Agent-based simulation of the bidding process in the wholesale electricity market in Colombia.

Verónica Mendoza Iguarán[1]

Main Advisor:
Paula Alejandra Escudero Marín[2]
Co advisor:
Jhon Jairo García Rendón[3]

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School of Sciences
Universidad EAFIT

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[1]Mathematical Engineering Student, Universidad EAFIT.
(CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod$_r h = 0001796849\#$)
[2]Professor Department of Sciences, Universidad EAFIT (Colombia). Telephone: (57)(4)261 9500 Ext.9806. Email: pescuder@eafit.edu.co - Main advisor of the project.
[3]Professor Department of Economics, Universidad EAFIT (Colombia). Telephone: (057-4)261 9500 Ext.9009. Email: jgarcia@eafit.edu.co - Co advisor of the project.

Abstract

The wholesale electricity market in Colombia is a complex system because multiple factors interfere, such as the climate, since the main source of generation is hydraulic. Another factor is the high cost of production, since it supposes great barriers to entry into the market, forming an oligopolistic structure that consequently makes agents act strategically seeking to maximize their benefits. For this and other factors, a computational tool is necessary to accurately represent this market. In this research, we present an Agent-Based simulation model to assess the benefit of using this tool to represent strategic behavior of agents in bidding in the wholesale electricity market in Colombia. The results show that the agents behave individually, so the tool is very efficient.
Keywords: wholesale electricity market, Agent-Based modelling, simulation, 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 structure of the short-term market or spot market 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 generate 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 (García & Pérez, 2019).

An important characteristic of this market is its oligopolistic structure due to high fixed costs (Botero *et al.*, 2013). This factor drives the desire of participating agents to strategize on pricing to maximize profits (Hurtado *et al.*, 2014). Another characteristic is that the 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 is known as El Niño, and cooling and rains known as La Niña, affect the generation of electricity in Colombia. El Niño causes the levels of the reservoirs to fall, causing more significant use of alternative energy than in the case of Colombia is thermal (García & Pérez, 2019). However, 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 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 has the support of the National Dispatch Center (CND), and the Administrator of the Commercial Exchange System (ASIC) to coordinate the operation and the daily dispatch of electricity (XM, 2020). XM 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).

As mentioned before, the electricity market is a very complex system where competitiveness plays a very important role and the strategies of the participating agents are entirely different according to their interests and possibilities (Bastidas *et al.*, 2012). These strategies play a fundamental role in the formation of the spot price since they are what make it increase or fall, affecting the price index to the final consumer (Lozano & Rincón, 2010). 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. However, few studies have investigated how to model key aspects of people's behavior in the energy market and its effect on price formation and in general on the whole market. Due to this, the need arises to investigate the benefit of using Agent-Based Modelling and simulation to represent strategic behavior of agents in bidding in the wholesale electricity market in Colombia.

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.

The problem that is being worked on here arises due to the importance of the Wholesale Electricity Market in Colombia as it 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 the presence of El Niño, the level of the reservoir decreases, also decreasing the water contributions to the system and creating the need for alternative energy that in the case of Colombia is thermal, but the supply of thermal energy it is much lower (García & Pérez, 2019) 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.

It is therefore pertinent to use Agent-Based modeling to incorporate the variables mentioned above in addition to modelling the strategic behavior required in the wholesale electricity market and particularly in the formation of the spot price. Being able to incorporate a large number of agents where each one has their strategies, the inclusion of variables for the climate and other variables of the economic theory involved in this system make the Agent-Based simulation tool play a relevant role for the study and evaluation of the formation of the 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). In particular 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 with the problem described here. Then the methodology with the ABS simulation approach is presented, followed by results for a number of strategic scenarios. Finally, the conclusions and future work are presented.

2 State of the art

The Colombian Wholesale Electricity Market (MEM) is inspired by the market in England and Wales (Arango *et al.*, 2006; Dyner *et al.*, 2008; Larsen *et al.*, 2004). In the 1991 constitution, a competition was admitted allowing free entry of agents interested in providing services, thus starting the operation of the MEM and the energy exchange (CREG, 2017). For the sector to function and develop properly, a scheme was established that contains the entities that produce the energy, those who coordinate the process, transport, sell, those who create the rules, and those who monitor compliance. The National Government, through the Ministry of Mines and Energy, is in charge of designing the sector's policy. The Energy and Gas Regulation Commission (CREG), is in charge of regulating the behavior of all those involved to guarantee economic efficiency, coverage, and quality. The market is made up of different types of agents: generators, transporters, distributors, marketers, and administrators (CREG, 2017). Generators produce electricity. Transporters transport electricity through the National Transmission System. Distributors transport energy locally to be distributed to consumption centers. Marketers are responsible for the direct purchase from generators in the Wholesale Electricity Market, to be sold to end-users. This last activity comprises the retail level of the energy market (García & Pérez, 2019). Finally, the administration is by the Administrator of the Commercial Exchange System (ASIC) who coordinates the operation and the daily dispatch of electricity (XM, 2020).

The study of the wholesale market has a long history as a highly influential sector in the world economy. The problems addressed have focused on the behavior of the market when implementing different political regulations such as Aliabadi *et al.* (2017), the forecast of the daily price of energy such as Hurtado *et al.* (2014), and currently the inclusion of renewable energy sources such as García & Pérez (2019). The main aim is to increase the efficiency of the system, promote deregulation, and the introduction of technological advances due to environmental concerns. Research on the integration of non-conventional renewable sources such as Botero & Garcia. (2020), in the case of Germany, a country that has been a world benchmark in renewable energy. The study by Botero *et al.* (2020b), in the event of the energy transition in the United Kingdom and also that of Botero *et al.* (2020a), for the case of France. García. (2020), also studies the Spanish market and highlights the impact of the implementation of remuneration mechanisms in that country.

The trend in this type of market is towards competition, which is why studies such as Ventosa *et al.* (2005) are dedicated to gathering the most relevant publications on market modeling to make a better analysis of it, and they identify three types of models that are trending in the area: optimization, equilibrium, and simulation models. They also affirm that Artificial Intelligence is a relevant tool for market modeling as it involves different technical, social, economic, political, and environmental dimensions. Similarly, Ringler *et al.* (2016),performed an exhaustive literature review focussing on Agent-Based models supported by other different approaches. Regarding models that incorporate artificial intelligence, there is that of Bastidas *et al.* (2012), in which they study the intelligent and strategic behavior of power generation agents in Colombia. They also use Clustering algorithms for data processing and ANFIS for prediction and agent learning. Hurtado *et al.* (2014) also incorporate artificial intelligence. They use Fuzzy Logic and Artificial Neural Networks to build models of daily prices offered for the most important hydraulic and thermal generation resources in Colombia. They make use of time series and the identification of dynamic systems to estimate the price offered, and also conclude that the estimation using autoregressive models is not reliable given the peaks and periods of stability that occur in the country.

Kristiansen (2014) also uses time series for price prediction but without any other tool. He presents three spot price forecasting models for the Nord Pool market. A regression model, a model that uses the spot price of the previous week as a predictor of the price of the next week, and a model that uses the futures price for the next week as a predictor of the spot price of the next week. However, electricity markets are increasingly complex as mentioned by Gencer *et al.* (2020), who affirm that after the market liberalization, competitiveness increased, giving way to the creation of multiple strategies by agents. For this reason, the use of time series without any other additional tool is not the most convenient way to predict the price, since behavioral factors play a fundamental role that cannot be modeled in this way. It is at this point where agent-based models play a very important role by allowing the aggregation of individual agent behaviors in addition to the usual mathematical models that other techniques also use.

Agent-based simulation models are an attractive methodology with great potential to overcome some of the shortcomings of other approaches in the electricity market (Weidlich & Veit, 2008). This is because this approach offers additional features compared to traditional balancing or optimization models. Aspects such as the interaction structure and individual behavior, learning in repeated interactions, imperfect and strategic competition, and asymmetric information are other fundamental aspects of this type of model (Frank *et al.*, 2007).

Some of the main simulation models based on electricity market agents found in the world literature since 2000 are presented. According to Frank *et al.* (2007), one of the pioneers in the field of Agent-Based simulation in the electricity sector are Day & Bunn (2001), who in their work model the three largest fossil fuel generating companies in England and Wales. In their model, generation companies are modeled as daily profit maximizers in a market with uniform price market compensation. They include contracts for differences, so the generating agents obtain benefits from the sale of electricity but also from this type of contract. Demand is modeled as an aggregate function with a defined slope. They compare their model with that of Klemperer & Meyer. (1989), who use equilibrium theory. Finally, they conclude that their approach allows the analysis of more complex and realistic scenarios than with the equilibrium model. Bunn and Day continue their research and present a second model (Bunn & Day, 2002) in which they focus even more on the behavior of the generator.

In the same vein, Bower & Bunn (2000), who make a detailed and very intuitive description of the agent-based approach. They compare the market for daily deals to that for hourly deals. The model is used to measure the impact of industry concentration on market power and strategic behavior in the market. The model contains a set of trade agreements, a set of agents, and a demanding schedule. Trade agreements consist of a daily auction repeated for every hour of the day with bids, representing short-term bilateral trade. Each agent represents a single competing company, equipped with a portfolio of generating plants, characterized by capacity, type of fuel, costs, among others. those who offer in a single electricity market. The programming of demand is modeled with a price inelastic aggregate demand curve. Agents seek to maximize their profits and achieve a specific utilization rate for the plant portfolio.

An key aspect of this work is that the agents learn because they can store information for two days. Agents can choose, according to the information stored, between four strategies: lower prices when expected utilization is not met, increase the offer price of a plant if it sold production at a lower price than all other plants, modify the offer price for each plant in the portfolio if the profit did not increase in the entire portfolio, and maintain the strategy of the previous day if the objectives were achieved. In the real market, the agent aims to guarantee a minimum level of market share in a given period. Therefore, for each agent, they have estimated a minimum target utilization rate for the portfolio of plants, expressed as a percentage of the total expected available capacity in their entire portfolio. This rate makes the model more realistic by limiting prices since to participate in the market the agent resorts to lowering its prices. At the beginning of each simulated trading day, each agent can submit an offer for each plant in their portfolio, it is assumed that they offer all their available capacity. The offer consists of 24 separate prices for each plant (one offer per hour). The market is cleared by stacking the plant supplies, from smallest to largest, and assigning demand to plants, in order of merit, until demand is exhausted for each hourly period. Any plant that has bid above the marginal plant's bid price in a given hour has a zero utilization rate.

There is an unambiguous relationship between agent based models and learning algorithms, as described Young *et al.* (2014), they are based on agents to model the New Zealand market and additionally use a modification of the Roth and Erev learning algorithm and state that their model can closely mimic electricity prices at short term (weekly) given fundamental inputs such as fuel costs, network data, and demand. Aliabadi *et al.* (2017), study the strategic behavior of generation companies under different market compensation mechanisms using an agent-based model that integrates game theory for the auction mechanism and a learning algorithm for simulating company learning. They observe that the market converges to a Nash equilibrium or a similar state in most combinations of parameters and it is also possible to maximize the profits of the generators. A broader approach is that of Wang *et al.* (2019), who propose a Hybrid Simulation Model (HSM) that combines Agent-Based Simulation (ABS) and System Dynamics Simulation (SDS). They achieve that the necessary variables for a model can be obtained through the output of the other model and to achieve the competitiveness of the agents, they use a learning algorithm so that the agents obtain information and adapt to the environment through continuous interaction. However, this type of model is usually very complex and less intuitive, which is why works such as Visudhiphan & Hie (2001) seem to be a better starting point for understanding the market, the interaction of agents with the environment and its form. Act. They propose an agent-based approach that characterizes the dynamics of the auction-type market. The method used captures the learning and decision making of rational agents without using specialized learning algorithms but by constructing matrices that contain the information of each agent in each of the games.

3 Methodology

The first step in this process 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. The ODD protocol is described below

3.1 Purpose

The purpose of the project is to assess the benefit of using Agent-Based Modelling and simulation to represent strategic behavior of agents in bidding in the wholesale electricity market in Colombia. The model is based on the research of Bower & Bunn (2000) that consists of an economic environment (market), populated by agents (generating companies) that are individually represented with their 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 strategies of the country's agents and other specific characteristics that occur due to the geography it presents, such as the climate. This to obtain information that can contribute to the control of the electrical operation in Colombia.

This project aims to simulate the interaction that occurs in the market and adjust the dynamics of the system in a simplified way to the Colombian case. It is also intended to incorporate the market feedback that arises from incorporating different strategies by 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 to try other alternatives and learn from past choices so that his next choice will have a better result.

We evaluate the model by its ability to reproduce some behavior patterns of the electricity market. Since this is an oligopolistic market, companies have a competitive behavior, so the patterns of the energy-generating agents are based on two objectives: increasing its overall profitability, from one period to the next, and reaching a target utilization rate on its plant portfolio in every period. To reach these objectives, agents may follow either a 'price raising' strategy, by adding a percentage to the bids they submitted in the previous trading day or a 'price lowering' strategy, by subtracting a percentage.

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.

3.2 Entities, state variables, and scales

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

Generating firms, 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 know their plants and capture information from the environment, but only regarding their 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 for firms or agents to behave strategically concerning 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 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.

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 ($/ kWh), the amount of energy it can generate in kWh, and the supply price with a Colombian peso unit ($).

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

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.

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 1, the 'day' is used for the plants to make their offers per day, and the 'month' will serve to assign the weather as shown in the Figure 2. 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.

3.4 Design concepts

Basic principles. The model is based on the work of Bower & Bunn (2000), who explains 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

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 1: Type of demand according to the hour in Colombia

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

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.

3.5 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 2.

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

Figure 3: Cost according to the type of electricity generation in 2019

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 3. 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 4, 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 5.

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

4 Results

The first result obtained comprises a literature review with the main references related to the problem described here; this made it possible to define the problem and also the literature served as a guide to address the solution to the problem raised in this research. The second result is a conceptual

	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 5: Range of values in which each type of demand is.

model in which the ODD protocol was used with a detailed description of the computational model. Finally, the simulation model that was carried out allows obtaining the results that are presented below.

A confidence interval was calculated with the values of the real spot price for the year 2019, the interval is $[225, 38; 229.48]$. We see that the values obtained in the simulation are in the same range as the real values, although since the simulation uses random values to carry out the price variations, the variations in the simulation and the real price are not equal, however, factors such as sudden changes in weather, inaccurate electricity demand, declared energy availability, scarcity price, actual generation, economic activity, reserve margin (maximum capacity/power demand), exchange rate and natural gas prices are factors that affect in real life and are not taken into account in the model.

Figure 6 shows the results of the hourly spot price and Figure 7 shows the monthly averages of the real and simulated spot price

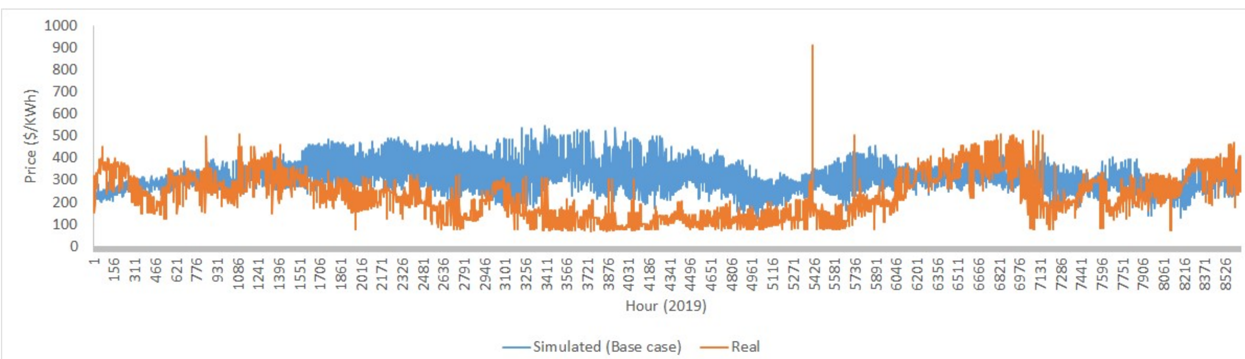

Figure 6: Comparison of simulated and real prices.

4.1 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 8 show that with a percentage of 70%, the more companies ignore the strategic impact of their behavior, when trying

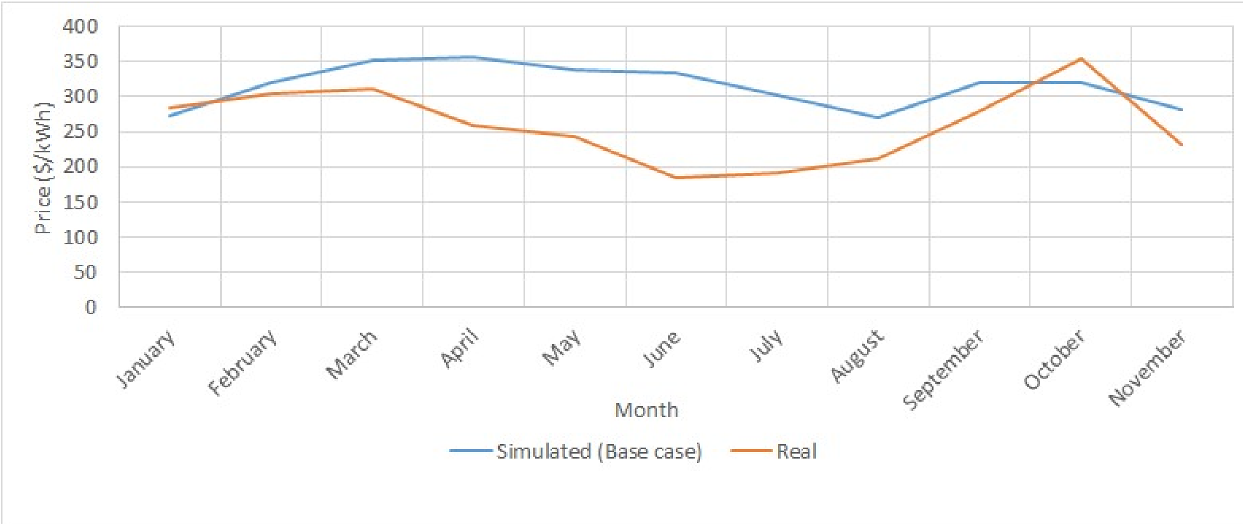

Figure 7: Comparison of simulated and real prices on a monthly basis.

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.

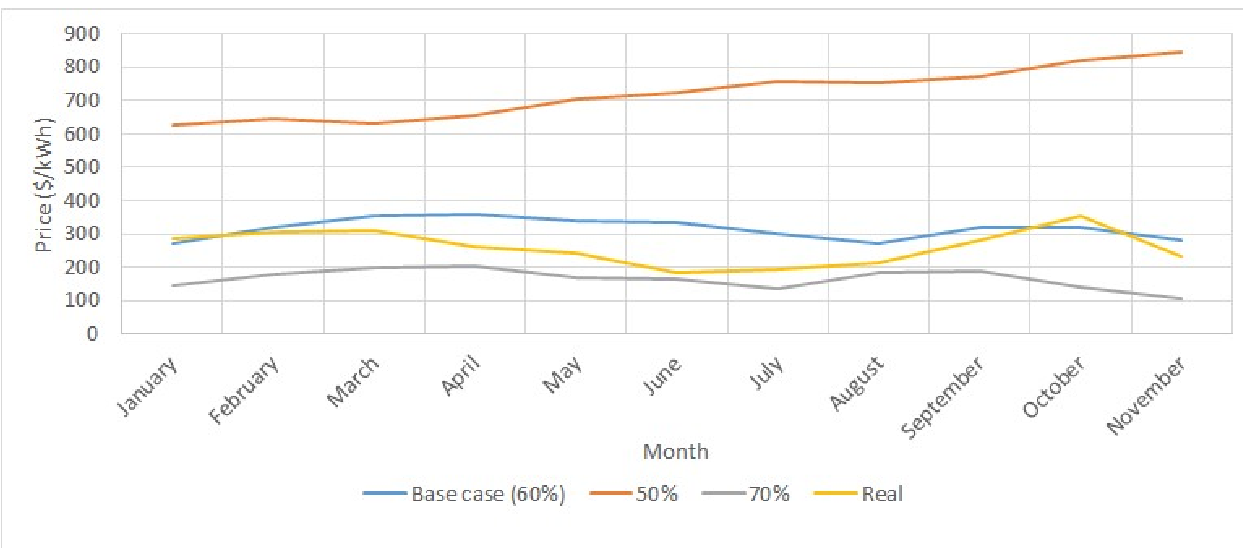

Figure 8: Comparison of simulated prices with different target utilization rate.

There are no studies to show that real companies need to coordinate on a particular utilization rate. However, as shown in Figure 8 , 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.

4.2 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 9 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.

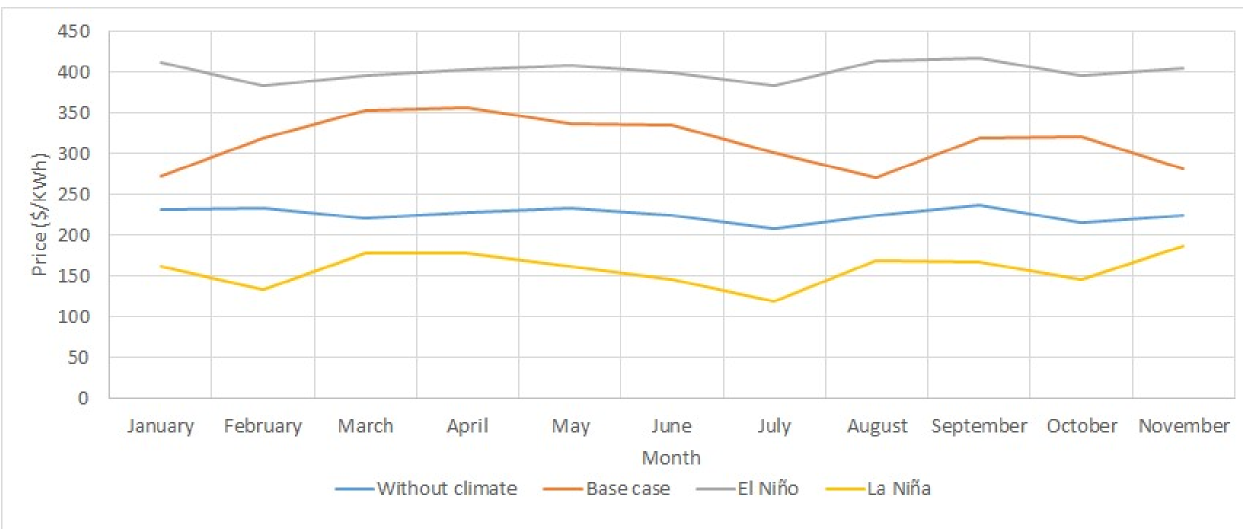

Figure 9: Comparison of spot price with variations in climate.

5 Conclusions and future research

Energy prices in the Colombian wholesale electricity market are influenced by multiple supply and demand factors that directly affect its behavior with non-linear and complex characteristics. In Colombia, market power is concentrated in very few companies. According to studies, the three largest companies have close to 60% of the installed capacity, and the set of smaller companies does not reach 20% of the offered availability, which shows strategic behaviors García *et al.* (2015).

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.

This research has also shown that the climate factor influences the spot price of energy. In dry periods the price increases due to the fact that 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 in order to participate in the market.

The agent-based simulation model has proven to be an efficient tool for the study of the electricity market as it allows representing individual behaviors; however, this model could be improved to be more accurate in the variations that occur during the year, improving the influence the climate on the price and including other factors that have not been taken into account here exactly, such as a more exact demand. In addition, currently, in order to improve energy efficiency, reliability in the supply of electricity service and the decarbonization of the environment, the inclusion of renewable energy sources, has been presenting changes in the operation of energy markets at the level world García & Pérez (2019). In this way, a research proposal for future work is to evaluate the effect that the inclusion of these sources may have in the Colombian wholesale electricity market.

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