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Modeling energy market dynamics using discrete event system simulation

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ABSTRACT

This paper proposes the use of Discrete Event System Simulation to study the interactions among fuel and electricity markets and consumers, and the decision-making processes of fuel companies (FUELCOs), generation companies (GENCOs), and consumers in a simple artificial energy market. In reality, since markets can reach a stable equilibrium or fail, it is important to observe how they behave in a dynamic framework. We consider a Nash–Cournot model in which marketers are depicted as Nash–Cournot players that determine supply to meet end-use consumption. Detailed engineering considerations such as transportation network flows are omitted, because the focus is upon the selection and use of appropriate market models to provide answers to policy questions.

1. Introduction

The electricity industry operates by means of a supply chain that extends from generating station to end-users. Each link in the chain is crucial to the chain's integrity. Actors at each level, organized as markets, make decisions that have ramifications throughout the chain. The quality of any given decision depends on the quality of the knowledge available to the decision-maker. As a result, the dissemination of accurate information is critical if the supply chain is to operate effectively [1,2]. Conventional optimization techniques are no longer adequate to answer important questions about the stability and dynamic evolution of each supply chain activity because the behavior of each market participant is unknown.

In recent years, the total number of available energy models has grown tremendously and the models themselves vary considerably. The question arises about how to select the model most suited to a specific purpose. A classification scheme will provide insights about the differences and similarities, thus facilitating the selection of the appropriate methodology [27]. Several models have been developed for policy analysis, forecasting, and to support global or local energy planning in an effort to better understand the interplay between the macro-economy and energy use. Generally, these models focus on a long-term planning horizon and their underlying methodology is based on macro-economic approaches and market equilibrium models.

In general, the energy market has been studied separately because liberalization of the different markets (i.e. natural gas, coal, oil, etc) has occurred sequentially. Consequently, the markets present varying levels of maturity. Methodologies and tools developed for these previously liberalized markets are being applied to today's electricity market. Market models for natural gas are numerous and varied. GRIDNET is a detailed model of the North American natural gas system but from the gas transactions and operational perspective [28]. The Gas Systems Analysis Model (GSAM) is another North American natural gas market model with a very detailed supply side representation consisting of over 17,000 production reservoirs with about 200 variables each. The Natural Gas Transmission and Distribution Module (NGTDM) simulates market equilibrium prices, flows, and quantities using a heuristic algorithm; previous versions of NGTDM used a linear programming formulation for computing market equilibria [29]. These models provided detailed level analyses based on a competitive market assumption and cover many aspects of the North American system.

Energy models have been developed to support local energy planning and recently to observe the effects of interdependencies in the case of terrorist attacks [3–5]. However, analyses to date have focused mainly on the interrelation between the energy sector and the larger economy over time. A useful example is the computer-based National Energy Modeling System (NEMS) in the United States that models energy markets driven by the fundamental economic interactions of supply and demand [6]. Additional large-scale energy models include Electricity Markets Complex Adaptive Systems (EMCAS) and Energy and Power Evaluation Program (ENPEP) [7,8]. EMCAS is an agent-based modeling system used to simulate various market operating rules [7], while ENPEP is a set of

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integrated energy, environmental, and economic analysis and planning tools [8]. A supply chain network perspective for electric power production, supply, transmission, and consumption is presented in [9]. Various decision-makers operating in a decentralized manner such as generation companies, transmission companies and market consumers are modeled. A novel electric power supply chain network model with fuel supply markets that captures both the economic network transactions in energy supply chains and the physical network transmission constraints in the electric power network is reported in [30]. The theoretical derivation and analyses use the theory of variational inequalities. In [10] the authors present market integration and agent participation in a multiple-market framework using the Leontief model. Static conditions for each interval and partial equilibrium analysis are considered. Ref. [11] shows how to replace the inter-industry component of the Leontief model by a few surrogate constraints corresponding to the industries associated with the sector of interest.

A generalized network flow model of a national, integrated energy system that incorporates production, storage, and transportation of coal, natural gas, and electricity in a single mathematical framework for a medium-term analysis has been reported in [12,13]. The model focuses on the economic interdependencies of the integrated system along with a detailed characterization of their functionalities (supply, demand, storage, and transportation) within a single analytical framework that allows for their simultaneous study.

This paper provides a dynamic model to study the interactions among fuel and electricity markets and consumers, and the decision-making processes of fuel companies (FUELCOs), generation companies (GENCOs), and consumers in a simple artificial energy market. We construct a simple artificial energy market to: (1) maintain tractability; (2) obtain theoretical results; and (3) develop intuitions about economic complexity. We assume the existence of hourly spot electricity and fuel markets where few producers compete to supply markets demand. The problem is formulated using Discrete Event System Simulation (DESS), also known as discrete control theory. DESS differs from agent-based computational simulation methods such as Multiagent Resource Allocation (MARA) in that time is represented in discrete quanta or units called *ticks*. Participant behaviors that occur within a tick are reported in aggregate as a tick-final state. The aggregation of behaviors across ticks decreases the elevated importance of individualistic participant traits that confound agent-based simulations when environments with few participants are examined. With DESS, it is possible to retain a focus on select variables or participant behaviors and these behaviors are seen to vary smoothly with time [14,15]. In our model, decision-makers, FUELCOs and GENCOs, utilize adaptive expectations to forecast their competitors' actions [16]. When companies are willing to make trade-offs between present and future profits, it is critical to incorporate learning strategies in the decision-making. For example, GENCO i may understand so little about its rival's past actions and the underlying rationales that GENCO i comes to believe ("static assumption") and accept that the circumstances it observes in the immediate past will repeat themselves. Adaptive expectations posit that future values may be calculated on the basis of previous values.

The paper is organized as follows: Section 2 describes the energy market supply chain and the role of information in the new market environment. Section 3 describes the energy market model considered in the development of its mathematical formulation. In Section 4, a case study is used to present our model using numerical data. Section 5 details a sensitivity analysis and Section 6 discusses computational issues. Section 7 offers conclusions and suggestions for future research.

2. Energy market supply chain

Energy models generally tend towards an economic equilibrium between consuming and producing sectors: Raw materials flow in one direction; orders and money in the other; and the flow of information in both directions. These flows of raw materials, capital, and information link the individual components of the system to form the supply chain.

In today's liberalized markets where it is possible that end-users can also be suppliers, information and commodities can flow in both directions as shown in Fig. 1.

The new electricity markets allow consumers to sell power back to the market through contractual agreements that are usually components of demand-side management programs. Although some utilities are wary of demand-side programs that may affect revenue, in most cases, both the short- and long-term savings from demand-side programs outweigh costs.

3. Energy model

Dynamic simulations allow the researcher to observe system changes over time so that he/she may understand how the system is likely to evolve, predict probable future system behaviors, and determine how to influence them [17,18].

This section describes the dynamic model developed to study the interactions between two FUELCOs, two GENCOs, and an aggregated consumer within (1) a fuel market for GENCOs, and (2) an electricity market and (3) a fuel market for consumers (Fig. 2 below). Time is considered to be discrete [19]. In the discrete form, the system state space model is:

$$\begin{aligned} X(k+1) &= A(k)X(k) + B(k)U(k) \\ Y(k) &= C(k)X(k) + D(k)U(k) \end{aligned} \quad (1)$$

where k is the time period index,$X(k)$ is the vector of state variables, $U(k)$ is the vector of input variables, $Y(k)$ is the vector of output variables and A, B, C, D are the system matrices function of k. [19].

3.1. Consumer decision-making

The consumer wants to minimize the total cost of energy:

$$\underset{\{q^{\mathrm{fc}},q^{\mathrm{ec}}\}}{\mathrm{Min}} \; P^{\mathrm{fc}}q^{\mathrm{fc}} + P^{\mathrm{ec}}q^{\mathrm{ec}} \quad (2a)$$

$$s.\ to\ h^{\mathrm{ec}}q^{\mathrm{ec}} + h^{\mathrm{fc}}q^{\mathrm{fc}} \geq \mathrm{Heat} \quad (2b)$$

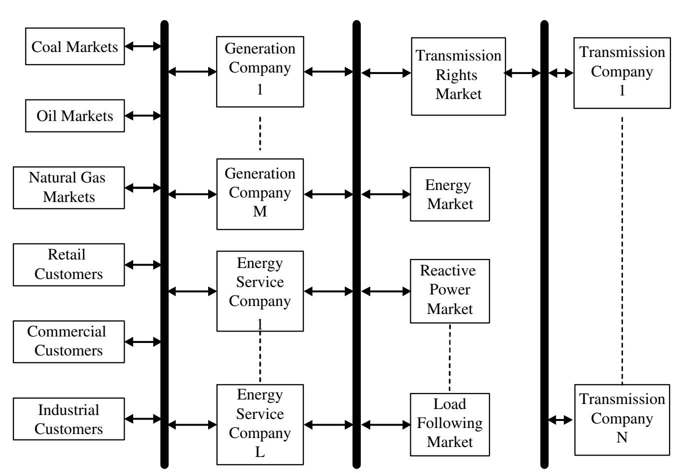

Fig. 1. Schematic information flowing in the electricity supply chain.