A model based in numerical simulation techniques as a tool for decision-making and risk management in a wholesale electricity market.
Part II: The market model

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Abstract: The algorithm we present in this paper defines a market model used in a tool for Risk Analysis. In this tool, scenarios for the uncertain variables (such as hydro inflows, demand values, fuel prices, etc.) are first generated, through simulation techniques. For each scenario a market equilibrium is obtained from the model we propose, and finally a scenario analysis module computes risk measures, such as Value at Risk, Profit at Risk, etc. The market model detailed in this paper obtains generator-side bids for the different market participants, taking into account their cost structures, the operational constraints of their generation plants, as well as other regulatory factors that influence market behavior, such as incentives for the consumption of domestic coal, compensation of stranded costs, etc. Based on these bids, the model computes wholesale prices, the resulting dispatch of the units, and the revenues and costs of each market participant.

Keywords: Marginal price, decision-making, risk management, agent's behavior, operational constraints.

I. INTRODUCTION

The recent changes in the electricity industry all over the world have lead to more competitive markets. One of the most important features in this new framework is the appearance of risks that affect electricity companies (see Part I and [3]). Therefore, models that reflect these risks and help in the decision-making process become very important tools for companies involved in these new markets.

These models for a competitive environment should still take into account all the random variables that currently exist in power systems, such as hydro inflows, demand values, etc. In addition to these sources of uncertainty, competition brings a new factor to electricity systems: the uncertain behavior of generation competitors and consumers. Decision-makers in this market environment do not only face the uncontrollable random events previously mentioned, but also deal with competitors and customers that make independent decisions.

It is thus critical the choice made when modeling the price behavior, especially in those relatively immature markets (as is frequently the case with electricity markets), where the mathematical treatment of historical data is of little use. In these kind of markets the best way of defining price or profits data and series, is to use a well defined price behavior model where the agents strategies are modeled when facing different market structures, competitors behavior or other issues.

The algorithm we present in this paper defines a market model used in a tool for Risk Analysis (Fig. 1). In this tool scenarios for the uncertain variables are first generated, such as hydro inflows, demand values, fuel prices, etc. (see Part I), through Monte Carlo based techniques. For each scenario a market equilibrium is obtained from the model we propose, and finally a scenario analysis module computes risk measures, such as VAR, Profit at Risk, etc.

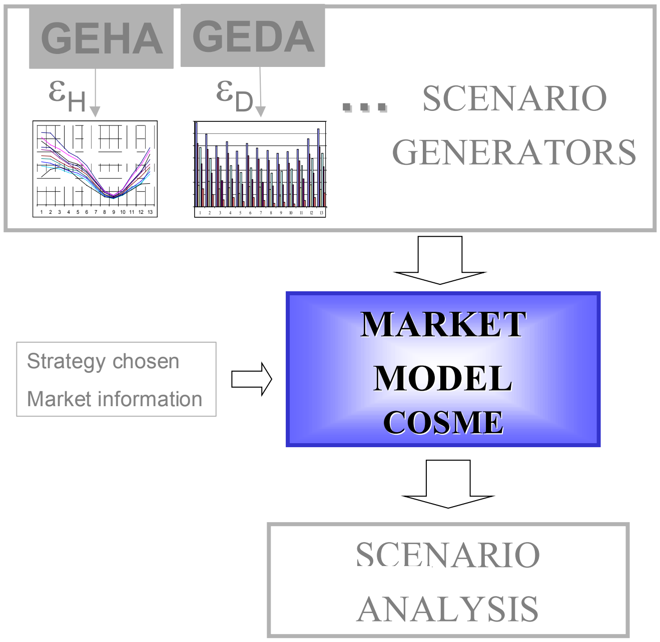

Fig. 1. The risk tool

II. THE MARKET MODEL

As it was said before the market model becomes crucial in any risk analysis tool, as the competitors behavior, their possible strategies and the regulatory rules of the particular market being studied are defined in it.

This paper presents a model of a wholesale electricity market. This model generates generator-side bids for the different market participants, taking into account their cost structures, the operational constraints of their generation plants, as well as other regulatory factors that influence market behavior, such as incentives for the consumption of domestic coal, compensation of stranded costs, etc. Based on these bids, the model computes wholesale prices, the resulting dispatch of the units, and the revenues and costs of each market participant.

Market agents in this model are assumed to maximize their profits without an a priori knowledge of their competitors' actions. Each participant manages a portfolio of generation stations, thermal and hydro, and makes decisions about plant start-up and stop, reservoir management, and bidding practices.

The model proposed can be used to test the effect of different bidding strategies and market circumstances (ranging from price wars to oligopolistic equilibria) in real size markets, and adequately reflects the effects of market structure (number and size of participants, vertical integration), costs and technical constraints, regulatory elements, etc. In the version presented in this paper, the transmission system is not explicitly modeled; however, its effects can be included through additional constraints in the production of a set of generation units within a specified area.

The market model follows the ideas proposed by Robert Wilson [2] for the Californian market that leads to a market equilibrium. The strategic behavior of the generating companies is modeled based on a generalization of the Cournot and Bertrand equilibria, as agents use both strategic variables: prices and quantities [3], [4].

The iterative approach uses the economic model in a dynamic way, since at each stage of the model agents can update their beliefs about their competitors, using the information they get from the market's results.

The model can simulate two kinds of markets:

- A perfectly competitive market (that will be called the unco-ordinated simulation) in which each generation unit acts as an independent competitor and is basically a price-taker player.
- An oligopolistic market (the so-called co-ordinated simulation) where groups of units belong to firms that try to maximize their profits managing their portfolio, and behave as price-setters agents.

The methodology presented has already been applied to the Spanish electricity market under realistic assumptions for a short-term horizon in [5], as well as for a long-term horizon [6], [1]. The algorithm described in this paper has been modified to consider all those terms of the profit equation that depend on market prices and link several time periods, such as energy contracts or the stranded cost recovery structure as it is defined in Spain.

Section III describes the market algorithm. The module where optimal strategic decisions are taken is described in Section IV. Section V presents results for different strategies applied to the Spanish market for a year horizon.

III. ALGORITHM PROPOSED

The algorithm proposed in this paper decomposes the market equilibrium problem into two different modules (Fig. 2) linked by the information they exchange between each other. In the *Optimal strategic decisions module* (Module 1), firms receive market prices and dispatches from the *Clearing module* (Module 2), and decide new offers (both in quantity and price) that are sent back to the *Clearing module*.

This iterative method reaches convergence when market prices have not changed from one iteration to another in more than a certain threshold; i.e. firms have not changed their offers as they have reached their best and feasible strategy.

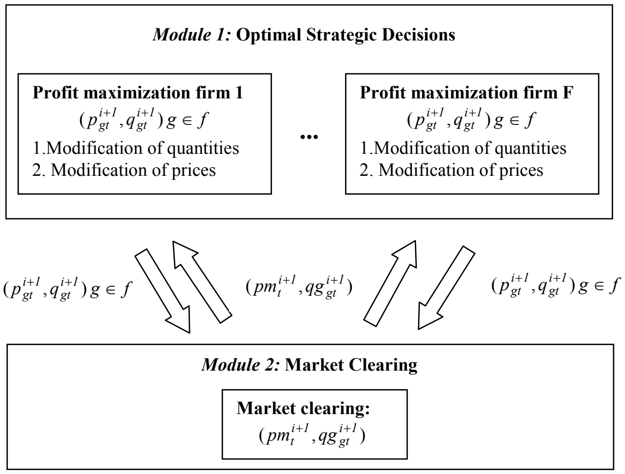

Fig. 2. Algorithm proposed

- *Clearing module:* The clearing method computes the spot price as the price of the most expensive bid accepted to supply the demand. Technical constraints and fixed costs are not explicitly taken into account in the clearing process, and thus generators have to internalize them in their offers. This is carried out in the strategic module.
- *Optimal strategic decisions*: In this module units decide their offers considering the results of the last iteration as a way of taking into account the competitors' behavior. To assure convergence, these modifications can only be reductions of the bid price, being the price decrement (ε), the aforementioned threshold, fixed. In this module

firms maximize their profits if the co-ordinated strategy is considered, and generation units maximize their own profits if the uncoordinated simulation is chosen. In both cases the optimal strategic decisions is divided in two different parts, one for each strategic variable considered: Modifications of quantities and Modifications of prices.

IV. NOTATION

q_{gt}^{i+1} ≡ Quantity to be offered by unit g, at time period t, and iteration $i+1$ (MW).

p_{gt}^{i+1} ≡ Price to be offered by the thermal unit g, at time period t, and iteration $i+1$ (€/MWh).

qg_{gt}^{i} ≡ Accepted quantity at the clearing module, of unit g, at time period t, and iteration i (MW).

mp_{t}^{i} ≡ Market price at time period t and iteration i (€/MWh).

IQ_{ft}^{i} ≡ Inframarginal quantity of firm f, at time period t, and iteration i (MW).

$$IQ_{ft}^{i} = \sum_{g \in f}^{G} \left[qg_{gt}^{i} \right] \tag{1}$$

$\overline{Q}_{ft}^{i}$ ≡ Maximum quantity that firm f can increase its dispatched quantity, at time period t, and iteration i (MW).

qd_{ft}^{i+1} ≡ Quantity decision of firm f, to increase its dispatched quantity, at time period t, and iteration $i+1$ (0,1).

eq_{ft}^{i+1} ≡ Extra Quantity that firm f offers at time period t, and iteration $i+1$ (MW).

sd_{gt}^{i+1} ≡ Start-up decision of unit g, at time period t, and iteration $i+1$ (0,1).

VC_{g} ≡ Variable cost of unit g (€/MWh).

NLC_{g} ≡ No-load cost of unit g (€/h).

SC_{g} ≡ Start-up cost of unit g (€).

$CMIN_{fuel}$ ≡ Minimum consumption of a certain fuel (GWh).

V. OPTIMAL STRATEGIC DECISIONS

In this module units update their offers considering the information from the previous market clearing, the strategy chosen and their operational constraints. This module is divided in two parts: Modifications of quantities and Modifications of prices.

$$(p_{gt}^{i+1}, q_{gt}^{i+1}) = f\Big((p_{gt}^{i}, q_{gt}^{i}), (qg_{gt}^{i}, mp_{t}^{i}), S_{f}\Big) \tag{2}$$

where

S_{f} ≡ Strategy chosen by firm f,

(p_{gt}^{i}, q_{gt}^{i}) ≡ Previous offers of unit g, which belongs to firm f,

$(qg_{gt}^{i}, pm_{t}^{i})$ ≡ Market results from the previous clearing.

When the un-coordinated simulation is considered units maximize their own profits independently, acting as price takers. The same equations and structure are used but formulated for each g unit instead of for each firm f.

A. Modification of quantities

The first stage of this module chooses the quantity that units offer at the next iteration. This is solved through a maximization problem where the objective function represents the total profit for each firm f. It considers the revenue, paid at the marginal price from the previous iteration, and the total costs, including variable, no-load and start-up costs. The acquisition of pumping energy is also considered as a cost, which is purchased at the marginal price.

Since in oligopolies firms might act as price setters, a non-linearity appears when profits are maximized and the strategic variable considered is the quantity. To avoid this non-linearity we have proposed a methodology in [5], [6] and [1] where the modification of quantities was divided in two different steps. In the first step firms decided the quantity they offered as a portfolio, while taking into account the effect on the price of the quantity they chose (price could be kept constant or could be reduced in ε). This was done uncoupling each time period. Once this was known, this quantity, chosen by firm f, was optimally split among its units. This was done through a maximization problem where technical and operational constraints were considered, and the total time scope was linked.

The methodology proposed in this paper avoids these two steps and solves the modification of quantities in one stage while using linear programming. The main advantage of this new approach is that all those terms of the profit equation that depend on market prices and link several time periods, can now be considered without having to unlink them for each time period t. An example of such kind of terms is given at the end of this Section, were the stranded costs recovery and simple contracts are modeled.

Considering a firm *f* that owns a generation portfolio, and that it has been dispatched at iteration *i* and time period *t*, a certain quantity, IQ_{ft}^{i}, and a market price, mp_{t}^{i}. For this time period *t*, firm *f* can do two different things: it can increase the quantity dispatched (which will lower the market price in ε, and therefore will reduce the inframarginal profits in $IQ_{ft}^{i} \cdot \varepsilon$), or it can keep the same amount dispatched IQ_{ft}^{i}, which will keep the market price constant at mp_{t}^{i}, and will not reduce the inframarginal profits. These economic effects (that reproduce a Cournot based approach) as well as the operational constraints of the units that belong to the firm, can be expressed through a linear problem defined as follows:

1. Objective function

$$
\begin{aligned}
Max \sum_{t}^{T}\Big(\sum_{g\in f}^{G}\big(q_{gt}^{i+1}\cdot mp_{t}^{i} - VC_{g}\cdot q_{gt}^{i+1} - \\
- NLC_{g}\cdot std_{gt}^{i+1} - SC_{g}\cdot sd_{gt}^{i+1}\big) - \\
- eq_{ft}^{i+1}\cdot\varepsilon - qd_{ft}^{i+1}\cdot\varepsilon\cdot IQ_{ft}^{i}\Big)
\end{aligned}
\tag{3}
$$

2. Constraints

i) Operational and technical constraints (thermal, hydro and pumping):

Table 1

Thermal constraints	Hydro constraints
Maximum power Minimum generation level State transition	Maximum power Hydro balance Hydro balance for pumping units

ii) Cournot constraint

Limits the total output of firm *f* at time *t*.

$$\sum_{g\in f}^{G}\left[q_{gt}^{i+1}\right] \le IQ_{et}^{i} + eq_{ft}^{i+1} \tag{4}$$

iii) Logical constraint

Defines $qd_{ft}^{i+1} = 0 \rightarrow eq_{ft}^{i+1} = 0$.

$$qd_{ft}^{i+1}\cdot \overline{Q}_{ft}^{i} \ge eq_{ft}^{i+1} \tag{5}$$

With this new formulation the two possibilities for firm *f* mentioned above, are considered. To illustrate it, we will use an example of a certain step time *t* and iteration *i*, where two companies A and B decide their new offers for iteration *i+1* (Fig. 3). Units U1, U2 and U3 belong to company A and only the first two have been accepted at iteration *i*. Thus the inframarginal quantity, IQ_{ft}^{i}, for company A is $q_{U1,t}^{i+1} + q_{U2,t}^{i+1}$. This company could try to get more power dispatched by reducing the offer of unit U3, which will shift the marginal unit UM, that belongs to the other company. The maximum power increase that company A can have, $\overline{Q}_{ft}^{i}$, is the minimum value between the accepted power of this marginal unit UM and the maximum power offered by unit U3. By doing this, the market price will be lowered to $mp_{t}^{i} - \varepsilon$, and so the inframarginal revenue of company A will also be reduced (Units U1 and U2 will receive $mp_{t}^{i} - \varepsilon$ instead of mp_{t}^{i}). The algorithm checks through the maximization problem, what will be more profitable for company A: to increase the power dispatched, despite the inframarginal revenue decrease, or to keep the offers constant.

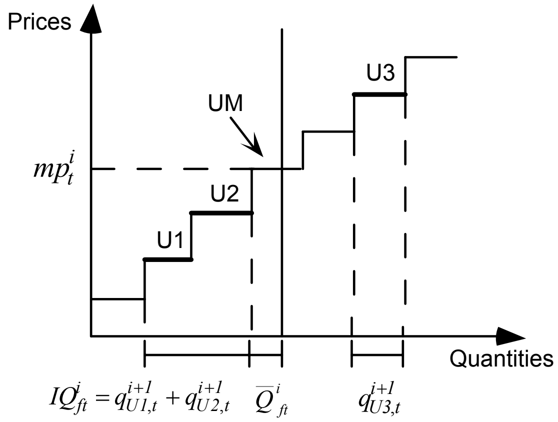

Fig. 3. Firms' *f* decisions for time *t*

In the formulation we propose, if firm *f* chooses to increase its previously accepted quantity, IQ_{ft}^{i}, then both variables, eq_{ft}^{i+1} and qd_{ft}^{i+1}, will be greater than 0, which reduces the market income, as both variables are penalized in the objective function. If this income's reduction is higher than the income's increase due to the extra quantity that will be dispatched in the market, then firm *f* will choose to keep the same quantity level, IQ_{ft}^{i}. In this case both variables eq_{ft}^{i+1} and qd_{ft}^{i+1} will now be 0, and the market income will not be reduced. In this last case the total amount that this firm can offer will be limited to IQ_{ft}^{i}, through the Cournot constraint (4). These two situations can be summarized as follows:

$$qd_{ft}^{i+1} = 0 \Rightarrow \begin{cases} eq_{ft}^{i+1} = 0 \\ \sum_{g\in f}^{G}\left[q_{gt}^{i+1}\right] \le IQ_{ft}^{i} \\ mp_{t}^{i} = mp_{t}^{i} \end{cases} \tag{6}$$

$$qd_{ft}^{i+1} = 1 \Rightarrow \begin{cases} eq_{ft}^{i+1} \neq 0 \\ \sum_{g\in f}^{G} \left[q_{gt}^{i+1} \right] \leq IQ_{ft}^{i} + eq_{ft}^{i+1} \\ mp_t^i = mp_t^i - \varepsilon \end{cases} \qquad (7)$$

All these economic influences are considered as well as the technical and operational limits of all the units. Therefore, the final offers will be feasible, and optimal from an economic point of view.

B. Modification of prices

Once each unit has decided the quantity to be offered at next iteration, prices are also updated, through a function that relates these new bid prices with the old ones, with the quantities to offer at iteration *i*+1, and with the results from the previous clearing.

$$\begin{aligned} p_{gt}^{i+1} &= f(p_{gt}^{i}, q_{gt}^{i+1}, qg_{gt}^{i}, mp_t^i) \\ p_{gt}^{i+1} &= \begin{cases} p_{gt}^{i} \ \mathit{if}\ qg_{gt}^{i} < q_{gt}^{i+1} \\ mp_t^i - \varepsilon \ \mathit{if}\ qg_{gt}^{i} = q_{gt}^{i+1} \end{cases} \end{aligned} \qquad (8)$$

C. Other objectives

Participants in the actual markets have been found to follow mixed strategies where market profits are maximized but other considerations, such as market shares, stranded costs recovery, regulator's and new entry's threat or capacity payments, distort the basic market profits maximization approach, making other possible strategies appear. Some of these strategies have been implemented in the model presented in this paper.

1. Minimum consumption of certain fuels

It represents the constraint over certain fuels to generate at least a specified minimum level. This is modeled through a generation constraint such as:

$$\sum_{t}^{T} \sum_{g\in fuel}^{g} \left[q_{gt}^{i+1} \right] \geq Cmin_{fuel} \qquad (9)$$

As the two market constraints (4) and (5), limits the total production to the level $IQ_{et}^{i} + \overline{Q}_{ft}^{i}$ it might produce some infeasabilities when combined with the minimum consumption of a fuel (5) which in general increases the company's output. To avoid it, the minimum consumption constraint has been given preference over the Cournot level constraint (2), and a slack variable has been introduced in this constraint (2) that will cancel the production limitation and the company will produce the amount necessary to respect the minimum consumption constraint. To assure that this constraint will be canceled only when necessary, this slack variable S_{ft}^{i+1} is penalized in the objective function. The value of this penalization depends on the inframarginal quantity that firm *f* has dispatched at each time period *t*. By doing this, constraint (4) will only be violated at those time periods when the effect on the inframarginal profits are cost less to the firm.

2. Stranded cost recovery

This is modeled as a simple contract for differences signed at a price PC_{ft}, and for a quantity QC_{ft} [7]. This two values, PC_{ft} and QC_{ft}, can be expressed independently for each time period *t*, or can couple various time periods, which represents the main advantage of the new approach presented in this paper. The only change in the equations for the maximization problem appears in the last term of the objective function.

3. Objective function

$$\begin{aligned} Max \sum_{t}^{T} \Big(\sum_{g\in f}^{G} \big(& q_{gt}^{i+1} \cdot mp_t^i - VC_g \cdot q_{gt}^{i+1} - \\ & - NLC_g \cdot std_{gt}^{i+1} - SC_g \cdot sd_{gt}^{i+1} \big) - \\ & - eq_{ft}^{i+1} \cdot \varepsilon - qd_{ft}^{i+1} \cdot \varepsilon \cdot IQ_{ft}^{i} + \\ & + (mp_t^i - qd_{ft}^{i+1} \cdot \varepsilon - PC_{ft}) \cdot QC_{ft} \Big) \end{aligned} \qquad (10)$$

VI. CASE EXAMPLE

The model described in this paper, called COSME, has been written in C language and GAMS (General Algebraic Modeling System) languages. GAMS has been used to solve the profit maximization modules using the CPLEX optimization software with mixed integer programming, following the simplex method.

The example we present in this paper corresponds to the Spanish wholesale market. It covers a whole year divided into thirteen periods (each one corresponds to four weeks), with two subperiods (working and non-working day types), and three load levels for each subperiod. Therefore the total number of time steps is 78, with variable lengths and a total demand of 183000 GWh, 31000 GWh of hydro inflows, which corresponds to a medium type year. Four companies were modeled with very different sizes (*FA*; *FB*, *FC* and *FD*) and fuel types, that corresponds to the real Spanish power system.

For the whole system 67 thermal units were considered, 19 hydro units and 10 weekly pumping units.

Different simulations were carried out following different kind of strategies, all for the same scenario (in terms of demand, hydraulicity, units availability and fuel costs). Comparing results it can be seen to what extent different behaviors and strategies lead to prices, profits and market shares that change due only to the influence of the firms strategic behavior.

Four simulations are presented in this paper:

- Case #1: It follows an un-coordinated strategy, where individual units maximize their own profits as price-taker agents.
- Case #2: It follows a coordinated strategy, where firms maximize their profits and behave as price-setters.
- Case #3: It follows a coordinated strategy, with certain fuels having a minimum consumption constraint.
- Case #4: It follows a coordinated simulation, where firms consider the stranded cost recovery as part of their strategy.

A. Case #1: Un-coordinated simulation

Fig. 4 shows period prices, considering the un-coordinated strategy and market shares for one of the biggest companies considered, *FA*. This situation is the closest to a perfect competitive market where agents behave as price-takers. Thermal units increase their offers during peak hours to recover their start-up cost, and lower them during off-peak hours (to values even lower than their variable costs), to avoid a start-up that would cost these units more than to generate at a loss during several hours.

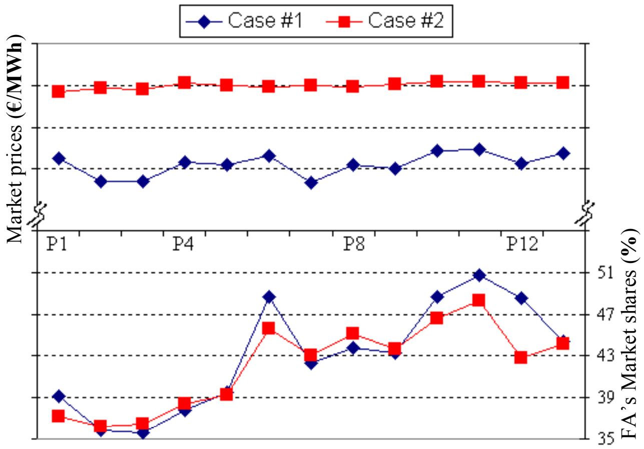

Fig. 4. Case #1 and Case #2 market prices & shares

B. Case #2: Coordinated simulation

In this case, firms influence market prices. Therefore prices and profits are higher than in the case before (Fig. 4), while the production of the two biggest firms is withheld in order to increase market prices.

As it can be seen from Fig. 5, prices increase mainly during peak hours, as when demand is lower bidding gets closer to marginal costs. In these kind of hours, demand can be fully dispatched by a single firm, which increases competition, and units depress off-peak prices to avoid a start-up, as also happened for the un-coordinated simulation.

In the short-term version of the presented model, as bottlenecks are modeled with more detail, this Bertrand competition during off-peak hours is increased [5], reducing market prices in the coordinated simulation almost to the same values as the ones obtained for the un-coordinated during off-peak hours.

Consequently, coordinated prices are smoother than those previously obtained for the un-coordinated strategy.

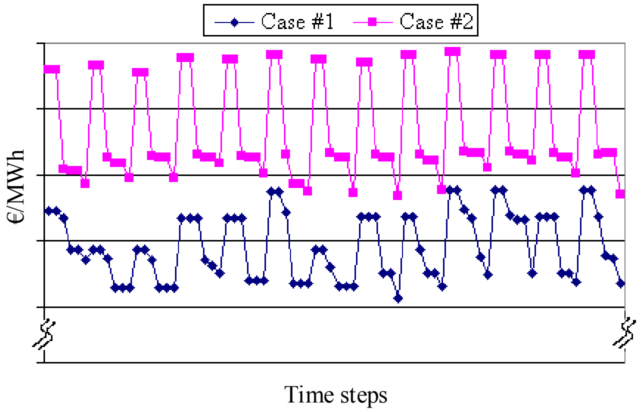

Fig. 5. Market Prices for Case #1 and Case #2

Although all firms were modeled as price-setters, not all of them changed their behavior from a price-taking strategy, due to their small size. As it can be seen in Fig. 6, the market shares of the two biggest companies (firms FA and FB) move inversely one respect the other along the thirteen periods considered. One of them, firm FB, has a higher hydro production, which increases its market share during the wet periods, while the other, firm FA, gets to its maximum market share during the dry summer periods.

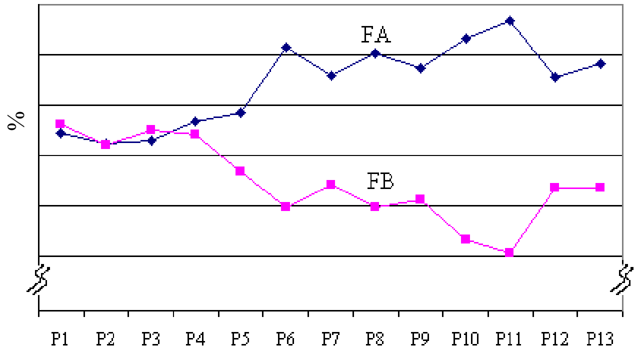

Fig. 6. Case #2 market shares of firms FA and FB.

C. Case #3: Coordinated simulation with minimum consumption constraints

In this case, a minimum consumption constraint is considered for certain fuels. Due to these constraints those companies that owned this kind of fuel type units, modify their bids. As it can be seen in Fig. 7, it especially affected the firms that owned more thermal units, firm FA, increasing its market share, and decreasing the market share of its more hydraulic competitors.

Prices fall compared to the previous case (although not down to the levels obtained from the un-coordinated simulation, see Fig. 9), especially during the wet periods and those with lower demand. As the minimum consumption constraint covered the whole simulation scope, firms can decide when to fulfill their consumption constraints depending on prices and inframarginal profits for each time period. Thus, the firm more affected by these constraints chooses to produce during those periods where prices are higher and their inframarginal income less affected (basically when demand is higher, hydraulicity lower and consequently competition is reduced).

Market profits are reduced, as prices are lower. These constraints do not follow pure profit objectives, as they represent other sort of aims.

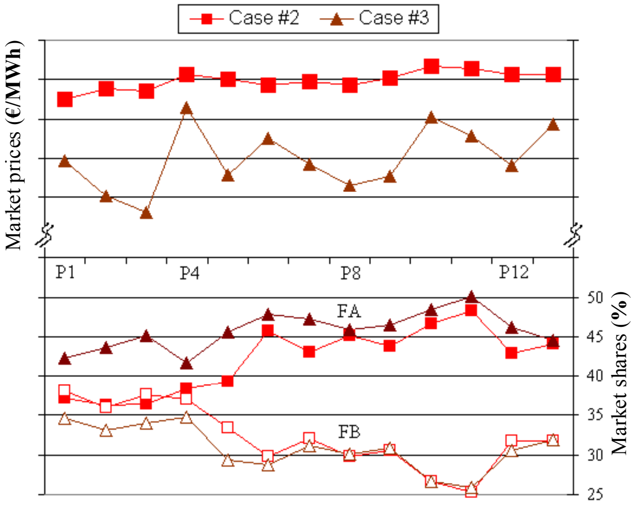

Fig. 7. Prices and market shares for Case #2 and Case #3

D. Case #4: Coordinated simulation with stranded cost recovery

Case #4 represents a mixed strategy where firms follow the coordinated strategy and also considered their stranded cost recovery as it is done in the Spanish regulation. The stranded cost recovery can be assumed as a CfD, where the contract price PC_{ft} is the consumer's tariff, and the contract quantity QC_{ft} has been assigned by the regulator to each company, as a fixed fraction of the total demand.

In this scheme some firms have a higher QC_{ft} than their coordinated market shares, while others can be assumed to be under-contracted.

The new equilibria reached when one of the two biggest firms is over contracted (firm FA) while the other (firm FB) is under-contracted can be seen expressed with their reaction curves in Fig. 8.

Firm FB reaction curve moves to bigger outputs when its rival (firm FA) decreases its output, while firm FA reaction function shows different incentives. As this firm is over contracted it behaves almost as a consumer, having a preference for low prices. Therefore, if firm FB reduces its output, prices will fall and firm FA will benefit from it. This shows that firm FA will push prices down to increase its total profits.

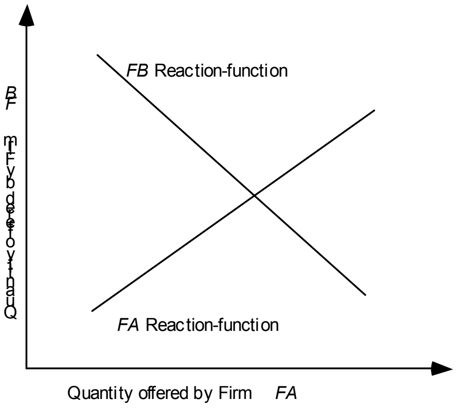

Fig. 8. *FA* and *FB* Reaction curves with Stranded Cost Recovery

Results are shown in Fig. 9, where market prices for each period and market shares for each period and firm, are drawn. Prices are close to the previous situation (they have fallen with respect to those obtained for the coordinated simulation). But although market profits have also decreased from Case #2, the total profit (that includes market profits and the stranded cost recovery payments) has increased, as the term that corresponds to the stranded cost recovery compensates the market profits' reduction.

The market share of firm FA is also close to the previous simulation where consumption constraints were considered, as this company has the biggest share in the stranded cost recovery payment (therefore behaves as an over contracted company) and was the most affected firm by the consumption constraints.

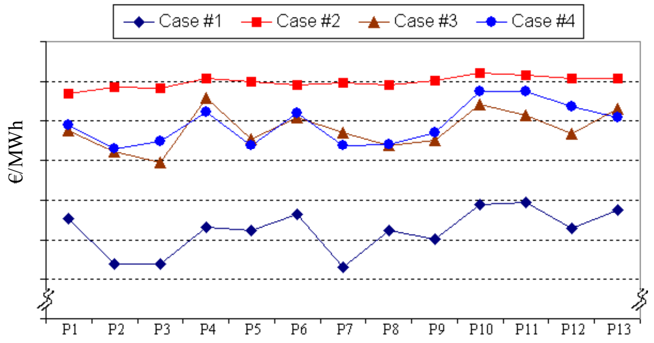

Fig. 9. Market Prices for Case #1 to Case #4

VII. CONCLUSIONS

In this paper we have presented a market model used in a risk analysis tool that focuses mainly on the effect of different strategies and different competitors behaviors. It models the strategic behavior of generation companies when they face a certain market structure and regulation, and handles both the economic objectives of these companies and their operational and technical requirements.

It considers not only the basic profit maximization strategy, but also other mixed behaviors that generation companies might follow, such as market shares' objectives, stranded cost recovery, capacity payments, etc.

The model presented, COSME, has been applied not only to the Spanish wholesale market but to several real-size power systems, producing realistic results.

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IX. BIOGRAPHIES

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