System Dynamics modeling for the assessment of technical and socio-economic impact of power system policies

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Keywords: System Dynamics, Power System Planning, System Costs, Uncertainty

I. ABSTRACT

The present paper introduces a model aimed at forecasting the long run evolution of a country's power system based on exogenous variables such as international commodity prices or national energy policies. In addition, the model can be used to assess the long run impact of the country's power mix on socioeconomic and environmental variables such as GDP growth or GHG emission abatement.

The model's main underlying methodology is System Dynamics, which is combined with market equilibrium models, input-output macroeconomic modeling and stochastic methods.

The model is only applicable to liberalized markets and has been calibrated against the 2008 – 2013 historical data of Spain's power system. Results show that the model accurately reproduces the evolution of Spain's power mix.

II. INTRODUCTION

The liberalization of power markets, which started worldwide a few decades ago, has entailed dramatic changes in power system planning as the industry has transitioned from scenarios with full information, stable prices and co-operative regulation to scenarios where price volatility, information asymmetry and uncertainty are present [1, 2].

Also, the growing penetration of alternative technologies, smart grids and distributed generation and storage [3] is expected to make system planning even more challenging as additional uncertainty is introduced in the planning process.

While in the past regulators had just to define the optimum target power mix and execute the required investments in order to meet the capacity goals, in liberalized scenarios regulators must set the required incentives for investors so that the latter execute the required investments [4, 5, 6, 7]. This fact introduces additional uncertainty in the form of investors' behavior.

Also, the evolution of a country's power system has not only technical but also environmental, social and economic implications, which regulators and power system planners must consider in order to maximize the overall well-being.

This paper presents a model aimed at the simulation of the evolution of a country's power generation mix as a function of exogenous variables (such as commodity prices) and levers (such as incentive policies). In addition, the model allows the assessment of the long-run impact of the country's power generation mix on socio-economic and environmental variables. Relevant considerations such as investors' behavior, imperfect foresight and bounded rationality have been introduced [6, 8, 9].

Therefore, the model developed in the present research constitutes a methodological framework that may be used in order to forecast the evolution of a country's power generation mix as well its impact on system reliability, environment and socio-economic variables from a long-run cumulative perspective.

The model has been calibrated against Spain's power system historical data, which has been reproduced very accurately. Different case studies have been developed in order to assess the long run impact of specific power system policies on the power generation mix structure as well as on its environmental, economic and technical impact.

III. THE MODEL

A. General description

The model developed in the present research is composed of the following different modules:

- Power Generation Asset Lifecycle Model: It is aimed at reproducing the dynamic characteristics of the power system, including delays, system inertia and feedback loops, as well as properties inherent to liberalized markets such as investor's behavior and bounded rationality.

- Merit Order Power Pricing Model: It is used to simulate the operation of the country's wholesale power market, by computing power plant dispatching and final power price.
- Environmental impact model: It is used to assess the environmental impact of the power generation mix in terms of CO_2 emissions.
- System cost model: It is used to compute the overall power system costs.
- Socio-economic impact model: It is used to compute the socio-economic impact of the power generation mix in terms of variables such as GDP growth, job creation and income levels.
- Stochastic model: It is used to introduce the uncertainty inherent to specific exogenous variables such as commodity prices or inflation.

The model endogenously computes (i) energy system variables such as power mix composition, power price, plant dispatching and reserve margin, (ii) environmental variables such as CO_2 emissions and (iii) macroeconomic variables such as the energy system-related GDP. Other variables such as market prices (e.g. natural gas price) or inflation are considered as exogenous. Finally, energy policies (e.g. technology subsidies) are considered as exogenous levers so that their impact in the power system can be assessed.

Ibanez-Lopez [10] shows the basic philosophy behind the modeling approach while Ibanez-Lopez [11] and Ibanez-Lopez, et al. [12] describe the models in further detail.

B. *The Power Generation Asset Lifecycle Model*

This is the main underlying model and is based on the System Dynamics modeling methodology.

System Dynamics is a very useful technique for simulating liberalized power markets as, among others, it allows the introduction of properties such as soft variables, investors' bounded rationality, delays, feedback loops and system inertias, which are always present in deregulated scenarios [4, 5]. While System Dynamics is in principle a deterministic approach, it can be used for probabilistic analysis when combined with stochastic techniques.

This model is used in order to reproduce the evolution of a country's power generation fleet across time as a function of exogenous variables (such as commodity prices) and levers (such as incentive policies).

Fig. 1 shows the simplified causal diagram of the model. The model's main assumption is that the deployment rate of each power generation technology is a direct function of the economic return expected by investors, which increases with operating revenues and decreases with operating costs and specific investment. Operating revenues increase with power price and capacity factor. Operating costs increase with fuel, O&M and other costs, and decrease with plant efficiency. Specific investment decreases with installed capacity as a result of a learning curve effect. Power price and capacity factor are computed by means of the merit order power pricing model. Power price increases with power demand and generation costs, and decreases with installed capacity. Capacity factor increases with power demand and decreases with installed capacity. Efficiency increases with installed capacity due to a learning curve effect.

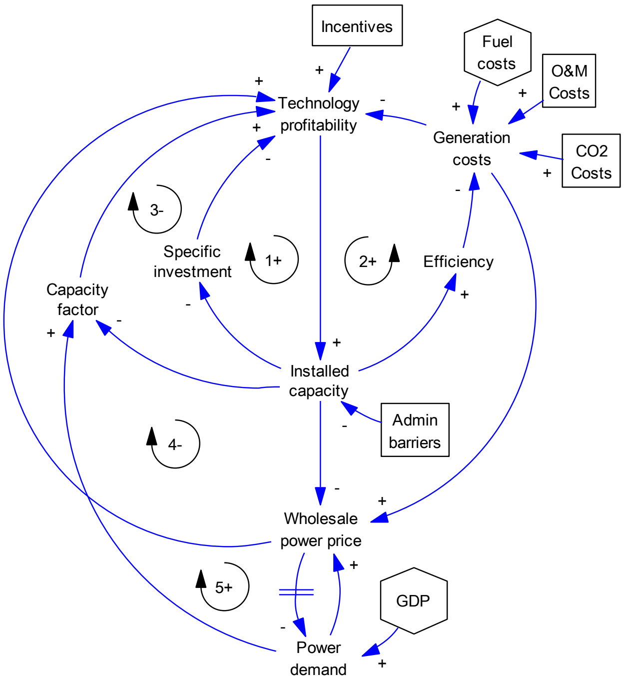

Fig. 1. Simplified causal diagram

New capacity is added when the economic return, measured as the IRR of each specific technology, exceeds a threshold value. The capacity addition rate for each technology increases linearly up to a maximum cap, which depends on the country's infrastructure. Fig. 2 shows this relationship graphically.

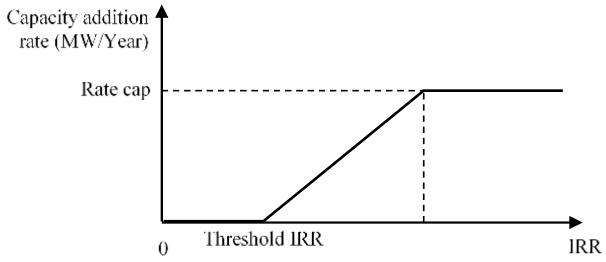

Fig. 2. Functional relationship between the capacity addition rate and the IRR

C. *The Merit Order Power Pricing Model*

This is a supply – demand equilibrium model which is used to simulate the operation of the country's wholesale power market. It endogenously computes the power price as well as the power plant dispatching based on inputs such as power mix composition, demand level and power plant operating marginal costs.

It assumes a fully liberalized market where the whole power produced is traded in a market where producers and consumers bid their respective production and demand. Both the power produced (and consumed) and the clearing price are set by the intersection between the power supply and demand curves. All generators and consumers who are awarded with any amount of energy get the same marginal price regardless of the price they actually bid.

While works such as [13] propose a perfect competitive market model where power generating firms bid their marginal generation costs and cannot strategically influence the clearing price, other works such as [9] consider sometimes-opportunistic bidding strategies so that bids depend not only on marginal costs but on biding strategies which may reflect sporadic market power. For the sake of this work a perfectly competitive market has been assumed while the reserve margin keeps over a specific threshold value but once this threshold is reached, market power has been considered by means of a scarcity price.

The following additional assumptions have been made:

i. The market is uniform and perfect. Power generators bid their actual marginal cost, they cannot strategically influence the price while reserve margin stays over a specific level and no complex bidding strategies have been considered.

ii. Power demand is a function of GDP, is price-inelastic in the short run but shows some price-elasticity in the long run [14].

iii. Costs other than generation such as T&D or system operation are not considered.

The supply curve is built by sorting all involved power generation technologies (10) and vintages (5) by increasing marginal price.

Wholesale power markets usually work on an hourly basis so that using annual averages for calculations can be misleading due to the large non-linearity introduced by the supply and demand curves. Therefore, instead of using annual average demand values, a model based on the load duration curve has been introduced. For the sake of simplicity, the load duration curve has been considered as linear, being its maximum the annual peak power demand and its minimum the lowest annual power demand. Fig. 3 shows an example of such a curve.

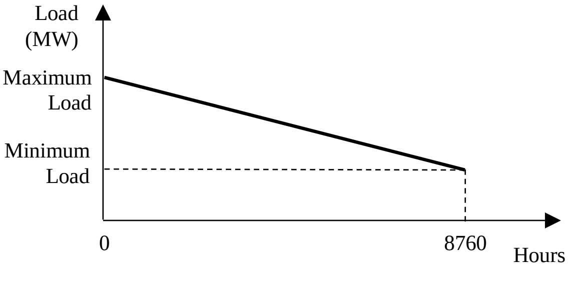

Fig. 3. Load duration curve

D. The Environmental Impact Model

This is an accounting model which computes the cumulative CO_2 emissions caused by the country's power generation fleet. Its inputs are the power mix composition, computed by the power generation asset lifecycle model, the actual dispatching of the different technologies, computed by the merit order power pricing model and each technology's characteristics in terms of emissions, which are exogenous variables.

E. The System Cost Model

This is also an accounting model which is used to compute the cumulative overall power system costs. It does not only include the power cost itself but also additional cost such as incentives and CO_2 emission credits. It uses the same inputs as the environmental impact model plus the CO_2 credit costs, which are assumed as an exogenous variable.

Although usually system costs include components such as generation, T&D, system management, system operation, trading and regulation costs, incentives, etc. for the sake of the present research and in order to be able to benchmark the impact of the power generation mix on system costs, only power purchase outlays, incentives, capacity payments, CO_2 costs and total investment have been considered.

While incentives can take many different forms such as grants, FITs, price premiums, tax credits or green certificates [15], at the end of the day, they are paid by end users through either higher power bills or higher tax rates. On the contrary to systems such as green certificates, which entail the operation of a parallel trading exchange or tax credits which sometimes require complex financial instruments in order to monetize tax savings, premiums are a very simple and intuitive incentive scheme which allows straightforward quantification. Because of these reasons, premiums have been chosen as the reference incentive scheme for the present research. Total incentive cost is calculated as the product of the power produced and the annual average premium price in EUR/MWh.

F. The socio-economic impact model

This model is used in order to assess the overall net economic impact of the power system in terms of variables such as direct, indirect and induced GDP growth, job creation and income level. The model is based on the Input-Output economic modeling methodology [16], which takes as data sources the country-specific Social Accounting Matrices [17, 18].

The model computes the changes in a country's economic output as a function of the investments made on the power generation mix, which are computed by the power generation asset lifecycle model and are considered as an increase in demand. Computations are made through the Leontief matrix [16], which is derived from the country's Social Accounting Matrices. Also, additional economic indicators such as job creation or income level change are computed through relevant country-specific multipliers.

In order to assess the impact of the power system on the economic flows, each power production technology must be allocated to the sectors included in each country's Input-Output tables. Investment and O&M costs must be broken down and each item must be allocated to said sectors. In addition, the share of imports must be computed and allocated in order to properly compute the impact on the nation's GDP [19].

Once each technology has been allocated to each productive sector and the share of imports has been defined, the capacity increase of each technology in MW can be translated into an increase of final demand in terms of output units.

G. The stochastic model

While System Dynamics is in principle a deterministic approach, it can be used for probabilistic analysis when combined with stochastic methodologies such as Monte Carlo simulations. This s used in order to model the uncertainty inherent to some exogenous variables such as commodity prices or inflation rates, which are modeled as random walks.

The values of some of some exogenous variables such as policy levers (e.g. incentive levels) can be easily predefined. Nevertheless, this is not the case of variables which show significant uncertainty, such as commodity prices or macroeconomic parameters (e.g. inflation).

Therefore, variables showing uncertainty have been modeled through a stochastic approach, which involves Monte Carlo simulations and "random walk" modeling.

Random walk processes are a particular case of ARIMA (p, d, q) processes where p = 0, d = 1 and q = 0. For the present case, random walk with drift models have been considered and have been modeled as follows:

$$y_t = y_{t-1} + a + \varepsilon_t, \quad \varepsilon_t \sim N(0,\sigma^2), \quad t = 2,\dots,n \qquad (1)$$

Where: yt = Variable value at time t

A = Drift coefficients

εt = Volatility coefficients

σ = Volatility standard deviation

The volatility and drift coefficients have been computed by taking the historical mean and standard deviation of the 1st difference of each variable. Normality tests (e.g. Q-Q, etc.) are performed on the 1st difference of the variables.

IV. SOFTWARE

The models here presented have been developed in Vensim [20], a specialized System Dynamics software package which allows intuitive and straightforward drafting of stock and flow diagrams as well as specific tools aimed at developing, testing, calibrating, optimizing and running System Dynamics models. Excel spreadsheets have been used as data inputs / outputs as well as for the development of the socioeconomic impact models.

V. RESULTS

A. Calibration against historical results

Before the actual parameter calibration the model has been validated from the structural and behavioral points of view [21] by performing the recommended boundary adequacy, structure verification, dimensional consistency, extreme conditions, behavior reproduction, behavior anomaly and behavior sensitivity tests [22, 23]

Calibration has been made based on historical data of Spain's power system. As the present model is applicable only to deregulated markets and Spain's power industry was liberalized in 1998 [24], only data after this year has been considered. 430+ power system variables have been collected for the 1998 – 2016 period including commodity and incentive prices, technical parameters (e.g. installed capacity, efficiency and capacity factors by technology), investment and operation costs and other macroeconomic variables such as inflation, interest rates and foreign exchange rates. The model has been calibrated using the 1998 – 2013 while the 2014 – 2016 data has been used as a test set.

The goal of the calibration was to reproduce Spain's installed capacity historical data series by setting the following variables for each technology:

i. Proportionality factor between the IRR of each technology and its investment rate.

ii. The IRR threshold over which investments take place.

iii. Proportionality factor between the IRR of each technology and its decommissioning rate.

iv. The IRR threshold below which decommissioning takes place.

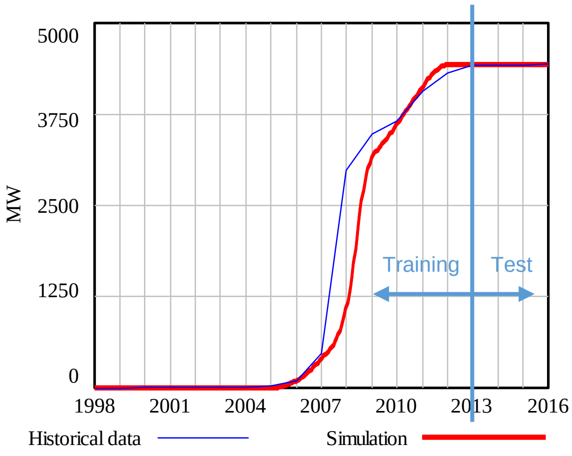

Fig. 4. Historical PV installed capacity

Once calibrated, the model has shown great accuracy when reproducing the evolution of Spain's power generation mix. As an example, Fig. 4 through Fig. 6 show the comparison between the historical and the simulated values for three different variables. Table 1 shows both the summary and Theil's inequality statistics [25, 22] for historical fit. As it can be observed low accuracy values are found only on those technologies where no significant changes in installed capacity have taken place (i.e. hydro, coal and nuclear) so that very small differences between historical and simulated data entail low R^2 values.

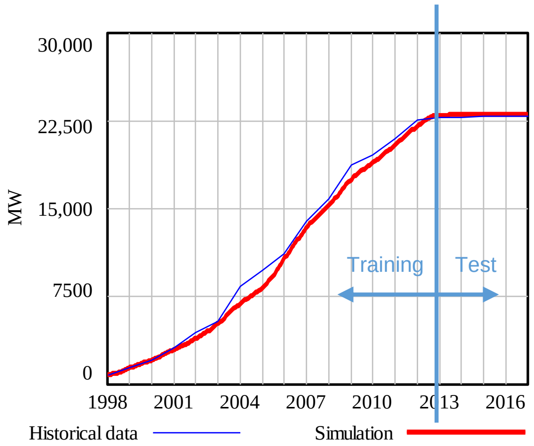

Fig. 5. Historical Wind installed capacity

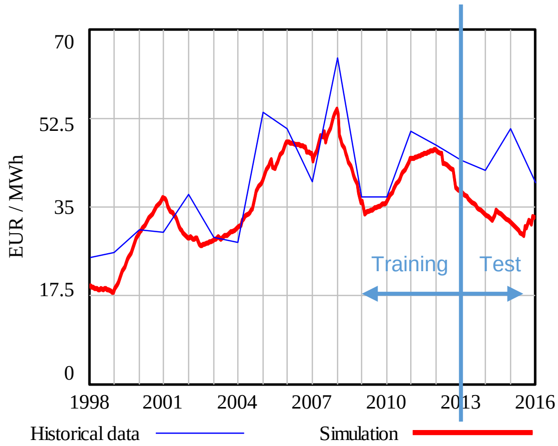

Fig. 6. Historical power price

Table 1. Summary and Theil's inequality statistics for historical fit

	R^2	U^M	U^S	U^C
Wind	0.993	0.73	0.00	0.27
Solar PV	0.971	0.15	0.04	0.79
Small Hydro	0.894	0.56	0.04	0.41
Solar CSP	0.976	0.19	0.54	0.27
Gas CC	0.970	0.16	0.14	0.70
Gas Peak	0.980	0.01	0.53	0.45
Hydro	0.651	0.49	0.48	0.03
Nuclear	0.000	0.83	0.16	0.00
Coal	0.219	0.80	0.19	0.18
Cogeneration	0.975	0.02	0.12	0.86

B. *Forecasting*

Several case studies have already been analyzed through the models here presented. As an example, Fig. 7 through Fig. 10 show the comparison between a scenario with a wind power incentive of 42 EUR/MWh and a scenario with no incentives. Two variables are shown (i.e. wind installed capacity and power price) although all system variables have been simulated.

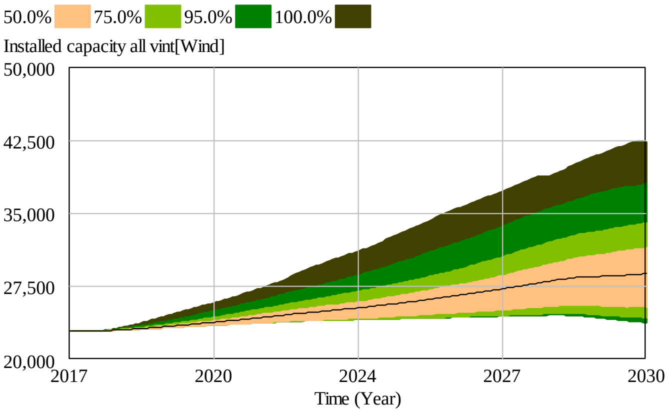

Fig. 7. Wind installed capacity – no incentives

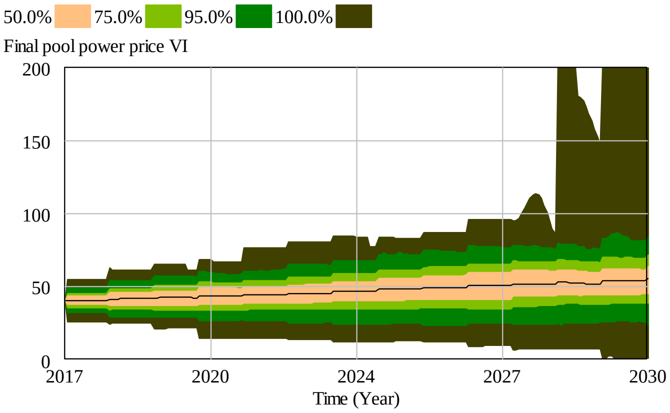

Fig. 8. Power price – no incentives

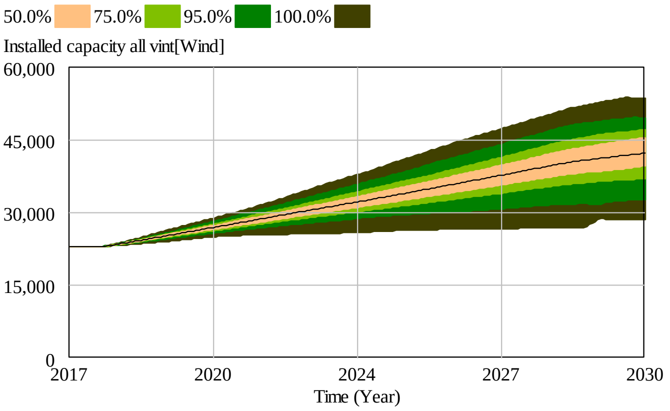

Fig. 9. Wind installed capacity – 42 EUR/MWh incentive

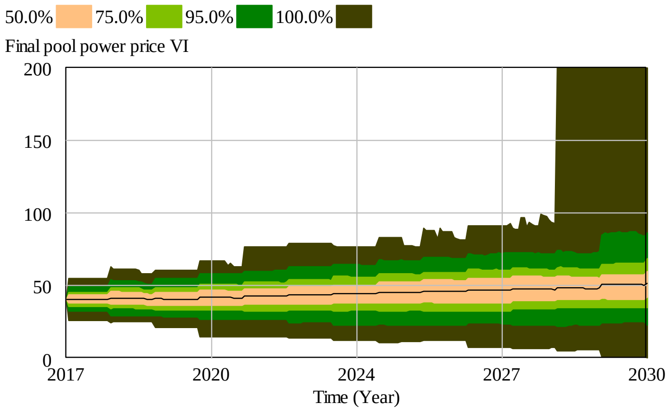

Fig. 10. Power price – no incentives

VI. CONCLUSIONS

The models here described have proven to accurately reproduce the evolution of a country’s power generation mix and therefore assess its impact from different perspectives. Therefore, System Dynamics seems to be a promising methodology for developing dynamic ‘soft’ simulations of non-equilibrium systems which, once calibrated against historical data, accurately reproduce the past evolution of the power system and enable to produce forecasts about its future evolution based on specific exogenous variables.

These forecasts may be of great interest for energy planners and policy makers in order to take the right actions aimed at achieving an optimal power generation mix from the technical (reliability), environmental (GHG emissions) and economic (system costs) point of view.

Additional work is required in order to assess the real economic cost of system blackouts and internalize it into the calculations, assess the optimum timing of policy actions (as only actions taken at the present time are considered so far) and assess unexpected events such as price shocks, supply constraints, or the development of breakthrough technologies.

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