SYSTEM DYNAMICS MODELING FOR ELECTRICITY GENERATION EXPANSION ANALISYS

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Abstract – This paper describes an advanced model based on system dynamics to help generation companies cope with investment decisions in the long term and regulatory authorities to design correct policies.

The main contribution of the paper is the introduction of detailed functions within the system dynamics model which are based in equilibrium approaches in order to obtain a more realistic representation of the market. Particularly, a detailed representation of the clearing market process has been used given as result the price duration curves, which allows taking into account peak hours effects.

The model represents investments decisions in new CCGT and wind power capacity based in expected profitability with the restrictions established by the regulator in terms of subsidies for wind power, capacity payments and CO_2 price in an emissions trading scheme.

Keywords: Electricity Generation Expansion, System Dynamics, Power Generation Investments.

1 INTRODUCTION

Restructuring, privatization and deregulation of electricity power systems have been accomplished throughout the world during the last years. Particularly, deregulation of electricity generation has implied both liberalization and decentralization. As a consequence, strategic and regulatory risks that generation companies have to face in the new framework are unprecedented.

Because of that, these new electricity markets raise a large number of problems, mainly design and operational problems, many of which have not been solved yet. As more markets around the globe are satisfactorily deregulated and competition is introduced, there is an increasing need to understand how previous methods used under monopoly and regulated frameworks for planning have to change in order to face the new deregulated environment.

Different kinds of mathematical methods to help generation companies to deal with operation and planning decisions are now under development. Particularly, models for the short- and medium-term operation have undergone a great development in the last few years. Generally, these models include technical characteristics of power generation systems within economic representation of the market and try to find an efficient equilibrium using different kinds of mathematical approaches. An example of this kind of models can be found in [1].

However, there has been less research in the field of long-term planning models to assist companies with their investments decisions and regulatory authorities with their policies to incentive these investments. The fact that there is no previous history of these markets and that all the participants in them have a reduced understanding on how they will evolve in the future seems to be the causes. Besides, deregulation in Europe has tended to start with a period of sufficient energy surplus, inherited from the previous coordinated expansion period. Because of that, the main regulatory concern in the first steps of deregulation has been, in most cases, to allocate existing generation to consumers in an efficient way. However, as energy demand increases, the challenge of providing new capacity appears. So, from both the regulator and the generation companies' points of view, the need for new methods and analysis tools to help them with decisions in the long-term surfaces.

Traditionally, electricity industry has been one of the largest users of operational research and many successful applications can be found in the area of capacity planning ([2]). The main reason for this success has been the monopolistic environment in which these models have existed. Stable prices, full information, demand that can be forecasted and a co-operative regulation were the main characteristics of the previous stage of electricity sectors. However, these conditions change dramatically in the new framework, where new sources of uncertainty appear and the existing ones grow considerably.

In the new context, the way to interpret the results of traditional models has to be changed and new planning methods are needed in order to complement those. In [3], a review of these new planning methods is raised.

Strategic simulations models, and particularly business dynamics models, seem to be a suitable approach in order to learn about the industry and gain insights into it. Business dynamics is a type of behavioral simulation modeling approach, descriptive and based on explicit recognition of feedback and time lags. In addition, there is a long tradition of use in electricity sector (see [4] and [5]). It does not provide forecasting tools, but rather should be used for creating a new understanding of a complex situation. A great review of this modeling technique is given in [6].

The majority of these models have the drawback of being less detailed than traditional models (equilibrium models for example). They try to study the dynamic complexity of the system by focusing on relationships and feedbacks among important variables and because of that tend to use simple functions and to simplify technical characteristics of the systems.

This paper tries to overcome these difficulties. It uses a system dynamic model to represent the long-term evolution of an electricity market and introduces some detailed functions and interactions between variables in order to obtain a more realistic representation of the market. Concretely, it takes advantage of the developments of short- and medium-term equilibrium models by representing the market clearing price using an algorithm based in an equilibrium approach.

With this, a model that helps to understand how the electricity sector may evolve in the long-term is presented in order to assist generation companies and policy makers with their long-term decisions. This model joins the advantages of system dynamics models in terms of behavioral, high-level and feedback characteristics with the advantages of equilibrium models in terms of system detail.

2 MODEL DESCRIPTION

2.1 General characteristics

The model simulates an electricity market in the long-term (20 or more years). Concretely, it includes investment decisions in new capacity in a single market. Two technologies for investment are considered: CCGT (combined cycle gas turbine) and wind power which currently seems to be the two technologies which the higher growth worldwide. The time resolution for the model is one year, although in each year price is calculated for each hour. The demand is considered inelastic and known for every year.

In the model, the investment decisions are based in the expected profitability of the new capacity. So the expected prices represent the main signals for investments. In the former regulated markets, the main objective of the new capacity investments was to meet the demand ensuring energy supply for all consumers and regulatory authorities were normally responsible for this. In the new liberalized markets, investments decisions are decentralized and are focused on maximizing profits with the restrictions established by the regulator. Nowadays, companies look for their welfare instead of the social welfare and because of that the balance between supply and demand is no longer ensured.

The price for each year is calculated using a strategic production costing model explained in [7]. It does not calculate an average price for the year but it calculates the price for every hour taking into account therefore peak hours effects.

Investment decisions are represented in a global way, that is, no matter which agent make the investment. Because of that, a perfect competition framework is assumed.

The expected price is calculated taking into account the historic prices, that is, the price of the previous years to the one that is being calculated including the price of the current year. The single value decomposition technique is used here as it will be explained later. When higher prices are expected, agents in the market will want to construct more new capacity, what leads to an increase of the generation capacity available in the system and produces a decrease in the electricity price levels. This decrease will make the agents to invest less in new capacity (balancing loop).

Delays constitute other important aspects of this system dynamics model. Once the expected profitability of new capacity is calculated, the number of construction permit applications is decided. Quite often, the approval of this construction permits is not immediate, which produces a first delay in the dynamics of the investments. When the permit applications are approved, the construction begins and this is not immediate either which causes a second delay. Moreover, some approved permits may not be transformed in new capacity because at the moment they are approved, market conditions have changed and companies do not see as much profitability as before and regret previous decisions. A model that takes into account these delays is shown in [8].

Different parameters that represent the possible intervention of the policy makers are included. One of these parameters is the subsidy given to the wind power plants. The greater this subsidy is the greater expected profitability these plants will see for the same market conditions. Another one is the CO_2 price if a trading emissions scheme is supposed. In such a scheme, this price must be internalized in each plant variable cost depending on specific CO_2 emissions of the plant. That will result in higher prices for the same demand and supply side. Also, depending on the specific emissions of each technology and on CO_2 price, the position of each plant in the supply curve may change and because of that, the number of hours they produce. Finally a capacity payment is also computed. This is a simple payment for any MW installed, which will increase the expected profitability of new capacity for the same situation as if it would not exist and represents and incentive given by the regulator in order to try to ensure supply in the long-term.

To sum up, it is a behavioral model that helps to gain an insight into how an electricity market may evolve in the long-term by focusing in the main variables of the problem and the relationships among them. Because of that, it can be used by both policy makers and generation companies in order to take their long-term decisions.

A detailed representation of the clearing market process has been modeled. Generally, system dynamics models use to represent relationships between variables with “soft” functions with very little detail of the system characteristics. However, this model goes beyond and calculates the price with a system detailed equilibrium model which provides price duration curves that allows considering peak hours effects.

2.2 Casual loop diagram

One of the most used tools in order to represent system dynamics models is the casual loop diagram (see [6]). This diagram represents the main feedback loops of the model and how a change in any variable influences in the value of the others. It can be drawn in several ways. In the one we present here, a relationship between two variables is represented by an arrow. A positive sign indicates that an increase in the value of the first variable produces, if all the other variables keep constant, an increase in the second variable. The opposite occurs for a negative sign. The double bar crossing an arrow implies a delay in that relationship. A circle arrow with a sign indicates a positive feedback loop (reinforcement) or a negative feedback loop (balancing).

A casual loop diagram of the system dynamics model is presented in Figure 1. It can be followed pretty easily with the explanation of the model given in the previous section. As it can be seen, provides a single balancing feedback loop, divided in two parts, one for each technology (CCGT and wind power). So it is not a model with a great dynamic complexity (apart form the delays). The most important relationships in the decision investment process have been included and then a certain detail complexity in the part of the model which calculates the price has been considered.

A more detailed description of each part is raised in the next sections.

2.3 Price calculation

The electricity price is calculated by means of a strategic production costing model which is thoroughly described in [7]. This model is an extension of the traditional production costing models approach in order to adapt it to the actual wholesale electricity markets without losing its typical advantages.

The model in [7] is used by the system dynamics model of this paper just to obtain the system price duration curve for each year (that is, the price for each hour), considering a perfect competition framework because investments decisions are represented in a global way, that is, no matter which company makes the investment. The price duration curve allows taking into account the effect of peak periods that can make some new plants profitable.

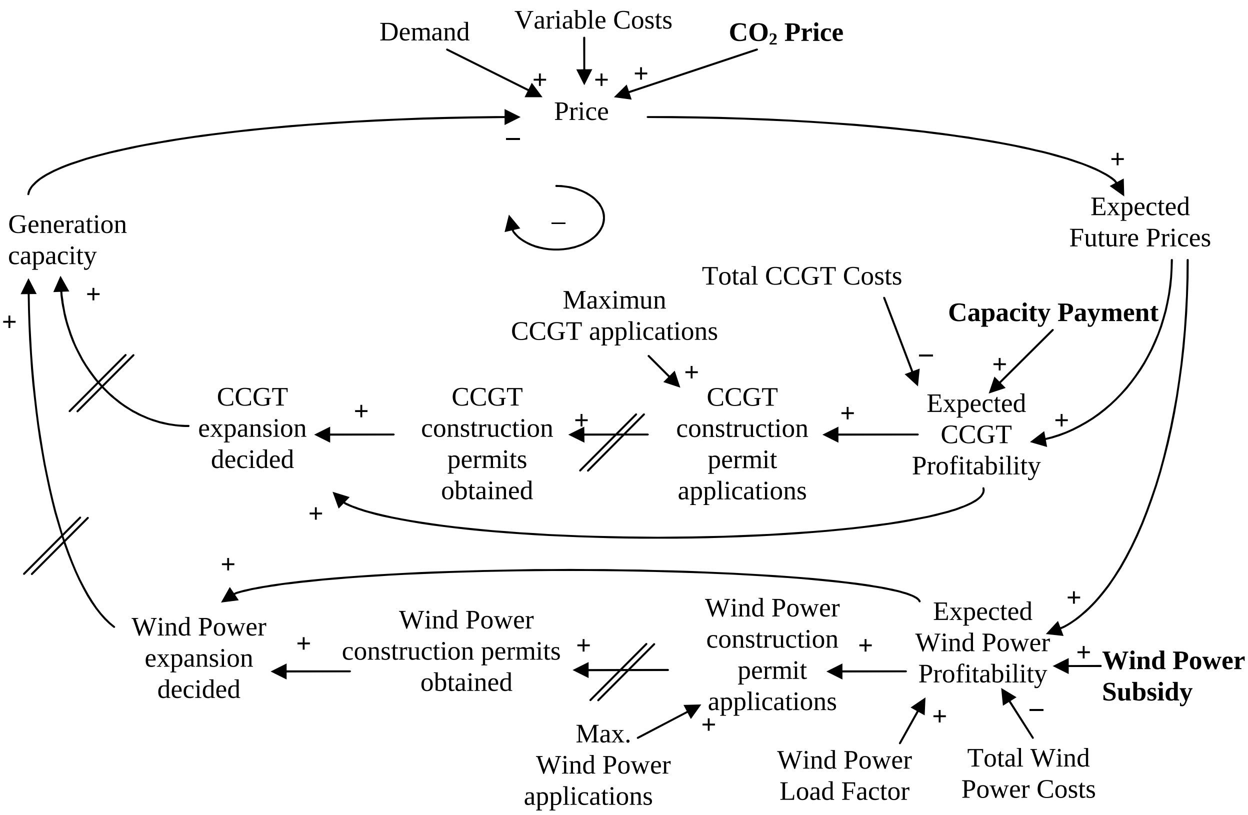

Figure 1: Casual loop diagram of the system dynamics model

2.4 Future price estimation

This is the main feedback signal for investment decisions in our model.

To calculate the future expected prices when the model is calculating the investment decisions in a particular year, the system price duration curves calculated for the current year and the previous years are used. With this, a matrix of price duration curves is obtained. In order to extrapolate these curves to the future years, the *single value decomposition* technique is applied as follows (see [9] for a similar use of this technique).

$$\log\left(p_{ty}\right)=\sum_{k}\sigma_k^2\cdot u_{tk}\cdot v_{ky}^{'} \quad \textbf{(1)}$$

In (1), p_{ty} represents the price duration curves being t each hour of a year and y each one of the years considered, which are the previous years to the current year, including this one.

Applying the singular value decomposition technique to the logarithm of the price duration curves' matrix the second term in (1) is obtained, where σ_k are the singular values of the logarithm of the price duration curves, u_{tk} a matrix which extracts information about the shape of the prices duration curves and v_{ky} a matrix that represents how this shape changes with the years.

To obtain an estimation of the logarithm of the price duration curves in the future years a linear extrapolation in y of the v_{ky} matrix is calculated.

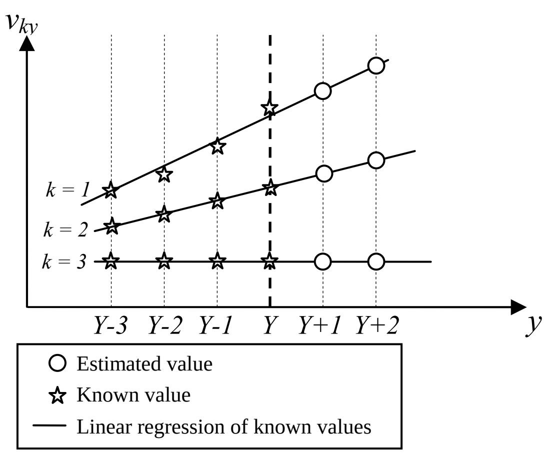

Figure 2: Linear extrapolation in years (y) of v_{ky} matrix.

With this, an expected matrix v_{kn} for the future years n is calculated, which allows estimating future price duration curves p_{tn} as in (2).

Therefore, the model estimates the price for every hour of a number of future years, which gives the possibility of considering peak hour effects, quite important in investment decisions.

$$p_{tn}=e^{\sum_k \sigma_k^2\cdot u_{tk}\cdot v_{kn}^{'}} \quad \textbf{(2)}$$

2.5 Expected profitability for CCGT plants

Expected profitability is calculated using the net present value *NPV* as it shown in (3) where *FCF* stands for free cash flow an r for discount rate. The FCF_y for each year is calculated as in (4) where p_{ty} is the system marginal price for an hour of the year, VC_y the variable cost of CCGT technology that year, CP_y a capacity payment, FC_y the fix costs and IC_y the investment costs. The calculation at this point is made per MW of CCGT not per plant.

$$NPV=\frac{FCF_1}{1+r_1}+\frac{FCF_2}{(1+r_2)^2}+\ldots+\frac{FCF_Y}{(1+r_Y)^{Y}} \quad \textbf{(3)}$$

$$FCF_y=\left(\sum_{t\in y}\max\left(p_{ty}-VC_y;0\right)\right)+CP_y-FC_y-IC_y \quad \textbf{(4)}$$

It is assumed that, if a plant is decided to be constructed this year, it will be ready to operate in a number of years later (delay). The investment costs are totally applied when the plant construction is ended. It has been also assumed that plants only enter the market at the beginning of the year.

2.6 Expected profitability for wind power plants

The profitability is calculated with the same equation as the CCGT plants (3), but this time the FCF_y is calculated with equation (5).

$$FCF_y=\left(\sum_{t\in y}\left(p_{ty}+subs_y-VC_y\right)\cdot LF_y\right)-FC_y-IC_y \quad \textbf{(5)}$$

In (5), $subs_y$ is the subsidy given to the wind power plants and LF_y is the load factor considered for this technology.

The wind power plants do not produce when the price of the market is greater than its variable cost as the CCGT plants but when there is enough wind. In this model, a load factor LF_y is considered, which gives the number of hours that a MW of wind power produces during a year. This load factor is multiplied by the total MWs of wind power that there are in the system and the result is the output of wind power for each hour of the year. This output is subtracted from the demand for every hour.

2.7 Construction permit applications

The number of construction permit applications CPA_y is a function of the expected profitability. The greater the expected profitability the more permit applications will be applied. An upper bound should be included in terms of physical capacity of the system.

More than one function could be suitable for representing this calculation. In this model, a function as the one in (6) is used. This function has an upper bound CPA_MAX_y which is an input of the model and which is based on a determinate percentage of the peak demand of the year.

$$CPA_y = CPA\_MAX_y - CPA\_MAX_y \cdot e^{-\frac{NPV}{K_y}} \quad \textbf{(6)}$$

K_y is a parameter of the model that represents how much near of the upper bound is the CPA_y, depending on the expected profitability. In this function, when NPV is equal to 2 times K_y, CPA is equal to 87% of the CPA_MAX_y. A reasonable value for this parameter could be the investment cost.

2.8 Delay for the constructions permit applications approval

This delay depends on the system which is under study, its laws, its administrative procedures, etc. In this model, the function for representing this delay is a function that approaches the total number of applications exponentially in time. This function is presented in (7):

$$CP_{(ny)} = CPA_y - CPA_y \cdot e^{-\frac{(ny)}{K2}} \quad \textbf{(7)}$$

In this equation *ny* represents any of the following years, *CP(ny)* the number of applications approved and *K2* a parameter of the model which represents how quickly the maximum number of approved applications is reached. For this case, a value from 0 to 2 years is recommended.

2.9 Number of MWs decided to construct

This calculation follows the same function as in equation (6) but substituting the upper bound value of the function CPA_MAX_y to the number of construction permit applications approved CP_y.

2.10 Delays for the construction of the plants

For the CCGT plants, a constant delay is used. That is, when any CCGT plant is decided to be constructed it will be ready to operate a constant number of years later.

For wind power plants, the delay follows the same function as in (7) substituting the CPA_y variable for the number of MWs of this technology that have been decided to be constructed.

3 STUDY CASE

3.1 Case description

The study case represents a hypothetical large-scale electric power system. The scope of the study is splitted into 30 years. The model time resolution is 1 year, but price is calculated for every block of 10 hours (each block representing a load level) of the 12 periods *w* (months) in which a year is divided. Three initial price duration curves are considered to estimate the future prices with a sufficient number of curves the initial years.

The energy is supplied by five generation companies (*f1* to *f5*) with different sizes. The main characteristics of thermal units are shown in Table 1. A CO_2 emission rate is considered for each unit. For CCGT plants, this rate is 0.35 tCO_2/MWh. Table 2 shows the number of hydro units of each firm and their aggregated characteristics for the first period *w* of any year. An average scenario of hydro production is considered for every year.

An initial base load is also computed for every year. This consist of a pumping storage of 1000 MW in the 50% of the hours of every period *w* and a cogeneration production of 5000 MW for the 50% hours of least demand of every period *w* and 8000 MW for the rest.

An hourly load based in the one of the Spanish electricity market in 2003 is considered to calculate the hourly loads of the years of the model. A 3% constant growth is considered for the rest of the following years being 2005 the first year.

General characteristics for CCGT and wind technologies are shown in Table 3. For the two first years, an investment in new CCGT capacity of 1600 MW is taking into account. For the rest of the years, the investments decisions are calculated by the model. CCGT plants have a constant construction delay of 2 years and a maximum output capacity of 400 MW by plant. The upper bound of constructions permit applications for both technologies is 10% of the peak demand of the year.

€/MWh	f1	f2	f3	f4	f5
Up to 5	400 (1)	0 (0)	0 (0)	0 (0)	0 (0)
5 to 10	4600 (5)	0 (0)	2000 (2)	0 (0)	0 (0)
10 to 15	100 (1)	0 (0)	0 (0)	0 (0)	0 (0)
15 to 20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
20 to 25	2500 (7)	1900 (5)	3000 (9)	1900 (5)	0 (0)
Over 25	9900 (40)	1800 (8)	5500 (19)	1900 (5)	0 (0)

Table 1: Capacity (MW) and Number (in parenthesis) of thermal groups by utility ranged by cost

	f1	f2	f3	f4	f5
#	2	10	3	0	2
E (GWh)	78.66	236.64	16.67	0	28.6
Pmax (MW)	1423	5681	485	0	606
Pmin (MW)	706	1301	64	0	241

Table 2: Aggregated hydro power characteristics by utility for first period of any year. Number of hydro plants (#), energy (E), maximun output (Pmax) and minimum output (Pmin).

	IC	*FC*	*VC*	*LS*	*K*	*K2*
	€/kW	*€/kW*	*€/kWh*	*years*	*€/kW*	*years*
CCGT	619	29	25	30	619	-
Wind	1211	28	0	25	1211	1

Table 3: General characteristics for CCGT and wind power. Investment costs (IC), fix costs (FC), variable costs (VC), life-span (LS), and parameters K (see (6)) and K2 (see (7)). (Source: [10]).

The different scenarios considered in this study case correspond to different values in the CO_2 price, in the subsidy to the wind power and in the capacity payment used by the regulator. These scenarios are resumed in Table 4.

Case	*CO_2*	*CP*	*Subs.*	**Case**	*CO_2*	*CP*	*Subs.*
#	*€/tCO_2*	*€/kW*	*€/kWh*	**#**	*€/tCO_2*	*€/kW*	*€/kWh*
1	0	0	10	**5**	0	35.71	10
2	7	0	10	**6**	0	0	0
3	15	0	10	**7**	0	0	20
4	0	71.42	10	**8**			

Table 4: Study case scenarios resume. CO_2 price (CO_2), capacity payment (CP) and subsidy for wind power (Subs.).

3.2 Results

By comparing scenarios 1, 2 and 3 it can be drawn conclusions of how an emissions trading scheme may affect to the evolution in the long-term of an electric power system like the one described here.

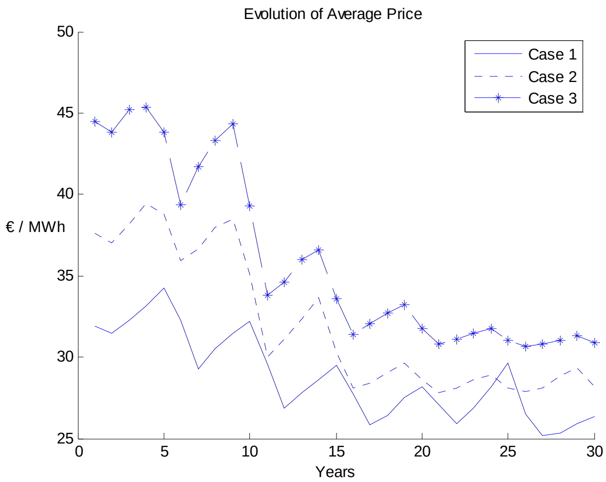

Figure 3: Evolution of average price for cases 1, 2 and 3

From Figure 3, it can be seen that the average electricity price increases because firms internalize the cost of the emissions in their bid supply functions. This price will decrease in the long-term near to the CCGT variable cost (emissions variable costs included) because this technology is the only one (apart from wind) that is being constructed in the system. These higher prices imply more expected profitability for the firms which invest more in new capacity improving the security of supply (Figure 4). The cycles shown in both figures are due to the reinforcement feedback loop of the system. That is, when price is high, firms invest more in new capacity. These new investments will decrease price when they enter the market making the firms to invest less.

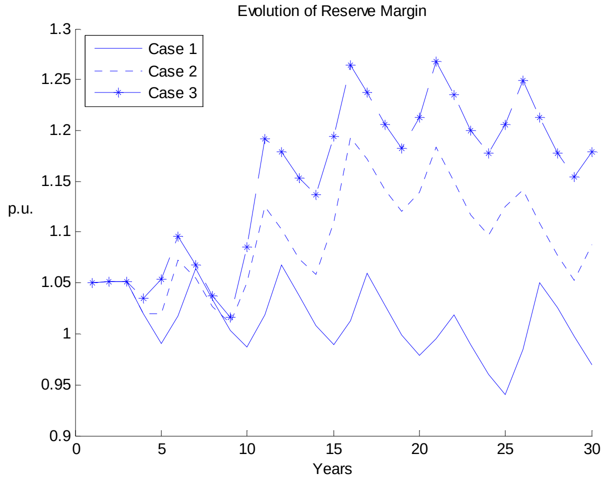

Figure 4: Evolution of reserve margin for cases 1, 2 and 3

The Figure 5 shows how an increase in the capacity payment may change the dynamics of the system. Although increasing the capacity payment may be seen as an incentive to invest in order to ensure electricity supply, it can give and opposite effect sometimes. When the capacity payment is high, firms tend to invest more and before at the beginning. If the capacity payment is too high it may result in an overcapacity in the system what is traduced in a critical decrease of the electricity price. So, although the firms are earning with the capacity payment, they can be loosing money by the electricity price what makes them to see less profitability and to reduce drastically their investments. With this model, this effect can be anticipated helping the policy makers not to introduce excessive capacity payments.

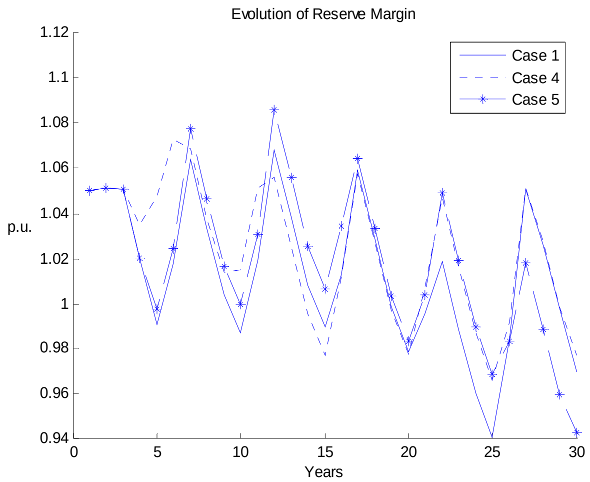

Figure 5: Evolution of reserve margin for cases 1, 4 and 5

Finally, the implications that a subsidy for the wind power has in their investments can be seen in Figure 6. High subsidies will incentive investments in new wind power capacity. However, that not means that these investments will be higher in all the years or set of years. A similar effect to the one of the capacity payment can occur. That is, the higher the subsidy is the more investments in wind power take place. This could lead to and overcapacity in the system that will decrease the prices to a level such that firms will not see profitability at all. This can be seen in the period near year 25. There, investments in wind power in a framework with a low subsidy for them or even with no subsidy are higher than investments in a framework with a high subsidy.

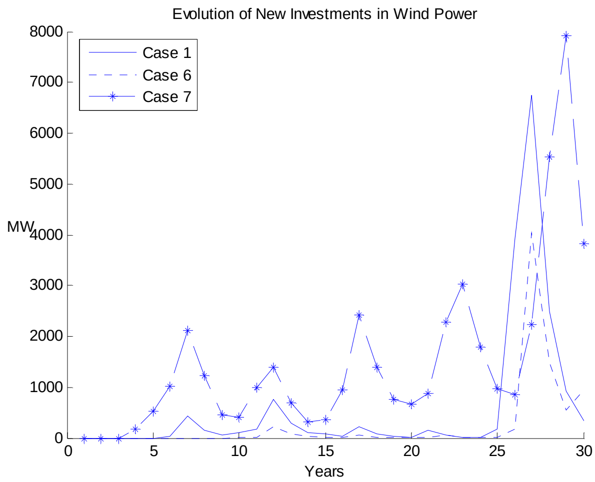

Figure 6: Evolution of new investments in wind power for cases 1, 4 and 5

These examples show how this model helps to learn about the possible dynamics of the system through simulation. By studying different scenarios it can warn opposite effects to the ones expected and can assist agents and policy makers to take more correct decisions.

4 CONCLUSIONS

A strategic simulation model that helps to get insights into how a liberalized electricity system may evolve in the long-term has been presented.

The model is based in the business dynamics technique although it overcomes some of the difficulties of these kinds of models. Business dynamics models use to focus on dynamics complexity by studying the relationships among the main variables of the problem, not taking into account most of the system details. However, this model deals with this problem by introducing some "complex" functions into the system dynamics model to obtain a more realistic representation of the electricity market. Particularly, it calculates the market price using a strategic production costing model based in equilibrium approaches. With this, a price duration curve is obtained for each year what allows to take into account peak hour effects.

This model joins the advantages of system dynamics models in terms of behavioral, high-level and feedback characteristics with the advantages of equilibrium models in terms of system detail.

Concretely, the model simulates investment decisions in new generation capacity in a deregulated framework where decisions are based in profit maximization. So, the main feedback signals of it are the expected future prices which, as it has been said, are represented by the price duration curves and not only by and average price.

By generating different scenarios with the model, learning of the real system can be accelerated given the different agents of it some experience of great value. Because of that, it can be used by generation companies to assess them with their investments decisions and by policy makers to introduce more correct policies.

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