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The value of information in electricity investment games.

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The Value of Information in Electricity Investment Games

By

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ABSTRACT: In this paper we look at the assumptions behind a Cournot model of investment in electricity markets. We analyze how information influences investment, looking at the way common knowledge of marginal costs, expectations on the competitors' marginal costs, expectations on the level and duration of demand, and conjectures on the others' behavior, influence the value of a project. We expose how the results are highly dependent on the assumptions used, and how the investment Nash-Cournot game with perfect and complete information implies such a degree of coordination between players that the outcome of the game would be classified by any regulation law as collusive behavior. Furthermore, we introduce the concept of Nash Value of Complete Information. As an example we use a stylized model of investment in liberalized electricity markets.

KEYWORDS: Cournot, Dynamic, Electricity, Game, Investment**.**

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1. INTRODUCTION

With liberalization, the electricity industry changed from a regulated monopoly, vertically integrated, and managed as to maximize social welfare, to a complex system of interacting players in which each one of them attempts to maximize profit (within the limits of the new market rules, generally overseen by a regulator). Generally, the new structure of this industry has been design to generate a self sustainable system of interacting firms who are able to decide how much to generate in each hour, and how much to invest in order to guarantee the long-term sustainability of the industry.

Such an important change in the nature of the electricity industry came with a shift in the modeling tools used to analyze decision making. These tools evolved from the centralized optimization paradigm of the unit commitment problem and investment planning to the decentralized paradigm based on game theory, including Bertrand games (e.g., Bunn and Oliveira, 2003), supply function games (e.g., Green and Newberry, 1992; Anderson and Philpott, 2002) and Cournot games (e.g., Ramos et al. 1998; Borenstein and Bushnell, 1999; Bunn and Oliveira, 2007). The complexity of the new problems faced by the newly privatized industry has required the use of other techniques such as risk analysis (e.g., Fleten et al., 1997), real options (e.g., Frayer and Uludere, 2001; Botterud, 2004; Botterud et al., 2005; Bøckman et al., 2007; Dyson and Oliveira, 2007), agent-based simulation (e.g., Nicolaisen et al., 2001; Bunn and Oliveira, 2001; Son and Baldick, 2004; Guerci et al., 2005; Chen et al., 2006) and system dynamics (e.g., Larsen and Bunn, 1999; Dynar and Larsen, 2001), among others.

The Cournot model of imperfect competition has arguably been the most successful one, mostly due to its mathematical tractability and ability to represent well short-term problems well. For example, it has been used to model inter-temporal decision making (e.g., Allaz and Vila, 1993) and geographical competition (e.g., Hobbs, 2001). Moreover, the Cournot model has been extended by the conjectural variations approach (e.g., Day et. al., 2002; Song et al., 2003; Centeno et al. 2003b, Centeno et al., 2007), in order to use it in practice. The conjectural variations method explains how the players' perceptions of the reaction functions of their opponents are important to explain the outcome of a game.

However, due to the lack of robustness of equilibrium models when applied to capacity expansion problems, imperfect competition are usually not used to study capacity expansion (Centeno et al., 2003a). For this reason, only a few game theoretical models of imperfect competition have looked at the investment problem (e.g., Ventosa et al., 2005) by using a

Stackelberg (Ventosa et al., 2002) or a Cournot approach (e.g., Chuang et al. 2001; Pineau and Murto, 2003; Centeno et al., 2003a; Murphy and Smeers, 2005).

These models tend to rely on very strong assumptions regarding the information available to the players and their reasoning abilities. More specifically, games based on the concept of Nash-Cournot equilibrium rely on the basic assumption of common and complete knowledge of the structure of the game (payoffs, number of players, rules of the game). In these models it is assumed that all the players know all the payoffs associated with each decision (both for them and for their competitors). There is a complete and common knowledge of the other players' costs, profit and reaction functions.

The main advantage of these strong assumptions are the development of transparent and solvable models, which are indeed realistic for the analysis of models of short-term decision such as spot and forward markets, bidding behaviors in auctions and short-term pricing policies. In fact, the assumption of complete information is not as questionable in short and mid-term models as in long-term models. However, their usefulness in the context of investment in electricity markets is problematic, let us see why:

a) In reality there is no complete knowledge of costs. Even though there may be a consensus around the merit order of the different technologies at a given moment, it is harder to defend that firms *agree* on the future costs. The Nash-Cournot models proposed so far for electricity markets assume that the firms agree on the level of marginal cost that should be used in the model, i.e., if a firm is modeling an investment it uses the same cost parameters (marginal costs) as the other firms in the industry.

b) It is also difficult to argue that firms can agree on the expected level and elasticity of demand. Even though the level of demand in the short and medium-terms can be forecasted with great accuracy, a very long-term forecast (over thirty years) is harder to be common knowledge of the industry. Moreover, the low elasticity of demand and the relatively small range of retail price variation make it hard to assume that there is a common knowledge of elasticity of demand. This elasticity tends to be based on guess work or, at the most, selected in such a way that the model produces acceptable outcomes (prices and levels of production).

c) Common knowledge of reaction functions. It is assumed that everyone agrees on the conjectures a player holds on the other players' behavior. This means that the players tell each other how they perceive the other players will behave.

d) From a), b) and c) it is easy to conclude that a Nash-Cournot equilibrium implies a level of explicit coordination of behavior and information sharing between players that is not acceptable under any regulation law (see Appendix for details).

The aim of this paper is to evaluate how these assumptions influence the way a firm values a project. More specifically, we want to analyze how important is the assumption of perfect rationality in models of investment. Within this framework we analyze how information influences investment, looking at the way common knowledge of marginal costs, expectations on the competitors' marginal costs, expectations on the level and duration of demand, and conjectures on the others' behavior, influence the value of a project. We relax these assumptions, one by one, and analyze how the main results of our analysis change. The results obtained in this study are for a very simple case (from Murphy and Smeers, 2005) which is enough for a qualitative analysis but of course cannot be used to obtain quantitative conclusions.

We show that, in games, complete information can have a negative value and that misinformation can have the same impact on consumer welfare as explicit collusion by generation companies. The analysis of the sensitivity of the model to its parameters also reveals that a small forecasting error in the long-term marginal costs can have a very significant impact on the technological mix of the industry, most particularly when it implies a change in the merit order of the technologies (the rank of technologies by generation cost). Similar conclusions arise from the analysis of the parameters relating to electricity demand, such as the level of peak demand and its duration. We show that the model is extremely sensitive to the level of demand and just a small change carries a very strong impact on the level of investment. This is particularly disturbing as this parameter cannot be estimated with any reasonable certainty: this implies that any long-term models of investment are dependent on an unknown parameter to which the model is very sensitive. The duration of peak demand has also a significant impact on the level of investment (again, this parameter is associated with high uncertainty).

The paper is structured as follows. In section two, we present a background on modeling investment in electricity generation and, more specifically, we introduce the simple investment game used in this paper. In section three, we present the concept of the Nash Value of Complete Information. In section four, we present the computational experiments. Finally, section five concludes the paper.

2. A DYNAMIC INVESTMENT GAME MODEL FOR ELECTRICITY MARKETS

Following Murphy and Smeers (2005), we model investment in electricity markets as a dynamic Cournot game in which each player decides how much to generate from each plant he owns, and how much to invest in each technology (we look at the open-loop Cournot model). We use a single-clearing Cournot game in which there is one clearing price for each hour of the day. This model simulates a game in which each player defines how much to sell at each hour (for different levels of demand), given the portfolio of plants owned. More specifically, we study what happens when the players do not hold the same expectation regarding demand profiles (for the level, elasticity or duration) and marginal costs, or when the conjectures regarding the players' behaviors are not consistent. (We believe this is an important analysis as there is no guarantee that in real markets the players' conjectures are consistent.)

2.1 The Open-Loop Cournot Model

The open-loop Cournot model is a stylized and simple representation of the problem of investment in electricity markets. This model has two main components: an investment game in which each firm decides how much to invest in a given technology, given its expectations regarding future demand, marginal costs, and conjectures on the opponent's behavior; an electricity market game in which each firm decides how much to sell in each one of the demand blocks of a typical year. As Murphy and Smeers (2005) explain there are two different ways to interpret this model: capacity is simultaneously built and sold using long-term contracts; the levels of investment and generation are decided simultaneously.

In this section, we assume that each player owns a different technology and investment is modeled as an open-loop Cournot game. In this model, we approximate the load duration curve with segments, $l = 1, \ldots, L$, as represented in Figure 2.1. In this dynamic Cournot game we model a typical generator seeking to maximize the value of his portfolio of power plants as a whole. Each player i chooses his output $Q_{i,l}$, in segment l, which is characterized by a certain demand, and the quantity invested by player i, I_i.

Let C_i and W_i stand for, respectively, the marginal cost and the investment cost of player i.

Further let A_l and α_l represent the intercept and slope of the inverse demand function, and D_l stand for the duration of segment l.

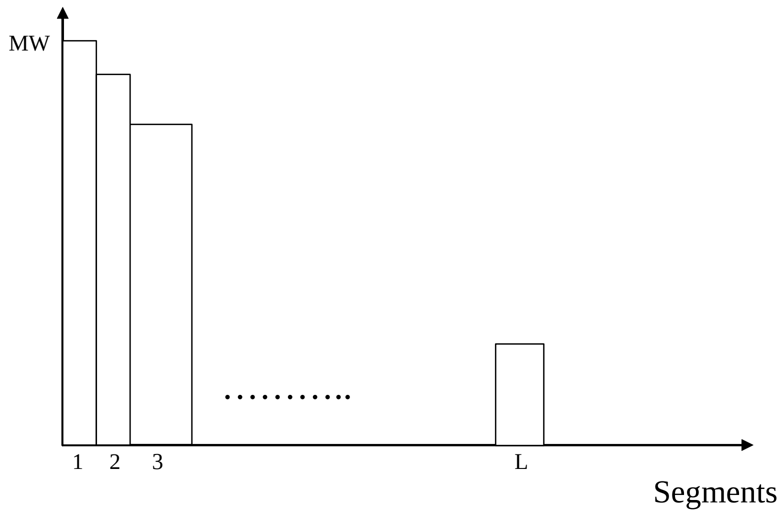

Figure 2.1: Demand Segments that Approximate the Load Duration Curve

The single-clearing market mechanism (uniform auction) allows only one price for any given trading period: a player receives the same price, P_l, for the electricity generated by any plant selling in segment *l*. For a player *i*, the profit (π_i) maximization problem is represented by equations (2.1). The *L* segments partition the yearly demand into blocks representing the duration of demand (these may have different lengths). Moreover, for each one of the demands segments there is an associated demand (here assumed linear, as in Murphy and Smeers, 2005), see Figure 2.2.

$$\begin{aligned}
&\max_{Q_{i,l}, I_i} \pi_i = \sum_l \left[(P_l - C_i) Q_{i,l} . D_l \right] - W_i . I_i \\
&s.t. \\
&P_l = A_l - \alpha_l \sum_p Q_{p,l}, \forall l \\
&0 \le Q_{i,l} \le I_i, \forall i, l
\end{aligned} \tag{2.1}$$

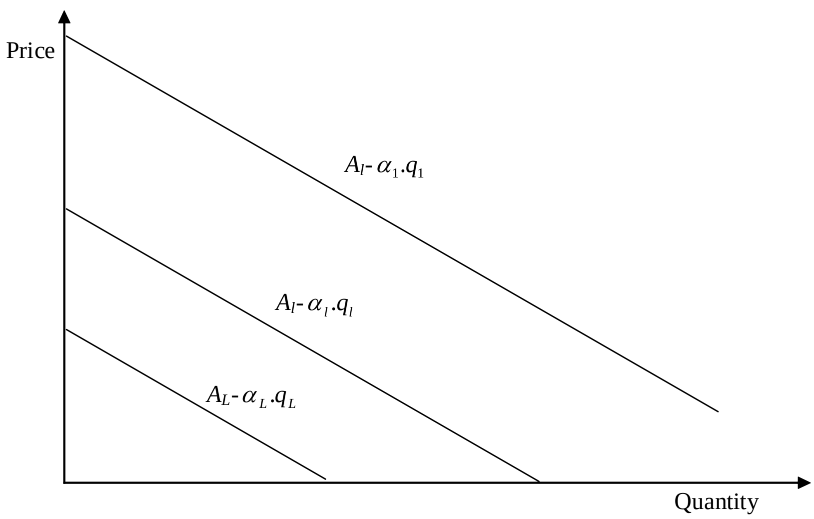

Figure 2.2: Demand Level per Segment

In order to compute the Cournot-Nash equilibrium of this investment game we need to write down the Lagrangian, see equation (2.2), and compute the short-term (2.3) and long-term (2.4) derivatives. In equation (2.2), $\overline{\lambda_{i,l}}$ and $\underline{\lambda_{i,l}}$ represent, respectively, the shadow price for the upper-bound and lower-bound on the generation of player *i*, for market *l*.

$$F_i = \sum_l \left[(P_l - C_i) Q_{i,l} . D_l \right] - W_i . I_i + \sum_l \overline{\lambda_{i,l}} . \left(I_i - Q_{i,l} \right) + \sum_l \underline{\lambda_{i,l}} . Q_{i,l} \ . \qquad (2.2)$$

The short-term optimal condition is computed by calculating the first derivative of the Lagrangian with respect to the quantities generated in each period and making it equal to zero, i.e., $\frac{dF_i}{dQ_{i,l}} = 0$, the result of which is represented by equation (2.3).

$$D_l \left[A_l - C_i - (2 + V_i) \alpha_l Q_{i,l} - \alpha_l \sum_{\substack{p=1, \\ p \neq i}}^{P} Q_{p,l} \right] - \overline{\lambda_{i,l}} + \underline{\lambda_{i,l}} = 0 , \quad \text{for all } i \text{ and } l. \qquad (2.3)$$

In equation (2.3), V_i represents the conjectural variation (Bowley, 1924) that player *i* uses to represent the behavior his opponents: it represents how this player expects the other players to react if he changes his production by one unit, $V_i = \frac{d \sum_{j \neq i} Q_{j,l}}{dQ_{i,l}}$, for all *l*. (An extensive analysis of conjectural variations can be found in Boyer and Moreaux, 1983; Bresnahan, 1981; or Perry, 1982. In electricity markets, conjectural variations have been used to model spot and geographical competition, e.g., Day et. al., 2002; Song et al., 2003; Centeno et al., 2003b; Centeno et al., 2007).

The Cournot model corresponds to conjectures in which $V_i = 0$. In this case, when a player behaves *a la* Cournot he conjectures that the decisions of the several players are independent of each other and no player reacts to variations in the production level of the other players, i.e., V_i = 0. In the case of cooperative conjectural variations, players coordinate their generation decisions so that the industry as a whole produces the monopoly solution. This translates in a conjectural variation of V_i = 1. In the case of perfect-competition conjectural variations each player conjectures that if he reduces generation in one unit that unit will be produced by his competitors, so that price remains constant and the player has no market power. In this case V_i =

-1. The use of conjectural variations may also enable the simulation of the behaviour of real markets, in which these conjectures are changed so that simulated prices approximate real prices.

Other important conjectural variations in electricity markets are those implicit in the Bertrand model, which assumes infinite conjectural variations; and the Stackelberg model which assumes zero conjectural variation for the follower and finite conjectural variation for the leader. The Bertrand case is particularly interesting as it shows that the Bertrand game can be modelled by the same basic model as the Cournot game, just with different conjectures. Usually, real oligopolistic electricity market can be modelled with conjectural-variations between -1 and 0.

The long-term condition is computed by calculating the first derivative of the Lagrangian with respect to investment, in each technology at time zero, and making it equal to zero, i.e. $\frac{dF_i}{dI_i}=0$, the result of which is represented by equation (2.4).

$$W_i = \sum_{l=1}^{L} D_l \overline{\lambda_{i,l}}\,, \qquad \text{for all } i. \tag{2.4}$$

2.2 The Open-Loop Cournot Model with Multiple Technologies

The open-loop game with multiple technologies relaxes the assumption in (2.1) which only allows a given player to hold one technology. In this model, each player *i* chooses his output from generation technology *g*, $Q_{i,g,l}$, in segment *l*, which is characterized by a certain demand, and the quantity invested by player *i* in technology g, $I_{i,g}$. Let $C_{i,g,}$ and $W_{i,g,}$ stand for, respectively, the marginal and the investment costs in technology *g* by player *i*. Then, for this player *i*, the profit (π_i) maximization problem is represented by equations (2.5).

$$\begin{aligned}
&\max_{Q_{i,g,l},I_{i,g}} \pi_i = \sum_l \sum_g \left[\left(P_l - C_{i,g}\right)Q_{i,g,l}.D_l\right] - W_{i,g}.I_{i,g} \\
&s.t. \\
&P_l = A_l - \alpha_l \sum_p \sum_g Q_{p,g,l}\,, \forall l \\
&0 \le Q_{i,g,l} \le I_{i,g}\,, \forall i,l,g
\end{aligned} \tag{2.5}$$

Furthermore, let $\overline{\lambda_{i,g,l}}$ and $\underline{\lambda_{i,g,l}}$ represent, respectively, the shadow price for the upper-bound and lower-bound on the generation from technology *g* by player *i* for market *l*. Then, the KKT conditions can be derived as in Section 2.1. Equations (2.6) and (2.7) represent, respectively, the short and long-term equilibrium conditions, in which $V_i = \frac{d\sum_{j\neq i}\sum_g Q_{j,g,l}}{dQ_{i,g,l}}$, for market *l*.

$$D_l\left[A_l - C_{i,g} - (2+V_i)\alpha_l \sum_g Q_{i,g,l} - \alpha_l \sum_{\substack{p=1,\\ p\neq i}}^{P}\sum_g Q_{p,g,l}\right] - \overline{\lambda_{i,g,l}} + \underline{\lambda_{i,g,l}} = 0, \text{ for all } i, g, l. \qquad (2.6)$$

$$W_{i,g} = \sum_{l=1}^{L} D_l \overline{\lambda_{i,g,l}}, \quad \text{for all } i \text{ and } g. \qquad (2.7)$$

3. THE NASH VALUE OF COMPLETE INFORMATION

Raiffa and Schlaifer (1961) defined the concept of expected value of perfect information (EVPI) presented in equation (3.1), in which $E\left\{\max_a \pi_{a,s}\right\}$ represents the expected profit under perfect information (as for each possible value of the uncertain parameter, *s*, the firm chooses an action, *a*, that maximizes its profit), and $\max_a E\left\{\pi_{a,s}\right\}$ represents the expected profit under previous information.

$$EVPI = E\left\{\max_a \pi_{a,s}\right\} - \max_a E\left\{\pi_{a,s}\right\} \qquad (3.1)$$

The expected value of perfect information enables the firm to evaluate how much it is willing to pay in order to reduce uncertainty regarding future outcomes. In this paper, we propose a similar concept, the Nash Value of Complete Information (NVCI), presented in equation (3.2), to evaluate the loss of profit resulting from the lack of information regarding certain parameters defining the structure of the investment game.

NVCI =	Profit under the Correct Nash Equilibrium - Profit under the original decisions	(3.2)

We now look at the meaning of the NVCI under different problems. Similarly to the EVPI, the NVCI represents the value a player is willing to pay for information that reduces uncertainty regarding the value of some parameters.

There is, nonetheless, a big difference between these two concepts. Whereas the EVPI implies that a firm can get some extra information that can improve its knowledge about the problem it is facing, in the case of the NVCI the knowledge is shared by all the players in the game. This is one of the main characteristics of the Nash-Cournot games as they assume common knowledge of the structure of the game: *if one player gets information regarding one of the parameters all the other players will share this information.*

This is a very important difference, as one of the surprising results of our analysis is that the NVCI can have a *negative value* to all or to some of the players. A negative value of the NVCI means that a player is worse off if the correct value regarding some information is available: it is actually better for the player to decide under the wrong information set. This negative value results from the fact that the player's profit is worsened by his opponents' ability to make better decisions, under the new information set.

Moreover, the NVCI can be simultaneously negative for all the players in the game. In this case all the players are simultaneously better if they decide under the wrong information set. This is quite puzzling. So why does it happen? The intuition behind this strange behavior is that misinformation has the same outcome as collusive behavior. For example, it is profitable for the players to collude into a total production less than the Cournot output, for example to the monopoly solution. This same result can be obtained if the players underestimate the level of demand in such a way that the Cournot production in the estimated game equals the monopoly production in the correct model.

4. COMPUTATIONAL EXPERIMENTS

In this section we use simulation to look at the impact of marginal costs, level of demand, duration of the demand blocks, and conjectural variations, on the outcome of the game. The basic demand parameters used in these experiences are as follows. We split demand into three different levels, peak, shoulder and baseload (times t_1, t_2 and t_3, respectively). The durations of each one of these segments of demand are for peak 760 hours/year, for shoulder 3000 hours/year and for baseload 5000 hours/year. The intercept of demand, $A(t)$, is also defined for each segment: it is 40 for peak demand, 28 for shoulder demand, and 22 for baseload demand. The slope of demand, α , is the same for each segment and equal to 0.001.

The parameters for the investment cost in thousands of monetary units per MW/year (000 m.u./MW/year) are: 170 for baseload plants, 55 for shoulder plants, 4 for peak plants. The marginal costs, in monetary units per MWh (m.u./MWh) are equal to: zero for baseload plants, 15 for shoulder plants and 30 for peak plants.

4.1. Analyzing the Forecasts for Marginal Costs

We start by looking at the sensitivity of the results to the forecasts regarding the marginal costs (assumed constant) during the period of the investment. We analyze a game with three firms (Player 1, Player 2 and Player 3) in which the marginal costs can assume different values for the six scenarios presented in Table 4.1.

In Table 4.1 we assume that, in scenario S1, Player 1 invests in baseload plants (with marginal costs of zero), Player 2 invests in shoulder plants and Player 3 invests in peak plants. We look at the impact of changes in the marginal costs of shoulder and peak plants on the level of investment of each player. In scenario S1 the shoulder technology is cheap when compared with the other two technologies. On the opposite side of the spectrum, in scenario six the peak technology is relatively cheap when compared with the other two technologies.

Marginal Cost per m.u./MWh						
	S1	S2	S3	S4	S5	S6
Player 1	0	0	0	0	0	0
Player 2	5	10	15	15	15	15
Player 3	20	25	30	20	15	10

Table 4.1: Marginal Costs for the Different Scenarios.

The aim of this first set of experiments is to test the impact of changes in the expected marginal cost on the merit order and on the level of investment in each technology, calculating how the assumption of complete information influences the final outcome of the game. Figure 4.1 shows that, in equilibrium, the player investing in the cheaper technology (when combining marginal and investment costs) is the one that invests the largest volume. In scenario 1 the baseload technology is not used as it is not competitive and all the investment is directed to the shoulder and peak technologies. In scenario six all the investment is directed to the peak technology (the cheapest one). In the other four scenarios investment is more significant in the cheapest technology.

So far, the results are as expected. The important question we want to ask relates to the impact of the expectations regarding marginal costs on the value of the investment project for each player. Let us assume that scenario S3 is the base case on which the three players are planning their investment. In order to evaluate the Nash Value of Complete Information we compare the profit received by players in the correct scenario (when everyone knows and agrees this was the correct scenario) with the profit received when the players are wrong and decide the level of investment and generation not using the correct information, but assuming as correct the base case (scenario S3).

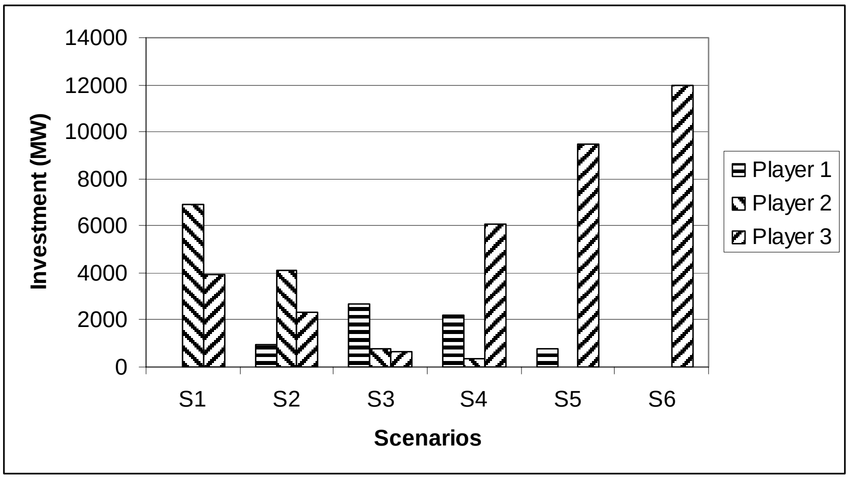

Figure 4.1: Investment as a function of the merit order

The results of this experiment, regarding the Nash Value of Complete Information, are depicted in Figure 4.2. Obviously, in the correct scenario (scenario 3) the NVCI is zero, as all the decisions are correct. If the correct scenario is 1, then by deciding as if scenario 3 is correct the players commit a forecasting error. In this case, for players 2 and 3 the NVCI is positive: had they known that scenario 1 was the correct one they could have improved their profits, as they underinvested. For player 1, the NVCI is negative. In this case, the NVCI is negative as, in scenario 3, player 1 has some profitable investment whereas, in scenario 1, his profit is zero, as there is no investment. The reason for the negative NVCI is that the errors are committed by all the players simultaneously. A player has a negative NVCI when he benefits from the mistakes made by his opponents.

In these experiments, firms' whose technology will become more expensive in the future do *not* benefit from complete information: if all the players believe that this is a cheap technology (i.e., cheaper than it will be in reality), in equilibrium, the player choosing this technology invests a large quantity, and the other players reduce their investment in alternative technologies. If this forecast is not correct, and the technology is relatively more expensive than expected, then, as the other players are already committed to a lower level of investment, the player owning the expensive technology has higher profits. On the other hand, firms' whose technology will become cheaper in the future benefit from complete information: if everyone knows that that a technology is cheaper, the player choosing it can invest more, and symmetrically, his opponents will invest less in the alternative technologies, in equilibrium. Therefore, for the same level of demand, the player has a higher level of more effective investment. Consequently he has higher profits and, therefore, a positive NVCI.

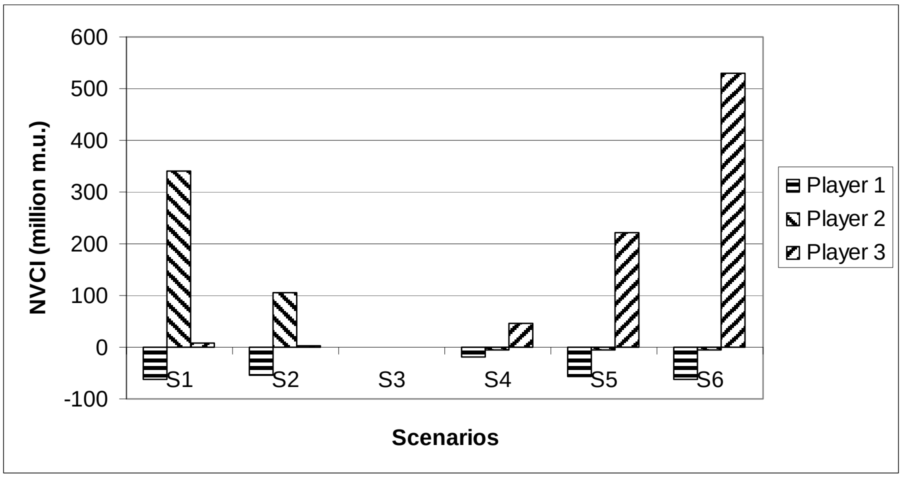

Figure 4.2: NVCI and the Expectations Regarding Marginal Costs

4.2. Analyzing Peak Demand Forecasts

Consider the basic scenario in which the level of demand, $A(t)$, is defined differently for each segment, respectively: peak (40), shoulder (28) and baseload (22). The slope of demand, $\alpha(t)$, is assumed to be the same for each segment and equal to 0.001. In this set of experiments, we compare the value of investment and information for different values of $A(peak)$. We test several parameters ranging from a reduction of 12.5% to an increase of 25%.

Figure 4.3 presents the relationship between the change in the average level of demand for the peak segment and investment. In this figure the base scenario has a zero percentage change in demand level. As expected, higher levels of demand lead to more investment, this is true for all the technologies but it is particularly true for the peak player.

The impact of a small change in the demand level is impressive: a 5% increase leads to a 150% increase in the level of investment in peak plants; a 12.5% increase in the level of peak demand leads to an increase of almost 400% in the investment in peak plants; a 25% increase in the level of demand leads to almost a 800% increase in the investment in peak plants. Moreover, a decrease of only 5% in the level of demand leads to the disappearance of the entire peak technology, as no investment occurs under this scenario (the same is true for a reduction of 12.5% in the level of peak demand). Investment in baseload is not very sensitive to peak prices (change in investment is about 1/5 of the change in price). Likewise, investment in shoulder plants tends to vary in the same proportion as the price (change in investment is about 2/3 of the change in price).

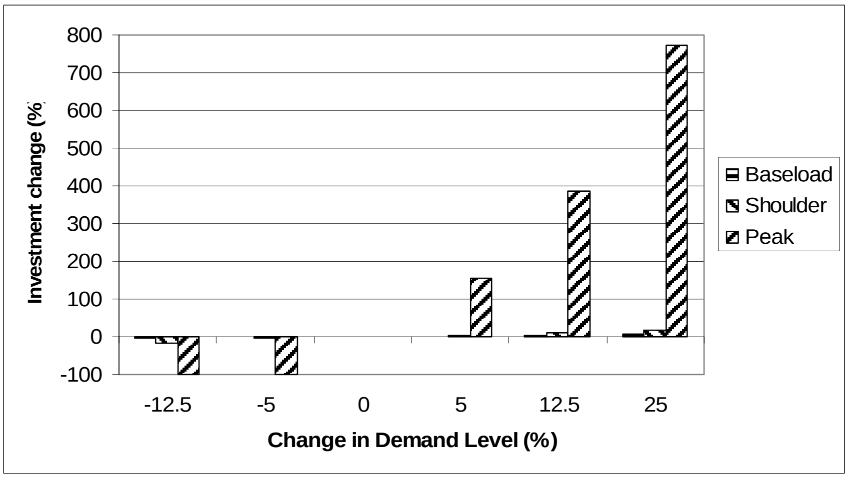

Figure 4.3: Investment Value as a Function of the Demand Level

These results show that the Cournot-Nash investment game is very sensitive to small changes in the level of the specific parameters chosen. The type of industry emerging from just a small error in forecasting the level of demand (5%) is completely different. However, as we know, the level of demand $A(t)$ cannot be estimated with any degree of accuracy, as statistically the estimation of such a parameter would imply extrapolation. Nevertheless, the level of demand seems to be central to the results of the model.

In Figure 4.4 we analyze the NVCI in this example. We have simulated the six different scenarios presented above: S1 (-12.5%), S2 (-5%), S3 (0%), S4 (5%), S5 (12.5%) and S6 (25%).

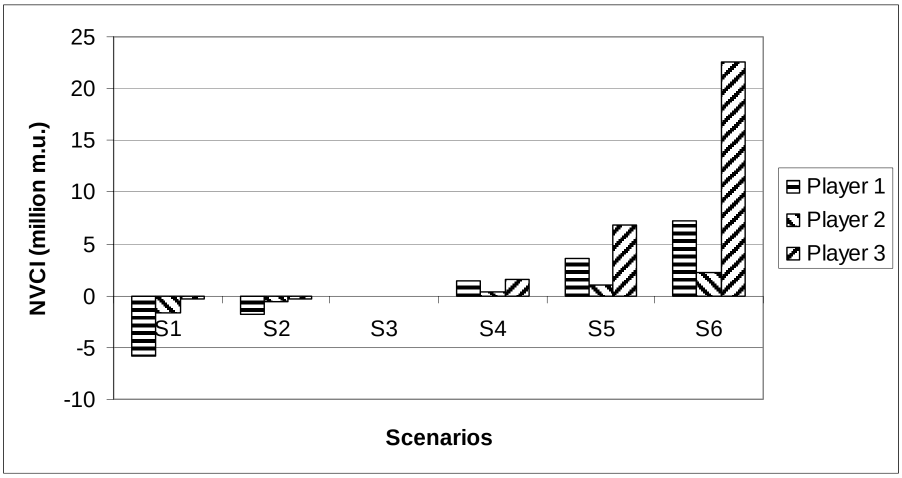

Figure 4.4: Demand Level *vs.* NVCI

We analyze how much the players' profit change if the true scenario was different from the one that they believe (S3), and how complete information would benefit the players. As expected, if demand increases complete information has a positive value: in this case, if players know that demand is higher they invest more and receive higher profits; the forecasting error leads to lower investment than the optimum and, therefore, to lower profits.

On the other hand, if demand decreases, complete information has a *negative value*. In order to understand why let us look at investment in peak demand. As we have shown, if the level of demand decreases in 5% there is no investment in this technology. So, why is the NVCI negative? If all the players have access to the correct information, i.e., a lower level of demand than expected, then the peak player has zero profit. However, due to the pre-commitment to a given level of investment, even if demand decreases the peak player still makes a profit, as the other players accommodate their investments to the level of installed capacity.

Moreover, the fact that all the players in scenarios S1 and S2 have negative NVCI shows that the industry as a whole benefits from misinformed players. A situation in which the players invest and decide production as if S3 is correct when the correct scenario is S1 or S2 can represent a situation of explicit collusion that is not detectable by a regulator. *The players benefit from misinformation.*

4.3. Analyzing the Forecast for Peak Duration

In this section, we look at another parameter of the model (duration of the peak demand) and analyze how it affects the level of investment. In Table 4.2 we summarize the six scenarios analyzed in these experiments. The duration of demand at baseload is kept at 5000 hours. The duration of demand for shoulder and peak demand change from one scenario to another. In scenario S1 peak demand has duration of 700 hours and shoulder demand has duration of 3060 hours. From scenario S1 to S6 the duration of peak demand increases (to a maximum of 860 hours) and the duration of shoulder demand decreases (to a minimum of 2900 hours).

Duration Levels						
	S1	S2	S3	S4	S5	S6
Peak	700	740	760	800	820	860
Shoulder	3060	3020	3000	2960	2940	2900
Baseload	5000	5000	5000	5000	5000	5000

Table 4.2: Durations of Demand for Different Scenarios

As before, assume that the base scenario is S3. As shown in Figure 4.5, and as expected, an increase in the duration of peak demand leads to higher investment in all the technologies. Inversely, a decrease in the duration of peak demand leads to a decrease in the level of investment. This effect is not linear as it tends to affect much more the player investing in peak technology. In this case an increase of 100 hours (approx. 13%) in the duration of peak demand leads to an increase of approx. 40% in the level of investment.

Furthermore, as shown in Figure 4.6, the NVCI is positive when the duration of peak demand is lower, and negative when the duration of peak demand is higher (with the exception of the NVCI for the peak player in scenario S6, which is slightly positive).

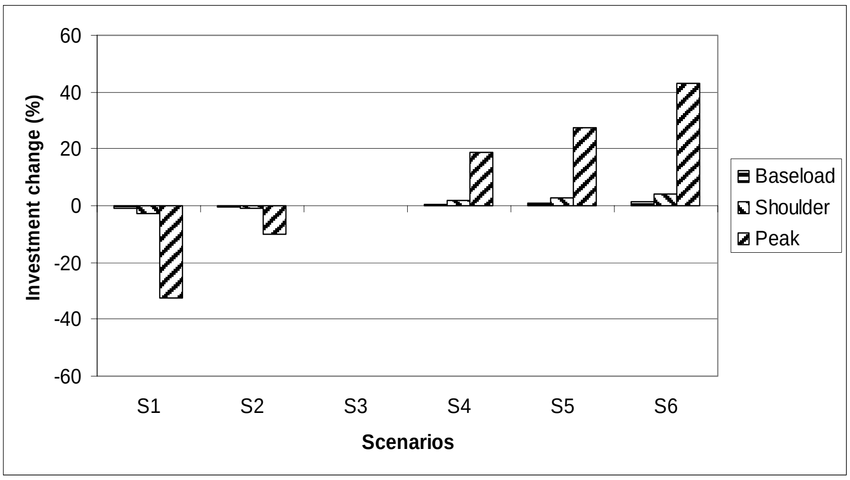

Figure 4.5: Investment for different scenarios of duration of demand

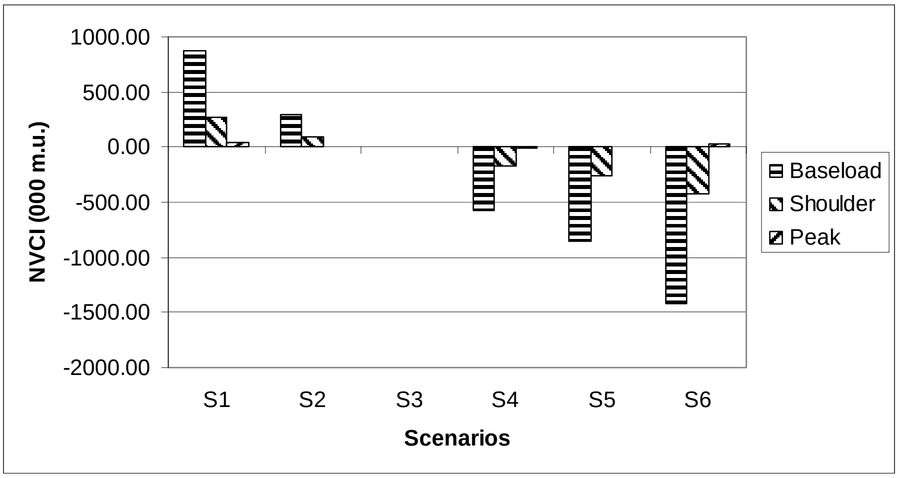

Figure 4.6: NVCI for Different Durations of Demand

The intuition for this case is very simple. When peak demand duration is below the expectations in the base scenario (S3) the Nash value of Complete Information is positive, as the players have invested expecting a higher average demand (this is the case in scenarios S1 and S2). In the case of the peak player, in scenarios S5 and S6, the NVCI is also positive. The NVCI for this player, in scenario S5, is approximately 3000 m.u. and, in scenario S6, is approximately 26000 m.u., as he could have invested more, had he known the correct value of this duration.

On the other hand, when the duration of peak demand is higher than expected, the NVCI is negative for the shoulder and baseload players. This happens has for higher durations of demand, under complete information, the peak player would increase substantially more (up to 40%, as we have seen) and, therefore, decreasing the profits of the baseload and shoulder players. This is why these players benefit from forecasting errors.

Another important point about these results regards scenario S4. In this scenario the NVCI is negative for all players. This means that had they forecasting wrongly demand (by underestimating the duration of peak demand) they would invest and generate less and, therefore, receive higher profits than in the case of complete information. In this case, once again, players profit from their mistakes. Hence, if the industry as a whole "agrees" that the duration of peak demand is lower than it will actually be, the players actually invest less and prices are higher.

4.4. Analyzing Conjectural Coordination

The final set of experiments analyses the issue of conjectural coordination. As presented in the discussion of equation (2.3), it is well known that by changing the conjectures a player holds on his competitors we obtained very different types of behavior. For a V_i = 0 we have a Cournot player, for a V_i = 1 we have collusion, for V_i = -1 we have a player a price taker.

In this set of experiments we analyze what happens in the investment game when coordination fails. As presented by Murphy and Smeers (2005), players behave *a la* Cournot, i.e., each player holds a conjectural variation on his opponents' behavior such that V_i = 0. Moreover, not only a player holds a given conjecture on his opponent's variations but he also knows the conjectural variations held by his opponents, and furthermore, he knows that his opponents know his conjectural variation. Obviously, such a reflexive knowledge of each others' conjectures implies a very high degree of behavioral coordination and communication between the players.

In this section we analyze the impact of these conjectures on the value of investment, and we look at the impact of coordination failures on the NVCI. In Table 4.3 we present scenarios for conjectural coordination. The rows represent the players and the columns represent the model held by the column players on the behavior of others.

Conjectural Variations

	Model of player			Correct Model
	Player 1	Player 2	Player 3	
Player 1	0	1	0	0
Player 2	0	1	0	1
Player 3	0	1	1	1

Table 4.3: Scenarios for Conjectural Coordination

In this example, the correct model is given in the last column. Player 1 behaves as a Cournot player (as he conjectures that the others will not change their output), and expects the others behave as Cournot players as well, i.e., V_i = 0, for i = 2, 3. Player 2 behaves as collusive player, as he believes that the others will change their generation in order to get the monopoly solution for the industry as a whole, V_i = 1 and that the others also believe in the monopoly solution, i.e., V_i = 1, for i = 1, 3. Player 3 behaves as a collusive player (as he believes that the others will follow is change). However, he thinks that the others do not hold the same conjectures, as he believes that they will behave as Cournot players, i.e., V_i = 0, for i = 2, 3. In Figure 4.7 we analyze the level of investment for each one of the models conjectured: one model for each one of the conjectures by each player, and a fourth model that represents the outcome when all the players hold the correct model on the others' behavior.

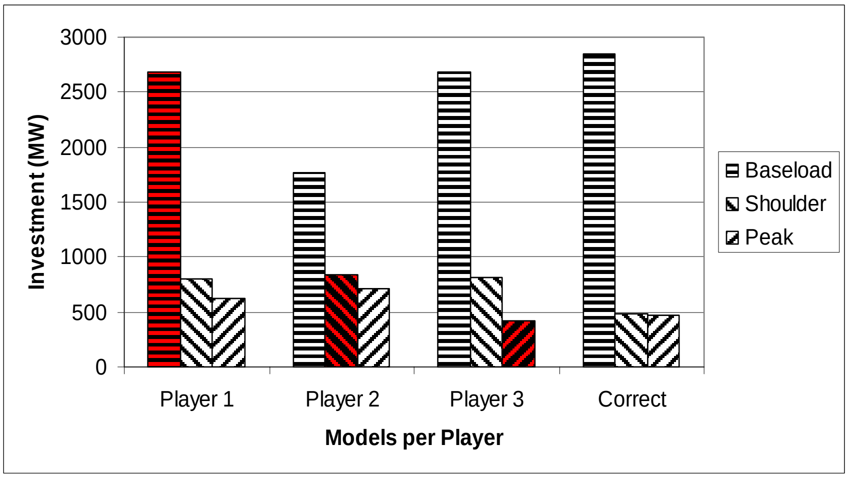

Figure 4.7: Investment for Different Models per Player

In Figure 4.7 the first bar for Player 1, the second bar for Player 2 and the third bar for Player 3 represent the actual investment of these players, as they believe that the others share the same model as they do. Player 1 believes that Players 2 and 3 decide by using the same model as him, Player 2 believes that Players 1 and Player 3 use his model, and finally Player 3 believes that the other two players are following his model instead.

The final three bars (correct model) represent the level of investment of each player if they knew the correct conjectures held by the other players. By comparing the actual generation with the one expected under complete information (correct model), we can see that Player 1 and Player 3 have underinvested slightly (as they were expecting a higher investment by others) and that Player 2 has over invested (as he was expecting the others to invest less than they did).

We are now able to analyze the NVCI for the case of conjectural coordination. In Figure 4.8 we can see that Players 1 and 3 have a positive NVCI whereas Player 2 has a negative NBCI. Player 1 (and Player 3) has a positive NVCI as he should have invested more, given that the other two players invested less than he expected. On the other hand, Player 2 has a negative NVCI, this implies that this player has profited from coordination failure.

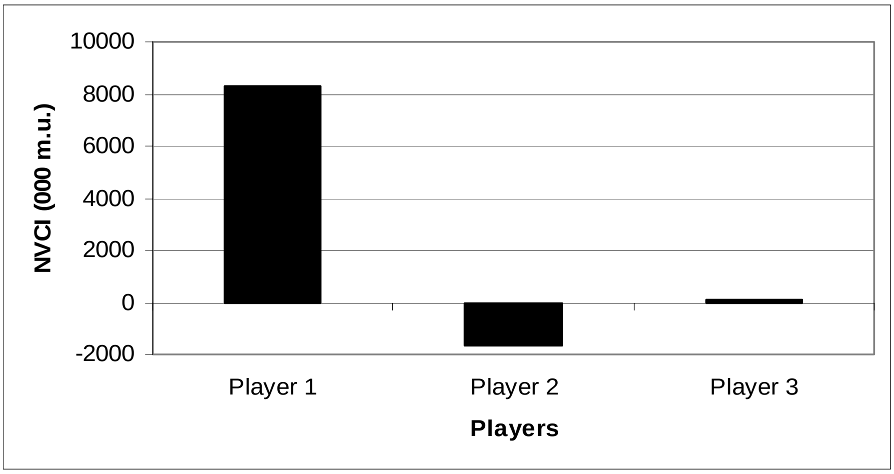

Figure 4.8: The NVCI under Conjectural Coordination

Player 2 expects all three players to collude into the monopolistic solution for the industry. However, as Player 1 broke the coalition by playing *a la* Cournot, Player 2 over-generates, when compared to the optimal value under complete information, and he receives a lower profit.

4.5. Modeling Similar Players

In this section, we relax the assumption that different players invest in different technologies and allow each player to invest in any technology, as in model (2.5). In this case, under the Cournot investment game with perfect and complete information all players in the industry always choose the same investment portfolio (i.e., they invest exactly the same quantities in the same technologies). As an example let us look at the base case in which the marginal costs of generation are as presented in Table 4.4.

Baseload	0
Shoulder	15
Peak	30

Table 4.4: Marginal Costs per Technology

In this case, the new levels of production and investment (which are equal) are presented in Figure 4.9.

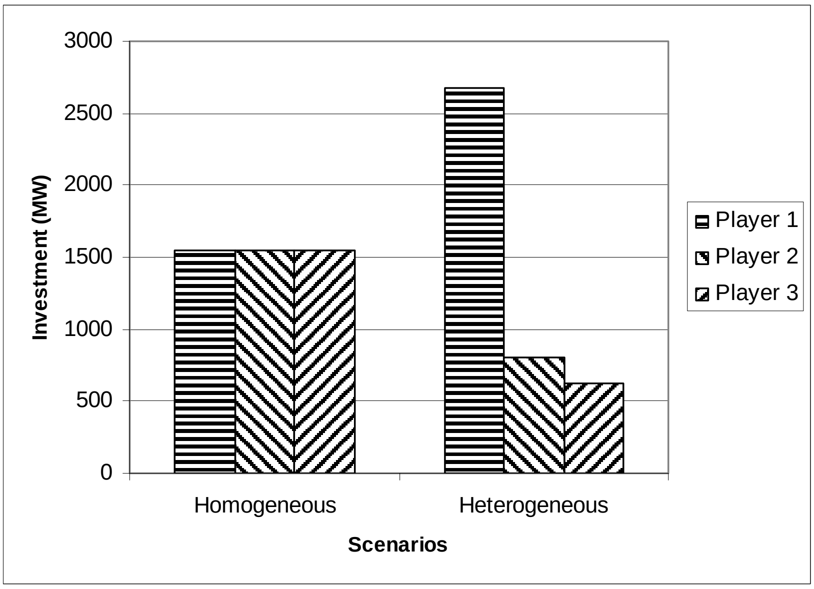

Figure 4.9: Investment by Player in the Cournot Investment Game

In Figure 4.9 the Heterogeneous results are the ones in the base case in which each player invests in a different technology, and the Homogeneous results represent the case in which the players are allowed to invest in any of the available technologies. In the case of the homogenous solution each one of the players invests 1552.5 MW in baseload capacity only. The total investment increases from 4108.2 MW in the case of heterogeneous players to 4657.5 in the case of homogeneous players.

The most important result from this analysis is that in equilibrium, if all the players are allowed to invest in any technology, all players have the same investment strategy. This shows that the Cournot model is not able to explain the diversity of portfolios and diversity of investment that happens in real markets. One possible solution for this issue is to allow the different players to have different marginal costs of investment or generation. However, in this case we would be back to the case of heterogeneous players.

5. CONCLUSIONS AND DISCUSSION

The main goal of this paper is the analysis of the implications of the complete information on the outcomes of an investment game. This game is particularly interesting as the values involved are very high and a small mistake can be very costly. Furthermore, we analyze its sensitivity to its parameters such as marginal costs, level and duration of demand, and conjectures.

A first important conclusion from our analysis and simulations is that complete information, in the context of investment games, can have a negative value. This implies that, under certain conditions, a firm can benefit from forecasting errors. Moreover, we show that in the case where all the firms simultaneously benefit from forecasting errors and, therefore, have a negative NVCI, misinformation has the same impact on total generation and profits in the industry as collusive behavior.

Furthermore, we show that a small forecasting error regarding the level and duration of demand or the marginal costs of the industry (all of which are hard to forecast in models of investment that look at long-term behavior such as investment games) can re-shape completely the generation structure of the industry. A similar conclusion is reached by analyzing marginal costs. Equally important are the conjectures on the other players' behavior and a player's perception on the conjectures his opponents hold on his own behavior.

Overall, our analysis of the investment game shows that even non-cooperative games require a very high level of coordination between players, regarding cost structure, payoffs, demand and conjectures. Most importantly, such a high degree of coordination would be classified under most competition laws as collusive behavior (as developed in the Appendix).

In this paper, we have restricted our analysis to deterministic models in order to emphasize the impact of the assumptions (and their failures) on the results of the investment game. This analysis can be extended to stochastic models. In this case there are two different issues: first, if there is complete and common knowledge of the moments of the distribution of payoffs then the same critiques to the deterministic model apply in this case; second, in stochastic models we need to use a new *subjective* parameter to model the players' attitude towards risk (risk aversion, risk neutral, risk seeking) which faces a similar problem to conjectural variations.

It seems, therefore, that the Nash-Cournot model game with perfect and complete information is a very limited away of modeling a very complex reality such as investment and long-term planning (in the Cournot model the players only choose quantities when in reality firms have a variety of decision variables), independently of the industry analyzed. (Moreover, this critique to the Nash-Cournot model also applies to any other model of investment with imperfect competition, as Bertrand or Supply functions, when assuming complete information.) There is, therefore, a need to develop better and realistic models for long-term analysis (by removing the assumption of complete and common knowledge) which, at the same time, preserve the elegance of the Nash-Cournot paradigm.

The results obtained in this paper are for a very simple case study. This case is enough for a qualitative analysis, but, of course, *quantitative conclusions cannot be extrapolated* to real-size studies. This model does not take into account investment lead times, load factors and availabilities; this rends it not useful for using in actual decision making. The development of such models would be, therefore, an important step forward in this area.

APPENDIX: The Cournot Model and Collusive Behavior

We start by analyzing the USA's Federal Energy Regulatory Commission rules of behavior regarding collusion, as described in the Stroock Special Bulletin (2005). This bulletin refers to section 284.288(a)(2) and 284.403(a)(3) of the Natural Gas Order which prohibit "collusion with another party for the purpose of manipulating market prices, market conditions, or market rules for natural gas." In the Stroock Special Bulletin it is noticed that "collusion" is undefined and it is argued that *collusion* does not imply intent as the Commission explains that sections 284.288(a)(2) and 284.403(a)(3), "merely expand our general manipulation standard … to include acts taken in concert with another party."

Furthermore, Consumers' Advocates (Roberti, 2003, p. 11) argue that from a consumers' point of view, market power in itself (as exercised by Cournot players) leads to a loss of consumer welfare. The Consumer Advocates' also defend that not only overt collusion but also strategic bidding can raise market prices well above competitive levels. Therefore, it should be forbidden as it leads to prices well above marginal cost bidding, "as this strategic bidding is likely to be the predominant means for generation owners to exercise market power and market manipulation", Roberti (2003, p. 27). The Cournot model captures the behaviour of players that by their actions manipulate prices to increase profits, taking into account the strategic interactions with other players. Therefore, following Roberti (2003) such behaviour should not be allowed, as it leads to prices above marginal costs.

The claim presented in this paper is stronger: in investment Cournot games of perfect and Complete Information, which imply knowledge of long-term marginal costs, demand functions and conjectural variations, and therefore explicit collusion, a situation in which "explicit communication between them [players] has occurred (constituting collusion)", Roberti (2003, p. 27).

In every model, assumptions have consequences and can be more or less justifiable. The Cournot model with perfect and complete information it is, arguably, a good approximation of how firms behave strategically in energy markets in order to increase profits. However, for the following reasons, its assumptions are too strong for modelling investment as a *one-shot game*:

1. Marginal costs of generation and investment are common knowledge. These costs are real numbers and, therefore, statistically, there is a zero probability that two different firms can hold exactly the same estimate for the marginal generation and investment costs, unless they communicate.

2. In the Cournot model it is assume that all the players have a conjectural variation equal to zero. It is well known from the research on this topic, e.g., Day et. al. (2002), Song et al. (2003), Centeno et al. (2003b), Centeno et al. (2007), that the conjectural variation is a subjective parameter, which usually can assume any real number usually between -1 (for perfect competition) and 0 (for Cournot). However, statistically, there is a zero probability of players choosing a Cournot conjectural variation, unless they communicate.

3. Demand parameters and duration. Once again, only through previous communication and sharing of all the information regarding the parameters for demand can the players use exactly the same parameters to decide how much to invest in a given technology.

Given the reasons in 1-3 it is obvious that in a one-shot investment game, the assumption of common knowledge of costs, conjectural variations and demand parameters is too strong, implying communication between players. This assumption is very good for short-term modelling as it explains the strategic interactions between players, as in Roberti (2003), but it is not acceptable to explain long-term behaviour, and to guide regulatory or investment policies.

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