

A Multidisciplinary Approach to Model Long-Term Investments in Electricity Generation: Combining System Dynamics, Credit Risk Theory and Game Theory

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Abstract—This paper provides a new multidisciplinary approach to model long-term planning of electricity generation. The aim of this approach is to improve several aspects of System-Dynamics based models in the literature in terms of companies' differentiation in imperfect markets. To do this, System Dynamics is combined with credit risk theory and game theory. Particularly, this paper presents in detail the part of the model which focuses on companies' differentiation when calculating the expected profitability of possible new investments. This approach can be used as a tool to analyse long-term dynamics of electricity markets and the way the new generation capacity enters into these markets under different hypothesis of companies' strategies and regulatory policies. A case study based in the Spanish market to show the potential of this approach is presented.

Index Terms— Electricity Markets, System Dynamics, Credit Risk Theory, Game Theory, Generation Expansion Planning.

I. INTRODUCTION

SINCE liberalization of electricity markets, an intensive research activity has been carried out in order to provide models which could help generation companies and regulatory authorities to evaluate and make their decisions in the new deregulated framework. Most of this research has been focused on short- and medium-term decisions, like bidding strategy behaviour, risk-hedging or market power mitigation. However, in the last years there is a growing interest in long-term models (5-30 years) due to adequacy problems in different systems and also to the worldwide concern about sustainable development.

In the old regulated frameworks, most of long-term models were based on optimization (see for example [1]) or multi-criteria trade-off risk methods (see [2]). These techniques were useful because the system was a stable one, with a unique centralised planner and with a low level of uncertainty, except for exogenous variables like fuel costs, demand or hydro conditions. In the new liberalised frameworks, these characteristics do not longer hold. Now, there are several

planners which make their own investment decisions in an unstable environment, competing among them in a market, trying to maximize their profits and with regulatory authorities that have to ensure generation adequacy without distorting market efficiency and enhancing sustainable development. Because of these reasons, new techniques are being applied to develop long-term models, each one with different objectives, advantages and disadvantages, as shown in [3].

System Dynamics (see [4]) is one of the techniques which has succeeded in analysing long-term dynamics of liberalised systems, particularly in representing the way the new generation capacity enters into the market, identifying the so-called boom and bust investment cycles ([5]). However, there are several aspects of these models that must be improved in order to gain better insights in these dynamics that could help regulatory authorities to decide correct long-term policies and companies to adapt their strategies to these new policies. Concretely, companies' differentiation in the investment decision process of imperfect markets has been greatly simplified, as well as the influence in the entry of new capacity of their different myopic-strategies in short- and medium-term (bidding strategy, risk-hedging, profits maximization in the medium-term).

The model of this paper overcomes these drawbacks, extending typical System-Dynamics models by combining them with other approaches based on credit risk theory and game theory. Concretely, this paper presents a new method based on credit-risk-theory concepts to differentiate the companies when evaluating the possible future new investments. Other parts of the model, as the companies' spot-market bidding-behaviour and their forward contracting decisions are modelled using game-theory ideas described in detail in ([6]).

In the next section, the main structure of most of the System-Dynamics based models for long-term planning of electricity generation is presented, focusing in the investment-decisions representation. Then, the method proposed by this paper to model these investment decisions, and particularly the credit-risk theory approach which differentiates companies' expected profitabilities, is described in detail.

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After that, a case study based on the Spanish system is presented to show the effects of considering an endogenous companies' differentiation as the one proposed in this paper. The paper finishes with the main conclusions of the method proposed and the study carried out.

II. MODELLING LONG-TERM PLANNING OF ELECTRICITY GENERATION WITH SYSTEM DYNAMICS

A. General structure

Most of System-Dynamics based models in the literature which focus on long-term planning of electricity generation have a structure which can be seen, at least in a simplified way, as if it is divided in three main parts. These three parts are shown in the next figure.

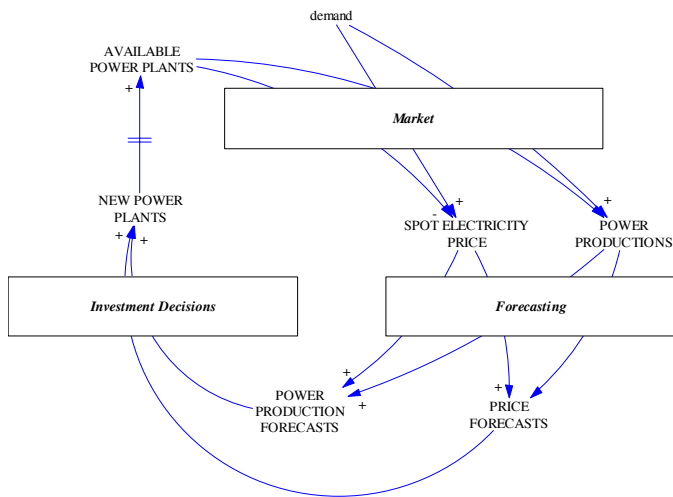


Fig. 1. General overview of the structure of System-Dynamics based models for long-term planning of electricity generation

As it is seen, there is a first part called “Market” in the figure where the models calculate electricity prices and power productions at each time step (usually a year). These prices and productions are used by the second part, “Forecasting”, to forecast future prices and outputs. Finally, these forecasts are used by the model to evaluate different generation-expansion alternatives and to take investment decisions in the “Investment decisions” part. These investment decisions enter in the system a number of time steps later in the simulation, varying the system’s generation portfolio and influencing the results in the market.

Each one of these three parts has been modelled with different methods in the literature. Regarding the “Market” part, some of these methods are reviewed and extended by combining System-Dynamics and game-theory ideas in [6]. This extension is the one used in the model of this paper to model the “Market” part. Thus, this market consists in a forward market where the quantities and prices are calculated using a two-steps market-equilibrium, and a spot market where the prices and quantities are solved using an equilibrium model based on conjectured-price responses, which are endogenously calculated using a supply-function

equilibrium approach. With this, oligopoly effects as the ones caused by market power are included in the market modelling.

The main characteristics of the “Forecasting” part, in the model used in this paper, can be found in [7]. Basically, what is done is that future price-duration curves are forecasted for each one of the following years to the one which is being simulated. To do this, first, the optimal generation portfolio at a system level is calculated for a given year in the very long term. Then, the price duration curve for that year is calculated with an exogenously-estimated demand, and considering perfect competition in that year. After that, the current price-duration curve calculated for the year which is being simulated is approximated to that one in the very long-term, reducing the differences between both of them successively along time. Once a price-duration curve have been estimated for each one of the following years, power productions of a new possible investment are calculated assuming this new power plant will be bided at its marginal costs in the market.

Finally, the above-commented forecasts allow the “Investment decisions” part of the model, computing the expected profitability that a new power plant of each technology would obtain and to calculate the number of new power plants that each company is going to construct. All of the models in the System-Dynamics literature calculate the number of new investments depending on this expected profitability (which can be calculated in different ways). In some cases additional strategic criteria are included. In the next section, the main characteristics of the models in the literature, concerning the “Investment decisions” part, are explained in detail.

B. Investment decisions

System-Dynamics models have usually represented investment decisions in a global and aggregated way, considering the total number of new power plants which enter the system without considering each company separately, or they have differentiated the companies using some exogenous strategic parameters (such as different market-share objectives) or even soft parameters which have to do with psychological aspects (for example, parameters reflecting the optimism of the companies). As it has been commented before, all the models consider expected profitability as the main decision criteria for building new plants, but in some cases additional criteria are included.

Some models consider new plants globally without assigning them an owner, as in [8]-[12]. In these models the expected profitability is the main signal for investment (except in [10] where although expected profitability is calculated to assess investments, an endogenous capacity payment is also calculated in order to the investments to keep pace with the demand). The higher this expected profitability, the more new investments are decided. This function of the number of new investments with respect to the expected profitability is usually an empirical function which has to do with variables like the expected need of capacity in the system to meet the future demand, the depreciation rate of the

installed capacity or financial restrictions to finance new investments.

The rest of models disaggregate the agents considering their decisions separately. In [5] decisions are different among companies because of different prices forecasts depending on generating agent's information. The companies are divided in believers, pre-counters and followers. The model in [13] distinguishes decision criteria for big generation companies that constitute a duopoly, that decide using profitability and an objective market share, and IPPs (independent power producers) that substitute the market share objective by an optimism factor. Profitability is also considered in [14] as decision criteria, and it is computed comparing capacity payments with a reference value based on reliability computations. The agents use different exogenous discount rates, to introduce their market share objectives.

The above-commented simplifications concerning companies' differentiation can be reasonable when carrying out global studies, at a system level, like future penetration of a particular technology in the market or the influence of different long-term-guarantee of supply mechanisms in the market performance, in quite competitive environments. However, when considering the oligopoly nature of most of liberalised systems, these simplifications can reduce the plausibility of the results in most of the cases and can not be used in some particular cases as for example when studying aspects related with market power exercise by dominant companies.

In order to cope with the implications of oligopoly structures in the investment decisions in new generation capacity, this paper proposes a sufficiently-realistic method to differentiate companies' investment decisions within System-Dynamics models, which is based on economic and strategic criteria, and which allows distinguishing the modus operandi of the different companies in an oligopoly market. The main criteria have to do with the risk perceived by the different companies in the market, which is endogenously calculated, and not only on the expected profitability. The next section, explains this method in detail.

III. DIFFERENTIATION OF COMPANIES' INVESTMENT DECISIONS: A CREDIT-RISK THEORY APPROACH

A. Introduction

The model of this paper calculates the number of new power plants of each technology that each company decides to build each year following six steps (see [7] for more details):

- It calculates the expected profitability of a new power plant of each technology for each company in the year which is being simulated. This expected profitability is calculated computing its net present value (NPV). As it will be explained later, the discount rate used in this NPV is different for each company and is calculated endogenously.
- The model calculates a number of construction-permits applications by computing an empirical

formula which relates the number of applications with the NPV obtained for a new group of that particular technology and that particular company. Details about this formula and this NPV calculation can be found in [7]. Basically, the higher the NPV, the more permits will be applied for. The number of applications by company each year is limited exogenously. Each year, just permits for the most profitable technology can be applied for.

- These permits are obtained by the companies a number of years later because of a delay.
- The permits that a company obtains a year can be used or not. Thus, the investments that can be made with these permits are revaluated calculating again their NPV.
- The number of new power plants that are going to be constructed finally is calculated computing an empirical formula which relates this number of new plants with the NPV, as it was done to calculate the permits applications.
- These new power plants enter in the market a number of years later because of a construction delay.

To differentiate companies' investment decisions, this paper proposes a method which calculates a different NPV for each company depending on a different endogenously-calculated discount rate. This method is based on credit-risk-theory concepts.

The basic assumption under this method is that when a company decides to build a new investment, it needs to issue new debt in order to finance the investment. This debt has a cost for the company, as the quantity perceived is lower than the quantity it has to payback to the creditor. This is shown in the next equation where D_{ii} is the face value of the debt, which is the quantity the company i has to pay to the creditor in T , and d_{ii} is the quantity that the creditor lends to the company in t .

$$d_{ii} = e^{-\rho_{ii} \cdot (T-t)} \cdot D_{ii} \quad (1)$$

The variable ρ_{ii} in the above equation is the cost of this debt. This cost can be seen also as the minimum required rate of return that the company has to apply to the new investment financed by this debt, and thus, it should be the discount rate to be applied in the NPV calculation.

There are several models in the literature that calculate this cost of the debt. Most of these models are based on the calculation of the default probability. Companies default when they can not, or choose not to, meet their financial obligations (that is, they do not pay the quantity D_{ii} in time instant T in the above example). The default probability calculation can be carried out using three different types of models as shown in [15]: structural models (in which the issuer's inability—or lack of incentive- to pay is explicitly modelled as the default-triggering event), reduced-form models (in which default is

treated as an unexpected event whose likelihood is governed by a default-intensity process) or statistical ones. The approach in this paper is based on one of the structural models: the Black-Scholes-Merton (BSM) debt pricing model (see [15] for details).

The method proposed by this paper to calculate the discount rate that each company is going to apply in its net present value calculations endogenously, can be divided in two steps:

- First, at each year, the financial structure (assets' value and debt value) of each company is calculated endogenously. This structure changes as the simulation advances in the time horizon, because of factors such as new investments, depreciations or debt redemptions.
- Then, using this financial structure, and other exogenous data as the assets' value volatility or the risk-free rate, the model calculates the cost of the debt that each company needs in the simulated year to finance the possible new investments. This is done using the above-commented BSM model.

With this method, the investment decisions of the companies in a particular year change the financial structure of the company, what modifies the cost of new debts in the following years. This makes the companies to use different discount rates and thus to calculate different expected profitabilities, which imply different investment decisions. Concretely, as it will be explained later, when a company invests it increases its assets' value but at the same time it increases also the debt, and the increase in the debt is higher than the increase in the assets' value. This reduces the ratio of the assets' value to the debt value. The reduction of this ratio implies a greater cost of the debt what makes it more difficult to invest more. So the investments in one year can be difficult to invest more the following years.

Next, the calculation of the financial structure of the company at each year is detailed. Then, the BSM method which calculates the cost of the debt (and so the endogenous discount rate) is explained.

B. Calculation of companies' financial structure

The assets' value A_{it} of the company i at year t , can be divided into liquid assets L_{it} and infrastructures I_{it} . The liquid assets can be calculated as:

$$L_{it} = L_{(t-1)i} + M_{it} - r' \cdot D_{(t-1)i} + D'_{it} - NI_{it} - \Phi_{it} \quad (2)$$

M_{it} are the operational profits obtained during year t , $r' \cdot D_{(t-1)i}$ the debt interests paid during year t (an interest rate times the debt at the end of the last year which is equal to the debt at the beginning of the current year), D'_{it} the new debt acquired in t , NI_{it} the cost of the new investments which entered the market in t and Φ_{it} the debt redeemed in t . The debt interest rate r' and the cost of a new power plant of each technology (used to calculate NI_{it}) are exogenous. The initial debt redemption is data and the redemption of the new debt that the company acquires within the simulation horizon is

calculated considering that the debt acquired in t is redeemed in a number of years $T-t$, being this number of years an exogenous data. As the costs of new investments NI_{it} (which are paid at the beginning of the year t) are assumed to be financed with new debt, the face value of this new debt D'_{it} , which will be redeemed in $t + (T-t)$, discounted at the discount rate calculated at the end of the last year, has to be equal to NI_{it} . This is shown in (3).

$$D'_{it} = \frac{NI_{it}}{e^{-(\rho_{(t-1)i})(T-t+t)}} \quad (3)$$

The value of the infrastructures (at the end of t) can be updated making I_{it} equal to its nominal value B_{it} , being this nominal value as in (4):

$$B_{it} = B_{(t-1)i} - a \cdot B_{(t-1)i} + NI_{it} \quad (4)$$

In the above equation, $a \cdot B_{(t-1)i}$ is the depreciation of the infrastructures during t (being the depreciation rate a an exogenous input parameter).

The total value of the debt is also updated at the end of t as in (5):

$$D_{it} = D_{(t-1)i} + D'_{it} - \Phi_{it} \quad (5)$$

C. Calculation of the companies' discount rate

To ease the understanding of the proposed method, a simple example is presented. In this example it is considered that a company wants to issue a bond in the time instant t , which pays back the quantity D_{it} to a creditor in the time instant T . The creditor is going to pay a quantity for this bond d_{it} in t , which is lower than the quantity that the bond returns to the creditor in T , that is D_{it} .

For this example, the approach proposed assumes default at time T in the event that the total value of company's assets at time T , that is A_{Ti} is lower or equal to the face value of the bond D_{it} .

The bond price is then (assuming that no other liabilities mature between t and T , and assuming recovery of all assets in the event of default), as it can be seen in (6), the total value of assets of the company in t less the market value of equity O_{it} in t (recall that the total value of assets of a company at a particular instant t must be equal to its liabilities, which are classified in debt and equity), which is priced using the Black-Scholes formula as though equity is a call option on assets struck at the face value of debt.

$$d_{it} = A_{it} - O_{it}(A_{it}, D_{it}, r, \zeta_i, T-t, \sigma_i) \quad (6)$$

To price the equity using this Black-Scholes formula, the market value of the company's assets is treated as a risk-neutrally log-normal diffusion process as in (7).

$$\frac{dA_{it}}{A_{it}} = (r - \zeta_i) \cdot dt + \sigma_i \cdot dB_t \quad (7)$$

In (7), r is the risk-neutral mean rate of return on assets, ζ_i is the proportional cash payout rate (the dividends paid to the shareholders), σ_i is the assets' volatility and B_t is a risk-neutral standard Brownian motion.

In (6), $O_{it}(A_{it}, D_{it}, r, \zeta_i, T-t, \sigma_i)$ is the Black-Scholes call-option pricing formula commented above. This formula is

expressed by:

$$\begin{aligned} O_{ii}(A_{ii}, D_{ii}, r, \zeta_i, T-t, \sigma_i) &= \\ &= A_{ii} \cdot e^{-\zeta_i(T-t)} \cdot N(\varphi_{1i}) - D_{ii} \cdot e^{-r(T-t)} \cdot N(\varphi_{2i}) \end{aligned} \quad (8)$$

The function $N(x)$ is the probability that a standard normal variable is less than x . Functions φ_{1i} and φ_{2i} are detailed in the next equations:

$$\varphi_{1i} = \frac{\log(A_{ii}) - \log(D_{ii}) + \left(r - \zeta_i + \frac{\sigma_i^2}{2}\right) \cdot (T-t)}{\sigma_i \cdot \sqrt{T-t}} \quad (9)$$

$$\varphi_{2i} = \varphi_{1i} - \sigma_i \cdot \sqrt{T-t} \quad (10)$$

Thus, with the above formulas, d_{ii} can be calculated and so the discount rate that the company has to apply to the investment in which it invests the money obtained with the bond (using (1)).

IV. CASE STUDY

A. System description

The aim of this case study is to analyse the effects of considering endogenous discount rates, calculated with the method proposed in this paper, to differentiate companies' investment decisions, instead of considering exogenous discount rates as in most of the System-Dynamics based models in the literature.

The case study presented in this section is based on the Spanish system. Details about the data used to model this system can be found in [6] and [16]. Basically, the system consists in two big companies, one medium-sized company, three small companies and several IPPs. The next table summarises the total thermal capacity and number of groups by utility, arranged by marginal cost, for the first year of the simulation, which corresponds with year 2005 (company *i7* represents the IPPs). Hydro capacity in this system is around the 8000 MW. The two big companies own most of the hydro plants.

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

€/MWh	<i>i1</i>	<i>i2</i>	<i>i3</i>	<i>i4</i>	<i>i5</i>	<i>i6</i>	<i>i7</i>
0-15	4984 (7)	5047 (8)	160 (1)	2417 (6)	0 (0)	0 (0)	0 (0)
15-20	5291 (15)	160 (1)	1699 (7)	160 (1)	732 (3)	1577 (4)	0 (0)
20-30	0 (0)	2715 (6)	1927 (5)	400 (1)	0 (0)	0 (0)	1980 (3)
30-45	1846 (6)	2715 (7)	1014 (3)	0 (0)	753 (2)	0 (0)	120 (1)

The system structure evolves during the horizon of study because of the companies' investments (endogenous) and the closures of old plants (exogenous). The companies can invest in nuclear, coal, combined cycle and gas turbines, although, as it will be shown, all of the investments are in the last two technologies in these cases. There is an exogenous constant capacity payment to incentive investments. The maximum capacity the companies can invest in each year is limited by an exogenous percentage of the assets' value. Two delays are

considered in the investment process: the delay to obtain the construction permits (1 year for all except for nuclear plants - 4 years-) and the construction delay (idem).

The financial data needed to compute the endogenous discount rate each year is summarised in the next table (the IPPs have an exogenous discount rate of 5%). The assets' value and debt value are the initial ones (recall that these values evolve endogenously in the model).

TABLE II
FINANCIAL DATA

	L_{oi} (M€)	B_{oi} (M€)	D_{oi} (M€)	r (%)	ζ_i (%)	$T-t$ (Year)	σ_i (%)
<i>i1</i>	6280	25120	11800	3	0	10	20
<i>i2</i>	4057	16228	8498	3	0	10	20
<i>i3</i>	3546	14185	6227	3	0	10	20
<i>i4</i>	2000	8000	4000	3	0	10	20
<i>i5</i>	1000	4000	2000	3	0	10	20
<i>i6</i>	1000	4000	2000	3	0	10	20

Four different cases have been run. Two of them consider a perfect competitive framework, with the companies bidding their plants at their marginal costs in the spot market. These two cases differ in that one of them considers an exogenous discount rate of 5% for each company ("*PC_Ex*") and the other one calculates the discount rates endogenously ("*PC_En*"). The other two cases consider imperfect competition with the companies contracting both in a forward market (they are obliged to contract forward half of their production for the next year) and in a spot market using the game theory approaches shown in [6], and again, one of them considers the discount rates exogenously ("*IC_Ex*") and the other one endogenously ("*IC_En*").

B. Results

The next figure illustrates the evolution of the reserve margin of the system (ratio of the installed capacity to the peak demand) in the two cases of perfect competition "*PC_Ex*" and "*PC_En*". As it can be observed, the reserve margin evolves differently. In the case with endogenous discount rates the reserve margin is higher at the beginning because these discount rates are below the fix exogenous ones in most of the companies. But then, companies stop investing because their debt increases considerably, what implies a higher discount rate. It can be observed that for the horizon of study the case with endogenous discount rates is more stable (less cycles), and that is because this endogenous discount rate acts like a self-regulating mechanism. The discount rates of the main companies in the "*PC_En*" are shown in Fig. 2. Note that company *i2* discount rate decreases continuously; this is due to the fact that its assets' value grows more rapidly than its debt value because of the profits this company obtains in the market (this company has more hydro power than its competitors).

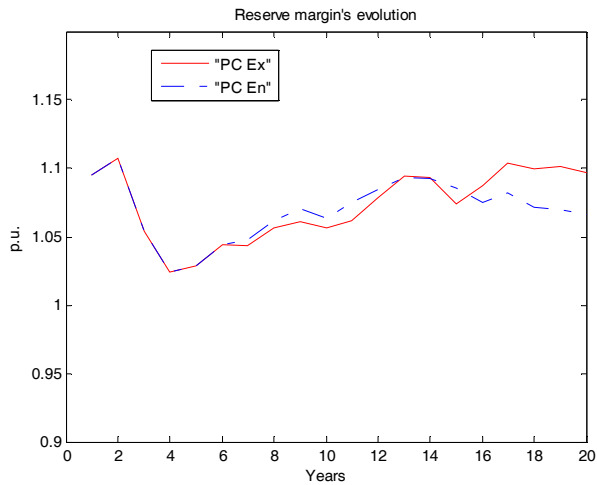


Fig. 2. Reserve margin's evolution in "PC_En" and "PC_Ex" cases.

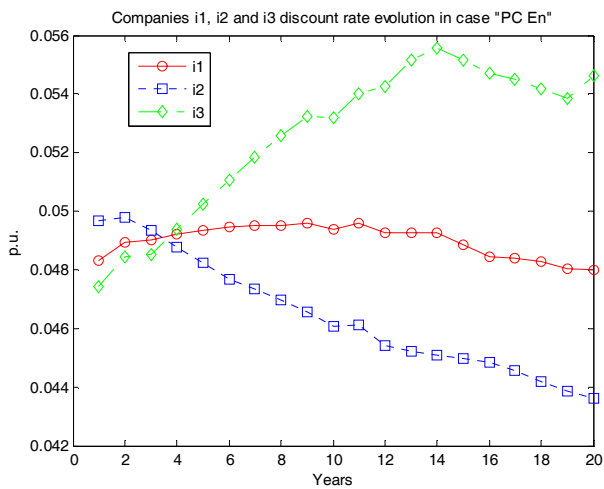


Fig. 3. Companies i1, i2 and i3 discount rate evolution in "PC_En" case

The next two figures show the new investments of the two main companies ($i1$ and $i2$) in combined-cycles and gas turbines for the "PC_En" and "PC_Ex" cases respectively. As it can be observed in Fig. 4, there are four different investment cycles: two of them in combined-cycle technology and other two in gas turbines. Companies begin investing in gas turbines (years 4-9) as prices are low (the capacity payment allows this technology being profitable). When there are enough gas turbines in the system, the expected profitability of combined-cycle plants increase, as the gas turbines begin to set the price more hours (combined-cycles have a lower marginal cost than the gas turbines). The more investments in combined-cycles (years 10-15), the more hours these plants set the price, decreasing its own profitability, and making gas turbines more profitable again. These two cycles are repeated in years 16-18 (gas turbines) and 19-20 (combined-cycles). These cycles appear also in the "PC_En" case, as shown in Fig. 5. However, in this case just two investment cycles appear for the second company. No matter the quantity of combined-cycles which enter in the system, the company $i2$ sees them as more profitable than the gas turbines from year 10 to year 20. This is due to its low discount rate

(see Fig. 3) which makes the present value of the expected profits to be obtained in the market in the first next years higher.

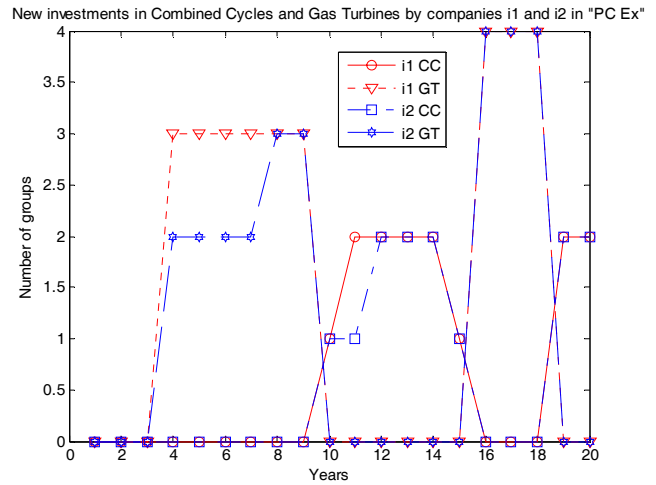


Fig. 4. New investments in Combined-Cycles (CC) and Gas Turbines (GT) by the two main companies $i1$ and $i2$, in the "PC_Ex" case.

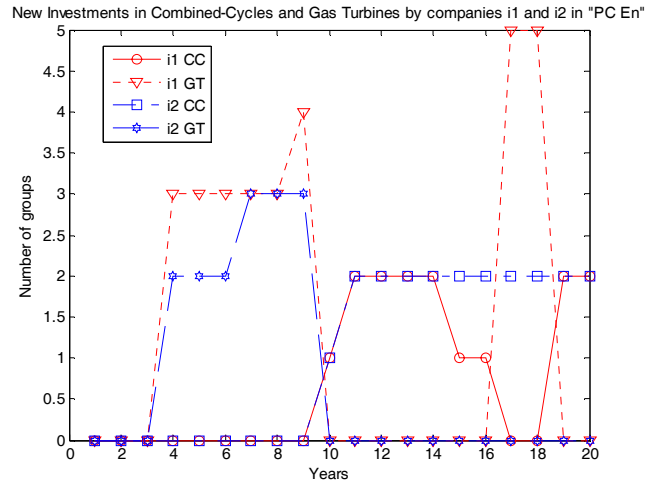


Fig. 5. New Investments in Combined-Cycles (CC) and Gas Turbines (GT) by the two main companies $i1$ and $i2$, in the "PC_En" case.

As it has been seen in the above figures, the consideration of an endogenous discount rate in a case where the companies behave in the market as in a perfect competitive market, induce significant differences in the behavior of the system and companies. In a case where the companies behave as in an imperfect competitive framework, using their potential market power, the results are similar as the one observed in the previous case. The implications of these results in the imperfect competitive case are even more important as the structural changes in the companies cause different behaviors in both the forward and the spot markets (as shown in the game-theory approaches described in [6]).

In the next figure, the combined-cycles and gas turbines' installed capacity of the two main companies is shown for the case of imperfect competition and endogenous discount rates. As it can be observed, each company tends to specialize in one technology more than its competitor: company $i1$ invests

in gas turbines more than $i2$ does, while $i2$ invests more in combined-cycles. This specialization did not occur in the case with imperfect competition but exogenous discount rates.

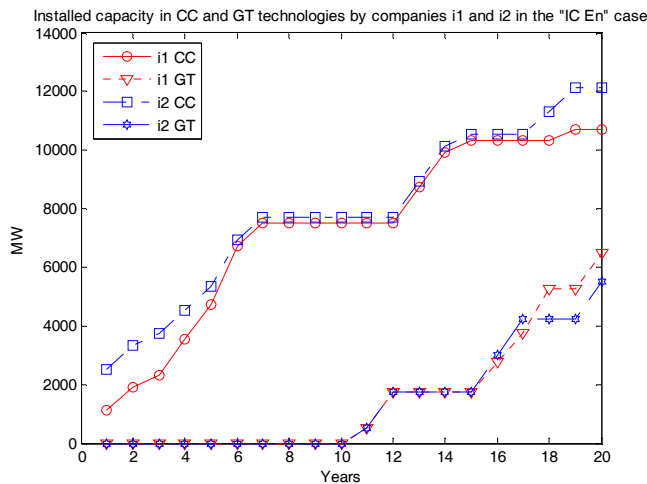


Fig. 6. Installed capacity in Combined-Cycles (CC) and Gas Turbines (GT) by the two main companies $i1$ and $i2$, in the “ IC_{En} ” case.

V. CONCLUSIONS

A multi-disciplinary approach which combines System-Dynamics with credit-risk theory and game-theory to model long-term planning of electricity generation has been presented. This approach extends System-Dynamics based models in the literature in order to improve the representation of imperfect markets, in several aspects like forward contracting, bidding behaviour and companies’ investment decisions differentiation.

Particularly, this paper has presented a new method based on credit-risk-theory concepts to differentiate the companies when evaluating the possible future new investments. This method calculates an endogenous discount rate for each company depending on the financial structure (which is also endogenously-calculated) of each company at each time step in the simulation. This discount rate makes the companies to perceived different new plants’ expected-profitability.

A case study based on the Spanish system has been carried out to show the potential advantages of using this method. It has been seen how by considering the endogenous discount rate the results in the market change significantly. On the one hand, a more stable reserve margin appears, as a consequence of the self-regulating mechanism of this discount rate. On the other hand, structural changes are observed in the companies, which tend to specialize in some particular technologies more than in the exogenous-discount-rate cases.

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