Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

A Decision Support Tool for Generation Expansion Planning in Competitive Markets using System Dynamics Models

A. J. C. Pereira, and J. T. Saraiva, *member IEEE*

***Abstract* — This paper addresses the generation expansion-planning problem describing a model that generation companies and regulators can use to get insight to this problem and to more completely study and characterize different investment decisions. The simulation model considers a number of possible generation technologies and aims at characterizing the corresponding investment plans from an economic point of view having in mind that market prices, the demand growth, investment and operation costs, as well as other factors, are affected by uncertainties. With the objective of helping generation companies and regulators to carry out this planning, we adopted an approach based on System Dynamics. This methodology allows simulating the long-term behavior of electricity markets, namely to help getting insight into the way new generation capacity enters in the market in a liberalized framework. Finally, the paper presents results from a case study illustrating the use of this approach.**

***Index Terms* - generation expansion planning, competitive market, uncertainties, system dynamics.**

I. INTROIDUCTION

The electric power industry all over the world has gone through a fundamental restructuring process in recent years from regulated or state-owned monopolies to competitive markets. The ongoing restructuring of the electric industry results in a higher degree of decentralized decision making in power systems [1]. This trend affects long-term expansion planning, as investment decisions are now taken by private investors with less centralized coordination. As a consequence, capacity expansions are driven by expectations regarding the behavior of future prices and the expected return on new investments.

Before the liberalization of the electricity industry, investments in power plants were the result of a long-term capacity expansion planning study, centrally optimized at the national or regional level. The aim of this exercise was to determine the most adequate generating capacity, the optimal mix of generation technologies and the required timing both for investments and for decommissioning of old stations to ensure that future demand in a certain region would be served at minimum cost with an adequate level of reliability. In such an environment, the future demand and future fuel prices were the only significant sources of uncertainty. Regarding the price of electricity, it was most of times determined by governments with the agreement of utilities and so it was not a source of uncertainty.

Adelino Jorge Correia Pereira is with the Instituto Superior de Engenharia of the Polytechnic Institute of Coimbra, Portugal, Rua Pedro Nunes, 3030-199 Coimbra, Portugal, ajcp@isec.pt

João Tomé Saraiva is with INESC Porto, Faculdade de Engenharia da Universidade do Porto, Campus da FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal, jsaraiva@fe.up.pt

However, deregulation altered the traditional Generation Expansion Planning (GEP) assumptions, models, and methods. While traditional utility practice involved solving centralized planning programs to identify cost-minimizing plans for the utility, under competition multiple firms individually prepare investment plans to maximize their profit. Other anticipated changes from competition include the shortening of planning horizons due to the elimination of traditional guaranteed return on investment and the advent of strategic interaction and gaming among firms involved in the generation planning process. That is, competition causes firms to face higher risks and thus they will most likely seek for quicker returns, and will certainly cause decisions of firms to mutually affect other firms' profits and decisions.

Having in mind these new challenges and characteristics, this paper describes the developed Generation Expansion Planning model to be used by individual generation agents and includes a Case Study to illustrate its application, namely considering the presence of various unit types and capacities, operating constraints, forced outages and timing for the addition of new units. The results are discussed to evaluate the interest of the proposed planning approach and its effectiveness.

II. CHARACTERISTICS OF INVESTMENTS IN GENERATION CAPACITY

The main characteristics of investments in power plants substantially influencing the planning process are [2]:

- Capital intensive - most investments in power plants involve huge financial commitments;
- One-step investments - a high percentage of total capital expenditures must be committed before the power plant can be brought on line;
- Long payback periods - power plants are expected to be paid off after several years;
- Investment irreversibility - because of the low grade of flexibility, generation capacity investments are seen as sunk costs because it is very unlikely that a power plant can serve other purposes if market conditions turn these investments unprofitable. Under these circumstances, power plants could not be sold without assuming significant losses regarding its nominal value.

Because power plants need a long time to be built and they will be amortized over several years, investment decisions must be based upon expectations on future profits. Unfortunately, the forecasting of these profits is an extremely difficult task, since they are highly uncertain and

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

volatile. These long-term uncertainties can influence the profitability of a project, either directly as an uncertain cost element or indirectly through the market price of electricity, or sometimes in both ways [3]. The most important fundamental uncertainties for investments in new power generation facilities are listed below:

- future electricity demand is a major uncertainty that is very important also in electricity markets, as demand naturally is a major price driver in the system. Total demand over the year is changing with time and influences the price and the profitability of new investments;
- changes in fuel prices can influence directly the operating costs of new investments regarding thermal units. It also affects the operating costs of existing units and therefore the price level in the electricity market;
- investment costs are also affected by uncertainty. The uncertainty about future currency rates might also have an impact on the current investment cost, and in such situations it should be taken into account in the project preparation and evaluation;
- uncertainty in capital costs, due to future variations in the interest rates, can also contribute to the value of a real option to invest in a new generation plant;
- the market design and system regulations can change before a stable long-term solution is obtained. The profitability of an investment in a specific technology can be highly dependent on the prevailing market design. Direct economic incentives, in terms of taxes and subsidies, are also important factors that can be crucial for the viability of some new technologies;
- the system's capacity balance and electricity price is dependent on the change in system load and on the investor's own investment decisions. However, investments in new generation from other participants in the market also contribute to improve the capacity balance and lower the price.

III. Expansion Planning Problem

A. Generation Investment in the Electricity Market

The investment decision process in power generation has changed with the introduction of competition in the electricity generation sector. Now, investment on new generation capacity additions is a commercial and risky activity. This is because investors are more interested in short-term investment return and are reluctant to invest on generation capacity that requires large investment while implying long recovery periods. On the other hand, this process has increasing uncertainties on load behaviour, restructuring policy and market management rules which can influence the benefits. Investors are expected to spend a considerable amount of time and effort in analyzing the interaction between investment and the decentralized decisions by participants. In taking a generation investment decision, expectations concerning future electricity demand, spot market prices, variations of regulatory policies, as well as the financial status are major considerations.

In the developed formulation of the GEP in restructured electricity market, the objective is to maximize the total expected profit of each individual generation company over a planning horizon (1), while guaranteeing the safe operation of the power systems through the competition between generation companies [4, 5]. The developed formulation incorporates the volatility of market prices for electricity and fuel and load growth. The expected revenues are based on the predicted market price, construction costs, fixed O&M costs, typical capacity factors for each technology and expected operation cost. Due to the volatile nature of the market, some sources of uncertainty in future operating conditions such as the forecasted market price of electricity, load growth rates, fuel costs and equipment availability are also considered in the planning exercise. The GEP problem formulated for a generation company *i* in a competitive environment can be formulated according to (1-6).

$$\max z = \sum_{t=1}^{T}\left[\left(\pi^{t}.CC_{t}^{i}\right)\alpha_{t}^{ij} - \sum_{j=1}^{M}\left(Cinv_{t}^{j}.X_{t}^{ij}\right) - \sum_{j=1}^{M}\left(Cop_{t}^{j}.X_{t}^{ij}\right).\alpha_{t}^{ij}\right] \quad (1)$$

$$\text{subj} \quad X_{t}^{i,j} \le \overline{CIT}_{t}^{j} \quad (2)$$

$$\sum_{j=1}^{M} X_{t}^{i,j} \le MIC_{t}^{j} \quad (3)$$

$$CC_{t}^{i} = CC_{t-1}^{i} + \sum_{j=1}^{M} X_{t}^{i,j} \quad (4)$$

$$\sum_{j=1}^{M} X_{t}^{i,j}.Cinv_{t}^{j} \le LCI_{t}^{i} \quad (5)$$

$$t= 1,\ldots,T; \quad i= 1,\ldots,N; \quad j= 1,\ldots,M \quad (6)$$

In this formulation:

T	number of stages in the planning horizon;
t	stage in the planning horizon (year);
N	number of GENCOs;
i	investment index for GENCO$_i$;
M	number of candidate technologies;
j	type of candidate expansion technology;
π^t	price of electricity in stage *t*;
$\alpha_t^{i,j}$	capacity factor in stage *t* for GENCO$_i$ and technology *j*;
$Cinv_t^j$	investment cost for technology *j* at stage *t*;
Cop_t^j	variable operation and maintenance cost for technology *j* at stage *t;*
CC_t^i	cumulative capacity installed in stage *t* for GENCO$_i$;
$X_t^{i,j}$	capacity addition of technology *j* in stage *t* of GENCO$_i$
LCI_t^i	maximum value specified for the capital investment of GENCO$_i$ at stage *t*;
MIC_t^i	maximum capacity installed in stage *t* by GENCO$_i$;
$\overline{CIT}_t^i$	upper bound established for the capacity installed technology *j* in stage *t* by GENCO$_i$.

This problem has a discrete combinatorial nature given that each agent has a limited number of candidate technologies and for each of them there will typically be a number of available normalized capacity values that can be selected. This problem can then be solved using Genetic Algorithms as described in [6]. In this formulation, a generation company first decides its new capacity investments based on its own decision criteria and the initial decisions of individual generation companies are then aggregated in order to assess the adequacy of future capacities, technology produced mixes, and expected price. In particular, adequacy can be evaluated using a reliability index as the Loss of Load Expectancy, LOLE, for which Grid Codes in several countries typically set a maximum number of hours during which the demand may not be attended. If at least one constraint does not hold, individual companies will update their plans and this process is repeated until every generation company does not change its decision. Fig. 1 shows the basic structure of the proposed new GEP problem. Further details on this approach can be obtained in [7].

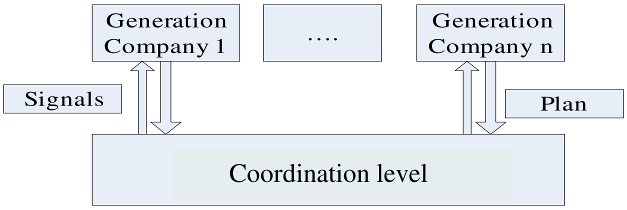

Fig. 1. Generation expansion planning framework.

B. System Dynamics Models

Most economic equilibrium models assume rationality of decision-makers. This is often far from the reality because it would mean that decision-makers have complete knowledge of the problem and of meaningful information, they are able and have the time to anticipate the consequences of their decisions [8,9]. Given these characteristics, the System Dynamics approach can be summarized in the following iterative steps:

- System Dynamics analysis implies an in-depth understanding of the problem and of the relevant relationships between variables and parameters. A system dynamicist should always keep in mind that the problem determines which factors are important to include and which to exclude in order to define the relevant system boundaries of the problem. A reference mode (the hypothesized behavior of the problem) and the time horizon of interest must be identified;
- a dynamic hypothesis is then developed in terms of a causal loop diagram and stock and flow diagrams;
- the model is then implemented for simulation.
- afterwards, the model should be tested in order to define the variables to be modeled in an endogenous way and which of them can be considered as exogenous or can be omitted. This will lead to the definition of the boundaries of the problem so that it can adequately replicate the system under analysis. In this step it can also be conducted a sensitivity analysis to eventually help deciding if further effort should be dedicated to increase the precision of input data;
- when a reasonable confidence level in the model is achieved, one can then perform simulations and studies using it.

System Dynamics models typically include several kinds of relations and equations [9]:

- state equation, representing accumulations within the input and output variables;
- rate equations, that are used to control the input or output variable in a state variable equation;
- assistant equations, corresponding to additional algebraic equations relating in a complex way state variables, rate variables and constants;
- table function, representing a set of time series data.

System Dynamics models typically display a number of characteristics such as direct description, natural and clear format, qualitative and quantitative form and robust ability to use data. As a result of these characteristics, they are used to investigate the structure, function relationship and dynamic behaviors of complex systems such as the ones mentioned in [10]. In this paper, System Dynamics is introduced in power markets, and the market dynamics is analysed based on the relationship among wholesale power market, power demand, power supply and the construction of new power stations.

C. System Dynamics Models in Electricity Market

To help GENCOS and regulators to develop generation planning exercises, several models and new approaches were proposed in recent years. In this scope, System Dynamics (SD) is referred as been particularly suited to capture and model the long-term behaviour of electricity markets and in gaining insight regarding the impact of new generation capacity entering in the system [9].

The dynamics of an electricity market is described by a set of non-linear differential equations that consider existing system feedbacks, delays, stock-and-flow structures and non-linearities. The evolution of the market is determined by modelling the variables that have a direct influence on the changes that can affect supply and demand. A simplify causal loop diagram of an electricity market is illustrate in Fig. 2.

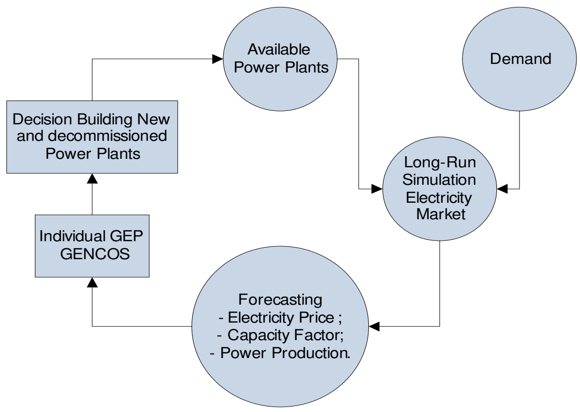

Fig. 2. Dynamic structure for an electricity market model.

The developed model corresponds to a system dynamic representation of an electricity market focusing the supply of different competing generation technologies. For illustration purposes, until now we considered three main types of technologies: wind power, hydro stations and thermal stations including both coal and gas. These technologies have very different economical, technological and environmental characteristics as well as investment and operational costs, operational characteristics, typical emission levels and potential for technological progress.

Modeling the dynamics of electricity markets can be organized in three main blocks. Taking into account the demand and existent power plants, the model forecasts electricity prices, power outputs and the capacity factor for every plant. The second block represents the individual GEP exercise to be run by each generation agent, using the information provided by the previous block. For each generation agent, the corresponding optimization problem is solved using a Genetic Algorithm. Finally, the available capacity is determined by the additions of new capacity and the decommissioning of old power plants given a specified delay. When running this simulation, it is important to consider a long planning horizon in order to give long-term impacts time to produce their influence. On the other hand, the time resolution should be sufficiently small in order to enable capturing the short-term mechanisms included in the model. In the simulations described in Section IV we adopted a 15-year time horizon, in order to allow the resource availability and technological progresses to have impact and 1 hour for the time resolution so that electricity prices can adjust the demand/supply balance over the year.

D. System Dynamics Model to Simulation the Demand Evolution of Electricity

Considering the increase rate of the demand as stochastic variable and aiming at simulating its long-term dynamic evolution, we used a Mean Reverting Process approach. The simplest Mean Reverting Process is also known as Orneisten-Uhlenbeck process [11]. The use of this approach is well suited to treat the uncertainty that can affect the long-term evolution of the demand rate. This process is modeled by expression (7).

$$d_X = \eta.\left(\bar{x} - x\right).dt + \delta dz \qquad (7)$$

In this expression:

- η represents the speed of reversion;
- δ represents the volatility of the process;
- d_z represents the increment of a Wiener process;
- $\bar{x}$ represents the mean value to which x tends to revert.

If we allow Δt to become infinitesimally small, we can represent the increment of a Wiener process, *dz*, in continuous time using expression (8).

$$\Delta z = \varepsilon.\sqrt{\Delta t} \qquad (8)$$

In this expression ε represents a random variable modeled by a normal probability function having zero mean and standard deviation 1. The expected value x for a given future instant t is then given by (9). In this expression x_0 represents the current value of x and the variance is given by (10).

$$E\left[x_1\right] = \bar{x} + \left(x_0 - \bar{x}\right).e^{-\eta.t} \qquad (9)$$

$$v\left[x_t - \bar{x}\right] = \frac{\delta^2}{2.\eta}.\left(1 - e^{-\eta.t}\right) \qquad (10)$$

The dynamic model developed to represent the evolution of the demand rate is detailed in Fig. 3 by the subprocess entitled Mean Reverting Process. The developed model also includes an initial rate specified for the evolution of the demand and a long term value. These values represent the forecasts of the demand rate for the initial period and for the long term. As a result, the mathematical formulation of the dynamic model is given by (11 – 15).

$$F_R = \left(t_{LP} - t_{annualdemand}\right).\varepsilon_t.\Delta t \qquad (11)$$

$$d_z \; d_z = \varepsilon_t * \delta * \sqrt{\Delta t} \qquad (12)$$

$$d_x = F_R + d_z \qquad (13)$$

$$t = t_0 + \int_0^T dx.dt \qquad (14)$$

$$\varepsilon_t = RandomNormal(\,0,1, seed\,) \qquad (15)$$

In this formulation:

- t_{LP} is the long-run growth rate (%/year);
- t_0 is initial growth rate (%/year);
- ε_t represents a normally distributed random variable with zero mean and a standard deviation of 1;
- η represents the speed of reversion;
- δ represents the volatility of the process;
- F_R is the reversion strength of the process;
- t is the annual growth rate (%/year);
- T is the planning horizon to simulate (years).

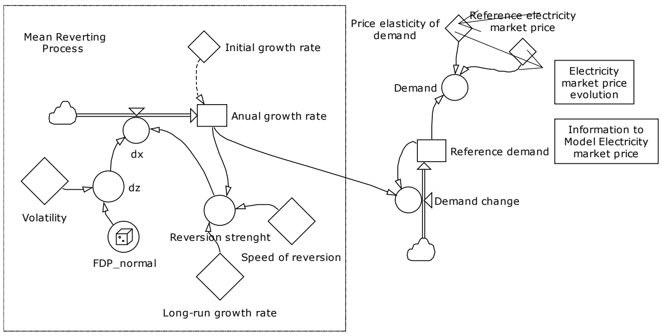

Fig. 3. Dynamic model to simulate the demand evolution.

The model in Fig. 3 emulates the evolution of the system annual electricity demand. As mentioned above, one of the input parameters is the annual demand rate modeled by a stochastic variable to incorporate the uncertainty affecting its evolution. Another parameter is the demand taken as reference. This parameter is set at the demand in the period previous to the beginning of the simulation horizon and it is set using historical information.

Another parameter that is relevant to model the dynamic demand evolution is the electricity price in the initial period and its evolution along the simulation horizon. The reference electricity price is set considering the current market data so that it emulates current market conditions. Regarding the price evolution, this is provided by the dynamic model developed to simulate its evolution as it will be described in Section III.E.

The mathematical formulation of the demand dynamic evolution is given by expressions (16) and (17).

$$D = Dref + \left(\frac{\pi^t}{\pi^{t0}}\right)^{E_{DP}} \qquad (16)$$

$$Dref = Dref_0 + \int_0^T t.Dref_0.dt \qquad (17)$$

In this formulation:

π^t	is price of electricity in stage t (€/MWh);
π^{t0}	is price of electricity the in initial stage $t=0$ (€/MWh);
D	is the demand of electricity (MWh/year);
$Dref_0$	is the reference electricity demand in the initial stage $t=0$ (MWh/year);
$Dref$	is the demand of reference (MWh/year) along the simulation;
t	is the annual growth rate (%/year);
T	is the planning horizon to simulate (years).
E_{DP}	represents the price elasticity of demand

The electricity demand is modeled by the Cobb-Douglas function (16). According to this expression, the demand evolution depends on the evolution of the relation between the reference price, the electricity price provided by the simulation itself and also on the demand elasticity regarding the price [9]. In any case, it should be mentioned that electricity typically displays a low elasticity to price. This means that even having large prices, the demand hardly gets reduced by a large amount. This aspect together with the continuous balance between the demand and the supply increase the probability of electricity prices are affected by large distortions and volatility.

E. System Dynamics Model to Simulate the Evolution of Electricity Price

Fig. 4 represents the model that was implemented to obtain the electricity price, π^t , along the simulation period. The evolution of π^t is influenced by the demand level, by changes in the generation system including available technologies and installed capacity and by the price considered for the initial simulation period π^{t0}. As mentioned before, the initial price is set according to the historical series of electricity prices in a specified interval.

Once the electricity price is set for the initial period, its evolution along the horizon is determined by expression (18). Price variations, $\Delta\pi^t$, are computed using expression (19). These variations are influenced by the relation demand and installed capacity variations. This formulation also considers a time interval to allow the price to be adjusted in the market so that one can take into account the past behavior of electricity prices.

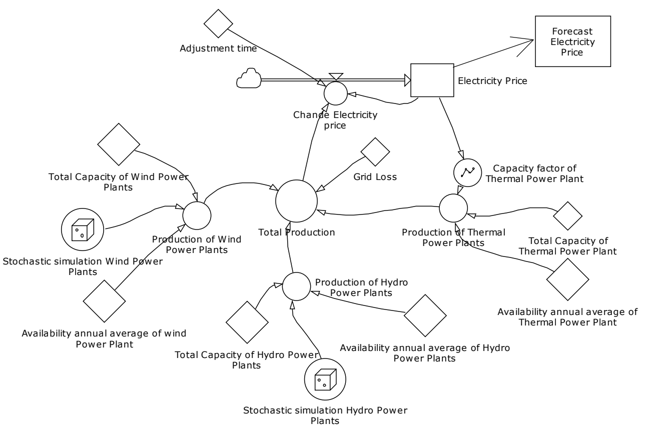

Fig. 4. Dynamic model to simulate the evolution of the electricity price, capacity factor and electricity production.

$$\pi^t = \pi^{t0} + \int_0^T \Delta\pi^t .dt \quad (18)$$

$$\Delta\pi^t = \pi^{t0} + \frac{D - P_G}{D} \quad (19)$$

F. Simulation of Electricity Generation

In order to simulate the electricity generation, the model considers thermal, hydro and wind power stations. Regarding wind parks, we considered the total installed capacity and the average annual number of hours that these stations generate. In this scope, we used typical values of 20 to 25% of the generated energy regarding what could be generated if the wind parks were at full capacity all along the year. As wind generation fluctuates in an intermittent way, we used a stochastic process to distribute the generation of wind parks along each year. This certainly increases the realism of the model and of the influence of this generation in electricity prices.

Regarding hydro stations and using again historical data, generation can typically range from 20% of the total energy that could be produced in a dry year and 40% for wet years. In order to model this type of uncertainty we considered three scenarios: 20% of generated energy for dry years, 30% for average years and 40% for wet years. Once again, we used a stochastic process to represent the uncertainty associated to these scenarios.

Finally, thermal stations were modeled considering different possible technologies and for each of them we used a typical value for its availability. The corresponding generation will depend on the electricity price coming from the simulation because this will influence the capacity factor of each of the technologies that were considered.

G. Application of the Simulation Model

The model detailed in Fig. 4 aims at simulating the evolution of the electricity price along time. This will then be used as input information for the optimization problem to be solved by each generation company in order to build it own expansion plan as detailed in Section III.A. This simulation model also provides the capacity factor considered in problem (1 - 6). In order to obtain this factor, thermal stations were organized in a merit order of their operation costs. When a new station is commissioned or an existing station is decommissioned, this merit order is updated considering the information regarding the new or the old power station.

The application of the model detailed in the previous sections can now be summarized in four main steps:

Step 1 – Considering the existing generation system and the demand rate, it is run the Dynamic System model in order to obtain an initial evolution of the electricity prices along the planning horizon as well as the capacitor factor for each technology and the reserve margin of the system.

Step 2 – Using the results of the Dynamic System model, each generation agent solves the optimization problem (1 – 6) to obtain its expansion plan. This means the technologies, installed capacities and commissioning years of new generation assets along the planning horizon.

Step 3 – Using the expansion plans obtained by each generation agent, the limits established for several coordination constraints are violated. These constraints include the minimum value specified for the reserve margin, the maximum value for the LOLE and the maximum power that can be installed for each technology. If at least one of these constraints is violated, then the iterative process didn't converge and the algorithm proceeds to Step 4. If all coordination constraints are checked, then the iterative process finishes.

Step 4 – If the iterative process didn't converge yet, then the Dynamic System model is run again considering the installed capacities and commissioning years according to the expansion plans obtained by each generation agent. The algorithm returns to Step 2.

IV. Case Study

In this section we present the results obtained with the developed approach in order to illustrate the application of the System Dynamics model and of the generation expansion optmization formulation.

Initially, we considered a power system having a total installed capacity of 5750 MW. The generation system includes a mix of several technologies, 3450 MW installed in thermal power plants, 1500 MW in hydro power plants and 800 MW in wind parks. The main characteristics of the thermal power plants are presented in table I. In the expansion process, the peak load at the initial stage was set at 4500 MW. The LOLE was set at 8 hours/year and the reserve margin of the installed capacity regarding the peak demand should lie in the range [20%; 35%].

We considered a planning horizon of 15 years, 3 investors and three available technologies among which new stations could be selected. The main characteristics of these three different technologies are detailed in Table II. For each new technology Table II indicates the available normalized capacities, the investment and operation costs, the construction time and the FOR. This means that, for instance if Tech_1 is selected for a particular year, the only available capacities to install are 100, 150 or 200 MW.

TABLE I
CHARACTERISTICS OF THE EXISTING TECHNOLOGIES.

no. Units	Technology	Generating Size (MW)	Operation Cost (€/MW.h)	FOR
2	Coal_1	300	30	0.02
3	Coal_2	400	25	0.02
3	Gas turbine	250	45	0.01
2	Oil	200	60	0.03
2	CCGT	250	35	0.01

TABLE II
CHARACTERIZATION OF THE POSSIBLE TECHNOLOGIES TO INSTALL.

Type of technology	Available capacities (MW)	Investment cost (€/MW)	Operation Cost (€/MW.h)	Construction time (years)	FOR
Tech_1	100 or 150 or 200	500000	40	2	0.02
Tech_2	100 or 125 or 150	650000	30	2	0.02
Tech_3	100 or 150 or 200	1000000	12	3	0.01

In Table III we present the parameters considered for the dynamic simulation of the electricity market, according to the formulation detailed in Section III.

TABLE III
DATA FOR SYSTEMS DYNAMIC SIMULATION

t_0 (%/year)	3	$Dref_0$ (GWh/year)	20 000
t_{LP} (%/year)	3	E_{DP}	0.3
η	0.5	T (years)	15
δ (%/year)	0.5	π^{t0} (€/MWh)	55

Using these elements, we ran the simulation, which means that we followed the algorithm detailed in Section III.F until it converged. Fig. 5, 6 and 7 present the expansion plans obtained for each generation company, GENCO_1, GENCO_2 and GENCO_3, for the three technologies previously mentioned. The results obtained comply with the constraints initially specified, namely that the reserve margin in each period should lie in the range [20%; 35%], and the LOLE should be smaller than 8 hours per year.

The new power stations to install are introduced in a chronological way in the dynamic model, taking into account the construction times mentioned in Table II for the three possible technologies. This will allow to consider the impact of each of the candidate technologies in the dynamic behavior of the model. Finally, Fig. 8 presents the evolution of the annual average electricity price as obtained from the dynamic model. There is an increase of the average price in the initial years, turning new investments more attractive. Afterwards, the electricity price tends to decrease as new power stations are built and commissioned.

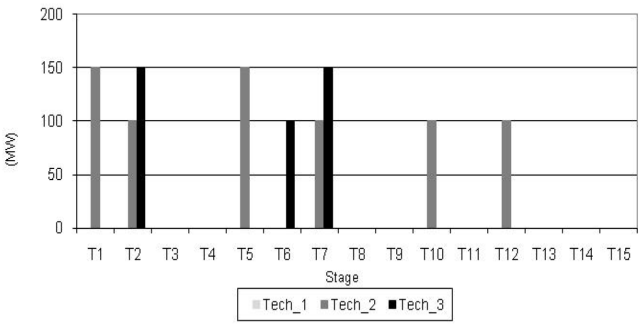

Fig. 5. Generation expansion plan obtained for Genco_1.

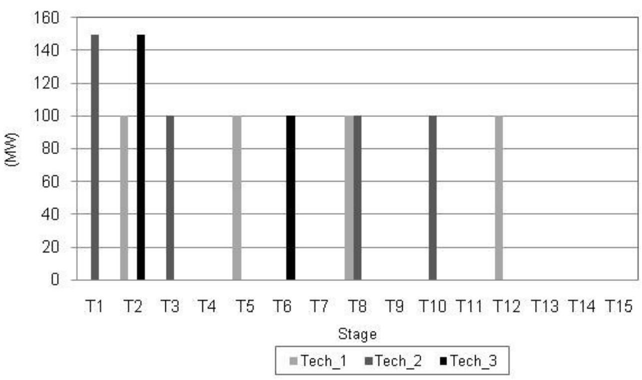

Fig. 6. Generation expansion plan obtained for Genco_2.

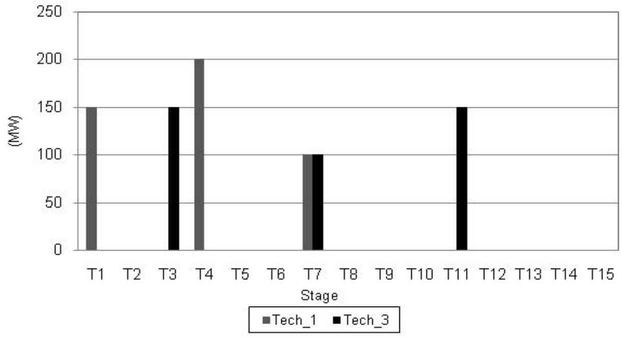

Fig. 7. Generation expansion plan obtained for Genco_3.

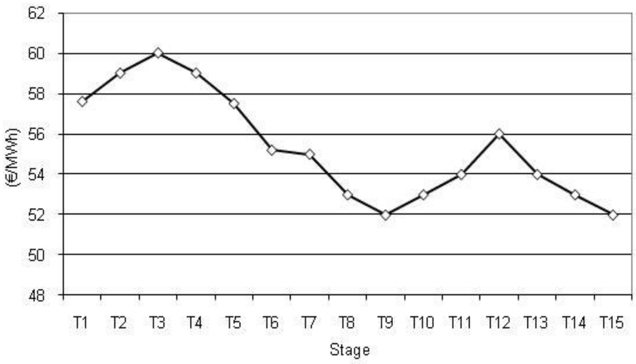

Fig. 6. Evolution of the electricity price along the planning horizon.

V. CONCLUSIONS

In this paper we described a model based on System Dynamics to obtain the long-term evolution of electricity prices. This model was integrated in a generation expansion planning approach that can be used in a profitable way by generation companies to help them building their plans, testing different scenarios, different input parameters and possible reactions of other competing agents. This will allow generation companies to get more insight about the possible evolution of the system and ultimately leading to build more robust and less risky expansion plans. This means that this approach can play an important role as a decision making tool to be used in a profitable way by generation companies.

In a different level, this type of simulations can also provide insight about how the system and generation agents will behave in the long term, namely admitting that these agents behave in a rational way. Regulators and governmental agencies will then have a powerful tool that can be used to detect situations to be corrected by the adoption of several measures. These can include for instance incentives to new emergent technologies, changing Grid Codes in order to impose more strict limits on reliability indices or maximum limits to one particular technology. As a result long-term generation system planning even if in a competitive environment will become a less risky activity, which means that the long term adequacy of the generation system will be more easily ensured with clear advantages for consumers.

VI. ACKNOWLEDGEMENTS

The first author would like to thank Fundação para a Ciência e Tecnologia, FCT, that partially funded this research work through the PhD grant nº SFRH/BD/29243/2006.

VII. REFERENCES

[1] S. Stoft, *Power Systems Economics: Designing Markets for Electricity*, IEEE Press/Wiley, New York, 2002.

[2] F. Olsina, F. Garces, H.-J. Haubrich, "Modeling Long-Term Dynamics of Electricity Markets", *Energy Policy*, vol. 34, no. 12, pp. 1411-1433, August 2006.

[3] A. Botterud, M. Ilic and I. Wangensteen, "Optimal Investment in power Generation Under Centralised and Decentralised Decision Making", *IEEE Transaction on Power Systems*, vol. 20, no 1, pp.254-263, Feb. 2005.

[4] B. G. Gorenstin, N. M. Campodonico, J. P. Costa, and M. V. Pereira,"Power system expansion planning under uncertainty," *in Proc. 1992 IEEE/PES Winter Meeting*, New York, 1992.

[5] J. Zhu and M. Chow, "A review of emerging techniques on generation expansion planning," *IEEE Transactions on Power Syst*ems, vol. 12, pp. 1722–1728, Nov. 1997.

[6] J.-B. Park, J.-H. Kim and K. Y. Lee, "Generation expansion planning in a competitive environment using a genetic algorithm," *in Proc. 2002 IEEE Power Engineering Society Summer Meeting*, vol. 3 , July 2002.

[7] A. J. C. Pereira, J. T. Saraiva, "Generation Expansion Planning in Competitive Markets", *in Proc. 2007 PowerTech Conf.*, July 2007, Lausanne, Switzerland.

[8] A. Ford, "System dynamics and the electric power industry", *System Dynamics Review*, vol. 13, no. 1, pp. 57-85, Spring 1997.

[9] J. D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill, 2000.

[10] A. Botterud, M. Korpås, K. Vogstad and I. Wangensten, "A Dynamic Simulation model for Long-term Analysis of the Power Market," in Proc. 2002 Power Systems Computation Conference, PSCC, 25th -28th June 2002, Sevilla, Spain.

[11] A. Dixit,, R. Pindyck, *Investment Under Uncertainty*, Princeton University Press, Princeton, 1994.

VIII. BIOGRAPHIES

Adelino J. C. Pereira was born in Sanfins, Portugal in 1975. He received his diploma and M.Sc. degrees in Electrical Engineering and Computers from the Faculdade de Engenharia da Universidade do Porto, FEUP, Portugal, in 1998 and 2003. In 1998 he joined the Coimbra Polytechnic Institute (ISEC) where he is currently Equiparado to Adjunct Professor. He is a Ph.D. student at FEUP and his main research interest includes competitive markets, power systems operation and planning.

João Tomé Saraiva was born in Porto, Portugal in 1962. In 1987, 1993 and 2002 he got his MSc, PhD, and Agregado degrees in Electrical and Computer Engineering from Faculdade de Engenharia da Universidade do Porto, FEUP, where he is currently Professor. In 1985 he joined INESC Porto – a private research institute – where he was head researcher or collaborated in projects related with the development of DMS systems, quality in power systems and network tariffs. Several of these projects were developed under consultancy contracts with the Portuguese Electricity Regulatory Agency.