Agent-based simulation to model the formation of the Spot price in the Colombian electricity market with the inclusion of non-conventional renewable energies.

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Abstract

The inclusion of renewable energies is a relevant issue nowadays which is influenced by multiple factors such as the strategic behavior of agents, the climate since the main source of generation is hydraulic, and the high cost of production since it supposes great barriers to entry into the market. Here, we adopt an agent-based approach to model the change that is generated in the decision-making of generating companies in the Colombian electricity sector by including non-conventional renewable sources and we assess the impact on the spot price. The results show that by including these sources the price decreases and presents greater variation.
Keywords: wholesale electricity market, non-conventional renewables energies, Agent-Based modelling, strategic behavior, spot price.

1 Introduction

The Wholesale Electricity Market in Colombia has been an important focus of research due to its high impact on the economy. This is a highly complex market as it includes a short-term market, a long-term market, and complementary services to satisfy the demand in real-time and international transactions (García *et al.*, 2015). The short-term market or spot market structure in Colombia is divided into four: generation, transmission, distribution, and commercialization (CREG, 2017). In the generation activity, the generating companies sell energy to traders through the spot market or bilateral contracts. The amount of electricity that a plant can produce is measured by the installed capacity in that plant. In the transmission activity, electricity is transported through the National Transmission System. In the distribution activity, energy is transported locally to be distributed to consumption centers. Finally, the commercialization is the direct purchase of the marketers to generators in the Wholesale Electricity Market, to sell it to the end-users. This last activity comprises the retail level of the energy market (Perez & J.Garcia, 2021). An important characteristic of this market is its oligopolistic structure due to high fixed costs (Botero *et al.*, 2013). This factor drives participating agents' to strategize on pricing to maximize profits (Hurtado *et al.*, 2014). The market must be fully coordinated to maintain a balance between supply and demand. The entity in charge of this activity in Colombia is XM S.A. who coordinates the formation of the spot price by creating a supply curve where all the individual offers from the generators who present the quantity and the price established for the whole day are gathered together and the market operator organizes them from lowest to highest price. The market operator also creates a demand curve with established projections. With the graph ready, the spot price that corresponds to the last price offered that satisfies the demand is determined (García *et al.*, 2015). Energy is a homogeneous good with highly inelastic demand for the price, that is, it has little sensitivity to a change in price due to a high asymmetry in information since users know their consumption two months later (Martínez, 2017). Another important factor is the climate. The climatic phenomena of warming and droughts are known as El Niño, and cooling and rains known as La Niña affect electricity generation in Colombia. El Niño causes the levels of the reservoirs to fall, causing greater use of alternative energy than in the case of Colombia is thermal (Perez & J.Garcia, 2021). But since the supply of thermal energy is much lower, the spot price tends to increase due to the mismatch between supply and demand (García *et al.*, 2015).

The energy transition is another important aspect of the sector in recent years, and it arises due to the need to implement renewable energies and thereby reduce emissions and the carbon footprint, which has become an obligation rather than an option (IEA, 2016). In particular, the Colombian Government introduced Law 1715 (Ley de Energías Renovables or ER) in May

2014, which aims to "promote the development and use of non-conventional energy sources, mainly renewable, in the national energy system, integrating them in the electricity market, unconnected areas and other uses of energy" (Congreso de la República de Colombia, 2014). Non-conventional renewable energy sources are defined as the renewable energy resources available worldwide that are environmentally sustainable, but that is not used in the country or are used marginally and are not widely commercialized (Perez & J.Garcia, 2021). As mentioned above, this is a highly complex market and the inclusion of non-conventional renewable energies requires investments in expansion, improvement, updating, automation, and digitization of transmission and distribution networks (UPME, 2020a). In addition, an instantaneous equilibrium, a limited storage capacity of electricity, in combination with the intermittent nature of these energies, which further increases the complexity of the electrical system (Kraan *et al.*, 2018). To date, various investigations have been carried out on the Colombian market such as the investigation by Sandoval (2004) who analyzes the performance of the said market to date or Arango *et al.* (2008) who studies the Colombian market and makes a comparison with other countries. Bastidas *et al.* (2012) also study the formation of the spot price and market intelligence with the use of artificial intelligence and Perez & J.Garcia (2021) who evaluate the effect that the inclusion of non-conventional renewable sources may have in the Colombian wholesale electricity market. However, there has been little discussion about modeling strategic behavior of generators related to the use of non-conventional renewable energies in Colombia. This might be because it is a recent and quite complex topic that requires exhaustive research. Due to this, the need arises to assess the impact of incorporating non-conventional renewable energies in the spot price of the Colombian wholesale electricity market through Agent-Based Modeling and Simulation. Through agent-based simulation, we will contribute to the understanding of individual and strategic behavior in the bidding process, an aspect in which there is still uncertainty in the literature. Furthermore, this model could be adapted for other types of problems and environments and even other areas of knowledge. This work will generate fresh insight into modeling people's strategic behavior in the Colombian electricity market and will serve as a tool for decision-makers to experiment with different strategies that can help understand different aspects of the market. The study of strategies can offer a broader panorama of the Colombian electricity system and thus be able to improve its operation, in addition to contributing to the control of the operation that is so important for the optimal use of resources for the provision of electricity service.

This problem arises due to the need to integrate renewable sources to reduce emissions and the carbon footprint (IEA, 2016). In addition, the development of new sources of production and forms of energy consumption open possibilities for investment, human capital formation, research and development of new products that add value to the country's economy (UPME, 2020b). Also, the Wholesale Electricity Market in Colombia is a strategic sector that moves billions of pesos annually, becoming a great source of income in the economy (Hurtado et al., 2014). As already said, this is a complex system involving multiple factors that require rigorous study. Some of these factors are dependent on climatic conditions; the Colombian electricity market is highly dependent on hydraulic resources (Hurtado *et al.*, 2014). For this reason, in drought conditions such as in El Niño, the level of the reservoir decreases, decreasing the water contributions to the system and creating the need for alternative energy that in the case of Colombia is thermal. Still, the supply of thermal energy it is much lower (Perez & J.Garcia, 2021) thus affecting prices. Another factor is the low elasticity of its demand for price. The high cost of production is another factor, since it supposes great barriers to entry into the market, forming an oligopolistic structure (Botero *et al.*, 2013) that consequently makes agents act strategically seeking to maximize their benefits. Of course, the inclusion of non-conventional renewable energies is another aspect that makes the system more complex since these sources have a limited storage capacity, require an instantaneous balance, and have an intermittent nature, making them less attractive to generating companies.

It is therefore pertinent to use Agent-Based modeling to incorporate the variables mentioned in addition to the strategic behavior required in the wholesale electricity market and particularly in the formation of the spot price with different sources of electricity generation. Being able to incorporate many agents where each one has their strategies, the inclusion of variables for the climate, renewable energies and other variables of the economic theory involved in this system, make the agent-based simulation tool play a relevant role for the study of the spot price of energy. Furthermore, this type of simulation allows experimenting with different strategies, different generation technologies, among others.

The use of mathematical and econometric models plays an important role in the evaluation and control of the market operation, as well as for assessing the impact of some market variables on the energy price (Bastidas *et al.*, 2012; Galvis, 2011; Barrientos & Toro, 2017). Agent-based simulation has proven to be a powerful tool for modeling social or behavioral aspects in different areas. Therefore, it offers good opportunities for modeling different aspects of the social and strategic behavior of agents in the electricity market.

The paper is organized as follows. In the next section, the state of the art is presented with the main references related to the problem described here and information on the Colombian electricity market and the inclusion of non-conventional renewable energies. Next, the methodology with the ABM simulation approach is presented, followed by results for several strategic scenarios. Finally, the conclusions and future work are presented.

2 State of the art

The energy transition is a relevant issue today due to the high levels of pollution that are generated, global warming and the greenhouse effect, as well as the increase in the world population and the overcrowding of cities, have made it necessary to use sustainable and renewable energies that minimize the negative impact (ENEL, 2020). However, as Perez & J.Garcia (2021), explains, the designs of mechanisms and the establishment of regulatory principles will be necessary to guarantee good quality in the provision of the service, and demand response mechanisms will also play a fundamental role. This means that the energy transition is not simple. In this way, Gaviria *et al.* (2019), has carried out a study to understand the dynamics and policy for the diffusion of renewable energies in Colombia, in this study the importance of the incentives for the diffusion of renewable energies. The incentives they present are reduction of taxes, food rates, negotiable certificates, and technical subsidies; and four sources of renewable energy: small hydroelectric, biomass, wind, solar and geothermal. They conclude that incentives can boost the deployment of renewable energies, avoiding significant price increases for the final consumer. Gómez & Rendón (2020), also carried out an analysis of the incentives for the diffusion of renewable energies, particularly economic incentives in the installed capacity of photo-voltaic solar energy in Colombia. The study shows that the incentives make it possible to improve market mechanisms to make them more efficient. One of these incentives is auctions to finance investment in these generation sources. They present a real example of this incentive, which was the second auction held by the Ministry of Mines and Energy of Colombia (MME), in October 2019, for the execution of long-term contracts in Colombia. They conclude that incentives are a viable alternative for diversifying the country's energy sources and, therefore, guaranteeing supply reliability.

Multiple authors worldwide study the impact of incorporating new sources of electricity generation in the market using various tools for modeling and simulation. These studies focus mainly on the economic impact and the merit order effect, as Acemoglu *et al.* (2021), who evaluate how wholesale electricity markets operate with an oligopolistic structure. Their results show how the merit order effect develops, showing that the magnitude of this effect varies with the degree of diversification of the companies' portfolios and the ownership structure of existing renewable resources. This effect consists of the drop in the spot price in response to increases in the supply of generation with renewable technologies. This is due to a greater supply of electrical energy by generators with renewable sources, whose marginal cost is close to zero. This changes prices along the aggregate supply curve, so that market prices fall. Kaffine *et al.* (2013), study the impact of wind energy concerning the potential to reduce emissions associated with conventional electricity generation at Texas. The estimation strategy implicitly captures both the marginal unit of generation displaced by the wind in the power grid and the marginal reduction in emissions. The results show that greenhouse gas emissions offset by wind generation increases are substantial, but these environmental benefits do not cover the government subsidies for wind generation.

In particular, the spot price can be affected by power generation with non-conventional sources. Forrest & MacGill (2013), conducted an empirical study that uses a variety of econometric techniques to quantify the impacts of wind penetrations on the Australian National Electricity Market and how the growth of wind generation has caused a drop in the spot price and the displacement of conventional technologies in the country. The study of Bushnell & Novan (2018), also concludes that the spot price can be substantially affected by implementing renewable sources. They study the California market by estimating how wholesale electricity prices respond to a dramatic increase in utility-scale solar capacity. This impact on the average price masks a substantial decline in midday prices combined with an increase in the intermediate prices hours.

Research has also been carried out with evidence for Colombia on the impact of incorporating new sources of electricity generation in the market as Perez & J.Garcia (2021), in their study they seek to evaluate the effect that the inclusion of non-conventional renewable sources may have on the Colombian wholesale electricity market. To do this, they estimate a structural behavior model of the firm and evaluate a scenario in which a firm that operates with 1,000 MW of installed capacity is included to compete in the wholesale market during 2018. The results show that the spot price of electricity would decrease. This is due to the strategic behaviors of the firms and the order of merit effect. They also calculate that approximately 367.32 thousand metric tons of $CO2$ would stop being emitted into the environment. Another novel study for the Colombian case is that of Rueda *et al.* (2019), in which they analyze international actions that have motivated different countries to establish strategies to reduce $CO2$ and their advances and challenges in the implementation of offshore wind technology. or the study by Jimenez *et al.* (2016), in which they use system dynamics to examine the effect of policies on the diffusion of renewable energies, considering the diffusion of solar energy on rooftops with both a battery support system and without any kind of storage system. An important conclusion is that policy is essential for the sustainability of the system when photo-voltaic diffusion is carried out.

The main researchers that use Agent-Based Modeling and Simulation are characterized by including the strategies taken by different agents in the market. For example, Kraan *et al.* (2018), takes an agent-based approach to modeling investor decision-making in the power sector. They highlight that the dynamics adopted by investors are emergent properties of the evolving electricity system that result from their own behavior. They experiment with different coal price scenarios and find that incorporating heterogeneous investor behavior results in a large number of possible transition pathways and that the depth of penetration of renewables is correlated with the variability of their energy. power generation pattern. Additionally, they observed a counterintuitive trend, investor profits increasing with coal prices. Likewise, L.J. De Vries *et al.* (2013), who simulate climate and energy policies for the European market, using an agent-based modeling approach and also create a toolbox, called the Energy Modeling Laboratory (EMLab). The document briefly reviews the central challenges and approaches to shaping climate and energy policy in light of the energy transition. The study of Wittman (2008), shows that through agent-based simulation it is possible to represent the different decisions of the agents that participate in the market, through a rational choice model, taking into account the different perspectives of companies with respect to the future evolution of the market. In the study, they obtained diffusion curves for conversion technologies and efficiency improvements in the residential sector and calculated total energy savings. In addition, the impact of company competition on the diffusion curves was estimated and different business models were tested. As mentioned in previous research and as indicated by Weidlich & Veit (2008); Frank *et al.* (2007), Agent-Based Modeling and Simulation is a tool that allows you to model the electricity market realistically, as it includes rich and flexible modeling techniques that help to understand the dynamics of the market. Weidlich & Veit (2008), conduct a literature review that guides the way through this research area, critically discussing the shortcomings of existing approaches and open problems that should be addressed by electricity researchers.

3 Methodology

To achieve the objectives set out in this work, the first step was the definition of the problem, for this a literature review was carried out in order to review the use of Agent-Based modeling to represent people's behavior in electricity markets. The second step consisted of collecting the information necessary for the model through the free access platform of XM S.A. The data were obtained for the year 2019 and the exploration and organization of these were carried out in Excel. The next step was to make the conceptual model using an ODD protocol Grimm V (2006). This is a document that contains a formal and detailed description of the computational implementation, and an analysis of the information necessary for the implementation.

3.1 The electricity market in Colombia

In the Figure 1 the distribution of generation by type of resource for the year 2018 in Colombia is presented. We see that hydroelectric generation represents most of the generation followed by thermal generation and to a lesser extent the other technologies. The generation with non-conventional renewable energies (wind, solar, and biomass), represents less than 1% of the total generation. It is important to mention that the two dominant generation technologies, hydraulic and thermal, have serious negative external effects that affect social welfare. Hydraulic generation affects aquatic ecosystems and can represent a danger for people living downstream of reservoirs. Thermal generation involves the emission of greenhouse gases. Wind and solar generation are non-polluting technologies and the negative effects they can have are almost non-existent.

Resource	Participation(%)
Hydro	**82.17**
Thermal	**16.69**
Gas	11.16
Coal	5.34
Liquids	0.2
Co-generator	**1.06**
Bagasse	1.05
Biomass	0.01
Wind	**0.06**
Solar PV	**0.01**
Total	100.0

Figure 1: Percentage of participation of each type of energy resource for 2018 in Colombia.

3.2 Statement of the problem

The formal statement of the problem is presented in terms of systems theory. Based on Schmidt (2005).

The system to be modeled consists of the representation of the behavior of a generating agent in the Colombian electricity market. The system contains inputs, that depend on time and on each participating agent; states that describe the current state of the system; a process, that includes a transfer function and an output function; and the output that is the spot price at each time step. The output affects the environment and with it the inputs, generating feedback in the system. The transfer function determines the behaviors to be followed, and the output function determines the spot price through the information obtained in the process. The Figure 2 exemplifies it graphically.

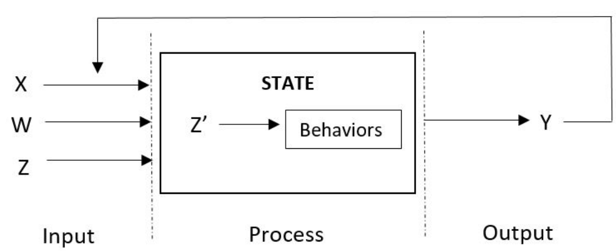

Figure 2: System diagram

Formally, the system is described in terms of 8 variables: $(T, X, W, Z, Z', F, G, Y)$

- T Set of time values
- X Set of agent-dependent inputs
- W Set of time-dependent inputs
- Z Set of initial state variables
- Z' Set of internal state variables
- F State transfer function, $F : (TxZxXxW) \rightarrow Z'$

- G Output function, $G : (TxXxWxZ') \rightarrow Y$
- Y Set of outputs

The input X_i, are the generation costs according to the energy source used by agent i

The input W_t, represents the energy demand at time t.

The initial state Z_i is made up of the different characteristics that agent i can present in the market, such as its generation capacity (capacity in kwt....... of energy), the types of sources it uses (hydroelectric, thermal, solar, etc.), whether or not it participates in the market at a specific time.

The internal state $Z'i$ is the update of the initial state after having gone through the‘ process ’.

In the ‘process’ actions are carried out by means of the F function that updates the state of each agent and according to the new state, this agent acquires different behaviors.

The transfer function F, transforms the inputs and the initial states of the agents through a process in which the behaviors to be followed are defined. Therefore, we have:

$$z'(t_{n+1}) = F(t_{n+1}, z(t_{n+1}), x(tn + 1), w(t_{n+1})) \tag{1}$$

The output Yt is the spot price of the energy at time t.

The output function G, determines the way in which the new internal state of the agent, described by the inputs $x(t_n)$ and $w(t_n)$, and the state variables $z'(t_{n+1})$, is transformed into an externally observable output $y(t_{n+1})$.

$$y(t_{n+1}) = G(t_{n+1}, x(t_{n+1}), w(t_{n+1}), z'(t_{n+1})) \tag{2}$$

3.3 ODD protocol

3.3.1 Purpose

The purpose of the project is to assess the impact of incorporating non-conventional renewable energies in the spot price of the Colombian wholesale electricity market through Agent-Based Modeling and Simulation. In this project, a conceptual approach has been adopted to identify the minimum set of agent types, behavior rules, and assumptions that could replicate the fundamental dynamics of the transition to non-conventional renewable sources.

The model is based on the research of Bower & Bunn (2000), and on the ODD protocol of Kraan *et al.* (2018). The research of Bower & Bunn (2000), consists of an economic environment (market), populated by agents (generating companies) that are individually represented with their own unique stock of assets, skills, knowledge and behavioral routines. This model is an adaptation to the Colombian electricity system, with which it is intended to introduce non-conventional renewable energies and important aspects of the market such as the strategic behavior of the agents, the climate, and other specific characteristics that are given by the geography of the country. This in order to expand existing research on renewable energy and its effect on the Colombian market, in addition to being able to contribute to the control of the electricity operation in Colombia.

The project aims to simulate the behavior of energy-producing agents when incorporating non-conventional renewable energies, represent the decisions that these agents make to choose their bidding prices, and with these obtain the spot price against different scenarios. It is also intended to incorporate the market feedback that arises from the incorporation of different strategies by the agents to improve their bidding decisions as they learn from the experience acquired through their interaction with the environment. Each agent represents a company that has multiple plants, each one with different ways of generating energy and therefore with different bidding prices that they can choose from considering the profits obtained with each election. In this way, the agent is programmed to change his choice in order to try other alternatives and learn from past choices so that his next choice will have a better result.

We evaluate the model for its ability to reproduce some patterns of behavior in the electricity market. As it is an oligopolistic market, companies have a competitive behavior, so that the patterns of energy generating agents are based on two objectives: increase their own global profitability, from one period to another, and reach a target utilization rate in your plant portfolio in each period. To achieve these goals, agents can follow a "price increase" strategy, adding a percentage to the offers they submitted the previous trading day, or a "price reduction" strategy, subtracting a percentage. In addition, the electricity market has focused on the merit order effect Figueiredo & da Silva (2019); Tveten *et al.* (2013); Woo *et al.* (2016) which consists of the fall in the spot price in response to increases in the supply of generation with renewable technologies. This is due to a greater supply of electricity by generators with renewable sources, whose marginal cost is close to zero, thus changing the price curve and the behavior of the market in general Perez & J.Garcia (2021), thus becoming a fundamental pattern to evaluate.

The agents also exhibit the following behaviors:

- Mutation: agents can select randomly from an infinite set of potential bidding strategies which they could potentially follow through time;
- Feedback: agents can observe the results of their bidding strategies;
- Selection: agents can measure the success of their bidding strategies against both a profit and capacity utilization benchmark, then repeating any successful strategies; and
- Competition: agents continually respond to the competitive behavior of other agents.

3.3.2 Entities, state variables, and scales

The model has three types of entities: generating firms, the market, and the observer or global environment.

Generating companies, are made up of multiple power plants, which together will be called "portfolio of plants." Each plant has a different generation form. According to XM Compañía Expertos en Mercados S.A, the 6 most relevant electricity generating firms in Colombia are modeled due to their high degree of market participation, and the other firms are joined together to form a seventh firm. These are shown in Table 1, where the number of each type of plant that the firms have is presented. Thermal plants refer to types of thermal generation that are neither coal nor gas.

Agents use simple internal decision rules, summarized in Table 2, that allow them to "discover" and "learn" strategic solutions that meet their profit and market share objectives over time. This allows the agent to search and explore successful bidding strategies while discarding failed strategies. As a result, the behavior of the simulated market is almost completely emergent, since it is created endogenously by the aggregate interaction between agents and their environment. The agents have knowledge of their own plants and capture information from the environment, but only regarding their own earnings, they do not have information from the other agents.

The agent's strategies can be: increase prices by adding a percentage to the offers they presented the previous trading day; or reduce prices by subtracting a percentage. For each agent, a target minimum utilization rate is assigned for its portfolio of plants, which depends on the number of plants it has. This utilization rate is created in order for firms or agents to behave strategically with respect to their prices and seek greater participation in the market as happens in real life. If an agent does not reach its target utilization rate on the previous trading day, then it lowers the offer price by all of its prices for the current trading day. This does not prevent the agent from continuing to explore strategies as the target utilization rate is added to the agent's portfolio and not to a specific plant. As the simulation progresses, the agents seek to meet their profit target taking into account the previous days. When an agent manages to increase his profit, another agent suffers a decrease, then he must change his strategy so as not to continue losing money, when he manages to find a better strategy, another agent will be affected and must change his strategy, thus creating a competitive environment.

The market, is the entity in charge of selecting the plants necessary to supply the expected energy demand at each hour of the day. The market organizes the prices of the plants from lowest to highest and selects one by one until the demand is met.

The observer, is a single entity that represents the global environment in which it is found. Control global variables such as time and demand. For this, a discrete-time step is used where each step represents one hour and the simulations are run for a year since this time period covers the two types of climate that affect power generation in Colombia, which are El Niño (drought) or La Niña (heavy rains) see Figure 4.

Each generation technology is modeled as a group, for example, hydroelectric plants make up one group, and coal plants make up another, but all plants have the same attributes that distinguish them from each other. These attributes are the generation cost, measured in weight per kilowatt-hour ($ / kWh), the amount of energy it can generate in kWh, and the offer price with a Colombian peso unit ($).

Firm	**Plants**
Firm 0	Hydroelectric (36), thermal (2), coal (2), gas (2), wind (1).
Firm 1	Hydroelectric (18), thermal (3), coal (4), gas (1).
Firm 2	Hydroelectric (14), thermal (3), coal (1), gas (2), solar (1).
Firm 3	Hydroelectric (15).
Firm 4	Hydroelectric (6), thermal (1).
Firm 5	Hydroelectric (8).
Firm 6	Hydroelectric (47), thermal (18), coal (11), gas (15), solar (1).

Table 1: Number of plants of each type

3.3.3 Process overview and scheduling

The model is developed to represent the auctions of the wholesale electricity market in Colombia. It is structured in four processes: an initialization process to establish the variables of demand (according to the time in which it is) and climate (according to the month), and the variables of each plant (amount, costs, and offer price). In the election process, each agent chooses their bid prices for each plant and every hour of the day. In the market process, the plants necessary to supply the demand are determined and finally, in the search process, the agents look at their profitability obtained and thus adjust your next offers.

At the beginning of the simulation, the time variables are initialized: 'hour', 'day', and 'month'. The 'hour' will serve to assign the demand as shown in the Figure 3, the 'day' is used for the plants

Rule 1. Self-awareness
Agents receive feedback data from their own trading activities for the previous trading days: i) portfolio rate utilization; ii) portfolio target utilization; iii) plant profit; iv) portfolio profit.
Rule 2: Information restrictions
Agents do not know the past, current, or future, actions of other agents or the state of the market
Rule 3: Objective functions
Agents have common objectives for each new trading day which are to achieve: i) at least their target rate of utilization for their own plant portfolio; and ii) a higher profit on their own plant portfolio than for the previous trading day.
Rule 4: Strategy selection
Agents submit bid price(s) for each plant in their portfolio, at the beginning of the current trading day, using decision criteria in the following order of precedence: i) if the target rate of utilization was not reached across the portfolio, on the previous trading day, then randomly subtract a percentage from the previous day bid price for each plant in the portfolio ii) if any plant sold output for a lower price than other plants across the portfolio, on previous trading day, then raise the bid price of that plant to the next highest bid price submitted; iii) if total profit did not increase across the portfolio, on the previous trading day, then randomly add a percentage from the previous day bid price for each plant in the portfolio; and iv) if profit and utilization objectives were achieved across the portfolio, on the previous trading day, then repeat the previous trading day decision.

Table 2: Rules that define the behavior of agents.

to make their offers per day, and the 'month' will serve to assign the weather as shown in the Figure 4. Then the amount, costs, initial offer, target profit, and target utilization rate are established. This is the initialization process. Then, in the election process, agents must submit their initial offers. Each agent presents 24 offers (one for each hour of the day), for each of its plants, that is, if an agent has 4 plants it must present 96 offers. We assume that the plant offers all its available capacity. In the market process, the bids of all the plants are organized from lowest to highest (order of merit) for each hour of the day, assigning the demand to the plants, so that the lowest value is chosen between the amount required and the capacity available, this so that when the last required plant is reached, only the amount required is paid and not all its available capacity. In the search process, the agents have already made their offers and already know the benefit obtained, so with this information they must decide whether to raise or lower their prices. In deciding, the agents also consider their minimum target utilization rate. If the agent did not achieve its rate the day before then it reduces the supply price in all its plants for the next trading day. This target utilization rate applies to the entire agent's portfolio and not to each plant. Each agent continually updates their profit target as the simulation progresses, always using the prior trading day's profit as a benchmark against which to compare the current day's profit. The results of the auction, that is, the earnings of each agent are calculated simultaneously, for 24 hours, at the end of the trading day.

All actions occur in the same default order:

1. Initialization process: The time and climate variables are updated, with this also the demand, the amount, costs, initial offer, target profit, and target utilization rate are established. The time includes the variable 'hour' that is updated in each time step until it reach-es 23, the variable 'day' that is updated every 23 hours, and the variable 'month' that is up-dated every 30 days.

2. Election process: each agent makes its offers for each plant.

3. Market process: the supplies are organized from lowest to highest for the respective hour of day and the required quantities are selected until the demand is satisfied. The benefit obtained from each plant for the hour is calculated, that is, the quantity supplied multi-plied by the last supply price in the round. This process is done 24 hours a day.

4. Search process: This process is done for every day (24 hours) and not for every time step (every hour). The benefits obtained in each hour are added to obtain the daily benefit obtained. It is verified if the target profit and the target utilization rate were reached in the entire portfolio, if this was not achieved, the strategy used must be changed. If the objectives were achieved, the same strategy continues.

Hour	Type of demand	Hour	Type of demand
0	Low demand	12	High demand
1	Low demand	13	Medium demand
2	Low demand	14	Medium demand
3	Low demand	15	Medium demand
4	Medium demand	16	Medium demand
5	Medium demand	17	Medium demand
6	Medium demand	18	High demand
7	Medium demand	19	High demand
8	Medium demand	20	High demand
9	High demand	21	High demand
10	High demand	22	Medium demand
11	High demand	23	Medium demand

Figure 3: Type of demand according to the hour in Colombia

3.3.4 Design concepts

Basic principles. This model aims to evaluate the impact of incorporating non-conventional renewable energies in the spot price of the Colombian wholesale electricity market. The model is based on

Month	Climate	Month	Climate	Month	Climate
January	Niño	May	**Niña**	September	**Niña**
February	Niño	June	**Niña**	October	**Niña**
March	Niño	July	Niño	November	**Niña**
April	**Niña**	August	Niño	December	Niño

Figure 4: Type of climate phenomenon according to the month of the year in Colombia

the work of Bower & Bunn (2000), and on the ODD protocol of Kraan *et al.* (2018). Bower & Bunn (2000), explain that the generating companies that participate in the market continuously compete in order to obtain greater profits, thus generating an oligopoly, that is the basic principle of the model: few companies participating in the market that are constantly competing and creating new strategies. The bidding decisions of the agents form another basic principle, the agents must decide whether to increase or decrease the offer price for each day depending on the results they obtained in the previous round. An important concept is the inclusion of the target utilization rate as it restricts supply prices and increases competition, making the model more realistic. As Bower & Bunn (2000) mention, the complexity of the wholesale market requires the use of tools other than the economic theories of equilibrium that are far from reality by assuming that agents have information about other agents and about the entire market.

Emergence. The main results of the model are related to the utilization rate, since the higher this rate, the lower the final price. This is because when an agent does not achieve its target utilization rate, it decreases its price to enter the market, that is, to be chosen to supply the demand. This utilization rate is an important factor as it restricts the bid price and increases competition in the market as it occurs in real life. Another result related to the utilization rate is that the supply price is equal to the marginal cost or even below it since the companies want to increase their participation in the market as the greater the participation, the greater their market power.

Adaptation. The adaptive behavior of agents arises from their purpose to meet two main objectives: to achieve their target utilization rate for their portfolio of plants and to increase the profit obtained in the portfolio of plants. Agents look at their results each day and use the decision criteria presented in Rule 4 of the Table 2.

Objectives. As already mentioned before, agents seek to meet two main objectives that are determined by the profit obtained and the utilization rate obtained on each day of the simulation for each portfolio of plants. Agents constantly update their goals to improve.

Learning. The adaptive behavior of the agents (who decide the bid prices) is modeled using an approach that includes learning as the agents take into account the information of the previous day to choose the price of the next day as explained in the adaptation section.

Sensing. The agent perceives and has only its information, the agent learns every day of the benefit it obtained the previous day because at the end of the day it has information about the amount that was required from its and the price that was paid to all the other agents because this price it is the same for everyone. The agent also perceives at the end of the day its utilization rate which helps it to make decisions for the next day. Another important thing that agents detect is the weather. If it is in the La Niña period, there are more rains and hydroelectric plants have an easier time producing energy, so their prices do not tend to increase. If, on the other hand, it is in the El Niño period, hydroelectric plants increase their prices because there is a shortage of water, which makes generation difficult.

Interaction. There is no direct interaction between the agents, each one operates their plants and has information only on them. However, the decisions of one agent affect others indirectly. For example, by preventing another agent from participating in the market, since by decreasing its bid price, the first agent enters the market selling all its capacity, which would leave another out because it is no longer required. In addition, the agents have interaction with the environment because they know the time and climate in which they are, which allows them to modify their prices. If it is in the La Niña period, there are more rains and hydroelectric plants have an easier time producing energy, so their prices do not tend to increase. If, on the other hand, it is in the El Niño period, hydroelectric plants increase their prices because there is a shortage of water, which makes generation difficult.

Collectives. Each different type of plant (each generation technology) is represented by a collective that has its costs, prices, and amounts. However, the behavior of the agents is the same regardless of the type of group that is.

Observation. The graphs that are made have the objective of allowing the analysis of the price of electric energy in Colombia at different times of the year in a market in which agents compete and use strategies to see themselves benefited.

3.3.5 Initialization

The model starts at hour 0, day 0, and month 0. The 7 firms are created and for each firm, the corresponding number of plants for each technology is created as specified in Table 1. The plants are associated with their respective firm through a link (a line) that allows identifying the associations. In total there are 212 plants. The location of the agents for this model is not relevant so it is assigned randomly but fixedly, that is, it is always the same for each firm. In the initialization, the quantity that each plant can offer is also established, the cost according to the technology it uses, and an initial price from which the other prices are generated later for all hours of the day. Another value that is set at initialization is the target utilization rate that will remain constant during the simulation, and the expected profit, but this is updated during the simulation. Besides, the demand and the weather are initialized. The demand is input data that was obtained from the XM S.A database of the real demand for the year 2019. The climate is represented with the number 0 or 1, 0 for months in which El Niño occurs (period of drought), and 1 for La Niña (rainy season). The allocation of the periods of drought and rain was done as shown in Figure 4.

Generation type	Cost ($/kWh)
Hydroelectric	40
Thermal	311
Coal	223
Gas	187,5
Wind	65,96
Solar	35,5

Figure 5: Cost according to the type of electricity generation in 2019

3.3.6 Input data

The input data used in the model are generation costs, the amount each plant can supply, and demand. The generation costs are estimated values and provided by XM S.A databases according to the type of generation, these values remain fixed throughout the simulation and are established at the beginning. You can see the values in figure 5. The amount offered by each plant also remains constant throughout the year, as these are values that each firm provides at the beginning of the year and that cannot be changed. The values are shown in figure 6, where each firm is presented with the amount for each of its plants in kilowatts. Demand is divided into three: high, medium, and low, depending on the time of day. For each type of demand, a range of values was obtained in which it can be presented, this information was also provided by XM S.A. and is shown in the figure 7.

Firm 0	Hydroelectric									Thermal	Coal	Gas	Wind
	810,00	2.600,00	512.000,00	3.150,00	5.000,00	1.000,00	350,00	1.800,00	400,00	353.000,00	5.000,00	2.440,00	18.420,00
	410,00	3.000,00	19.000,00	1.400,00	207.000,00	19.000,00	870,00	300,00	18.500,00	44.000,00	9.400,00	9.900,00	
	3.500,00	4.500,00	960,00	19.000,00	405.000,00	2.000,00	860,00	306.000,00	13.200,00				
	18.000,00	30.000,00	19.800,00	750,00	700.000,00	135.000,00	560.000,00	11.600,00	15.000,00				
Firm 1	Hydroelectric									Thermal	Coal	Gas	
	540.000,00	9.900,00	2.600,00	18.000,00	10.200,00	14.200,00	150.000,00	600.000,00	1.800,00	56.000,00	34.000,00	9.900,00	
	19.400,00	18.000,00	14.200,00	396.000,00	35.000,00	14.200,00	14.200,00	1.250.000,00	8.000,00	62.000,00	63.000,00		
Firm 2	Hydroelectric							Thermal	Coal	Gas	Solar		
	429.000,00	132.000,00	6.700,00	19.900,00	19.170,00	700,00	5.000,00	12.000,00	9.900,00	9.900,00	9.800,00		
	19.900,00	56.000,00	51.000,00	315.000,00	19.900,00	19.900,00	1.800,00	19.900,00		167.000,00			
Firm 3	Hydroelectric												
	450,00	2.800,00	820,00	19.900,00	3.750,00	700,00	750,00	750,00	1.440,00				
Firm 4	Hydroelectric						Thermal						
	80.000,00	396.000,00	1.240.000,00	19.900,00	170.000,00	819.000,00	279.000,00						
Firm 5	Hydroelectric												
	19.900,00	19.900,00	9.500,00	19.900,00	9.500,00	19.900,00	2.300,00	44.000,00					
Firm 6	Hydroelectric					Thermal		Coal		Gas		Solar	
	7.290,00	1.000.000,00	4.520,00	19.600,00	4.000,00	160.000,00	19.900,00	164.000,00	70.000,00	1.100,00	19.300,00	19,80	
	15.000,00	4.500,00	1.500,00	5.700,00	1.670,00	157.000,00	3.000,00	273.000,00	154.000,00	19.900,00	19.300,00		
	19.400,00	1.200,00	3.000,00	19.900,00	10.000,00	157.000,00	17.000,00	143.000,00	17.000,00	19.900,00	3.750,00		
	600,00	1.250,00	470,00	5.100,00	19.800,00	213.000,00	2.000,00	143.000,00	163.000,00	19.900,00	19.900,00		
	3.400,00	2.280,00	4.800,00	1.480,00	1.650,00	200.000,00	1.700,00	36.000,00	170.000,00	450.000,00	30.000,00		
	700,00	19.900,00	1.420,00	4.900,00	2.500,00	1.600,00	64.000,00	72.000,00		45.000,00			
	4.320,00	4.320,00	700,00	1.000,00	468,00	19.900,00	63.000,00			45.000,00			
	78.000,00	5.400,00	19.600,00	750,00		10.000,00	88.000,00			791.000,00			
	1.100,00	1.300,00	6.000,00	19.700,00		19.900,00				9.700,00			
	1.030,00	338.000,00	700,00	380,00		16.000,00				19.300,00			

Figure 6: Net effective capacity in kW (kilowatts) for the year 2019

4 Results

A hypothetical scenario was simulated as close to reality as possible, controlling the strategic behaviors of the companies existing in the market, this resulted in the electricity spot price for each hour of the day for a year. When comparing the prices of the simulation with the real data

	Demand (kWh)	
High	6.413.256,51	6.930.967,37
Medium	6.498.249,63	8.467.591,10
Low	7.928.380,83	9.152.452,73

Figure 7: Range of values in which each type of demand is.

presented in Figure 8, we see that the price remains within the confidence interval calculated for the real data, between $[225, 38; 229.48]$. In Figure 8, the hourly price is shown and in Figure 9, the average daily spot price. It is true that the real price has more pronunciation which is not captured by the simulation. It must be taken into account that the simulation uses random values to make the variations in the price when the agents do not achieve their objectives. Other factors such as sudden weather variation, inaccurate electricity demand, declared energy availability, scarcity price, actual generation, economic activity, reserve margin (maximum capacity / energy demand), and lack of accuracy in the real prices of the different sources, deviates the simulation from reality. We also can see that on several occasions it is possible to capture the same behavior of reality, for example, between days 134 to 197 of the Figure 9, that is, from May 14 to July 16, 2019, both the simulated spot price and the real take the lowest values of the whole year. This period of time coincides with a period of Niña in which there is more rain and the spot price of energy tends to decrease as there are more offers from hydroelectric plants. There is also a similar behavior in simulation and reality between days 249 to 291 which corresponds to September 6 to October 18, 2019. We see that the price increases and remains between \$181 to \$396.

In the Figure 8, we see that there is a very pronounced peak at point 5414 that corresponds to day 226 hour 14, that is, on August 14, 2019 at 2 in the afternoon a price of \$910.5 was presented, which is an extreme value for the spot price of energy this year. At this time of the year, it was in a period of Niño so it is very likely that the weather was the main cause. However, this behavior is not captured by the simulation as it is really extreme.

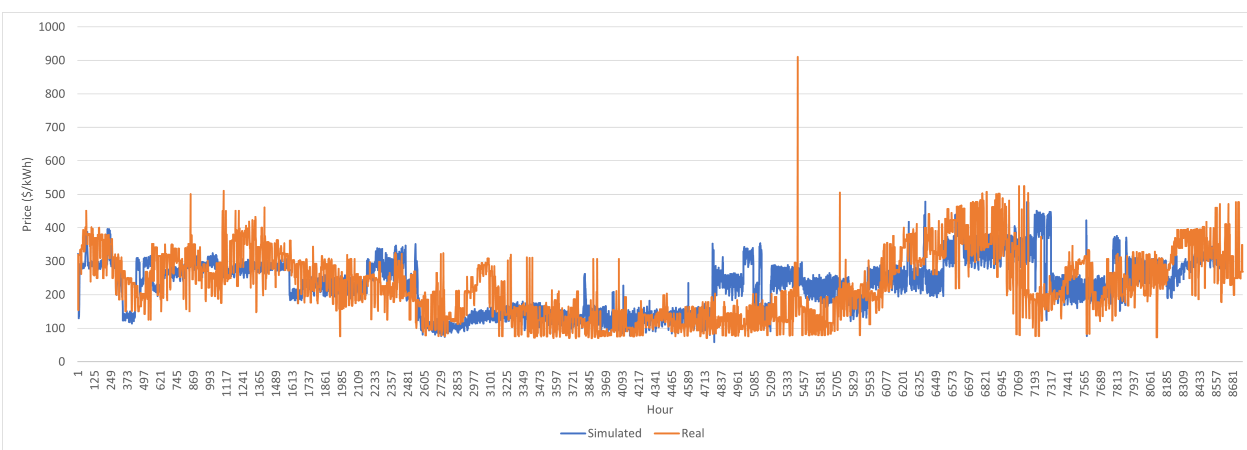

Figure 8: Comparison of simulated and real prices.

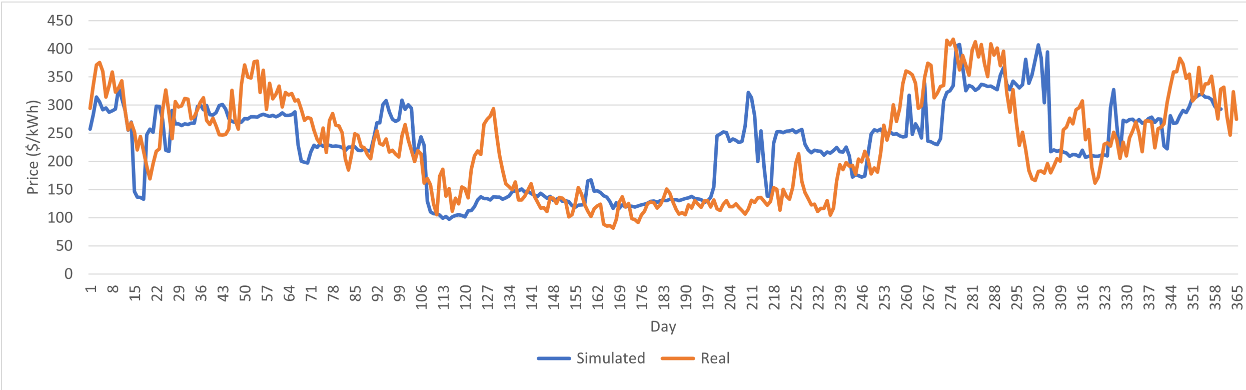

Figure 9: Comparison of simulated and real prices on a daily basis.

4.1 Non-conventional renewable energies

This work seeks to evaluate the impact on the spot price of electricity with the inclusion of non-conventional renewable energies. However, due to the fact that Colombia in 2019 has almost zero inclusion of this type of energy, a hypothetical scenario was simulated in which priority is given to non-conventional energies so that they are always involved in the market and in this way see the impact that would have had the inclusion of non-conventional renewable energies in Colombia in 2019. The main results are observed in Figure 10, these show that the average daily spot price of electricity would decrease, this is explained by the strategic behavior of the agents and by the merit order effect of the market because non-conventional energies do not have generation costs, they are always the first to enter the market, generating a shift in the supply curve.

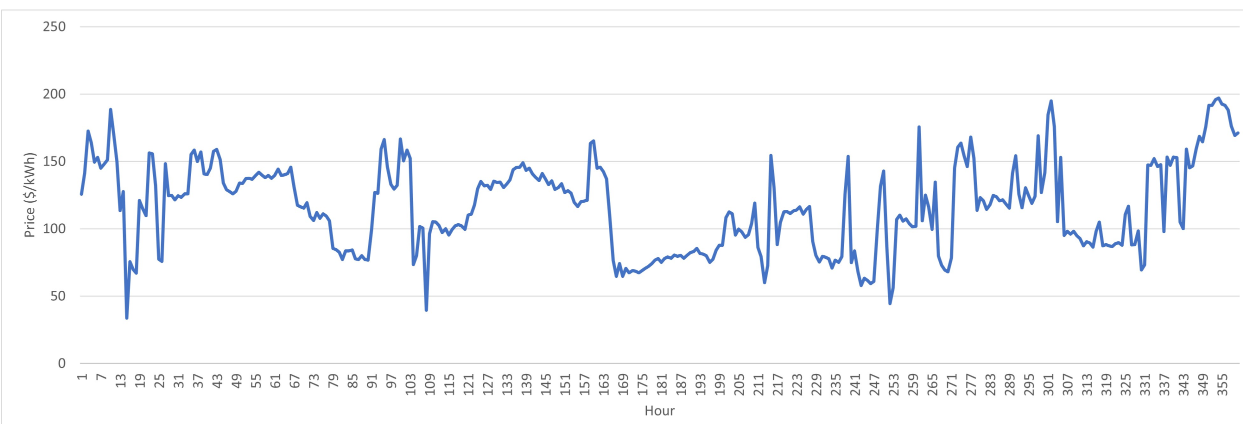

Figure 10: Non-conventional renewable energies scenario.

Also in Figure 10, we see that the spot price presents much more variation, this agrees with reality since the problem with non-conventional renewable energies is that they are very intermittent, they present instability because the resources are not continuously available for their conversion into electricity and external direct control because the primary energy used cannot be stored. For example, the energy produced by the wind, at any moment the wind can stop and stop producing energy, and while there is wind, it cannot be stored. Intermittent power sources can be predictable but cannot dispatch to meet the demand of the electrical power system. It is true that the price decreases since these energies have no cost, but there are greater fluctuations in the supply at a certain moment, which forces to have in reserve thermal energies that are essential to be able to attend to these fluctuations that are now greater in this scenario. Although the spot price decreased, the variability of the supply at a given time, the sensitivity, and the need for support also increased.

4.2 Simulating strategic bidding

The market prices observed in the simulation show an upward or increasing trend, this can be justified by the pressure of higher demand, compared to a practically constant supply. Furthermore, the results indicate that companies are sometimes willing to bid at marginal cost or even below it to gain or retain market share. Generating companies initially behave as if they did not have market power as they lower their prices in order to enter the market. To change this, several simulations were run by changing the target utilization rate parameter assuming that companies are willing to restrict their competitiveness as they lower their utilization target to 70%, 60%, and 50%. This change in this parameter is intended to simulate that companies give up a limited amount of market share in exchange for higher prices and higher profits. The results of the figure 11 show that with a percentage of 70%, the more companies ignore the strategic impact of their behavior, when trying to sell more of their production, that is, when they do not reduce their utilization targets, the prices remain in marginal cost or even below. When companies are willing to lower their utilization targets by, for example, a 50% rate, and thus their market share targets, marginal prices rise.

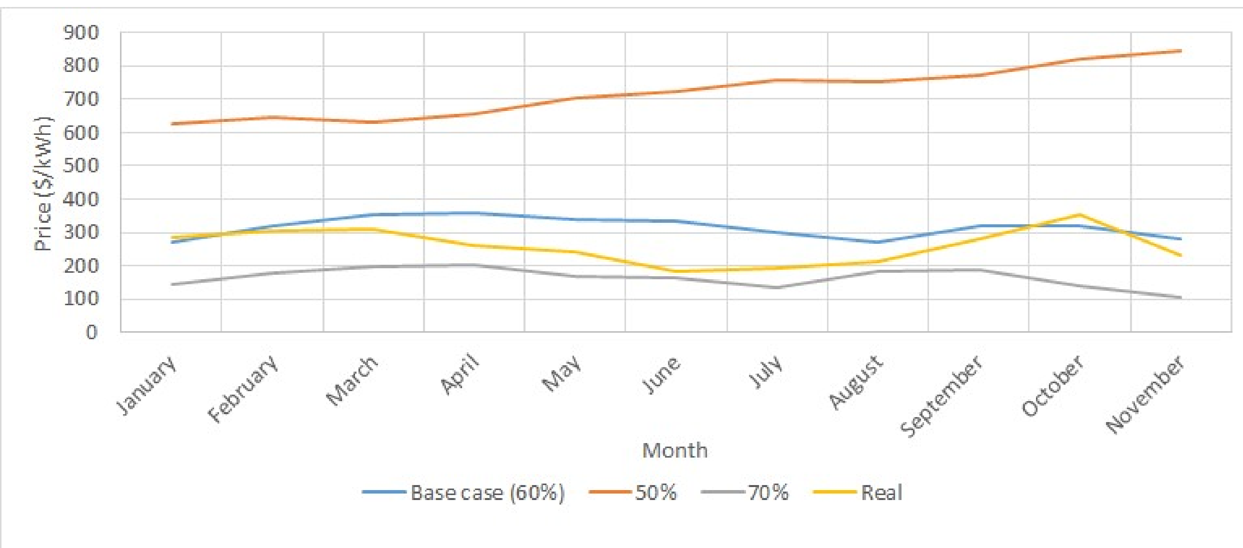

Figure 11: Comparison of simulated prices with different target utilization rate.

There are no studies to show that real companies need to coordinate on a particular utilization rate. However, as shown in Figure 11 , there is a greater degree of correlation both in the level pattern and in the variation of real and simulated prices for 2019 with a utilization rate of 60%. Therefore, the real and simulated price data in this way has allowed us to calibrate the model to replicate the strategic objectives of the generating companies in the Colombian market that would not otherwise be observable. Using this model output, which contains the 2019 industry structure and a target utilization rate of 60%, as a base case, allows us to compare the simulation results with alternative industry structures.

4.3 Changing the weather

The El Niño phenomenon has an impact on the rains and therefore on the water inputs that entered the generation system and additionally produces a heatwave that increases the demand for Sierra & Castaño (2010) electricity. Given that water resources are the main source of generation in Colombia, the price of electricity depends to a great extent on the supply prices of water resources in the market. In turn, the supply prices of hydraulic resources depend on the amount of water stored in the reservoirs, the current hydrological situation, and the future situation (not observable).

A simulation in which the weather does not influence the system was carried out to see the effect it has on the spot price of energy. In the figure 12 it is observed that the price always stays below the real price and varies much less from one month to another, in most months the price increases by a small amount without showing great changes. That the price is lower throughout the simulation may be due to the fact that there is a greater potential supply from the hydroelectric plants causing the price to decrease, since the level of the reservoirs remains constant since the climate is not changing. In another scenario that was carried out, the phenomenon of the child affects to a greater extent, it is observed that prices increase a lot, and in another scenario in which there is more rain, a much lower spot price is evidenced. These results are consistent with reality due to the influence of water resources in the electricity market.

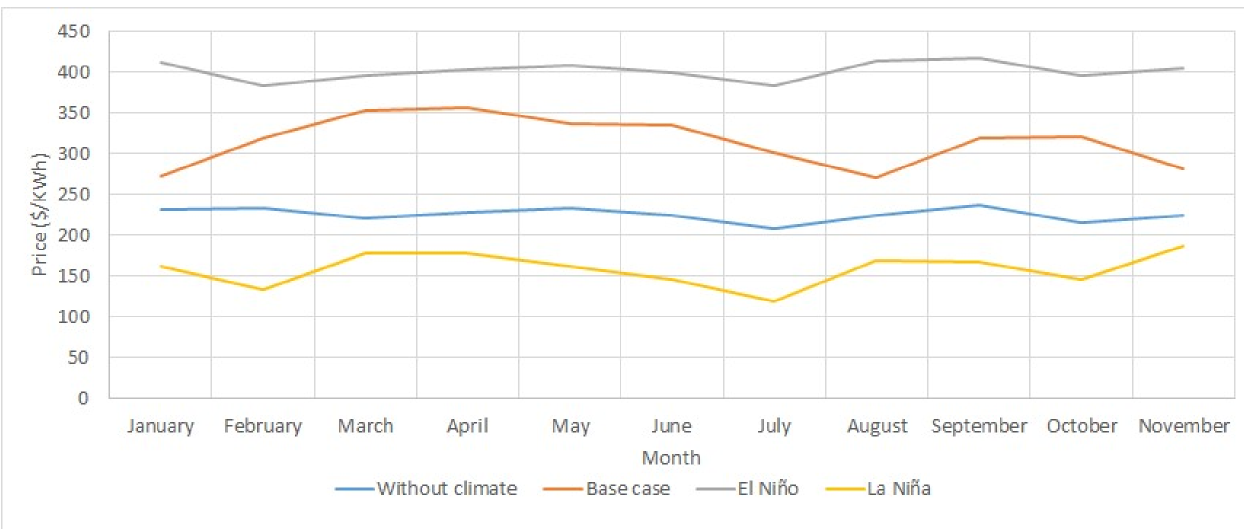

Figure 12: Comparison of spot price with variations in climate.

5 Conclusions and future research

This study has shown that the variation in prices with the inclusion of non-conventional renewable energy sources and the long-term impact of these sources will increase. The intuitive explanation for this is that when renewables are abundant, for example during periods of wind or sun, prices are extremely low, while at other times when demand is high and renewables are in short supply, prices are higher. Prices may be much higher, due to the strategic bidding of generators that exercise market power, thus generating greater variation (Auer & Haas, 2016). The second major finding was that the spot price of electricity, on average, decreases due to the strategic behavior of the companies and a merit order effect. We have been able to simulate the influence of heterogeneous agents in the Colombian electricity market.

It is important to mention that the transition to a sustainable electricity system requires new thinking that consists of accepting a paradigm shift in the entire electrical system (Auer & Haas, 2016). In other words, a change to a more flexible and intelligent system that allows a greater margin of participation in the demand, storage options, and other measures of flexibility. The development of such a system also implies that politically motivated capacity mechanisms are not needed.

The research has also shown that other factors such as market power and weather are very important for the spot price. The results suggest that the firms were capable to exercise market power as they have been able to maintain prices above marginal cost during the period under study. To achieve this, firms must have been bidding strategically and be willing to reduce their target utilization rate and thus their market share targets, otherwise prices would have remained at marginal cost throughout the year. By calibrating the model to the market prices achieved in 2019, we have been able to abstract a target utilization rate of 60%. This represents a measure of the degree to which firms are willing to lower their overall market share objective and cooperate with each other to keep market prices above marginal cost.

The climate scenario confirms that the climate factor influences the spot price of energy. In dry periods the price increases since water resources are the main source of electricity generation in Colombia, and in rainy periods the price decreases because there is greater supply so that agents decide to lower their prices to participate in the market.

The agent-based simulation model has proven to be an efficient tool for the study of the electricity market, it has allowed experimenting with different scenarios such as one that includes non-conventional renewable energies. This type of modeling has made it possible to represent individual behaviors and important factors that affect the Colombian electricity market. However, this model is not completely accurate in the variations that occur during the year of the spot price, for this reason, a research proposal for future work is to assess the same system but with other methods such as the financial theory of pricing, in order to compare the results and obtain the best possible ones.

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