Applied Energy 216 (2018) 504–520

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Simulation of demand growth scenarios in the Colombian electricity market: An integration of system dynamics and dynamic systems

José D. Morcillo[a,*], Carlos J. Franco[a], Fabiola Angulo[b]

[a] Facultad de Minas, Universidad Nacional de Colombia, Sede Medellín, Medellín 050041, Colombia
[b] Departamento de Ingeniería Eléctrica Electrónica y Computación, Universidad Nacional de Colombia, Sede Manizales, Manizales 170003, Colombia

HIGHLIGHTS

- A simulation model was constructed based on SD and DS approaches.
- Seasonality and growth demand uncertainty on the Colombian power market are studied.
- The DS/SD integration provides further understanding and a new and broad analysis methodology.
- Colombia needs new capacity before 2019, otherwise it might undergo rationing events during 2020/2021.

ARTICLE INFO

Keywords:
Electricity markets
System dynamics
Dynamic systems
Growth rate of demand

2010 MSC:
93C15
91B26
65C20
37H20
37N35

ABSTRACT

Modeling and simulation of electricity markets have increasingly involved the use of a system dynamics (SD) approach. Accordingly, the resulting dynamic hypothesis and the stock-flow structures are represented and simulated using softwares such as Stella, Powersim, iThink, or Vensim. However, SD models can be exploited even more, of which the investigation of signals in the time domain or the sensitivity analysis is just a small part of the study. Since SD models are mathematical objects, they deserve an analytical or numerical study using tools provided by the dynamic systems (DS) methodology. Therefore, this paper not only studies the dynamic hypothesis or the stock-flow structure of an electricity market model in the classical form, but also uses its inner mathematical object to provide a deeper insight into the system. Using MATLAB/Simulink®, the system is evaluated from a different approach not yet reported in the literature. The combination of the SD and DS methodologies can open the door to a new and alternative method of analysis for electricity market models and even for any SD model. In fact, this paper demonstrates that with this methodologies combination, more detailed analysis strategies and novel insights of the SD models can be developed, which can be easily exploited by policy makers to suggest improvements in regulations or market structures. Moreover, considering that the energy market is evolving, and a series of macro and microstructural changes are impacting demand, we consider as an example a simplified version of the Colombian electricity market to report a detailed description of its dynamics under a broad range of growth rate of demand (*GRD*) scenarios. Our study, inspired by the bifurcation and control theory of DS, primarily shows that Colombia is in dire need of a new capacity before 2020 to avoid rationing events expected to occur in the upcoming years.

1. Introduction

Simulation plays an important role in academia and industry. It is well known that experimentation with real systems is not possible in most cases given the undesired consequences or high costs that can be incurred. In particular, in the case of electricity markets, simulations are the basis for policy design and regulation improvements. Simulations allow the suppliers to invest in the best energy mix to stimulate the appropriate market price and to meet adequately the energy demand, among others.

In particular, the simulation of electricity markets has been increasingly addressed with the system dynamics (SD) approach. Currently, in the literature, countless papers that investigate the different schemes of electricity markets under the SD approach can be found. For instance, energy efficiency [1,2], renewable technologies diffusion [3–5], capacity adequacy [6], policy planning [4,7], demand response [8], among others, are topics of great interest for the SD community. In fact, the SD methodology has been applied successfully

* Corresponding author.
E-mail address: jdmorcilloba@unal.edu.co (J.D. Morcillo).

https://doi.org/10.1016/j.apenergy.2018.02.104
Received 4 October 2017; Received in revised form 3 February 2018; Accepted 15 February 2018
0306-2619/

and many important works have been developed accordingly [9]. The most remarkable advantage provided by the SD technique is the ability to efficiently capture the complex structure of real systems under a holistic overview. Indeed, modelers who are not familiar with mathematical models can find it easy to represent their problems using the SD approach. In this sense, modeling complex systems such as electricity markets have evolved from a simple stock and flow diagrams to large and hybrid models, involving engineering optimization, genetic algorithms, decision–tree approaches, and agent–based modeling [9]. This tendency to mix SD models with other strategies enhances the overall analysis, provides deeper insights, and covers more variables or scenarios. In essence, SD has shown to be compatible with other modeling techniques.

In fact, it is clear within the SD community that Forrester created SD inspired by the control theory and that an SD model always involves an indirect treatment with ordinary differential equations. In this sense, the formulation of a model in the SD world corresponds to a dynamic system or a set of ordinary differential equations; therefore, the compatibility of SD with other modeling techniques lies on the fact that an SD model is a mathematical object, and the dynamic systems (DS) community is aware of the immense mixing possibilities available to address an DS model. This is significant because the use of hybrid modeling techniques always leads the scientific community to further exploration and understanding of the nonlinear behaviors and feedback relations of the complex systems.

Nevertheless, literature is lacking not only in the electricity sector modeling, but also in other disciplines that integrate the SD modeling technique with different tools provided by the DS methodology, that extend the reduced routes of analysis to a broader spectrum of possibilities, only limited by the modeler knowledge. In this sense, our paper seeks to demonstrate the importance of integrating DS tools in the classic SD modeling cycle aimed at providing deeper understanding and insights into the SD models, as well as showing that this combined methodology can be implemented by using much simpler steps, i.e., without resorting to complex mathematical processes. In fact, the integration of SD and DS is not a new trend. Javier Aracil pioneered the stability concept applied to SD models from the DS perspective at around 1980 [10]. Subsequently, in [11] Aracil officially reported the importance of studying the qualitative behavior of SD models under their mathematical properties, to provide a more solid foundation of the analysis; however, his work has not been given much attention by the SD community since then. However, a few years ago, some authors have raised Aracils investigations again. In [12–14], the dynamics of small electricity market models were described using the DS perspective. In particular, the set of dynamic equations were studied analytically and programmed in MATLAB® to investigate the bifurcation regimes in electricity markets for the first time. However, their proposed models were a small version of the real one and many assumptions were considered. Unfortunately, by considering the small–version models and neglecting several important properties of the electricity markets, the results are not accurate enough and the corresponding conclusions may change. In addition, although working directly with the system equations is possible and feasible in some cases (the system equations can be programmed in any software package to obtain a solution under the numerical methods; subsequently, anything can be developed to analyze the system behavior), most of the models, and even most of the electricity market models have a high level of complexity, involving several feedback relations, state variables, and delays. Therefore, the models are almost impossible or cumbersome to study analytically or even programmed in any software package. Hence, we believe this particular methodology is not awakening the interest of the SD community, who are not familiar with the engineering design cycle since it does not support the way SD modelers think. As a result, in this work we propose the combination of the SD and DS perspectives in a simpler way such that SD modelers can be more comfortable working with DS tools. Thus, we believe that our study in this paper will be encourage the SD community, especially those interested in gaining more knowledge from the SD models, to further their studies to more than just a time series or a limited sensitivity analysis, and to open the door towards an infinite spectrum of possibilities for analyzing SD models.

To pursue our objective, we propose to create, in MATLAB/Simulink®, block diagrams analogous to the classic stock–flow structures that facilitate the deeper insights or analysis of the SD models. In particular, based on the bifurcation theory and the describing functions (DF) commonly used in control theory, we develop an advanced sensitivity analysis, a tool for determining the time of occurrence of the confidence limits and a scheme for describing in great detail the rationing events of our system. As an example, we investigate a simplified version of the Colombian electricity market; in particular, two important issues are analyzed: (i). How the variability of hydrogeneration affects its performance and (ii). What should Colombia be aware of under different growth rate of demand (*GRD*) scenarios. It is noteworthy that our developed methodology can be used for the electricity market models or any model of any disciplines regardless of its level of abstraction.

Although Simulink was already used in [15] to show the compatibility of the stock–flow structures with the block diagrams modeling, the authors did not implement the complete model (as we propose) in Simulink; they only linked MATLAB and Vensim to take advantage of MATLABs capability to manage the algebraic constraints. More recently, other authors have also developed algorithms in MATLAB for computing certain complex functions and then sent them to Vensim for subsequent processing [16,17]. In other words, the authors implemented some functions in MATLAB for computing, with more precision and simplicity, complex algebraic expressions of the model. However, from our perspective, linking MATLAB with SD software packages is cumbersome and also restricts the full potential of the MATLAB tools.

Furthermore, it is noteworthy that the SD/DS simulation through function blocks has been already introduced in other disciplines not related to the electricity markets. For instance, using Simulink for SD modeling was briefly mentioned in [18] for comparing the three major paradigms in simulation modeling: SD, discrete event, and agent–based modeling. Nevertheless, it was first reported in [19] that an SD model was converted into DS function blocks for combining genetic algorithms parameter search, fuzzy logic expert input, and SD modeling, to a very general market growth model. Similarly, in [20] the potential of block diagrams modeling was also used for an SD supply chain model with a capability limit. Finally, in [21], the Simulink block diagram modeling of an SD manufacturing supply chain model with uncertain demand was utilized once again. Even though all these works show that the SD/DS simulation through function blocks results in better strategies for decision making, since this methodology provides much more freedom in customizing and implementing global analysis techniques, they do not suggest the methodology for other disciplines or consider it as a new research trend in the classical SD modeling cycle. Indeed, in the referenced papers, bifurcation or control theory concepts were not considered for their research.

On the other hand, the variability in the generation of renewable sources has been addressed in several countries, especially for solar and wind energies. However, intermittency has been used more frequently when referring to the variability in these sources of generation. In fact, intermittency has been primarily addressed in Germany [22], the Alpine region [23], Spain [24], Canada [25], USA [26], and China [27]. In summary, these works state that intermittency highly affects the electricity tariff, demand and supply, investments, reliability, and dispatchability of electricity markets. However, the variability in hydrogeneration has only been addressed in Africa [28], USA [29] and China [30]; in particular, climatic variability issues in Colombia has been studied but only for explaining hydroclimatic anomalies and their impacts on biodiversity, ecosystems, and global environmental change [31]. Evidently, the variability in hydrogeneration and its impacts on