[7]. This instrument follows Hausman's instruments and is the standard in the literature for estimating structural demand models (Hausman, 1996; Nevo, 2001). The logic of our instrument is that the specific cost variations of firms in one market can be correlated with those in other markets. However, a firm's specific demand variations are not correlated with the demand variations in other markets. Other instruments are temperature measures. Finally, from data, we have determined the participation of firms and the average retail price that they charge to unregulated users in market *d* for each period *t* (s_{idt} and P^r_{idt}, respectively).

From Equation (7), estimates of θ_{dt} can be obtained. In this case, we assume that the value of θ is the same for all retail firms. Regarding the temporal variation, we assume that the value of θ differs between periods with normal conditions and El Niño[8]. Otherwise, we estimate the average value of θ for each market under normal conditions and in the presence of El Niño.

The estimate of θ_{dt} is based on Equation (7):

$$\mathrm{P^r} = \left(\frac{-\hat{\beta}}{-\hat{\beta}-\theta_{dt}s_{idt}}\right)$$
$$\left[\varphi_{it}\mathrm{P}_t^w + \left(1-\varphi_{it}\right)\mathrm{P}_t^c + \nu_{id} + \tau_{dt} + \tilde{\varepsilon}_{idt}\right]$$

The estimation process follows the logic of the generalized method of moments (GMM). To use this method, we only need to assume that $\tilde{\varepsilon}_{idt}$ follows an independent and identical distribution. This assumption is reasonable because, as explained above, the wholesale cost follows a behavior equal to $\varphi_{it}\mathrm{P}_t^w + (1-\varphi_{it})\mathrm{P}_t^c + \nu_{id} + \tau_{dt}$. Therefore, $\tilde{\varepsilon}$ does not capture any important or systematic elements.

Alternatively, the value of the estimated demand elasticity β_b is entered into the equation. The estimation, which is calculated for each department separately, has three steps:

1. For an initial value θ^*_{dt}, we rewrite Equation 7 as:

$$\mathrm{P^r} = \left(\frac{-\hat{\beta}}{-\hat{\beta}-\theta^*_{dt}s_{idt}}\right)\left[\varphi_{it}\mathrm{P}_t^w + \left(1-\varphi_{it}\right)\mathrm{P}_t^c + \nu_{id} + \tau_{dt} + \tilde{\varepsilon}_{idt}\right],$$

$$\left(\frac{-\hat{\beta}-\theta^*_{dt}s_{idt}}{-\hat{\beta}}\right)\mathrm{P^r} = \varphi_{it}\mathrm{P}_t^w + \left(1-\varphi_{it}\right)\mathrm{P}_t^c + \nu_{id} + \tau_{dt} + \tilde{\varepsilon}_{idt},$$

Defining

$$\widehat{\mathrm{F}}_{idt} \equiv \left(\frac{-\hat{\beta}-\theta^*_{dt}s_{idt}}{-\hat{\beta}}\right)\mathrm{P^r} - \varphi_{it}\mathrm{P}_t^w - \left(1-\varphi_{it}\right)\mathrm{P}_t^{c\,\prime}$$

we have:

$$\widehat{\mathrm{F}}_{idt} = \nu_{id} + \tau_{dt} + \tilde{\varepsilon}_{idt}$$

2. We estimate the following equation with OLS

$$\widehat{\mathrm{F}}_{idt} = \nu_{id} + \tau_{dt} + \tilde{\varepsilon}_{idt},$$

to obtain an estimate of $\tilde{\varepsilon}_{idt}$.

3. We organize $\tilde{\varepsilon}_{idt}$ into vector $\tilde{\varepsilon}_d$. We define $\boldsymbol{Z}_d = (\mathrm{W}, \boldsymbol{P}^{str}_{-d}, \mathrm{T}^{max}, \mathrm{T}^{min})$ as an instrument matrix. θ_{dt} solves the following problem

$$\min_{\{\boldsymbol{\theta}_d\}} q\left(\boldsymbol{\theta}_d\right) = \tilde{\boldsymbol{\varepsilon}}_d^{\mathrm{T}}\boldsymbol{Z}_d\boldsymbol{A}\boldsymbol{Z}_d^{\mathrm{T}}\tilde{\boldsymbol{\varepsilon}}_d.$$

where *W* is the aggregate water inflows of hydroelectric power plants in period *t* - 1, $\boldsymbol{P}^{str}_{-d}$ is the average retail price in markets other than *d* that belong to the same STR zone (north or south) in period *t*, T^{max} and T^{min} are monthly average maximum and minimum temperature in market *d* in period *t*. *A* is a matrix of weights.

We used bootstrapping to include noise in the estimation of elasticity ($\hat{\beta}$) and the estimation of the standard errors of $\hat{\theta}_{dt}$. We took 100 random samples of $\hat{\beta} \sim \mathrm{N}\left(\mu_\beta, \sigma^2_\beta\right)$ and calculated the estimated value of θ for each sample. We calculated the standard deviation of the 100 estimates for each coefficient. Additionally, the estimation of standard errors by bootstrapping is robust to the presence of heteroscedasticity and autocorrelation (Cameron and Trivedi, 2005; Horowitz, 1998).

4.3 Spot price formation

We must specify the stochastic process followed by spot prices to identify the effect of changes in climatic conditions on retail electricity price formation. For the prices of unregulated user contracts, Figure 3 shows that they have stable behavior over time and do not respond to the presence of adverse climatic events, such as El Niño. Thus, we do not consider it relevant to model the short-term response of contract prices to extreme weather events. In this work, we express changes in climatic conditions that involve meteorological phenomena like levels of water inflows from the rivers that feed hydroelectric power plants. The channel through which the weather affects retail electricity prices is wholesale costs. They are a function of the spot price, unregulated contract

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[7] The transmission and distribution charges of the northern zone, which includes the Colombian Caribbean departments, has differ from those of the rest of the country.

[8] Because that the February–March 2019 El Niño was short and did not have relevant effects on the hydroelectric generation, we considered it part of the standard conditions for the estimation of the model.

price, scarcity price and weights that retail firms assign to spot and contracts. Following Perez et al. (2022a) we modelled the average spot price P^w on day t as follows:

$$P_t^w = \gamma_0 + \gamma_1 D_t + \boldsymbol{z}_t^T \boldsymbol{\lambda} + w_t, \quad (8)$$

where D is the quotient between the GWh demand and aggregate level of water inflows from hydroelectric power plants converted to GWh. This quotient measures the importance of renewable energies in determining the spot price. When D is low, the possibility of meeting the demand with renewable energy is also low; thus, fossil fuel energies tend to determine the price. For a high D, thermal energies have little relevance in spot price formation. Vector z contains fuel prices, a measure of generator market concentration, available renewable energy concentration and the interactions between these variables with D. According to Perez et al. (2022a), this functional form captures nonlinear relationships between fundamental variables and spot price. Finally, w is a stochastic perturbation term.

4.4 Comments on the identification

The effect of extreme weather events on retail electricity prices can be analyzed based on Equations (6)-(8). When El Niño occurs, water inflows tend to decrease; thus, spot prices are expected to increase, which are transmitted to retail prices depending on retail firms' market power. El Niño weather pattern affects electricity demand through temperature increases that also increase residential users' electricity demand (e.g., increase in the use of air conditioners). However, in this study, we focused on unregulated users, namely large industrial and commercial consumers with an electricity demand that does not react to temperature increases and depends fundamentally on economic activities and prices of substitutes such as natural gas. If this assumption about the relationship between demand and temperature for large consumers is not valid, then the effect of the El Niño weather pattern on prices would be underestimated, as the price increase results from greater demand. Regarding the scarcity price, the regulator determines it exogenously depending on the behavior of the international price of Fuel Oil No. 6. Therefore, it does not directly respond to Colombian climatic conditions.

We assume that θ does not depend on market conditions. This assumption is reasonable because we are examining the case of a homogeneous product such as electricity. Different applied works have studied the electricity market using the quantity competition structure in a symmetric oligopoly (Bushnell et al., 2008; Wolfram, 1999; Mirza and Bergland, 2012; Duso and Szücs, 2017; Ribó-Pérez et al., 2019). Considering the assumption that θ is common among all firms in a market, we focused on the average behavior of prices in the market. Additionally, we contrasted whether θ varies between periods of normal weather conditions and El Niño. Firms' conjectural variations may vary between these periods because El Niño implies a strong shock to the availability of hydrological resources, the primary generation factor in the Colombian market. Therefore, firms could exploit these conditions to exercise market power.

5. Results

To estimate the demand model, for each market we calculated the monthly consumption of all unregulated industrial and commercial users. Then, we divided this total consumption by the number of users to obtain the average consumption per user and calculated the average retail price that users pay for electricity. Additionally, as controls for demand, we used the economic activity index and natural gas price. Figure 4 presents the time series data of the average consumption per user, average retail price, economic activity index and average price of natural gas for industrial and commercial users for the department of Antioquia. It was selected because it is relevant to the country's total demand. The average consumption per user showed a substantial change starting in 2017, from average levels greater than 260 MWh to average levels of 240 MWh. This change coincides with the upwards trend in average prices paid by unregulated electricity users. Furthermore, natural gas prices substantially increased in the last few years of our sample.

The average consumption series presents a seasonal behavior, captured by our variable, which measures economic activity. Additionally, the presence of the El Niño weather pattern does not lead to substantial changes in the average consumption per user or economic activity. Regarding the gas price, substantial increases are observed. However, this behavior has been observed before El Niño weather pattern. For the retail price, it substantially increased during El Niño and continued to increase after it.

From Figure 4, we can infer that variables of interest in the demand model are not stationary; therefore, the relationships estimated in Equation (6) are long-term. To corroborate this finding, we performed a panel unit root test and a cointegration test on the variables of interest. Table 2 presents the results of the Levin–Lin–Chu unit root tests and the Kao and Pedroni panel cointegration test. The Levin–Lin–Chu test has a null hypothesis that panels contain unit roots, whereas Kao and Pedroni tests state that no cointegration exists in any panel, and the alternative is cointegration in all panels. Regarding stationarity, we tested several lags of the series and found evidence that the unit root hypothesis cannot be rejected in the panels at the 5% significance for all variables of interest, except temperature measures. Furthermore, the null hypothesis for the Kao and Pedroni tests is rejected, thus providing evidence of cointegration in all panels.

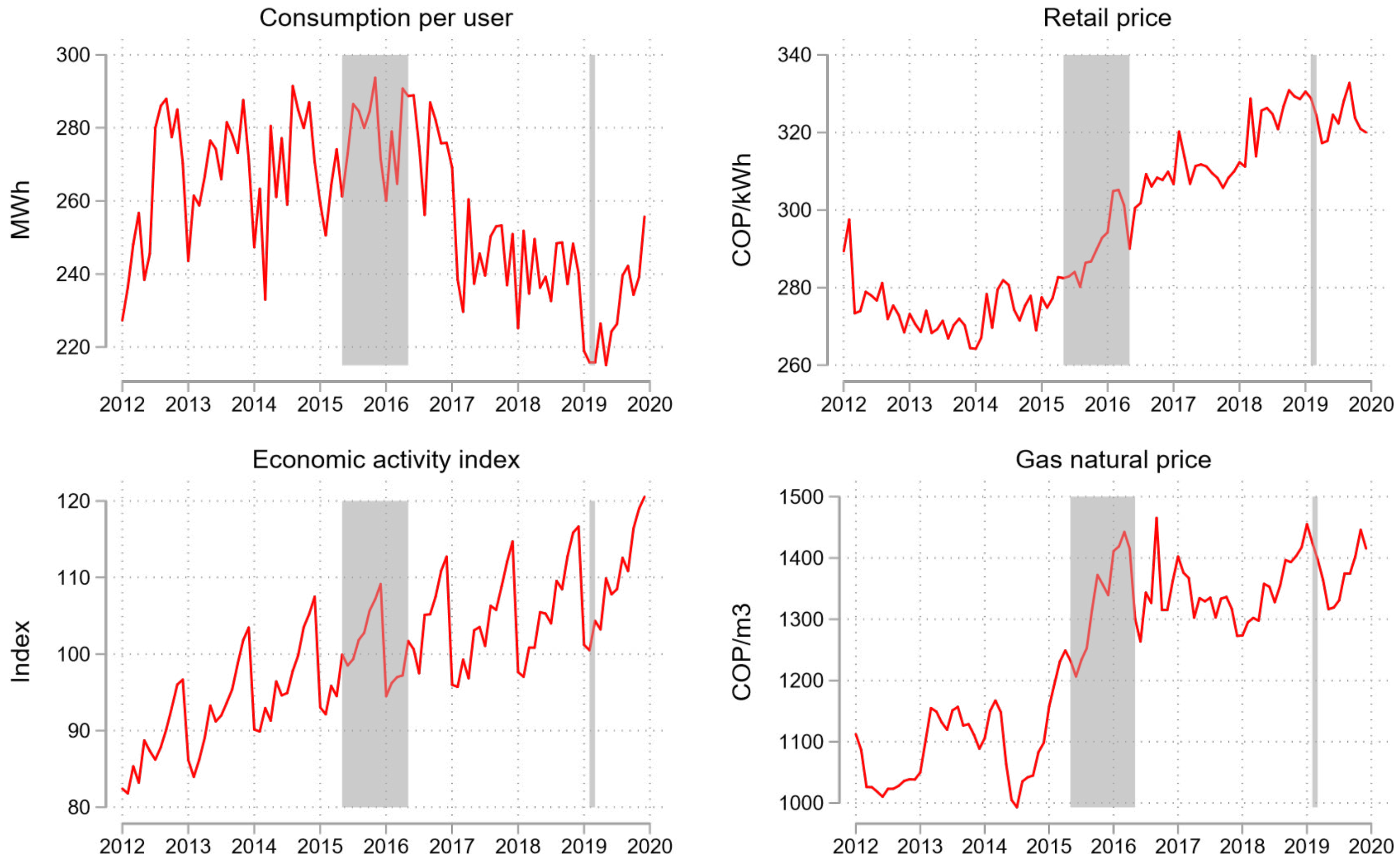


Figure 4. Variables for the demand model (Antioquia market).
Source: own elaboration based on Superservicios and DANE.

Table 2. Panel unit-roots and cointegration tests.

Panel Levin-Lin-Chu Unit-Root tests: p-value				
Lags	**1**	**2**	**3**	**4**
Consumption per user	0.000	0.062	0.1544	0.4711
Retail price	0.000	0.0010	0.0383	0.1578
MPI	0.000	0.000	0.000	0.4805
Price of gas	0.0016	0.0109	0.0572	0.0816
Max temperature (day)	0.000	0.000	0.000	0.0014
Min temperature (night)	0.000	0.000	0.000	0.000
Panel Cointegration tests				
			Statistic	**p-value**
Kao: Modified DF			-7.8652	0.0000
Kao: DF			-6.6496	0.0000
Kao: Augmented DF			-2.3941	0.0083
Pedroni: Modified DF			-6.4533	0.0000
Pedroni: Augmented DF			-9.7029	0.0000
Pedroni: PP			-10.2687	0.0000

Note: DF is Dickey-Fuller, PP is Phillips-Perron.
Source: own elaboration

Table 3 presents the OLS and IV estimation results of the demand model. For the IV, we take the aggregate level of water inflows (in logs) to the system's plants from the previous month as a price instrument (in logs). We considered additional lags of the aggregate level of water inflows, but only the first lag was relevant. This is explained by the rule of retail price formation in identity 1. Regarding the demand model estimation results, evidence indicates a positive relationship among consumption per user, level of economic activity, and natural gas price. These signs are expected because greater economic activity motivates electricity consumption and a high natural gas price leads to greater electricity consumption on average. However, the relationship with natural gas prices is not significant. Regarding temperature measures, we found evidence that electricity consumption increases with maximum and minimum temperature, that is, an increase in temperature during day or night implies an increase in electricity consumption by users.

The coefficient of interest is the elasticity of demand. Table 3 shows that the OLS and IV estimates of this parameter are -1.046 and -0.727, respectively, which are both significant. The weak identification test gives a value of 28.318(>10); thus, the hypothesis stating that the instrument is weak is rejected. Other authors have obtained estimates of the elasticity of demand with values close to our point estimate. Barrientos et al. (2018) showed evidence that demand is inelastic for various sectors within the Colombian industry, and Acuña et al. (2013) presented a complete summary of the different estimated values of the elasticity of demand for Colombia, finding a consensus on inelastic demand. Acuña et al. (2013) found short-and long-term estimates of the elasticity of industry demand at -0.475 and -0.905, respectively. The long-term value is similar to ours. Csereklyei (2020) found international evidence for the European Union markets. The author estimated the elasticity of demand for residential and industrial users. The long-term price elasticity of residential and industrial electricity consumption is estimated between -0.53 and -0.56 and between -0.75 and -1.01, respectively.

Table 3. Estimation results for the demand model

	(1)	(2)
	Consumption per user	
	OLS	IV
Retail price	-1.046***	-0.727*
	(0.278)	(0.380)
Economic activity index	0.576***	0.576***
	(0.0668)	(0.100)
Price of gas	0.237	0.227
	(0.167)	(0.173)
Max temperature (day)	0.824***	0.644***
	(0.150)	(0.218)
Min temperature (night)	0.607***	0.655***
	(0.198)	(0.192)
Weak identification test		28.318
Observations	1,680	1,660
R-squared	0.880	

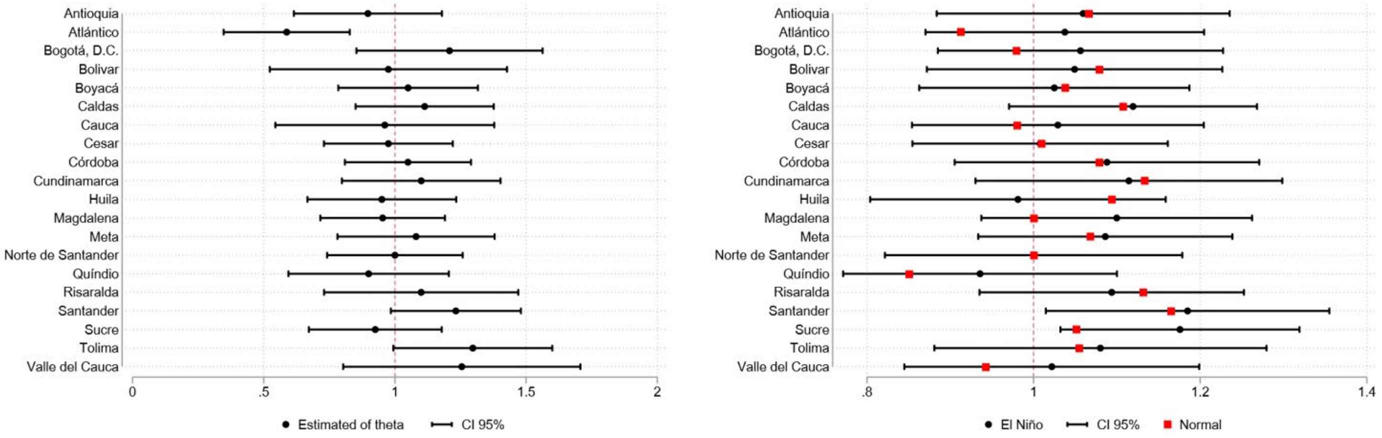
Note: Standard errors with cluster by market are presented in parentheses. Variables included in the model are in logs. We included fixed effects by department and year. We instrumented the electricity retail price (in logs) with the aggregate water inflows (in logs) for the previous month. We used the Kleibergen–Paap rk Wald F as the weak identification test. *** p<0.01, ** p<0.05, * p<0.1.
Source: own elaboration.

We can obtain estimates of the vector θ from the point estimate of the demand elasticity. Figure 5 presents results for two specifications. Specification 1 (baseline) assumes that θ does not vary over time or between firms but only between markets. Specification 2 assumes that θ varies between periods of normal weather conditions and El Niño. For the baseline model, we present the estimated value of θ, along with the 95% confidence interval. We find evidence that firms tend to charge prices above their marginal costs, implying that firms exercise market power on average. We also found a high degree of heterogeneity in the estimated values of θ, with values ranging [0.5,1.5]. The hypothesis test θ = 1 for symmetric oligopoly behavior is not rejected for 19 of the 20 markets at 5%, respectively. It is rejected for the Atlántico market. Specification 2 presents the estimated value of θ^{Nino} and its confidence interval and the estimated value of θ^{Normal}. Results indicate no significant differences between the values of θ for normal weather conditions or El Niño. This evidence indicates that firms do not maintain a different level of market power during El Niño and, therefore, do not alter their profit margins depending on its occurrence.

From the estimated values of θ, we can estimate the firms' profit margins following the expression $\frac{-\hat{\beta}}{-\hat{\beta}-\theta s_i}$. For the study period, we found that margins per market have an average value of 19%, with a median of 17%. Similar results for the regulated user market were found by Correa-Giraldo et al. (2021). They showed that firms tend to have a pass-through greater than unity, which may be associated with their market power. Authors found that in the face of a cost shock of 1%, firms increase their final prices by 1.15% on average; that is, they maintain a 15% profit margin on average.

The implication that retail firms have control over the pass-through of wholesale costs to prices is that cost shocks are completely transmitted to retail prices. However, we find no evidence that firms' behavior differs between periods with normal weather conditions and El Niño, except for one of the 20 markets. These results indicate that the impact of extreme weather events on retail prices can be understood by studying the response of wholesale costs exclusively, without focusing on changes in retail firms' strategic behavior.

For the model estimation of the response of spot prices to their fundamentals and the presence of El Niño, we present the results of Perez et al. (2022a) in Table A1 of the Appendix. Those authors found that high levels of water inflow, keeping demand constant, imply low spot prices on average. Similarly, the scarcity of hydrological resources, keeping the demand



(a) Baseline

(b) Normal weather condition vs El Niño

Figure 5. Estimated values of θ.
Source: own elaboration.

level constant, implies high spot prices. We used these results to simulate spot prices under normal weather conditions and El Niño weather pattern and used them as inputs for the scenario we propose in the following section.

5.1 El Niño weather pattern

Climate patterns such as El Niño impact electricity price formation through their direct effect on water inflow levels. We assume that other price fundamentals, such as fuel prices, do not vary with changes in weather conditions. This assumption is reasonable in the short term but not in the long term, particularly when considering factors such as climate change. In Colombia, the availability of NCRE is limited. Therefore, the effect of extreme weather events, such as El Niño on the availability of solar radiation or wind will have almost no impact on electricity price formation. Thus, we only focused on the relationship between water inflows and extreme weather events.

To study how El Niño affects water inflows, we estimated the relationship between the aggregate level of water inflows that supply hydroelectric power plants and the MEI of NOAA (2022). We applied a broader time window covering 2005-2019 to estimate the effects of La Niña and El Niño on water inflow levels. Figure 6 illustrates water inflow levels in logs and the periods of El Niño and La Niña in grey and blue bands, respectively. This series shows stationary behavior over time and seasonality that tends to be monthly. Results of the Dickey–Fuller (DF) unit root test on the residuals from the regression of water inflows on logs and fixed effects by month reject the null hypothesis of the unit root. Therefore, the series is stationary and seasonal monthly. Considering this evidence, this series has a constant mean over time, though this condition may be different during El Niño or La Niña.

Accordingly, variations in the aggregate level of water inflows in month *t* can be explained through El Niño or La Niña. To test this hypothesis, we estimated two specifications for the relationship between water inflows W_t and El Niño's and La Niña's presence. Specification 1 assumes that the relationship occurs between $\ln W_t$ and the monthly MEI value; specification 2 assumes that the relationship occurs between $\ln W_t$ and dummy variables that identify the presence of El Niño or La Niña. Specification 2 considers the nonlinearity of the relationship between $\ln W_t$ and the MEI.

$$\ln \mathrm{W_t} = \delta_0 + \delta_1 \mathrm{MEI_t} + \boldsymbol{\rho} + \mathrm{v_t} \quad \textit{(Specification 1)}, \qquad (9)$$

$$\ln \mathrm{W_t} = \delta_0 + \delta_1 \mathrm{Nino_t} + \delta_2 \mathrm{Nina_t} + \boldsymbol{\rho} + \mathrm{v_t} \quad \textit{(Specification 2)}. \qquad (10)$$

The parameter of interest is δ_1. It measures the percentage change in water inflows when the index increases by one unit (for specification 1) and the percentage change in the level of water inflows in the presence of El Niño (MEI > 0.5) and La Niña (MEI < -0.5) (for specification 2). To control seasonality, ρ is set as month and year fixed effects. These specifications allowed us to estimate the average level of water inflows under three scenarios: normal conditions, El Niño and La Niña.

Table 4 presents the OLS estimation results of Equations (9) (column 1) and (10) (column 2). Both specifications show the expected relationships. An increase in the MEI implies a decrease in water inflow. When the MEI is 0.5, 1, and 1.5, the predicted drop in water inflow is 10%, 21% and 33%, respectively. Specification 2 shows that water inflow tended to decrease by 23% on average ($\exp[\delta_1] - 1$) during El Niño,

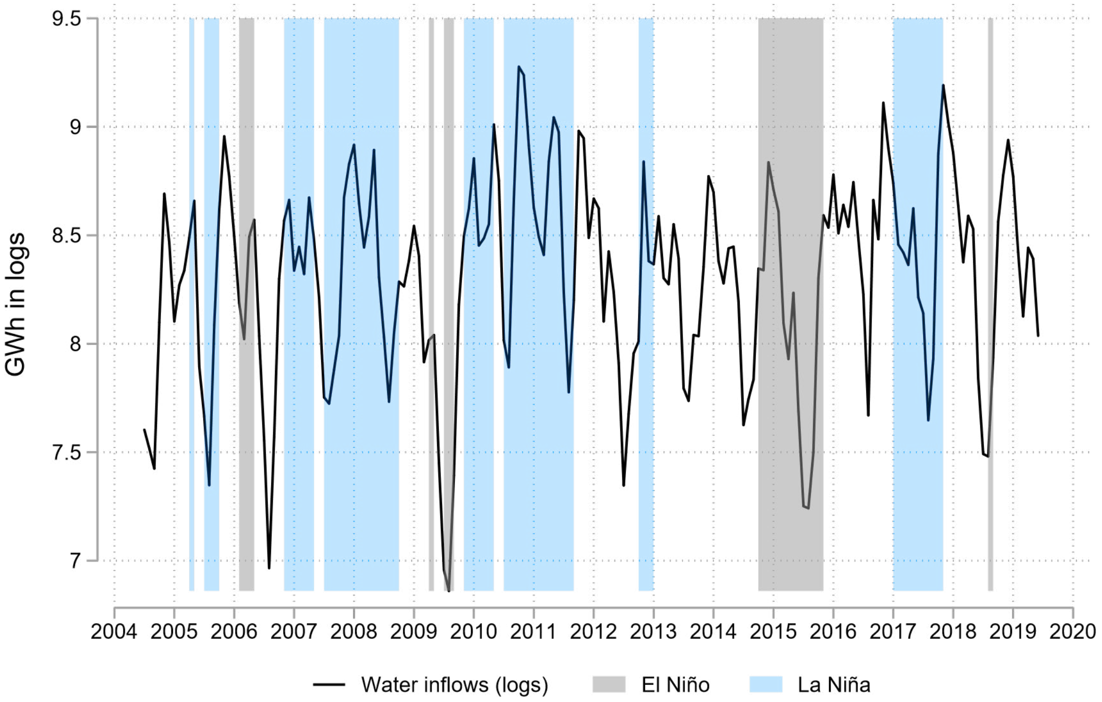


Figure 6. Aggregated water inflow levels for hydroelectric power plants converted to GWh (in logs).
Source: own elaboration based on XM.

relative to normal conditions. These calculations show that water inflow to hydroelectric power plants can substantially decrease by more than 20% during a strong El Niño. Finally, we found evidence that La Niña tends to increase water inflow. However, the magnitude of this effect is considerably smaller than El Niño's impact. For simplicity, we used specification 2 for the following exercises because e it allowed us to capture non-linearities between $\ln W_t$ and El Niño weather pattern.

Table 4. Water inflow and El Niño

	(1)	(2)
	Water inflows	**Water inflows**
MEI	-0.192***	
	(0.0294)	
Niño		-0.207***
		(0.0661)
Niña		0.0947*
		(0.0524)
Observations	180	180
R-squared	0.795	0.765

Note: Robust standard errors are in parentheses. Water inflows are measured in GWh, and we take the logs. All regressions include months and year fixed effects. *** p<0.01, ** p<0.05, * p<0.1.
Source: own elaboration.

Given that $D \equiv demand/W$ in Equation (8), from (10), we can estimate the impact of electricity associated with the presence of El Niño on the spot price. The estimation results of Equation (10) allowed us to predict the average water inflow level for 2019 under normal weather conditions and in the presence of El Niño. Subsequently, using the estimation results of Equation (8), we predicted the average spot price under normal weather conditions and in the presence of El Niño. Otherwise, we estimated the average spot price in 2019 using the observed average water inflows of that year and when these values are 23% lower. The effect of reduced water inflow on retail prices is pass-through by firms' wholesale costs.

Wholesale costs are a function of the spot price, scarcity price, contract price, and the weights that firms assign to spot and contract purchases. For this scenario, we assume that scarcity price does not change between periods of normal weather conditions and El Niño because its formation depends on international fuel prices. We assume that the weights that firms assign to spot purchases and contracts do not change between periods of normal weather conditions and El Niño. Under these assumptions, we used the estimation results of Equation (7) to evaluate how retail prices respond to El Niño. We considered the demand elasticity (ß) and transmission, distribution and other charges established by regulation (τ) as fixed. Similarly, the market share of retail firms are fixed (*s*). Under these assumptions, we calculated the average values for 2019 wholesale costs for each firm in each market under normal weather conditions and in the presence of El Niño. Finally, following Equation 7, we calculated the average values of 2019 retail prices in each market under normal weather conditions and in the presence of El Niño. Figure 7 summarizes the results of this exercise. At the top, we show a table summarizing results for the spot price, and at the bottom, results for retail prices. We present average price levels, along with the percentage change between normal conditions and El Niño at the top of the bars. Blue and red bars represent the average retail price by market and in the presence of El Niño, respectively.

Under normal conditions, the average spot price in 2019 was 199.21 COP/kWh. In the presence of El Niño, we estimate that the average spot price would increase to 237.55 COP/kWh; that is, 19.24% higher. Regarding the scarcity price, it was 525.45 COP/kWh on average, much higher than the average level of spot prices with and without El Niño. Concerning retail prices, we present the results at the market level. Under normal conditions, retail electricity prices were between 275 and 415 COP/kWh. In the scenario of El Niño, these prices increase between 0.9% and 3.9%. As expected, the increase in retail prices is more significant in those markets where firms are more exposed to spot market purchases, such as Sucre, Caldas, Cesar, Quindío, Meta, Bolívar, and Bogotá D.C. (see Table 1).

6. Conclusions

We examined the effect of extreme weather events on retail electricity prices in Colombia using data from unregulated electricity users, namely large industrial and commercial consumers. These users openly negotiate the generation and commercialization components of retail prices with their retailers. We focused on the El Niño weather pattern notably affecting electricity prices and developed a structural competition model for retail firms. Weather events affect retail prices, particularly electricity spot prices, through wholesale electricity supply costs. To model the response of the spot price to El Niño, we followed the strategy of Perez et al. (2022a). It studies how water inflows that feed hydroelectric power plants respond to El Niño as well as how the spot prices respond to this variation in water inflows. Finally, we analyzed how variations in wholesale costs are passed through to retail prices.

Results of the structural competition model show no differences in firms' degree of market power between periods with normal weather conditions and El Niño. Therefore, in the most relevant markets, El Niño affects retail prices exclusively through the retail firms' response to spot price increases and not to market power variations. Furthermore, we found that retail firms control the pass-through of wholesale cost shocks to retail prices. This evidence indicates that retail firms operate under conditions that do not match model predictions for a competitive market. Accordingly, retail firms tend to pass through a cost shock more than completely to the retail prices of unregulated users.

We examined the response of retail prices in 2019 during El Niño. A strong and extensive El Niño weather pattern was recorded between 2015 and 2016 but not in

	Normal conditions	El Niño	%
Scarcity price	525,45	525,45	-
Spot price	199,21	237,55	19,24

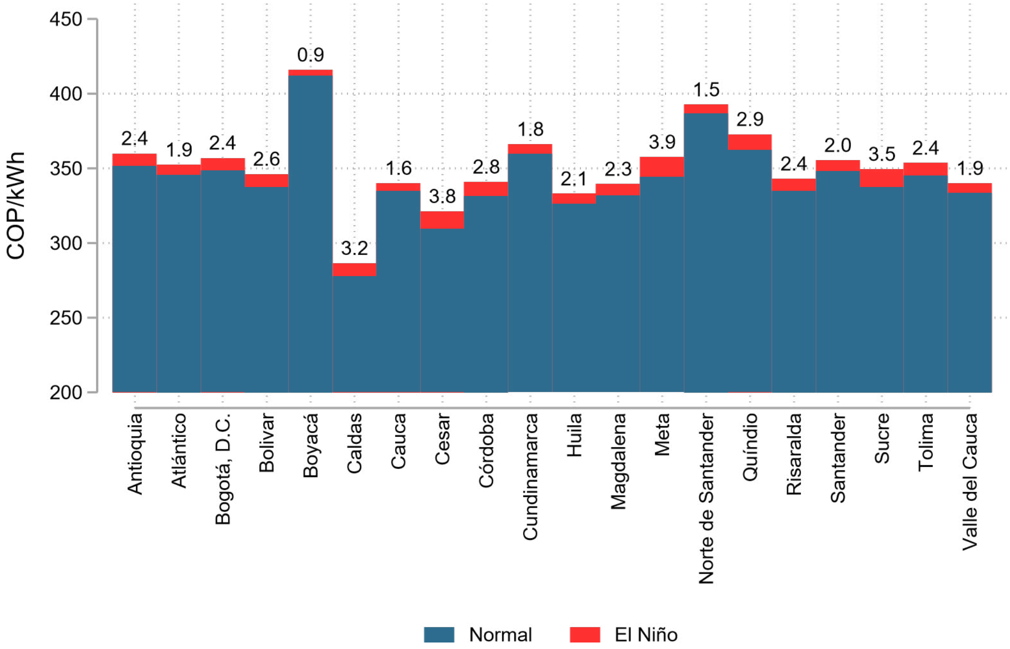


Figure 7. Retail prices: Counterfactual analysis with El Niño.
Source: own elaboration.

2019. To study its effect on retail prices, we developed a three-part strategy for analyzing (1) how the water inflows of hydroelectric power plants respond to the presence of El Niño; (2) how water inflow changes affect the electricity spot price; and (3) how spot price changes are passed through to retail prices in the market. Results reveal that El Niño implies a 23% reduction in the aggregate average level of water inflow. This drop implies an average of 19.2% increase in spot prices for 2019. Subsequently, retail prices increased between 0.9% and 3.9%.

We highlight two policy implications for our results. First, no evidence supports differentiated regulation under normal conditions or under El Niño. This implies that policymakers should not worry that firms are playing differently under El Niño and should focus on how to prevent the marginal costs of generating plants from increasing substantially. This brings us to the second policy recommendation: to support greater inclusion of NCRE. These types of technologies allow for supporting hydroelectric generation in drought conditions. However, this greater inclusion of NCRE must be accompanied by a more significant generation of natural gas to provide resilience to the system due to the intermittency of these non-conventional sources.

This work has various limitations, mainly the impossibility of observing the prices of the contracts established between generating and retail firms. The evidence we collected showed that the wholesale cost of the firms we built with data available allowed us to capture the development of retail prices. This wholesale cost is measured as the weighted average between spot and contract prices. However, because the contract prices reported are the average values among all firms, the degree of heterogeneity of the response of contract prices to El Niño cannot be determined. Finally, our evidence explains the short-term effects of extreme weather events on retail prices. Future research can focus on studying the long-term effects relevant to the conduct of climate policy in developed and developing countries.

Conflict of interest

The authors declare no conflict of interest.

Statement on the Use of AI

The authors declare that they used generative artificial intelligence (AI) tools solely as support in the manuscript writing process. ChatGPT were used for writing suggestions, idea organization, and style editing. All content was subsequently reviewed, validated, and edited by the authors, who assume full responsibility for the accuracy, originality, and validity of the work presented.

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Appendix

Table A1. Spot price model results.

	(1)	(2)
	Spot Price	**Marginal Effects**
D	23.85	11.004***
	(24.20)	-1.093
Delta	343.9***	151.05***
	(103.4)	-53.115
Dxdelta	-43.06*	
	(22.52)	
Nino	480.5***	
	(10.54)	
HHI	456.2	456.05
	(340.4)	(340.39)
Gas	111.2***	40.297***
	-8.026	-4.208
DxGas	-15.82***	
	-1.763	
Coal	-6.559***	-3.858***
	(0.616)	(0.341)
DxCoal	0.603***	
	(0.0940)	
Brent	0.670	2.011***
	(0.494)	(0.222)
DxBrent	0.299***	
	(0.0913)	
EXR	0.0326	0.060***
	(0.0225)	(0.010)
DxEXR	0.00622	
	(0.00405)	
Constant	-356.8***	
	(127.8)	
Observations	2,922	2,922
R-squared	0.649	

Note: Robust standard errors are in parentheses. D is the quotient between the demand and the aggregate level of water inflows. ER is renewable energy by its Spanish acronym. HHI is a measure of market concentration constructed from the declared availabilities of the plants operated by firms.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Source: Perez et al. (2022a).