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An investment game with complete and incomplete information applied to the power market

Un juego de inversión con información completa e incompleta aplicado al mercado eléctrico

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Abstract

This paper aims to present two investment games with complete and incomplete information in three stages that allow identifying equilibria games of the players in the oligopoly market. The restructuring of the power market brought with it new competitors' appearance to become a sector with high risk and uncertainty due to demand, electricity, oil price volatility, competence between firms, among others, thus making it difficult to make decisions regarding investment in electricity generation. This proposal applies the games theory methodology that helps making-decisions in an imperfect competence market. This study shows that when the firms have enough information, the best option for the incumbent and potential entrants firms is to invest. When the information is asymmetric, the best option for Entrants Potential firm is to invest.

JEL Code: C72, C73, D43
Keywords: oligopoly; game theory; power market; hydro-power; wind-power; cournot model

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Resumen

El propósito de este trabajo es presentar dos juegos de inversión, con información completa e imperfecta en tres etapas, que permita la identificación del equilibrio de los jugadores en un mercado oligopólico. La reestructuración del mercado de energía trajo consigo la aparición de nuevos competidores convirtiendo al sector en un escenario con alto riego e incertidumbre, como consecuencia de la volatilidad de la demanda, competencia entre agentes, los precios de la electricidad y de los combustibles, dificultando de esta forma la toma de decisiones en relación con la inversión en la generación de la electricidad. Esta propuesta aplica como metodología la teoría de juegos que ayuda a la toma de decisiones en una estrategia de competencia imperfecta. Se concluye que cuando hay suficiente información tanto para el titular como el potencial entrante, la mejor opción es invertir, pero cuando la información es asimétrica, la mejor opción para el Potencial Entrante es invertir.

Código JEL: : C72, C73, D43
Palabras clave: oligopolio; teoría de juegos; mercado de energía; hidráulica; eólica; modelo cournot

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Introduction

The restructuring of the electricity markets began during the mid-1980s. The liberalization of the sector was due to deficiencies such as: the inability of state-owned companies to meet the demand of users, the increase in electricity prices, corruption in some state-owned companies, and mismatches between tariffs and true generation costs, among others (Carvajal & Jiménez, 2012; Dubash, 2002). This new economic model is intended to improve economic efficiency and energy supply.

This restructuring was designed to separate generation, transmission, and distribution to eliminate the electricity industry's vertical structure. The reform was intended to attract private investment, increase the sector's efficiency, and turn the State into a regulatory entity. Faced with this reality, the sector became a high-risk and uncertain environment due to price volatility, changes in demand, availability, and prices of fuels, and the entry and exit of competitors, among other factors that complicate the decision-making process regarding investment.

From this point of view, studies are being developed that aim to create methodologies for decision making in the expansion of generators, considering the strategic behavior of competing agents—among them is Game Theory. This methodology tries to describe complex strategic situations in a simplified context. The knowledge of the expected reactions of the opponent can improve the company's ability to propose an adequate competitive strategy.

According to the works presented for the analysis of the electricity sector corresponding to the competitive strategy among agents, it is observed that non-cooperative games and oligopolistic models—especially the Cournot model—are widely used to describe this type of market operation. It is also noteworthy that the possession of information can affect the value of the project; and regarding the energy market, there is the possibility of a greater expansion of the sector by increasing the number of investors and, consequently, providing greater security to the system.

Based on the above, this paper aims to present two investment games, with complete and imperfect information in three stages, to identify the players' equilibrium in an oligopolistic market.

The content of this proposal is organized into four parts. The first part begins with an introduction. The second part describes game theory in electricity markets. The third part describes the state of the art of game theory applied to electricity markets. The fourth section specifies the game to be developed with its respective assumptions, which in turn is divided into two games: perfect information and incomplete information; and the last part shows the conclusions.

Game theory in electricity markets

Electricity is crucial for the industrial and economic development of a country. A region that intends to achieve growth in its production levels must deal with an increase in its energy demand. Therefore, policymakers face the challenge of increasing the installed generation capacity to meet the population's needs, reconciling the agents' interests in the economic, legal, environmental, social, and other aspects.

The activities of the electricity sector used to be vertically integrated monopolies, mostly with public investment (in some countries, they were privately owned, with special regulation by the government). Planning and decision making were centralized (García et al., 2010). Nonetheless, from the 1980s onwards, deficiencies became evident, such as the inability of monopolistic companies to meet user demand, the increase in electricity prices due to rising costs caused by inefficiencies in management, corruption in some state-owned companies, a mismatch between tariffs, and the true costs of generation (basically due to political motives), among others (Carvajal & Jiménez, 2012; Dubash, 2002). For this reason, there was a need to liberalize the electricity market to improve economic efficiency and energy supply.

Restructuring the electricity sector involved several measures, including the elimination of the vertical structure of the electricity industry by separating generation, transmission, and distribution, and the horizontal separation of these activities to attract private investment and increase the sector's efficiency. The government would no longer be an actor in the system but rather a regulator (Niknam et al., 2013, 2013; Pinto et al., 2015).

The new economic model led to the creation of a competitive market in which the State not only assumed the system's expansion but also made possible the entry of private investors to expand generation capacity. However, this occurred in scenarios of risk and uncertainty due to the volatility of electricity prices,

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the evolution of demand, the availability and prices of fuels, or the entry and exit of competitors, which made it difficult to make decisions regarding investment (Mercure et al., 2019).

Authors such as Hobbs (1995) or Ahmad et al. (2016) point out that some of the reasons for the increase in the complexity of the planning process in relation to the expansion of the electricity system are: the existence of many investing agents to act in the electricity sector, the increasing number of options for the realization of investments, great uncertainty associated with the growth of consumption, increased volatility of the fuel market, technological development, government regulation and, finally, the inclusion of new objectives, in addition to costs (Pereira & Saraiva, 2013).

In recent years, several studies have been presented (Fosso et al., 1999; Phupha et al., 2012; Rouhani et al., 2013; Zhang et al., 2013; Alizadeh & Jadid, 2015; Fitiwi et al., 2015; Gil et al., 2014; Maceira et al., 2015;) to develop methodologies that can be used for decision making regarding the expansion of generators. Game Theory is among them.

Game theory is a tool that studies the strategic behavior of (rational) players interacting, motivated by utility maximization (Fischer, 2012; Smit & Trigeorgis, 2004). This tool attempts to describe complex strategic situations in a simplified context. Knowing the rival's expected reaction can improve the company's ability to apply an appropriate competitive strategy. The anticipated response of the competitor is an essential element in the design of a competitive strategy (Smit & Trigeorgis, 2004). Game theory can be classified into the following types of games: finite and non-infinite, complete information (perfect) and incomplete information (imperfect), and static and dynamic.

A game can be defined as any situation in which individuals must make strategic decisions and in which the final result depends on what each one decides to do. According to Aristotle's theory of categories, every game is composed of a series of characteristics, regardless of whether they are board games, card games, video games, sports games, or leisure games. On the other hand, the assumptions of this theory are (i) companies are rational, i.e., they seek profit maximization, (ii) company managers use all the knowledge they possess to form their expectations about how their competitors will behave in the market, i.e., they apply rationality to the strategic reasoning process (Varian, 2010). Figure 1 shows these characteristics.

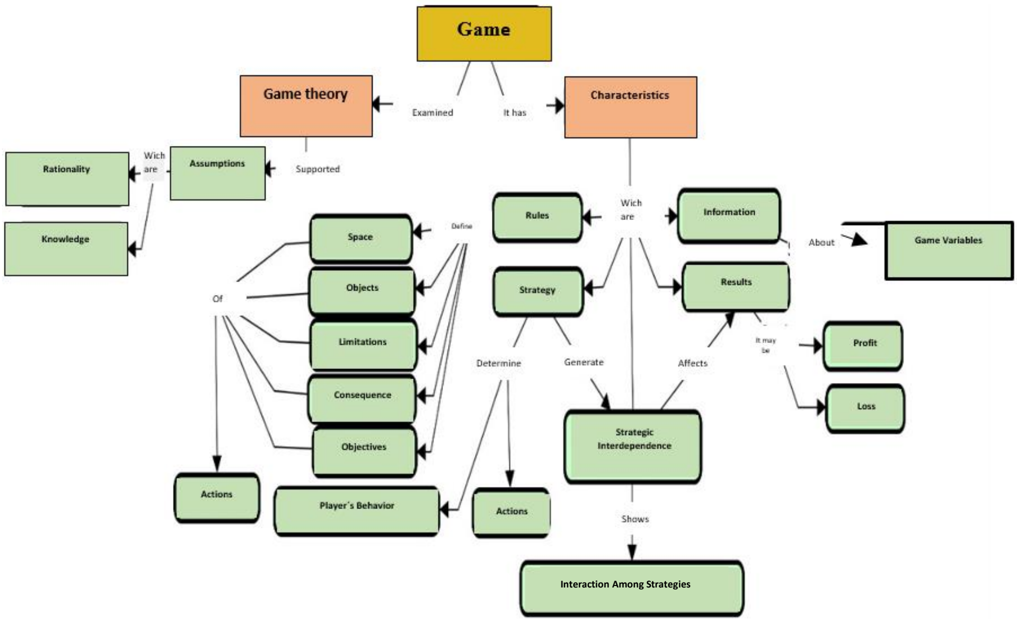

Figure 1. Characteristics of the game
Source: created by the authors from (Waldman & Jensen, 2013)

In the economic theory of markets, "equilibrium" is a concept that indicates that consumers are satisfied with what is offered in the market; given the equilibrium price and quantity, no agent has an incentive to change its behavior. In game theory, a notion of equilibrium is constructed, and several ways exist to formalize it. It was initially proposed by Cournot in the 19th century, in which he posits a "competitive model of several companies competing for the same good, and in which each of them tries to determine the optimal quantity to produce to maximize its profits" (Pindyck & Rubinfeld, 2009, p. 516).

In the early 1950s, John Nash used mathematics to prove the existence of equilibrium in a general way. Nash equilibrium was created, which is reached when none of the players or agents in a game have incentives to change their decision because if they do so, their welfare may worsen. This concept is regularly used in situations of competition between companies (Varian, 2010).

According to Smit & Trigeorgis (2004), game theory can be useful in the analysis of strategic investment decisions for several reasons. First, it can help to reduce a complex strategy problem into a simple analytical structure consisting of different dimensions, identification of players and strategies, the set of available actions and information, and the payoff structure for the possible outcome. Secondly, it is a useful tool for assessing strategic decisions since it encompasses a solution concept that can help understand or predict how competitors will behave. It also provides an equilibrium strategy and values for strategic decisions.

On the other hand, the agents must be clear about the game's structure to determine the players' strategies and the game's solution. Dixit & Nalebuff (1991) propose the following points to be addressed when solving a game:

- Finding the dominant strategies: initially, it is necessary to identify whether a player has strategies or a set of actions that outperform those of all the others, regardless of what the other player does. If the agents present dominant strategies, the solution of the game is less complex, to the point that the outcome of the game can be predicted, because it is possible to find out the optimal strategy of each player without worrying about what the others do (Pindyck & Rubinfeld, 2009).
- Eliminating the dominated strategy: eliminate those strategies that are inferior, i.e., dominated by others, until a unique solution is found. If that solution is not reached, at least the game has been simplified.
- Finding the Nash equilibrium in pure strategies: not all games can be solved by eliminating dominated strategies. Consequently, it is necessary to look for those strategies of each player that are the best response to the strategies followed by the other agents; in other words, to find the Nash equilibrium.
- Finding the Nash equilibrium in mixed strategies: this type of strategy includes chance. An agent uses this type of strategy when they do not want to be completely predictable; what they do is assign probabilities to their actions.
- Backward induction to solve sequential games: this involves analyzing the game from the end to the beginning, making it possible to identify the Nash equilibrium in pure strategies.
- Finding a perfect equilibrium in subgames: this is used for dynamic games, which consist of a player moving before their competitors, and these competitors observe the player's decision before playing.

Smit & Trigeorgis (2004) add further rules to this set of rules: using real options in the backward induction methodology for sequential games in conditions of uncertainty. In this case, the expected utility—a concept widely used in game theory—is replaced by the option value. This new approach makes it possible to value complete strategies in a competitive context in a way that is consistent with modern economics and finance theory.

State of the art of game theory in electricity markets

As mentioned above, Game Theory is a useful technique for modeling generation expansion planning because it helps analyze the behavioral strategies of these agents (Alishahi et al., 2011). With the liberalization, the creation of a competitive market was sought. However, with the presence of economies of scale and the increasing capacity of the companies to bear risks through diversification, the power generation industry tends to be organized as an oligopolistic market, with some agents taking dominant positions (Lopez et al., 2017). These dominant positions are achieved through the exercise of market power, obtaining as a result an increase of their profits above competitive levels, or by raising entry barriers (investments to limit or prevent the entry of new market participants). To do so, participating agents implement various strategies or games, making the modeling of the behavior of oligopolistic markets much more complex to describe and anticipate (Lopez et al., 2017).

This tool has been widely used in different economic sectors, with significant interest in the electricity market. Some proposals oriented to this market will be presented below to give theoretical support to the approach of the games to be developed:

Ferrero and Ramesh (1997) studied the competitive behavior of generators and the eventual coalitions that could be formed. The authors used game theory to simulate the decision-making process to define the prices offered in a deregulated environment. According to the results, participants try to maximize their profits by cooperating in the pool market. The notion that increased competition will contribute to lower operating costs seems to be supported by the results obtained in the paper. Mathematically, increasing competition makes coalition more attractive to all participants. Carpio and Pereira (2006) described the competitive strategies of subsystems in the Brazilian electricity sector. The aim is to present a model in which the operation of each subsystem is managed independently. The decision-making processes are described through game theory. The players or operators of each subsystem carry out their strategies based on the quantities produced, resulting in a Nash-Cournot equilibrium.

Shafie-khah et al. (2013) proposed a virtual energy market model to investigate the behavior of players in this market from the regulator's point of view. The results indicate that it is necessary to simulate the strategic and collusive behavior before any change in the market rules. Ossa (2012) analyzed the strategic behavior of generating agents in the Colombian electricity market. The author shows generators' operational and commercial strategies in the Colombian market. The proposal is made with an analytical scheme using some strategy theories. One of the conclusions of this work is that large generation companies are in a possible dominant position to exercise market power, and therefore, the market is less competitive.

Ferrero and Ramesh (1997) addressed the problem of incomplete information for each generator when setting the price at which they will sell their product. The authors modeled a non-cooperative game with incomplete information, and the problem is solved by computing the Nash-Bayesian equilibrium. Yang et al. (2018) proposed an incomplete information game for pricing strategy among several electricity companies. The authors posited a Bayesian game as it is a suitable method for modeling this type of game and consider consumer participation to balance the electricity market when modeling the cost of the electricity company. Among the results of this work are that the Bayesian game can significantly improve companies' profits and is also suitable for solving the incomplete information problem.

Wolfram (1999) formulated an empirical study of market power in the British electricity industry. The author evaluated the applicability of several oligopolistic models, including the Cournot model. Using that model, Chuang et al. (2001) applied a non-cooperative game for Generation Expansion Planning (GEP) in the electricity sector. The results show a higher system expansion and reliability when there are several players rather than a traditional monopolist. Oliveira (2008) proposed an investment game using the Cournot model in the electricity market. The author analyzed how expectations about the marginal costs of competitors, the level of demand, and the behavior of others influence the value of a project.

Navidi & Bidgoli (2011) proposed a perfect information game with two companies (Retail) competing for quantity and wishing to decide on the optimal quantity of their bids. Chuang et al. (2001) presented an application of the non-cooperative game for Generation Expansion Planning (GEP) in the electricity sector. The results indicate greater industry expansion and system reliability under Cournot competition than under centralized planning. Ventosa et al. (2002) pointed out that when electricity markets are open to free competition, they have few participants, so they conform to an oligopolistic model. The authors developed two alternative models based on game theory for the expansion planning problem. Initially, they proposed two games: the Cournot model and the Stackelberg model (there is a leader company that anticipates the reactions of its followers). The main result is that the leader company invests more and obtains higher profits than the follower company, as indicated by the theory.

García et al. (2013) analyzed the Market Power in Spot Markets for electricity generation in the Colombian market. The authors proposed an exponential model for the supply function, considering variables such as weather, regulation, or costs. Then, they used the convulsion technique (similar to a Kalman filter) and a Cournot model to estimate agents' effects on the spot price, behaving strategically via quantities and making transactions both in the Stock Exchange and in long-term contracts to obtain a higher profit. Venslauskas-Duarte & García (2014) used the System Marginal Price (SMP) to find the optimal quantities to be offered by generators in the spot market and then used these estimates to construct variables such as the Residual Demand Index and the Herfindahl and Hirschman Index. The results show a more strategic behavior of the hydro generators compared to the thermal generators when there is a low demand; this is due to the storage capacity of the hydro generators. In the opposite case, when demand is high, thermal plants are more strategic due to the reduction of hydro resources (water).

Fabra and Toro (2005) analyzed the performance of electricity market prices using the Cournot model. The authors characterize the company's optimal deviations from a collusive agreement, concluding that generators may have obtained a tacit agreement that distorts market outcomes, where the company with higher production levels may have produced at prices below marginal cost. Garcia & Arbelaez (2002) used the dynamic Cournot Model to evaluate the possible impacts of mergers in the Colombian Wholesale Electricity Market on the spot market price. The authors showed an increase in the system marginal price when the capacity offered before the merger is retained. On the other hand, by incorporating high levels of ex-ante contracting into the model, post-merger prices did not increase or decrease below pre-merger prices. Franco-Arboleda (2012) analyzed a short-term wholesale energy market model using game theory based on the Cournot market model and game theory, where the participants in the game are the generating agents.

Lise et al. (2006) developed a static calculus game theory model to investigate the impacts of price, demand, and different types of pollutant emissions in the competitive market. The model is empirically estimated for eight countries in northwest Europe: Belgium, Denmark, Finland, France, Germany, the Netherlands, Norway, and Sweden. The authors analyze the impact of competition on the wholesale price of electricity, electricity demand, company profits, and different types of pollutant emissions based on two types of competition. The results indicate that the effects of liberalization depend on the resulting market structure but that a reduction in the market power of large producers can benefit both the consumer (i.e., lower prices) and the environment (lower greenhouse effect).

Vega (2006) proposed an investment model using a non-cooperative game in a static and dynamic context to simulate a hydro-thermal system based on an Energy Exchange. Blyth et al. (2007) proposed a model based on the analysis of the evolution of the technological market structure in the electricity market. This is done by developing a power plant exchange game, which simulates how players coordinate their behavior in purchasing and selling power generation assets through computational learning. The authors model the electricity market through a Cournot-like game, and one of their conclusions is that a diversified basket leads to greater competition among generators and lower prices.

Motalleb et al. (2018) applied a repeated game-theoretic game to model competition among agents (bidders of energy stored in electrochemical storage cells) and to provide demand response to a system with increasing penetration of renewable energy. The authors consider two types of non-cooperative games: an unregulated game with no constraint on transaction powers and price, and a Stackelberg game with a leader to control transactions between agents and price (like a regulated game). The Stackelberg game is relatively realistic and provides a suitable alternative to current market structures. This model finds the optimal bidding strategy for each firm in a game with incomplete information. The results showed that players' profits decreased in the regulated (Stackelberg) game compared to unregulated competition. Abapour et al. (2020) considered a non-cooperative game with incomplete information for supply-side strategies in response to electricity market demand. This game is solved using Nash equilibrium. The authors show that implementing this method increases the operator's utility by seven (7) percent.

Askari et al. (2015) proposed a model to simulate the restructured energy market. In this study, demand, fuel price, wind uncertainties, and strategic behavior of investors were considered using game theory. A Cournot model is proposed to determine the Nash equilibrium for each stochastic programming state. In addition, the impacts of fixed and variable Feed in Tariff (FIT) as two regulatory policies for wind generation units were considered in the model. The results describe the effect of FIT on the average profit of each investor in each season. In addition, this study showed the incremental effect of the price cap on the total average profit of the restructured power market. This model could be very useful for generation expansion planning.

De Frutos-Cachorro et al. (2020) designed a structural model using optimization and game theory approaches to analyze the uncertainty about the elimination of nuclear power in the Belgian power system and how it affects the investment capacity decisions of Belgian electricity suppliers depending on the type of market structure: Oligopoly (simplified to a duopoly, in this case), Monopoly, and Perfect Competition. The authors show that increases in new electricity generation capacity occur when there is a reduction in nuclear power and higher levels of competition in the market.

Wang et al. (2020) proposed a multilevel (high, medium, and low) generation planning model in the Chinese electricity market. The upper level is shown as a non-cooperative game equilibrium problem from a generation investment decision. The middle level represents the profit maximization problem of generation investment. The authors use linear programming to solve it as a scenario-based multistage market equilibrium model. Considering the fluctuation of the system load, the lower level reveals the market equilibrium problem in multiple scenarios and periods. Given the complexity of the model, this paper proposes a nested genetic algorithm to solve it. The results show that when competition is reduced, agents can reduce investment to create a supply shortage situation and obtain high profits by raising market prices. On the other hand, regulators should do their best to remove barriers to generation investment and attract more investors to enter the market.

Andoni et al. (2021) proposed a game theory model to study the strategic interactions between profit-maximizing players investing in power grids, renewable generation, and storage capacity. The authors model the problem of determining the capacity to be built by each player by posing a non-cooperative Stackelberg-Cournot game between a dominant player (leader), who invests in renewable generation capacity and transmission networks, and local investors, follower agents, who react to the installation of the transmission line by increasing their own capacity. This methodology provides a realistic mechanism for analyzing investor decision-making and investigating viable tariffs that encourage investment in electricity grids for renewable energy. They apply this approach to an electricity grid improvement project in the United Kingdom. Aryani et al. (2021) presented a regulatory tool for coordinating risk-based generation investments in conventional and renewable capacities, considering the regulator's adequacy and environmental conditions objectives. The model is given at two levels. At the first level, the regulator designs investment incentives for conventional and renewable generation by considering investors' responses to regulatory

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decisions. At the second level, a game theory model is considered to capture the competitive interactions between risk-averse generators. The main advantage of the proposed model is that both the regulator's objectives for techno-environmental considerations and the generators' concerns about investment risks are taken into account at the same time in an economic manner.

Table 1 summarizes some of the main contributions in game theory, as outlined above.

Table 1
Studies using game theory methodology in the power generation sector at the international level

Author(s)	Year	Target	Model	Contribution
Ferrero et al.	1997	To study the competitive behavior of the generators and the eventual coalitions formed.	Game Theory	Participants try to maximize their profits by cooperating in the pool market to obtain maximum profits.
Ferrero et al.	1998	To address the problem of incomplete information from each generator when setting the price at which they will sell their product.	Non-cooperative game with incomplete information	The competition is modeled as a non-cooperative game with incomplete information, and the problem is solved by computing the Nash-Bayesian equilibrium.
Wolfram	1999	To present an empirical study of market power in the electricity industry in Great Britain.	Cournot Model	The author evaluates the applicability of several oligopolistic models, including the Cournot model.
Chuang et al.	2001	To present an application of the non-cooperative game for Generation Expansion Planning in the electricity sector.	Non-cooperative game - Cournot model	The results point to a greater expansion and reliability of the system when there are several players than when there is a traditional monopolist.
Ventosa et al.	2002	To develop models for the planning problem related to expansion.	A non-cooperative game: Cournot and Stackelberg models	The main result is that the leading firm in the Stackelberg game invests more and obtains higher profits than in the Cournot game, as the theory indicates.
García & Arbeláez	2002	To evaluate the possible impacts of mergers in the Colombian Wholesale Electricity Market on the spot market price.	Cournot model	The authors show that an increase in the System Marginal Price when the capacity offered before the merger is retained.
Fabra & Toro	2005	To analyze the performance of electricity market prices using the Cournot model.	Cournot Model	Generators may enter into a tacit agreement that distorts market outcomes, in which the company with higher production levels may

				have produced at prices below marginal cost.
Lise et al.	2006	To investigate the impacts of price, demand, and different types of pollutant emissions in the competitive market.	Static game theory	The results indicate that the effects of liberalization depend on the resulting market structure, but a reduction in the market power of large producers can benefit both the consumer (i.e., lower prices) and the environment (lower greenhouse effect).
Vega	2006	To propose a non-cooperative game in a static and dynamic context	Static and dynamic non-cooperative game	The purpose of the model is to simulate a hydro-thermal system based on an energy exchange.
Tapia & Pereira	2006	To present a model in which the operation of each subsystem is managed independently.	Non-cooperative game - Cournot-Nash model	The players or operators of each subsystem carry out their strategies based on the quantities produced, resulting in a Nash-Cournot equilibrium.
Blyth et al.	2007	To develop a model based on the analysis of the evolution of the technological market structure in the electricity market.	Cournot-style game of computational learning	One of its conclusions is that a diversified basket leads to greater competition among generators and lower prices.
Oliveira	2008	To present an investment game using the Cournot model in the electricity market.	Cournot model	The author analyzes how information influences investment. Common knowledge of marginal costs, expectations about competitors' marginal costs, expectations about the level of demand, and the behavior of others influence the value of a project.
Ossa	2012	To analyze the strategic behavior of generating agents in the Colombian electricity market.	Oligopolistic model	One of the conclusions of this work is that large generation companies are in a possible dominant position to exercise market power and, therefore, there is a less competitive market.
Franco	2012	To analyze a short-term wholesale energy market model using game theory.	Cournot Model	It presents a short-term wholesale electricity market model based on the Cournot market model and game theory, where the participants in the game are the generating agents.

Shafie-khah et al.	2013	To propose a virtual energy market model to investigate the behavior of players in the energy market from the regulator's point of view.	Dynamic game model	The results indicate that it is important to simulate collusive strategy and behavior before any changes in market rules.
García et al.	2013	To propose an exponential model for the supply function, considering several variables such as climate, regulation, or costs.	Cournot model	A methodology is proposed according to the Colombian electricity market (exponential model, the convulsion technique—similar to a Kalman filter) and a Cournot model to estimate agents' effects on the spot price, behaving strategically.
Duarte & García	2014	To estimate the marginal price of the Colombian electricity system: a view from industrial organization.	Residual Demand and the Herfindahl-Hirschman Index	The results of the proposal show a greater strategic behavior of hydroelectric plants concerning thermal plants when there is a low demand due to the storage capacity of hydroelectric plants. In the opposite case, when demand is high, the thermal plants are more strategic due to the reduction of resources (water) of the hydroelectric plants.
Askari et al.	2015	To propose a model to simulate the restructured energy market considering demand, fuel price, wind uncertainties, strategic behavior of investors, and fixed and variable Feed in Tariff (FIT).	Cournot model	The authors simulate a model of the uncertainty and impact of both fixed and variable Feed in Tariff (FIT) regulatory policy. The results describe the impact of FIT on average investor profitability and the effect of increasing the price cap on the total average profit of the electricity market.
Yang et al.	2018	To propose an incomplete information game for pricing strategy among several electric utilities.	Bayesian game	The Bayesian game is suitable for modeling situations with incomplete information.
Motalleb et al.	2018	To apply a repeated theoretical game to model competition among agents.	Non-cooperative game - Stackelberg	The results showed that players' profits decreased in the regulated game (leader to control transactions between agents and price) compared to the unregulated competition (no limits).

de Frutos-Cachorro et al.	2020	To design a structural model to analyze the uncertainty about eliminating nuclear power in the Belgian energy system.	Combination of optimization models and game theory	The authors show that increases in new electricity generation capacity occur when there is a reduction in nuclear power and higher levels of competition in the market.
Wang et al.	2020	To propose a multilevel generation planning model in the Chinese electricity market.	Non-cooperative game	The results indicate that, with a reduction in competition, agents can reduce investment by creating a situation of supply shortage and thus raise market prices.
Andoni et al.	2021	To propose a model to study the strategic interactions between players investing in electricity grids, renewable generation, and storage capacity.	Non-cooperative Stackelberg-Cournot model	The model provides a mechanism for analyzing investor decision-making and investigating viable tariffs that encourage investment in electricity grids for renewable energy.
Aryani et al.	2021	To propose a regulatory model to coordinate investments in conventional and renewable generation.	Game Theory	The model considers both the regulator's objectives for techno-environmental considerations and GENCOs' concerns about investment risks.

Source: created by the authors based on the authors cited

The related studies show that modeling oligopolistic markets is useful since it provides a better understanding of the generation market in the competitive context of the sector. This provides an insight into the importance of deepening the analysis of information symmetry or asymmetry when making investment decisions for the leading or following companies. Two investment games are presented below, with complete and imperfect information in three stages, which allow the identification of the players' equilibrium in an oligopolistic market.

Model

For illustrative purposes, an investment game (duopoly) in the electricity market is presented to illustrate the importance of competitive strategy. The description of the example is shown below:

An energy system requires investment in new generation technologies to cover increases in energy demand. The purpose is to promote the entry of new projects (renewable energy) that allow a progressive replacement of units with high costs, such as those that use liquid fuels for those that manage to remedy this situation in the medium and short term.

The current market has one plant, Incumbent (T for *Titular* in Spanish), serving the entire market, with a nominal installed capacity equal to 40 MW with costs equal to C2=4q2. A competing company, Potential Entrant (PE), is interested in entering the market. The Incumbent knows this and decides whether to anticipate the investment to reinforce its position or to let the other enter.

To solve this problem, two investment games have been proposed. The first proposal is a sequential three-stage game with complete information. The second is also a three-stage game but with incomplete information.

Sequential inversion game with perfect information

The game has the following components:

- Players: Two energy generators (Player 1: Potential Entrant and Player 2: Incumbent) competing in a duopoly decide to invest or not to invest in a new capacity. The characteristics of the investment can be seen in the following table.

Table 2
Investment characteristics

Company	Capacity to be Installed (MW)	Price* ($/MWh)	Initial Investment (Millions)**	Plant factor
Incumbent	25	38	140	100%
Potential Entrant	25	38	160	100%

Source: created by the authors
*Electricity prices are calculated considering variable costs, fixed costs, and initial investment. Data are obtained from (IRENA, 2018)

The players know the structure of the game, i.e., the set of actions and payoffs of all players and the rationality of all players.

- Actions: Player 1 (Potential Entrant) must choose between the actions: Invest (I)- Not Invest (NI), and then player 2 (Incumbent), once having observed the Potential Entrant's action, decides whether to invest or not to invest. The players compete in quantities.
- Information: Players know the capacity and costs of each technology. This is a three-stage sequential game. The companies sell homogeneous goods. The actual generation level corresponds to the amount of energy generated in a period, obtained by multiplying the plant's nominal capacity (MW) by the plant factor. There is no weather uncertainty, so the plant factor equals 100%.

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- Strategies: Each player's strategies are as follows:

Player 1: {Invest; Not Invest}.

Player 2: {Invest-Invest; Not Invest-Invest; Invest-Not Invest; Invest-Not Invest; Not Invest-Not Invest}.

- Payouts: Payoffs depend on the players' choices and the type of market that results after making those choices (see Table 3).

Table 3
Criteria for the construction of the Payment Matrix

Action	Strategy	Market Type	New Capacity (MW)	Potential Entrant		Incumbent			Total System Quantity (MW)
				Optimum quantity (MW)	Profit	Total capacity (MW)	Optimum quantity (MW)	Profit	
Potential Entrant Does Not Invest	Incumbent Does Not Invest	Monopoly	0	0	0	40 + 0= 40	Monopoly	Incumbent Profit	40
	Incumbent Invests		0	0	0	40 + 25 = 65	Multiplant Monopoly	Incumbent Profit	65
Potential Entrant Invests	Incumbent Does Not Invest	Duopoly Competition (Cournot Model)	25	Cournot Quantity	Potential Entrant Profit	40 + 0= 40	Cournot Quantity	Incumbent Profit	65
	Incumbent Invests		25	Cournot Quantity	Potential Entrant Profit	40 + 25 = 65	Cournot Quantity	Incumbent Profit	90

Source: created by the authors

Furthermore, the inverse demand is equal to P=100-Q. Total costs of the installed plant are equal to $C_2=4q_2$; and for the new plants: Player 1 (PE): $C_1=500-q_1^2$; Player 2 (T): $C_2=2q_2^2$. With the above information, the game can be represented graphically as in Figure 2.

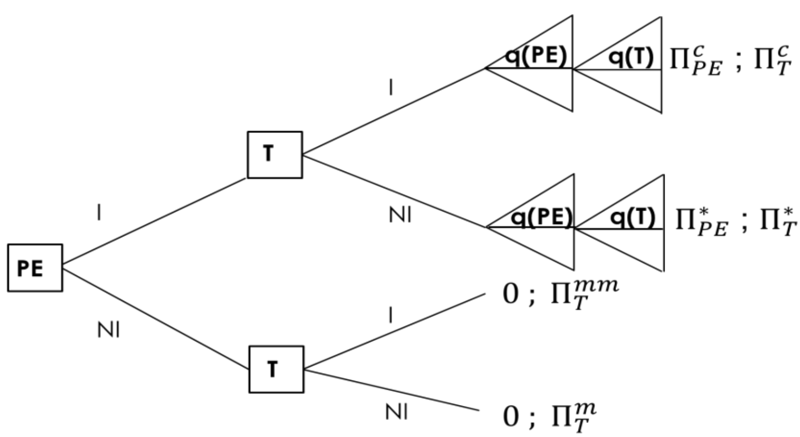

Figure 2. Perfect information set in Extensive Form
Source: created by the authors

The payoffs for each decision are calculated according to the formulas presented in Table 4, and the game is played with the information obtained

Table 4
Calculation of the profits of each decision

Strategy	Calculation of profits
Potential Entrant does not invest; Incumbent does not invest.	$\pi_i^m = (100 - q)q - 4q^2$
Potential Entrant Does Not Invest; Incumbent Invests.	$\pi_i^{mm} = \left(100 - (q_2^{TV} + q_2^{TN})\right)\left(q_2^{TV} + q_2^{TN}\right) - 4q_2^{2TV} - 2q_2^{2TN}$ Where: C_2^{TV}: cost of Titular plant − installed capacity, C_2^{TN}: cost of Titular plant − new plant.
Potential Entrant Invests; Incumbent Invests.	$\pi_i^{PE} = \left(100 - (q_i + q_j)\right)(q_i) - 500 - q_i{}^2$
Potential Entrant Invests; Incumbent Does Not Invest.	$\pi_i^{PE} = \left(100 - (q_i + q_j)\right)(q_i) - 500 - q_i{}^2$

Source: created by the authors

The results obtained are shown in Figure 3.

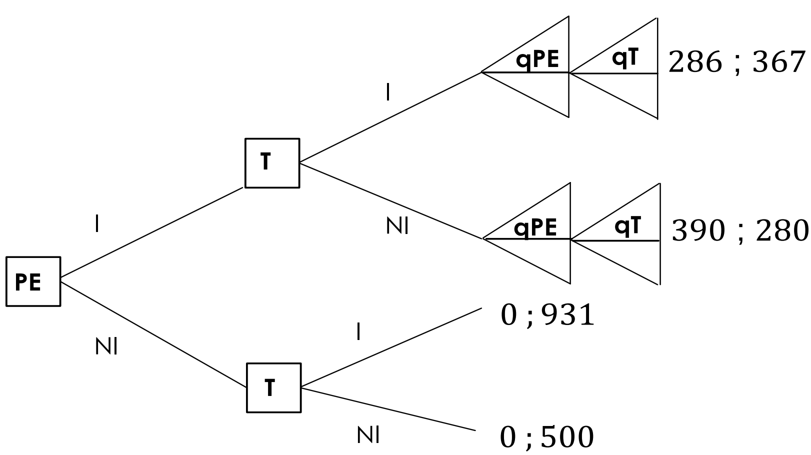

Figure 3. Perfect information set in Extensive form with its respective utilities
Source: created by the authors

To solve this game, the backward induction method is used, starting from the end of the game and finding the optimal decision of the player in the corresponding turn, i.e., moving node by node from the end of the game to the beginning and finding the optimal action in each node. The first to decide is the Incumbent, depending on their payoffs. After performing the backward induction at each node, equilibrium is reached when both companies invest, obtaining a result in their payoffs equal to {286 ; 367} (see Figure 4).

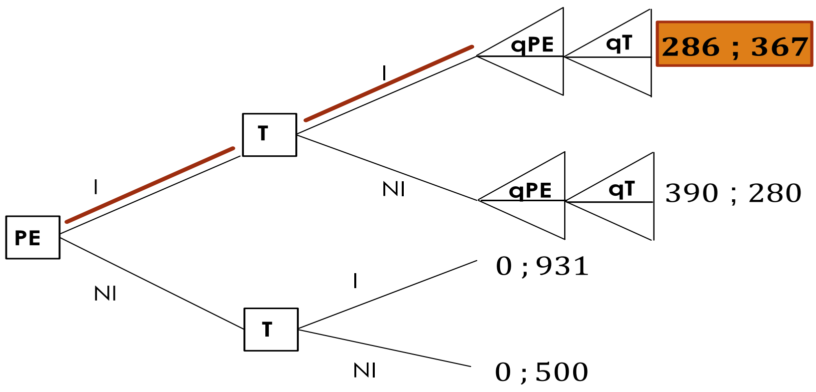

Figure 4. Perfect information game in Extensive form with optimal equilibrium
Source: created by the authors

Sequential investment game with incomplete information

Some technologies, such as hydro, wind, and solar, among others, have the disadvantage of not being able to know exactly the actual electricity generation that can be obtained since their main inputs are water, wind, and sun, and these depend on the weather. The Incumbent company, because of its knowledge of the market, can know the actual power generation, which is reflected by the high plant factor (100%) with a probability of p=½, or low (50%) with a probability of 1-p= ½, but company 2 does not know it. The same assumptions of the previous game are assumed regarding the characteristics of the new plants. Given the above, the game is set up as shown in Figure 5.

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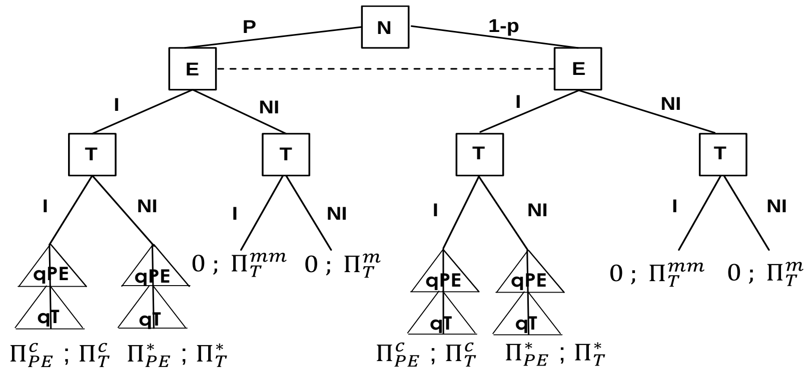

Figure 5. Incomplete information game in Extensive Form
Source: created by the authors

Initially, to develop this game, the payoffs for each decision must be found:

➢ Potential Entrant invests-Incumbent Invests:

e has $\mathrm{P} = 100 - \mathrm{Q};\ \mathrm{C}_{1=}500 - \mathrm{q}_1{}^2.;\ \mathrm{C}_{2=}2\mathrm{q}_2{}^2.$

In this case, company 2 presents two types: high quantity (high plant factor) and low quantity (low plant factor).

Actual Energy Quantity = Capacity x Plant Factor

Payment of company 2, when actual energy quantity is high ($\mathrm{q}_2^{\mathrm{H}}$, plant factor =100%):

$$\pi_2^{\mathrm{T}} = \left(100 - (\mathrm{q}_1 + \mathrm{q}_2^{\mathrm{H}})\right)\left(\mathrm{q}_2^{\mathrm{H}}\right) - 2\mathrm{q}_2^{2\mathrm{H}}$$

$$\pi_2^{\mathrm{T}} = 100\mathrm{q}_2^{\mathrm{H}} - \mathrm{q}_1\mathrm{q}_2{}^{\mathrm{H}} - \mathrm{q}_2^{2\mathrm{H}} - 2\mathrm{q}_2^{2\mathrm{H}}$$

Then the first order conditions are found, obtaining: $\mathrm{q}_2^{\mathrm{H}} = \frac{100-\mathrm{q}_1}{6}$, then it is multiplied by the plant factor:

$$\mathrm{q}_2^{\mathrm{H}} = \left(\frac{100 - \mathrm{q}_1}{6}\right) * 100\% = \left(\frac{100 - \mathrm{q}_1}{6}\right) \tag{1}$$

Payment of company 2, when actual energy quantity is low ($\mathrm{q}_2^{\mathrm{L}}$, plant factor =50%):

$$\pi_2^{\mathrm{T}} = \left(100 - (\mathrm{q}_1 + \mathrm{q}_2^{\mathrm{L}})\right)\left(\mathrm{q}_2^{\mathrm{L}}\right) - 2\mathrm{q}_2^{2\mathrm{L}}$$

Then, the first order conditions $\mathrm{q}_2^{\mathrm{L}} = \frac{100-\mathrm{q}_1}{6}$ are obtained. This result is multiplied by the plant factor:

$$\mathrm{q}_2^{\mathrm{L}} = \left(\frac{100 - \mathrm{q}_1}{6}\right) * 50\% = \left(\frac{100 - \mathrm{q}_1}{12}\right) \tag{2}$$

Now, the optimal quantity of company 1 must be obtained:

$$\pi_1^{PE} = \frac{1}{2}((100 - (q_1 + q_2^H))(q_1) - 500 - {q_1}^2) + \frac{1}{2}((100 - (q_1 + q_2^L))(q_1) - 500 - {q_1}^2)$$

The first-order conditions are obtained, getting the following result:

$$q_1 = \frac{200 - q_2^H - q_2^L}{8} \tag{3}$$

Now replacing (1) and (2) in (3), the result is:

$$q_1^* = \frac{2100}{93} = 22.508 = 23 \tag{4}$$

The above information is used to determine the profits of each company.

- Potential Entrant Invests-Incumbent Does Not Invest:

The Incumbent does not Invest in new capacity, $q_2^H = q_2^L = 0$

$$\pi_1^{PE} = \frac{1}{2}((100 - (q_1 + q_2^H))(q_1) - 500 - {q_1}^2) + \frac{1}{2}((100 - (q_1 + q_2^L))(q_1) - 500 - {q_1}^2)$$

The first-order conditions are calculated to find the quantities. The same procedure is done to find the Incumbent quantities. After determining the optimal quantities, the profits of each player π_1^{PE} and π_2^T are found.

- Potential Entrant does not invest - Incumbent does not invest: In this case, the Incumbent company still holds the monopoly. The following was developed to find the profits:

The monopolist's revenue is $I(q) = P(q) * q$, $P = 100 - q;\ C_2 = 4q_2$. The payoff of company 2, when real energy quantity is high (q_2^H, plant factor =100%):

$$\pi_2^{mT} = (100 - q_2^H)(q_2^H) - 4q_2^{2H}$$

The payment of company 2, when real energy quantity is low (q_2^H, plant factor =50%):

$$\pi_2^{mT} = (100 - q_2^L)(q_2^L) - 4q_2^{2L}$$

The profits of the PE are equal to zero since it does not invest.

- Potential Entrant Does Not Invest - Incumbent Invests: this case is a Multiplant monopoly. $P = 100 - Q;\ C_2^{TV} = 4{q_2}^2;\ C_2^{TN} = 2{q_2}^2$.

Where: C_2^{TV}: cost of Incumbent plant − installed capacity, , C_2^{TN}: cost of Incumbent plant − new plant. The initial investment cost of the new plant is 140.

Payment of company 2, when actual energy quantity is high (plant factor =100%):

$$\pi_2^{mm} = (100 - (q_2^{TV} + q_2^{TN})) * (q_2^{TV} + q_2^{TN}) - 4q_2^{2TV} - 2q_2^{2TN}$$

Payment of company 2, when actual energy quantity is low (plant factor =50%):

$$\pi_2^{mm} = (100 - (q_2^{TV} + q_2^{TN})) * (q_2^{TV} + q_2^{TN}) - 4q_2^{2TV} - 2q_2^{2TN}$$

After obtaining the payoffs of each decision, the equilibrium of this game can be calculated (see Figure 6).

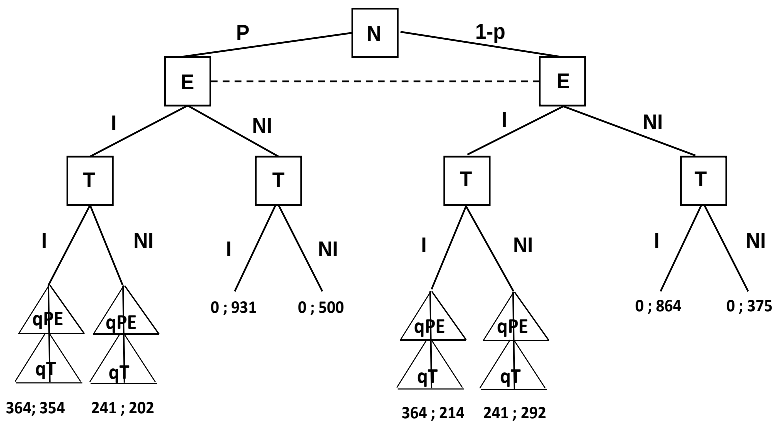

Figure 6. Incomplete information game in Extensive form, including payments
Source: created by the authors

This game has the representation of Harsanyi (1967), where N corresponds to a move from nature.

The strategies of each player are:

Player 1 (Potential Entrant): {Invest; Not Invest}.

Player 2 (Incumbent): {Invest-Invest; Not Invest - Invest; Invest - Not Invest; Not Invest - Not Invest}.

The strategic form of the game, given the defined strategies, is in Table 5:

Table 5
Strategic form of the game of incomplete information

		Player 2 (T)			
		I-I	NI-I	I-NI	NI-NI
Player 1 (PE)	I	364 ; 284	303 ; 208	303 ; 323	241 ; 247
	NI	0 ; 898	0 ; 682	0 ; 653	0 ; 438

According to the above results, it is observed that:

For Potential Entrant strategy, I dominates NI. The best strategy for PE is I.

For Incumbent: Type 1: NI is preferable to I: INI dominates II, INI dominates NINI

For Incumbent: Type 2: NI is preferable to I: INI dominates II, INI dominates NINI

In this case, there is a Nash equilibrium in pure strategies: {I ; I-NI}

Conclusions

Through the development of this proposal, it can be corroborated that decisions in oligopolistic markets are interdependent and face the strategic behavior of competitors, creating spaces of interest for the analysis of information asymmetry.

According to the works presented, it is observed that non-cooperative games and oligopolistic models—especially Cournot's model—are widely used to describe this type of market operation. It is also important to mention that the knowledge of the information can affect the value of the project. Furthermore, regarding the energy market, there is the possibility of a greater expansion of the sector by increasing the number of investors, and therefore, greater security can be provided to the system.

When all the information is available, the balance for Potential Entrant and Incumbent investors is to invest since it is better for the Incumbent to invest if it enters into competition, for it will obtain a higher profit compared to the strategy of not investing. Moreover, this company must manage its market share to retain its customers. This game does not entail uncertainty due to market conditions or external variables such as weather, so the quantities offered are higher.

The incomplete information game, the equilibrium of the game, in pure strategies, is {I ; I-NI}. The strategy Invest dominates Not Invest for player 1 (Potential Entrant). Not Invest dominates Invest for player 2 (Incumbent).

The Incumbent company receives a higher profit when the Potential Entrant does not invest. This profit is even higher when it is a Multiplant monopoly, i.e., Incumbent invests. The Potential Entrant company will obtain a higher profit if the initial investment is slightly lower and it does not pay a fee for entering the market.

Uncertainty can affect agents' decisions because they cannot predict their actions' effect on the other player (even if they assume that the other participants will act rationally).

The proposal of this investment game only contemplates the uncertainty of competition among agents. For further analysis and better results, other methodologies are proposed, such as Game Options, which combine Real Options with game theory. With the Game Options methodology, the investor will obtain a more complete evaluation for investment decision making because this tool incorporates the flexibility and uncertainty of the market and the strategic interaction between economic agents, in this case, the investment generators.

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