System Dynamics models for generation expansion planning in a competitive framework: oligopoly and market power representation

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Abstract: This paper proposes several alternative methods to improve system dynamics models used in the literature for generation expansion planning in liberalised electricity markets. Concretely, these methods provide a better representation of oligopoly structures and market power. These improvements focus on market price and productions calculations, future markets modelling and companies' differentiation when deciding new investments. The methods presented in the paper are based on equilibrium approaches and credit risk theory.

Keywords: system dynamics, generation expansion planning, electricity markets, future markets, investments.

1 Introduction

Since electricity systems began to be liberalised, new planning problems appeared for both electricity companies and regulatory authorities. One of these planning problems is the so-called generation expansion planning which deals with investments in new electricity generation capacity looking into the long-term.

To help the companies and the regulators to carry out this planning, an intensive research activity has provided new methods and models. Among these new models, system dynamics has succeed in representing long-term behaviour of electricity markets, and concretely it has helped to gain insights into the way the new generation capacity enters in the market in a liberalised framework.

However, there are some aspects of these markets that have not been represented accurately yet and which could help to gain new insights and to make better decisions by companies and regulators. Particularly, the oligopoly structure of most of these markets and the main consequence of this structure, market power, has not been taken into account or has been greatly simplified.

This paper proposes improvements for the system dynamics models in the literature, in order to obtain a better modelling of oligopoly structure and market power. Concretely, new approaches for market price and outputs calculations, future markets modelling and agents' differentiation regarding investment decisions are provided.

In the next section, the problem of planning the expansion of electricity generation is explained in detail. Alternative techniques to system dynamics, used to help to solve this problem, are presented here. Section 3, compares system dynamics with the alternative techniques and presents the state of the art regarding system dynamics for generation expansion planning. The improvements proposed by this paper, are explained in section 4. Then, a case study based on the Spanish electricity market is shown in section 5. Finally, section 6 concludes the paper.

2 Electricity generation expansion planning

2.1 The problem of planning the expansion of electricity generation

Electric systems, as well as other utilities, require a careful planning of production resources. This planning, for the case of electricity has some peculiarities that complicate this kind of decisions. Mainly, it is an absolutely essential good which leads to significant regulator vigilance. Moreover, generation plants require big investments that spread over long time periods. Finally, demand randomly fluctuates and must be instantly and exactly supplied by generation while electricity can not be easily stored.

Depending on the system, building new plants is in charge of either a regulatory authority or the generation companies. In the one hand, in centralized systems, responsibility for generation expansion decisions devolves upon a regulatory authority that makes decisions based on cost, reliability and fulfilling production constraints (for example technical, strategic or environmental ones). This framework commonly corresponds to traditional electric systems. In the other hand, in liberalized systems, companies independently undertake the setup on new power plants at their own risk, while the regulatory authority plays a supervising role by means of regulatory actions. This schema is nowadays followed in most of developed countries all over the world.

Planning electricity generation can be studied both from generation companies or regulatory authority point of view. The major aim of companies is obtaining the maximum profit, but they also may follow strategic objectives (i.e. market share or generation technologic mix) and have also to respect some production limits. Regulatory authority mainly pursues system reliability, i.e. required energy is available with a reasonable reserve margin, and additionally other strategic goals always oriented to maximize social welfare.

From the previous, electric generation expansion planning in liberalized systems can be defined as the function to be performed by generation companies to properly evaluate their decisions of building, closing down, buying, selling or repowering power plants, whereas in the case of regulatory authority, the actions to assess are regulatory actions oriented to guide companies' decisions. This function considers a set of objectives, depending on the standpoint, is analyzed with a long-term perspective and normally considers as main conditioning elements: demand growth, different available generation technologies, fuels cost and availability, system reliability criteria, environmental constraints and established diversification policy.

2.2 Alternative techniques

Electric generation expansion planning is a complex decision problem that has been addressed using system dynamics among other different analysis techniques. Those different to system dynamics will be briefly mentioned in this section. Next point deals with system dynamics models.

Regulatory authorities of centralized systems face a problem with a set of influencing factors that are exogenous to the electric system that include demand growth, fuel prices, hydro inflows, technology evolution, and macroeconomics. The most used techniques, in addition to system dynamics, for this kind of systems are optimization (cost minimization) and multicriteria decision. The later technique corresponds to a more sophisticated approach where an integrated resources planning is considered including decisions as demand-side management and environmental and social criteria, beyond cost. Some examples of both types follow. (Lee *et al.*, 1990) presents a survey that includes planning models. (EIA, 2002) presents a model developed by USA Energy Department that contains an optimization module for planning. In (Millán *et al.*, 1998) an optimization model is used to analyze Central America generation expansion planning. (Hobbs and Meier, 2000) summarize the use of multicriteria techniques for decisions in the area of energy. (Merrill and Schweppe, 1984) and (Connors, 1996) present a trade-off risk model used for example for planning in New England. Environmental aspects of generation expansion are studied in (Schenler and Gheorge, 1998) with a similar model.

For liberalized systems, analysis gets more complicated, because of additional uncertainty sources that are endogenous to the system: electricity prices, regulatory changes and competitors' decisions. Generation companies require new models to manage the high level of risk that is present in these systems. The main techniques used in this framework are scenario analysis, risk analysis, real options, agent-based simulation, game theory and system dynamics (Dyner and Larsen, 2001). The focusing of these techniques is different, but all of them contribute to analyze planning decisions. Scenario analysis is a broad concept that allows dealing with uncertainty of planning, as in (UPME, 2000). Risk analysis is an interesting alternative and allows coping with the study of long-term contracts that are associated to planning decisions, (Fleten *et al.*, 1997), (Cabero *et al.*, 2005). Real options approach assess the investment in generation assets considering them as a financial product and is broadly used (Frayer and Uludere, 2001), (Botterud, 2003). Agent-based simulation is more adapted to short- and medium-term analysis, for example for market bidding strategy, but it can be also used to address generation expansion planning problems while it explicitly represents each system agent, its objectives and its decisions to achieve them. An interesting example can be found in (Costa and Oliveira, 2005). Other technique that has been mainly used for medium- and short-term studies, including market bidding elaboration, is game theory. Nevertheless, there exist some interesting works devoted to generation expansion planning: (Murphy and Smeers, 2001), (Ventosa *et al.*, 2002), (Centeno *et al.*, 2003) and (Murto, 2000).

3 System dynamics for electricity generation expansion planning

3.1 Comparison with other techniques

The set of techniques presented in the previous section, can be classified in two groups: the first three -scenario analysis, risk analysis and real options- that are focused on uncertainty analysis, and the other two, -agent-based simulation and game theory- that mainly deal with strategic analysis of competitors and system. These two approaches are complementary and a complete generation planning study should be addressed with models from both sets. System dynamics can be seen as a complementary tool for any of the other techniques.

Rather than a forecast of the future, system dynamics models are used to gain insights into the system behaviour, by representing in detail the relationships between the main variables of the system, with explicit recognition of feedbacks and delays. System dynamics models may provide information about dynamics of how new plants enter the system extending the previous techniques scope. First, scenario analysis requires a previous definition of the alternative situation that will be considered as alternative solutions to the problem. As liberalization has been recently introduced in most of the countries, there is no much experience about long-term evolution of electricity markets and system dynamics models can be of help to build these scenarios. The second technique, risk analysis, when applied to planning usually evaluates a determinate investment, in a particular plant. A previous analysis of the most suitable alternatives can be performed by means of system dynamics. Real options theory is the third possibility that has been mentioned. It is also centred in profitability of a determinate new plant and additionally determines the best moment to build it. Some hypothesis about system behaviour must be made (mainly price evolution), and system dynamics technique allow to set these hypothesis. With respect to the fourth technique, agent-based modelling is oriented to situations where agents' decisions are made in a continuous way. Thus, generation expansion planning problem, in which decisions are more separated in time, is more naturally address tackled with system dynamics approaches. Finally, game theory, the fifth alternative, provides a solution to dynamics games when they are not too complicated and do not extend too much in time. An alternative to represent more complicated problems is to use the so-called open-loop Cournot games, but here, the decisions depend just on the time. The analysis of dynamics of more detailed games that represent faithfully planning dynamics can be advantageously performed with system dynamics paradigm.

3.2 State of the art

System dynamic techniques have been extensively used to analyze different aspects of electric energy systems, generation expansion planning among them. Two interesting surveys can be found in (Ford, 1997) and (Bunn and Larsen, 1997). Centralized systems have been represented with different models as IDEAS (AES, 1993), Energy 2020 (CMPC, 1989) or RPSM (Ford and Bull, 1989).

Electricity systems liberalization has required updating this kind of models including the new characteristics of expansion decisions made by companies and market dynamics. System dynamics acquires a new significance in this situation. Centralized systems models usually represent a whole country or a big region, with a lot of details about the system, oriented to assess regulatory authority decisions. This makes an important difference with models that represent liberalized systems, that tend to be smaller and are oriented to analyze particular problems. However, some extensions to previous models have been suggested (Amlin and Backus, 1996), (BPA, 1994) and (Dyner and Bunn, 1996).

The first main works in the field of liberalized model for electricity generation planning can be classified in three big sources: Andrew Ford and collaborators, Derek W. Bunn -

with his research group from London Business School- and works carried out for the Nordpool electricity system by A. Botterud and K. Vogstad among others.

Andrew Ford´s work covers different aspects related to generation planning. He has studied inherent dynamics to building new plants in the west USA market that forecast cycling dynamics (boom and bust) producing periods of overcapacity and other of scarcity that can be dangerous for the system. A constant capacity payment is suggested to mitigate this effect (Ford, 1999). An improved version of the model used in the previous work was widely used to study Californian market and the causes that led it to a critical situation during 2000 and 2001 (Ford, 2001a), (Ford, 2001b), (Ford, 2002).

Derek Bunn's researches center on the English market, but its conclusions can be extended to other countries. In (Larsen and Bunn, 1999) the usefulness of system dynamics models both for generators and regulators in liberalized markets is justified as a powerful tool to face arising new risks. In (Bunn *et al.*, 1993), complementarities with other alternative techniques are shown. Dynamics likely to appear after electricity market liberalization in England, considering the different sizes and characteristics of the new agents that constituted that system are analyzed in (Bunn and Larsen, 1992) and (Bunn and Larsen, 1994). Other model, the one in (Gary and Larsen, 2000), includes interaction with gas markets and how it impacts in plants profitability and consequently in planning.

In (Botterud *et al.*, 2002), a planning model to study Norwegian electricity market is presented. Other works for the Nordpool consider: regulatory mechanism to promote renewable energies (Vogstad *et al.*, 2003), dynamics of transition to a technological generation mix including more renewable production capacity (Vogstad *et al.*, 2002), coordination between hydraulic and wind power (Vogstad, 2000) and effects of massive entering of gas plants in liberalized markets (Vogstad, 2004).

In the recent years, some new works have appeared, improving some modelling aspects of previous studies such as market price representation, transmission network modeling, dynamics of exports and imports or interaction between system dynamics and other different modelling approaches. Main references here are (Olsina *et al.*, 2006), (Kadoya *et al.*, 2005), (Ochoa, 2007), (Ford, 2006) and (Vogstad, 2006).

In (Olsina *et al.*, 2006), no actual market is simulated but it focuses on the formulation of the mathematical framework to extend the previous modelling methodology. They include several technologies for new investments decisions, a vintage model to represent progress in thermal efficiencies, an annual distribution representation of market price and a delay concerning the option to defer irreversible investments under uncertainty. A different modelling approach for the annual distribution of market price within a system dynamics model can be found in (Sánchez *et al.*, 2005).

The main contributions of (Kadoya *et al.*, 2005) are the representation of a full merit-order dispatch and the calculation of a complete NPV to assess investment decisions, using "forward curves" of expected future values for prices, capacities and capacity factors based on historical averages and a trend extrapolated from current conditions. This model was calibrated successfully for PJM and ISO-NE markets. Both contributions have been addressed also in (Sánchez *et al.*, 2005) were a price duration curve is calculated for each year (using a full merit-order dispatch) and extrapolated into the future (taking into account historical price-duration curves) to calculate a complete NPV. In this case, the model was based in the Spanish market.

An interesting new representation of the dynamics governing imports and exports of the Swiss market is carried out in (Ochoa, 2007) to test the influence of different policy changes in this country concerning de-regulation, nuclear dismantling and imports dependence reduction.

Finally, both in (Ford, 2006) and in (Vogstad, 2006) a combination of system dynamics with complementary modelling approaches is made. On the one hand, in (Ford, 2006) an engineering model which simulates load power flows is combined with a system dynamics model to simulate long-term behaviour in six different regions of the west of the US. Concretely, it studies the potential reductions in carbon emissions in the US western electricity system, under a cap and trade market. On the other hand, (Vogstad, 2006) combines financial stochastic price models with a system dynamics model described in (Vogstad, 2005) in order to provide long-term price prognoses for investment decisions, which take into account stochastic processes for gas and coal prices, hydro inflow and wind.

4 *Proposed alternatives for oligopoly structure and market power modelling*

4.1 General structure of a generation expansion planning model

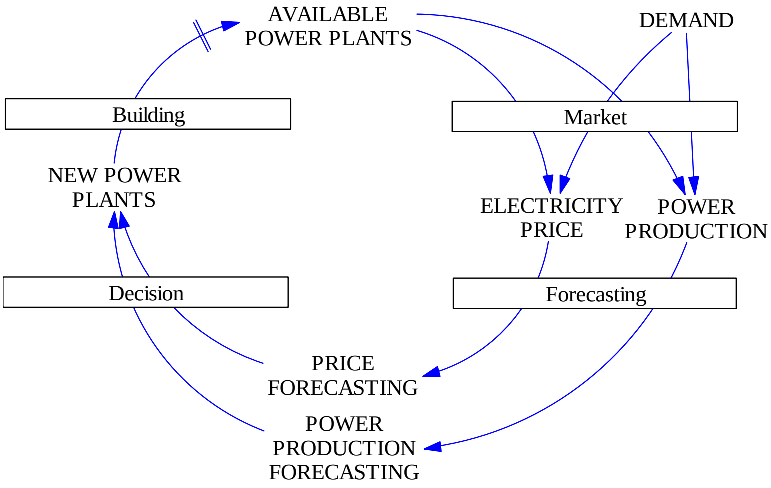

Fig. 1. Overall structure for an electricity generation planning model.

In a global view, the feedback representing the new generation capacity investment decisions in most of the generation planning models cited in the state-of-the-art section can be divided in four main blocks as shown in Fig. 1. Starting from demand and available power plants, a representation of the market determines electricity prices and power outputs for every plant. The second block represents the forecasting of prices for a determinate time horizon that market agents make as well as plant production forecasting. These results allow making the decision -third step- of how many plants to build, which each generation company makes depending on its own characteristics and with its profitability criteria. Finally, new plants enter the system with some delay that represent permit obtaining and plant building.

Using this structure, the different models commented above have succeed in representing some particular liberalized electricity markets, permitting the different actors to gain insights into their long-term behaviour, and concretely into the way the new generation capacity enter in the market. However, these models have not been so accurate representing some other important aspects of the current liberalized electricity markets, as market structure and market power. This paper proposes some improvements in the first ("Market") and third ("Decisions") blocks shown in Fig.1, to cope with these drawbacks. The influence of an oligopoly structure in the second block ("Forecasting") is less important as different companies could use the same forecasting methods. However, some differentiation between companies could be represented by considering different available information as is done in (Ford, 2001a). The fourth block ("Building") is the simplest one and makes no a significant difference between systems with different market structures. A slightly modification could be considering different delays between companies (dominant companies could have greater advantages to obtain construction permits).

Most of these models assume perfect competition when calculating prices and plants outputs, whereas most of current liberalized markets are dominated by an oligopoly. Although some of the models have represented this fact with some simplifications as assuming some groups bidding above marginal costs, this has been done most of the times using parameters indicating the quantity of the over-bid and adjusting these to obtain credible prices. In this paper, we present an alternative method to represent oligopoly behaviour in the market, based on equilibrium approaches which have been proved successfully in the medium-term.

Long-term contract markets are another important aspect of current liberalized electricity markets which have not been represented accurately. Nowadays, most of liberalized systems, are introducing this kind of markets or similar tools, in order to reduce market power. Interactions between spot markets and long-term contract markets are a hot research topic today, and system dynamics models could provide new insights into it. This paper proposes different alternatives to model these interactions.

Finally, companies' differentiation has been avoided in most of these models, by considering investments in a global way. Other models, have made simplifications dividing the companies in big groups like leaders-followers or incumbents-new entrants. A more detailed representation of this fact could make system dynamics models to provide better understanding on the possible market structure evolution and its effects on investments and prices. In this paper, a new idea to differentiate generation companies when making new investments is shown.

Next, improvements proposed in each block are explained. Previously, how these blocks have been represented in the previous models is commented and then enhancements are detailed.

4.2 Market

Market representation in the above-mentioned models range from those which do not require explicit price computation to those which explicitly include a competitive market representation. In (Bunn and Larsen, 1992), (Bunn *et al.*, 1993) and (Bunn and Larsen, 1994) profitability is determined, without computing price, from capacity payment that is estimated from system power reserve margin. This is an interesting simplification when details about price are not required. Other models represent a perfect competition market where the agents bid their marginal costs (Ford, 1999), (Botterud *et al.*, 2002), (Vogstad, 2005), (Olsina *et al.*, 06). In this representation, obtained price is the same as marginal cost in a centralized system and may represent a liberalized market under certain assumptions. A simplified competitive market is represented in (Gary and Larsen, 2000), where price depends on reserve margin, and with more detail in (Ford, 2006) and (Kadoya *et al.*, 2005), dividing groups in those that bid their marginal cost and those that make a strategic bid over marginal cost using some a-priori parameters (actually, in (Kadoya *et al.*, 2005) it is not explained how the bidding strategy is modelled).

Regarding long-term contract markets or future markets, (Vogstad, 2006) suggest the combination of system dynamics with financial stochastic price models in order to obtain forward prices expectations at each time in the simulation. These prices, which could be the prices of forward contracts, are used by the companies as the main signal for investment. However, the possible interaction between long-term contract markets and spot markets and its effects on market power evolution is not represented here.

This paper suggests a detailed market representation that includes: a conjectured-price-response based market equilibrium to calculate prices and productions under oligopoly structures, a dynamic computation of conjecture-price-responses and an explicit representation of future markets.

As it will be explained next, we based the new representations on some equilibrium ideas. It may be argued that one of the common assumptions of system dynamics is bounded rationality, and so, combining these two techniques may not be coherent. However, when companies are looking at different time horizons at the same time it can be argued that companies may behave in terms of equilibrium in the short-term (when actions are more repetitive, uncertainty is lower and companies have more information) and considering bounded rationality in the long-term (investment decisions).

4.2.1 Market equilibrium

Some electricity markets can not be assimilated to perfect markets and oligopoly effect must be explicitly and accurately represented. Besides, profitability of investment in generation assets is heavily conditioned by the first year's prices, and thus special care must be paid to represent it. For these requirements, a widely accepted approach is market equilibrium in the sense that was defined by (Nash, 1950). Market equilibrium is the set of outputs of every generator such that any generation company can not improve its benefit by unilaterally modifying its production. Let us suppose that each company i receives as revenue, its spot market production q_i- f_i , at market price p, and besides the previously contracted quantity f_i at a price $p_{i'}$. Profit can be computed as revenues minus cost:

$$\pi_i = p \cdot (q_i - f_i) + p'_i \cdot f_i - c_i \tag{1}$$

Equilibrium conditions can be obtained by maximizing the profit with respect to production for each generation company:

$$\frac{\partial \pi_i}{\partial q_i} = 0 = p + \frac{\partial p_i}{\partial q_i} \cdot (q_i - f_i) - \frac{\partial c_i}{\partial q_i} \tag{2}$$

The derivative of price with respect to production is the so called conjectured price response (Centeno *et al.*, 2007) and will be considered as known for each company. Then the previous expression reduces to:

$$\theta_i = -\frac{\partial p_i}{\partial q_i} \quad \Rightarrow \quad p = \frac{\partial c_i}{\partial q_i} + \theta_i \cdot (q_i - f_i) \tag{3}$$

If demand is considered as a function of price, it must be equal to the total producer's output. Then, the previous equilibrium conditions can be joined with demand function to constitute a set of *i+1* equations with *i+1* unknown values, productions and demand:

$$\begin{cases} p = \dfrac{\partial c_i}{\partial q_i} + \theta_i \cdot (q_i - f_i) \\ \sum\limits_i q_i = d(p) \end{cases} \tag{4}$$

Depending on the application, this market formulation can be implemented with different detail levels:

- Production can be considered in a single production block, in two production blocks –peak and base-load for example– or more blocks, up to hourly or smaller blocks. The rest of parameters must be also disaggregated block by block so the size of the problem increases. For example, in (Sánchez *et al.*, 2005), a load duration curve for each month, divided in blocks of 10 hours was considered. However, in (Sánchez *et al.*, 2005) there were no oligopoly but perfect competition, which is equivalent to use a conjectured price response equal to 0.
- The derivative of cost with respect to production –marginal cost– can be considered as a constant, as a linear function, or a stepwise function if marginal cost is considered as constant for each power plant. For example, in (Sánchez *et al.*, 2005), the stepwise function is considered, as each group was represented individually, with its own marginal costs.
- Conjectured price response can be considered as a constant value or it can be actualized as will be explained later.
- The quantity that is contracted can also be considered as a known value, but can be also computed from market conditions, as will be shown.
- The function that establishes the relationship between price and demand can be a constant (inelastic demand), a linear function, a quadratic function or a stepwise linear function.

So, at each simulation step, having the available generation capacity of each company with its costs, the demand, the quantities contracted previously that call for deliver at this step and the conjectured price response, the price and the power produced by each group and by each company can be obtained. In (Batlle and Barquín, 2005), a detailed description of a medium-term model which calculates prices and outputs using this theory is explained.

4.2.2 Conjectured-price-responses estimation

In the previous section, conjectured price response has been considered as a known value for each generator. Computation of these values is complex and requires sophisticated techniques to analyze historical data, see chapter 2 of (Bunn, 2003). When no historical data are available or when a long-term representation is required, as in our case, alternative approaches must be chosen.

If a generic supply function *S(p)* is supposed for each company, the previously contracted quantity for each company is considered as proportional to demand $f_i=\alpha_i.d$ and supply function of the companies is accepted as proportional to company size (homogeneity hypothesis) $S_i(p)=\beta_i.S(p)$, then it can be proven that market equilibrium conditions lead to the following differential equation:

$$S_i(p)-\frac{1-\beta_i}{\beta_i-\alpha_i}\cdot\frac{\partial S_i(p)}{\partial p}\cdot\left[p-\frac{\partial c_i}{\partial p}\left(S_i(p)\right)\right]=0 \qquad (5)$$

This is the Rudkevich equation, a well-known expression in the study of electricity market price using the so-called supply function equilibria (Rudkevich *et al.,* 1998). Solving this equation, an analytical expression for price with respect to the production of the company is obtained, that can be differentiated to obtain the conjectural price response. This response will be an analytical formula depending on the marginal cost function of the company, among other variables.

Some different alternatives are possible at this point:

- Cost functions can range from linear to stepwise.
- Demand could be elastic; however it requires reformulating the previous expression.

With this, at each time step in the model and previously to the market price calculation, a conjectured price response for each company can be obtained from cost functions, quantities previously contracted and companies' sizes.

4.2.3 Future markets

So far, forwarded contracted quantities f_i have been considered as known. These quantities are periodically decided by generation companies and depend on market and system conditions. There is an open discussion in the literature questioning whether forward contracting increases or reduces market power, starting with the seminal paper (Allaz and Vila, 1993). What is obvious is that the presence of this kind of markets modifies generator's behaviour and price dynamics and as a consequence condition planning decisions.

Main conclusion in (Allaz and Vila, 1993) is that, even in the absence of risk-aversion, the introduction of a future market previous to a spot market, increase competition. Some other authors have reached the same conclusion in what has been called the pro-competitive trend. But in the last years, a different trend has appeared which concludes the opposite. The main different assumption between these two trends is that in (Allaz and Vila, 1993), a two-period game is considered (future market followed by a spot market) while in the opposite trend, a multi-period game is considered. When considering multi-period, some particular effects appear reducing the competitive effect of the two-period case. Some of these effects are collusion -see for example (Liski and Montero, 2005)- and the influence of the current spot price in the price of the next future markets -see (Amaya *et al.*, 2006)-.

(Allaz and Vila, 1993) compute an equilibrium model in two stages in order to obtain optimum quantities contracted in the future market. Main assumptions for this model are Cournot competition, symmetric duopoly, constant marginal costs for each company and a future market where contracts traded call for delivery during the next spot market. With this, a formula for the quantity to be contracted by each company in the future market is obtained as a function of costs, and demand elasticity. In (Amaya *et al.*, 2006) the same problem is solved under the same assumptions but considering the influence of the current spot price in the next future market. The function obtained depends now also on the estimated quantity to be contracted in the next future market and on a discount factor.

For the symmetric duopoly case these formulas can be expressed as:

$$f_{1i} = \frac{a - \frac{\partial c_{1i}}{\partial q_{1i}} + \frac{\partial \lambda_2}{\partial p_1} \cdot \delta \cdot \left(f_{21} + f_{22} \right)}{5} \tag{6}$$

$$a = d + \sum_i q_{1i} \tag{7}$$

In these formulas, f_{ji} is the quantity contracted by company i in the future market at instant j. When calculating quantity for future market 1, quantities for forward market 2 are estimations. Parameter δ is the discount factor. The derivative of the next future market price λ_2 with respect to the current spot price p_1 is equal to 0 in (Allaz and Vila, 1993) and equal to 1 in (Amaya *et al.*, 2006).

Computing these formulas within the system dynamics model for each simulation step allows calculating quantities contracted in long-term contract markets that call for delivery in the next spot markets. The above formulas can be easily extended to include several asymmetric companies. Moreover, other assumptions can be introduced in these formulations like different competition models (Bertrand, conjectured price responses), inelastic demand, quadratic functions for the costs of each company or even risk aversion. Without risk aversion, price for the long-term contracts is equal to the expected spot price. When considering risk aversion, a risk premium is added to the expected spot price. For example, a risk-averse demand can be considered using a simple utility quadratic function like this:

$$U = \mathrm{E}\left[p_r - p_{elec} \right] - \frac{\mu}{2} \cdot \mathrm{var}\left[p_r - p_{elec} \right] \tag{8}$$

$$p_{elec} = f \cdot \lambda + \left(q - f \right) \cdot p \tag{9}$$

In these equations, p_{elec} is the price to be paid by the demand for the electricity, $\mathrm{p_r}$ is a reservoir price for the demand, E[x] is the expected value of x, var[x] is the variance of x and μ is a risk-aversion parameter.

Maximizing this utility function, a function which relates the risk premium with the quantity contracted is obtained.

$$f = 1 - \frac{\lambda - \mathrm{E}\left[p \right]}{a \cdot \mathrm{var}\left[p \right]} \tag{10}$$

So, future markets representation within a system dynamics model can be done using formulations as the above explained, with different complexity levels depending on the assumptions considered. The functions for the quantities contracted and the price of the contracts depend on variables that can be obtained easily, either exogenously or endogenously, with the system dynamics model for each simulation step. These variables are cost functions, demand, conjectured price responses and risk-aversion parameters. Is important to note, that whatever approach and assumptions are chosen, they must be coherent with those chosen in the spot market equilibrium and in the conjecture price variation estimation method. For example, if demand is considered elastic in the future markets equations, it should be elastic also in the conjectured-price-response estimation.

Alternatives at this point are:

- extending formulation to consider more types of contracts (peak and off-peak contracts or longer contracts, for example)
- consider effects of current spot prices for the next year only, or for more years

4.3 Investment decisions

All the models consider expected profitability as the main decision criteria for building new plants. In some cases additional criteria are included. Some models consider new plants globally without assigning them an owner, as (Ford, 1999), (Botterud *et al.*, 2002), (Vogstad, 2005), (Olsina *et al.*, 2006), (Ochoa, 2007) and (Kadoya *et al.*, 2005). The rest of models disaggregate the agents considering their decisions separately. In (Ford, 2001a) decisions are different because of different prices forecasting depending on agent's information. The agents are divided in believers, pre-counters and followers. The model in (Gary and Larsen, 2000) distinguishes decision criteria for big generation companies that constitute a duopoly, that decide using profitability and an objective market share; and IPPs (independent power producers) that substitute market share by an optimism factor. Profitability is also considered in (Bunn and Larsen, 1992), (Bunn *et al.*, 1993) and (Bunn and Larsen, 1994) as decision criteria, and it is computed comparing capacity payments with a reference value based on reliability computations. The agents use different discount rates, to introduce their market share objectives.

This paper suggests an alternative method to differentiate the agents when they decide their investments based on credit risk theory ideas. In many real situations, agent's decisions are based on net present value (NPV) that is computed for each of them using a different discount rate. Differences in this discount rate are related to credit risk. Discount rate uses to be constituted by risk-free rate *r*, that is commonly known, and a risk premium *w*, that is related to credit risk.

If no dividends are paid to shareholders ($\gamma = 0$) the value *v* of a quantity *V* that is lent in time *t* to be returned in time *T* is affected by this risk:

$$v(t,T) = e^{-w(T-t)} \cdot V \tag{11}$$

This credit risk can be advantageously modelled using the Black-Scholes-Merton debt pricing model (See chapter 5 of (Duffie and Singleton, 2003). In this model a debt is failed by a company if its assets value A_T goes below its debt *V*. Company assets value is its equity value plus its debt. Consequently, at time of debt issue and evaluating shares value as a call option *C* over assets with *V* strike:

$$v(t,T) = A_t - C(A_t, V, r, \gamma, T-t, \sigma) \tag{12}$$

$$C(A_t, V, r, \gamma, T-t, \sigma) = A_t \cdot e^{-\gamma(T-t)} \cdot N(v_1) - V \cdot e^{-r(T-t)} \cdot N(v_2) \tag{13}$$

$$v_1 = \frac{\log A_t - \log V + \left(r - \gamma - \sigma^2/2\right) \cdot (T-t)}{\sigma \cdot \sqrt{T-t}} \tag{14}$$

$$v_2 = v_1 - \sigma \cdot \sqrt{T - t} \tag{15}$$

N(x) is probability for a standard normal to be below x and σ is a parameter that can be estimated from company value A_t evolution volatility. From the previous expressions w can be obtained.

The use of this schema in the model requires separately computing agents' discount rate $r+w$ for each simulation step to compute NPV of a possible investment. Assets value A_t and debt D_t must be also recomputed at each step.

A_t includes company liquid assets L_t and infrastructures I_t. Liquid assets are updated as:

$$L_{t+1} = L_t + M_t - rD_t + D_t^{'} - NI_t - \varphi_t \tag{16}$$

M_t is operational profits, rD_t debt interest, D'_t new debt, NI_t new investment (assuming $D'_t = NI_t$) and φ_t debt redemption.

I_t can be updated making I equal to its nominal value B. Let aB_t be infrastructures depreciation, then:

$$B_{t+1} = B_t - aB_t + NI_t \tag{17}$$

Other alternative is to compute I from market value. If infrastructures profitability is assumed as constant with a value:

$$r^{'}_{t} = \frac{M_t}{B_t} \tag{18}$$

then infrastructures, with a estimated life spam T', have a value:

$$I_t = \sum_{t^{'}=0}^{T^{'}} e^{-r \cdot t^{'}} \cdot r_t^{'} \cdot B_t \tag{19}$$

Debt is also updated, using the following expression.

$$D_{t+1} = D_t + N_t - \varphi_t \tag{20}$$

By computing the above equations for each simulation step, and applying Black-Scholes-Merton debt pricing model, a value for the discount rate of each company is obtained based on its financial and economic structure. This discount rate allows computing a different NPV for each company which leads to different investments.

A different aspect regarding investment decisions is the total quantity that a company is going to invest depending on the expected profitability calculated. This paper does not provide a concrete alternative to this point. What is obvious is that the greater the expected profitability, the greater the quantity invested. And it seems obvious also that there should be a maximum limit. Reasons for this maximum limit are discussed in (Olsina *et al.*, 2006). For example, under a very high expected profitability situation, companies area aware of the potential danger of massive entries. Moreover, in oligopoly markets, dominant players might limit their own investments because it could decrease the profitability of their own capacity in place. Finally, there is a financial constraint to fund simultaneously many investment projects. Increasing the debt of the company will increase its credit risk and would make new investments less profitable. Furthermore, nowadays, companies are very worried about their credit rating, which depends also on the debt to equity ratio.

The method proposed in (Olsina *et al.*, 2006), where the quantity invested by each company depends on a profitability index (internal rate of return –taking into account the opportunity cost of postponing the investment- divided by the required rate of return) seems to be an accurate method to represent this quantity choice. This method could be combined with the Black-Scholes-Merton debt pricing model explained above in order to calculate endogenously the required rate of return for each company.

5 Case Study

In this section, a simple case study based on the Spanish electricity market is presented. In order to test the model rigorously, more cases and sensitivity and robustness analysis should be carried out, apart from the results shown here. As the main aim of this paper is a methodological one, we have preferred to avoid this in order to focus the paper on the explanation of the new methods proposed (previous sections). So the objective of this case study section is just to present a simple case in order to show one possible application of a model including a detailed representation of oligopoly structures and market power like ours.

The case study analyses the influence of the introduction of a future market in a system which is based mainly in a spot market. Strategic interactions between future and spot markets have been a hot research topic in the last years as explained in section 4.2.3. These studies focus mainly on evaluating the effectiveness of future markets as market power mitigation tools. In our case, we analyse not only this effectiveness but also the possible long-term effects of these markets on investments.

The system under study is the Spanish market which is represented in great detailed (each group of each company). The total capacity and number of thermal groups by utility, arranged by marginal cost, are shown in Table I. Other characteristics of this system used in this case study can be found in (Sánchez et al., 2005).

TABLE I
CAPACITY (MW) AND NUMBER (IN PARENTHESIS) OF THERMAL GROUPS BY UTILITY ARRANGED BY COST

€/MWh	C1	C2	C3	C4	C5	C6	C7
0–15	4984 (7)	5047 (8)	160 (1)	2417 (6)	0 (0)	0 (0)	0 (0)
15–20	5291 (15)	160 (1)	1699 (7)	160 (1)	732 (3)	1577 (4)	0 (0)
20–30	0 (0)	2715 (6)	1927 (5)	400 (1)	0 (0)	0 (0)	1980 (3)
30-45	1846 (6)	2715 (7)	1014 (3)	0 (0)	753 (2)	0 (0)	120 (1)

The model used follows the structure explained in 4.1 but including some of the improvements commented in this paper. Concretely, to calculate market prices and outputs, the model explained in (Batlle and Barquín, 2005) is used. This model was used also in (Sánchez et al., 2005) but considering perfect competition. Now, the difference is that the equilibrium approach based on conjectured price responses explained above is used. The conjectured price responses are calculated endogenously using the method presented in this paper, considering linear marginal cost functions for each company and inelastic demand. Note that when calculating the market equilibrium we used the stepwise function for the marginal cost but when we estimate the conjectured price response we make a simplification considering them as linear functions.

The future market is modelled following (Allaz and Vila, 1993) formulation but extending this to consider conjectured-price-responses competition in the spot, inelastic demand, quadratic cost functions for each company and risk-averse companies. Demand is considered risk-averse using the method shown in the previous. One-year contracts are assumed, that call for delivery in the next spot market. That is, each year, a future market is simulated and then a spot market which takes into account the quantities contracted in that previous future market in the companies’ strategy is calculated. To simplify, we consider that just the two main companies in the Spanish system are able to contract forward.

Companies based their investment decisions on a NPV calculation. To calculate the discount rate used by each company in their own NPV, the Black-Scholes-Merton debt pricing model commented in this paper is used. Then, each company invests each year just in the most profitable technology and builds a number of groups of this technology which is function of the NPV and which has a maximum value expressed as a percentage of the assets value of the company.

To compute the NPV, the companies make forecasts of prices and productions of a new group of each technology. To do this, an estimated price-duration curve is calculated for a given year in the future (in our case, 40 years after the current one) as if in that year there is an optimal generation portfolio in the system. Then, the current price-duration curve is approximated softly to the one estimated in the future during the following years. With this, an estimation of the future prices is obtained which takes into account the current situation and a reasonable hypothesis for the long-term (optimal portfolio). Once the forecasts of price-duration curves have been made, the estimated production of a new group of each technology is calculated considering it is going to be bided by its marginal costs.

Regarding the building block of the general scheme in 4.1, we have considered two delays: one for obtaining the construction permits and one for building the new plant (different delays for each technology). Once a permit is obtained, the investment may be revaluated, and the company may decide not to use the permit.

In our case study we compare a situation without future markets with one where a future market is introduced at the beginning of each year, from the second year on. The aim is to observe the influence of this new future market in the exercise of market power and also in the investment decisions.

In Fig. 2 it can be seen how, when a new future market is introduced the electricity price decreases considerably. In our case, this occurs because the two main companies enter voluntarily in future contracts and because of that they have less market power in the spot where they behave more competitively. As it has been proved in the literature regarding interactions between future and spot markets, the effectiveness of future markets as market power mitigation tools depends greatly on the modelling assumptions. As we have commented before, we have considered similar assumptions as the ones in (Allaz and Vila, 1993), which are the most commonly accepted, but we have extended them. Even with these extensions, the results in (Allaz and Vila, 1993) do not change significantly and it seems that the future market helps to reduce the exercise of market power.

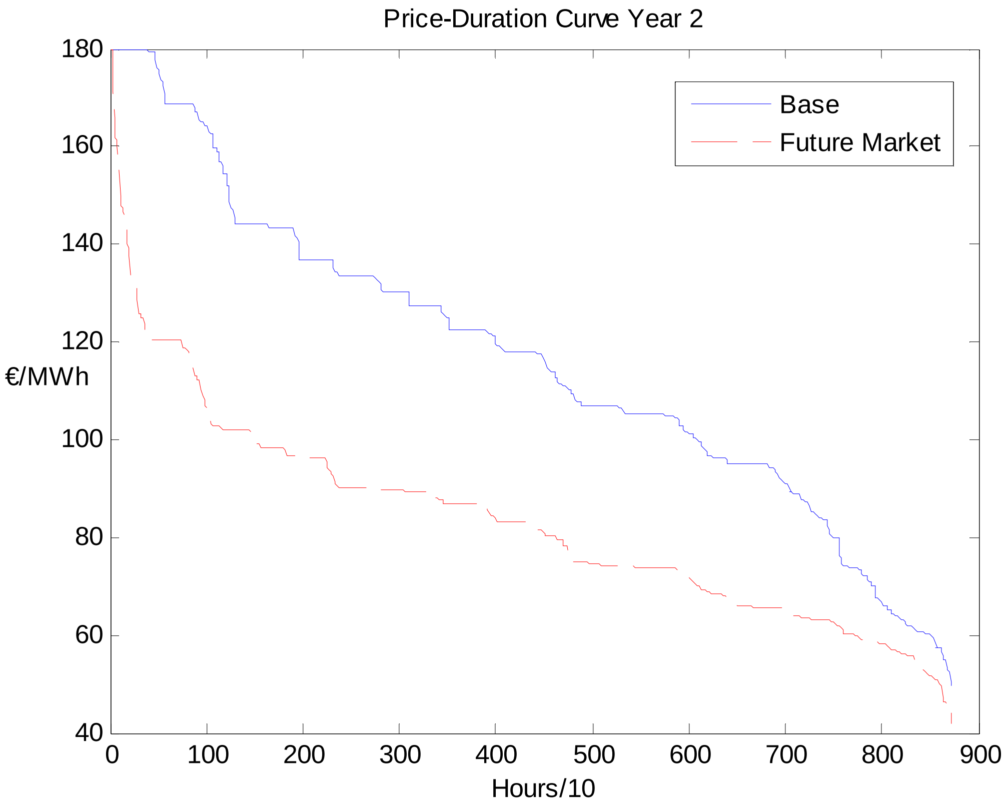

Fig. 2.- Price-duration curve of year 2 in the base case and in the case with the future market

The average electricity price for each year of the study horizon (20 years) is presented in Fig. 3. If we look just at the 4 first years, the conclusion commented before is still valid: that is, future markets help to introduce competition in a system. However, if we look to the whole horizon, it can be seen that the prices in the future market's case are sometimes even higher than in the base case. Here, our model is pointing out a possible dangerous effect of future markets. Without modifying other characteristics of the system, future markets imply a reduction in the expected profitability of the market. This reduction leads to a situation where companies wait too much in order to make new investments what make the system to enter in dangerous zones of non-supplied energy as it can be seen in Fig. 4, when the reserve margin (installed capacity divided by peak demand) is below 1.

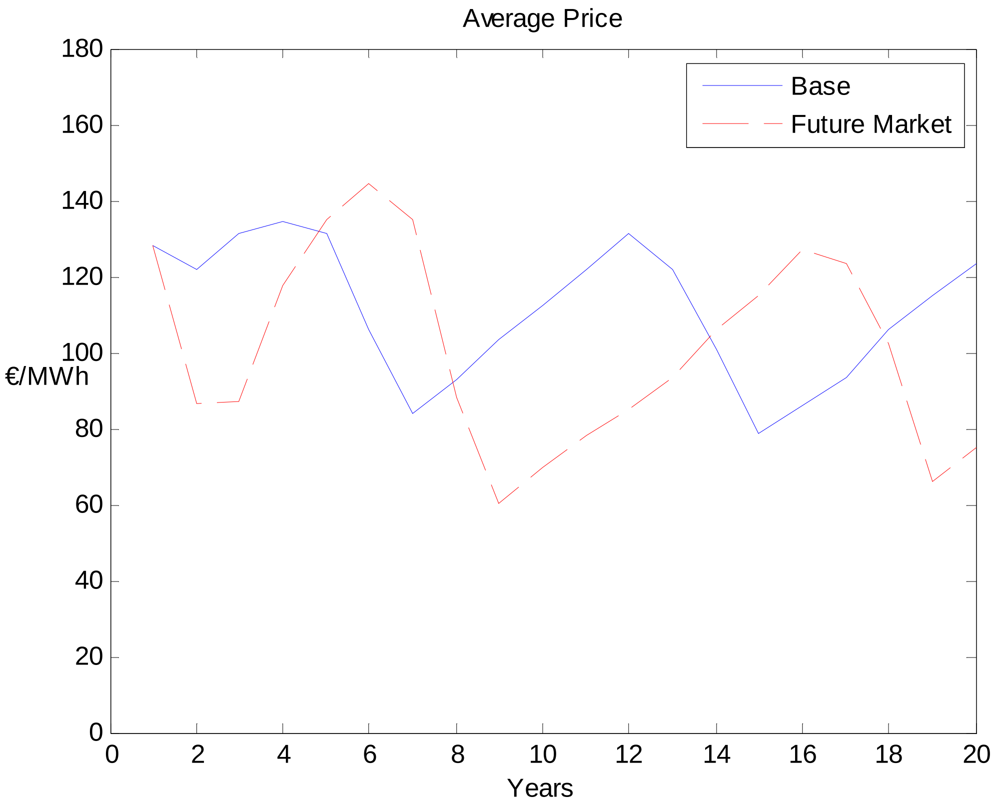

Fig. 3.- Average electricity price in the base case and in the case with the future market

Fig. 4.- Reserve margin in the base case and in the case with the future market

The quantities contracted by each company can be seen in figure Fig. 5 (as a fraction of the maximum output of each company). Changing the hypothesis here, considering for example the influence of the current spot-price in the following future-contract price as in (Amaya *et al.*, 2006) may change these quantities contracted and so the conclusions.

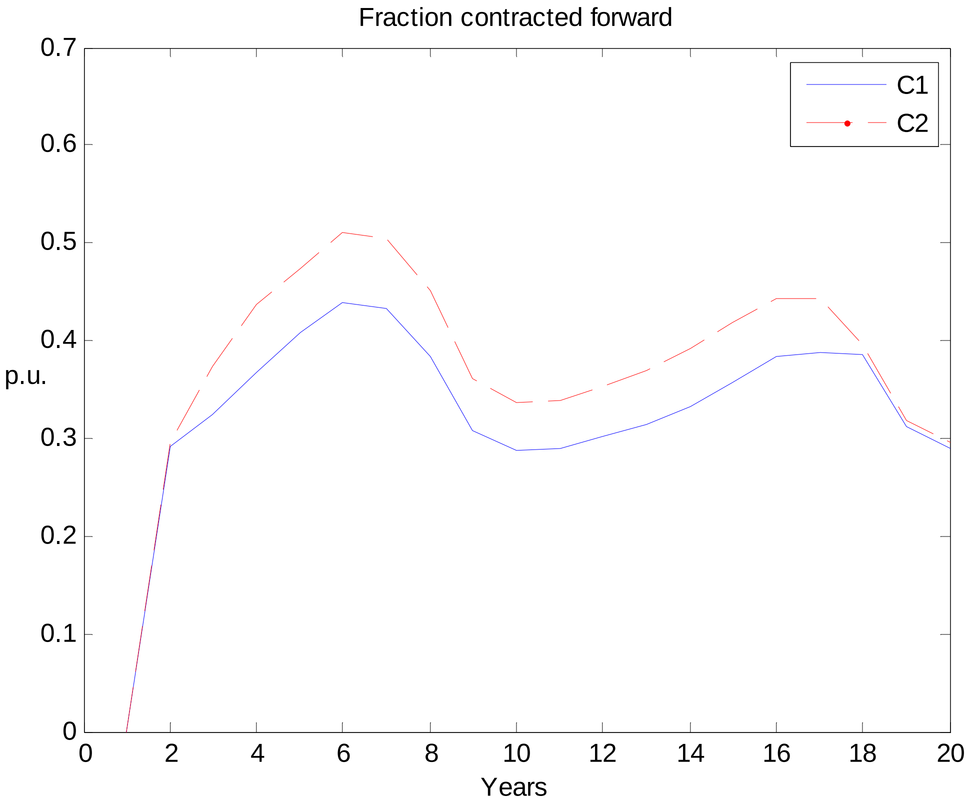

Fig. 5.- Fraction of the maximum output of each company (C1 and C2) which is contracted in the future market

In our cases, investments are leaded mainly because of current price levels. Although the discount rates change considerably during the horizon (in Fig. 6 it can be observed the discount rate calculated for the main company) they do not seem to influence the level of investments significantly. Because of our forecasting method, the current situation of the market influences too much the decisions of the companies and so the discount rates are less important. Regarding the values observed in figure Fig. 6, in the two cases of our study, as profitability obtained by the companies is quite high (either because of the exercise of market power or because of the high prices induced by non-supplied energy) the liquid assets of the companies increase a lot during the horizon. This makes the ratio between assets and debt to become higher and higher during the study horizon, decreasing considerably the discount rate.

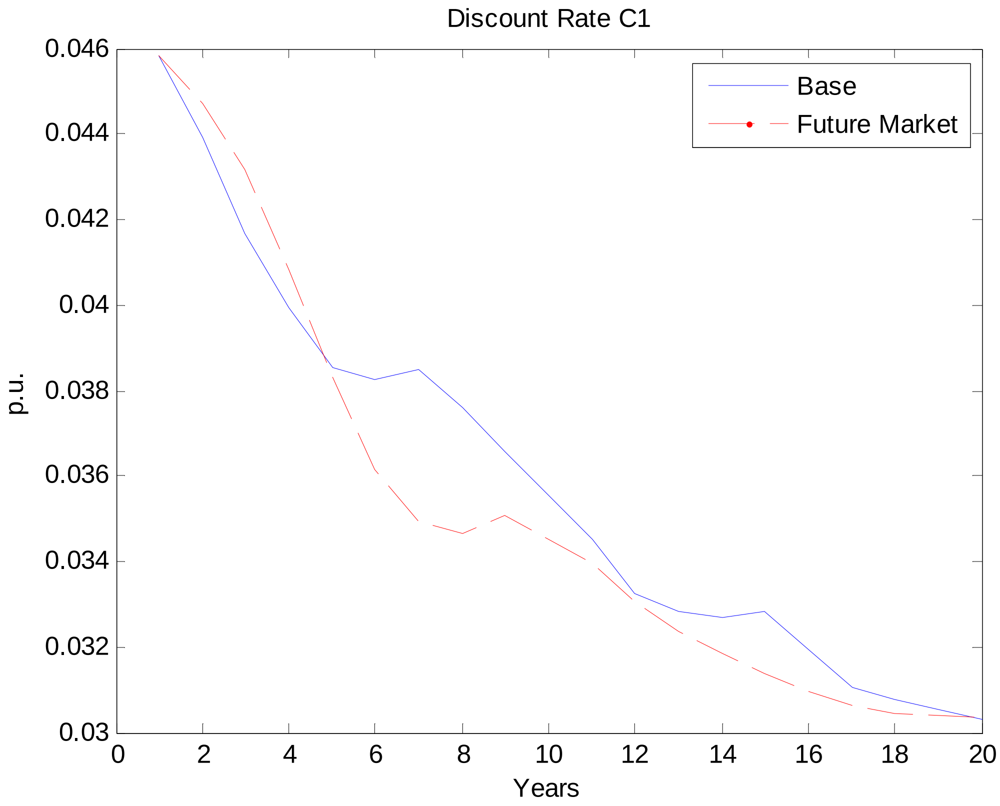

Fig. 6.- Discount rate for the main company in the base case and in the case with the future market

6 Conclusions

This paper presents improvements in the system dynamics models in the literature that have been used for generation expansion planning, in order to obtain a better representation of oligopoly structures and market power.

Several current liberalized electricity markets are dominated by few companies which use or could use their market power to obtain greater profits being detrimental to social welfare. These facts should be taken into account when planning generation expansion by both the companies and regulatory authorities. In the present literature of system dynamics, oligopoly structures and market power have not been represented or have been represented greatly simplified.

This paper proposes improvements in market prices and output calculations, future markets modelling and agents' differentiation when deciding new investments. To calculate market price and productions, an equilibrium approach based on conjectured price responses is proposed. Additionally, a new estimation method for the conjectured price responses parameters is shown. A future market modelling approach based also on equilibrium ideas is presented. This approach allows calculating quantities and prices contracted in future markets that called for delivery in spot markets. Finally, a method to differentiate companies when deciding new investments based on credit risk theory is explained. This method allows calculating different discount rates for each company in order to obtain the expected profitability of new investments perceived by them. These discount rates depend on economic and financial structure of each company.

A simple case study has been presented to show one of the possible applications of a model including the above improvements. This case study analyses the influence of the introduction of future markets in oligopolistic systems based mainly in a spot market. It has been shown how future markets may reduce market power in the system but also how these future markets may have dangerous effects in the long-term, reducing the expected profitability in the system and so the level of investments, decreasing the system reliability.

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