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Cleaner power generation through market-driven generation expansion planning: an agent-based hybrid framework of game theory and Particle Swarm Optimization

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ABSTRACT

In power markets, the competition on both price and quantity can be used as a trigger towards development of a sustainable power sector furthermore; it can increase the use of renewable energy sources and enhance energy efficiency on the supply and demand sides. In this regard, it is required to develop a reliable decision support system for sustainable generation expansion planning under a good understanding of the aforementioned issues. Game theoretic models as decision support tools have recently received increasing attention from many researchers in this field; however, they assume the supplier entities make a long-term strategic plan with perfect foresight in a certain problem environment, without considering inter-temporal dynamics of market and effects of demand side interactions on generation expansion decisions. In this paper, we propose a two-side multi-agent based modeling framework which undertakes these tasks using a hybrid simulation approach of game theory and Particle Swarm Optimization (PSO). A Case Study of Iran's power system is used to illustrate the usefulness of the proposed planning approach and also to discuss its efficiency. The results showed that the proposed integrated approach provides not only an economical generation expansion plan but also a cleaner one compared to the game theoretic approach.

1. Introduction

The Generation Expansion Planning (GEP) problem has historically addressed the issue of identifying the most adequate technology, expansion size, and timing for the power generation through a long-term planning horizon. The advent of electricity market deregulation has induced a number of important consequences to sustainable GEP activities (Clark and Lund, 2007; Heikkurinen and Bonnedahl, 2013). The most striking consequence of it is the change in electricity market price. The increased price competition forces suppliers to minimize operational and environmental costs. In order to succeed in this competition, supplier entities need to return to efficient production plants as a means of reducing electricity losses; fossil dependency and greenhouse gas (GHG) emissions for a decreased market price. In this context, demand entities also modify their demand levels in terms of market price and correspondingly affect it. These interactions among market price value, demand level, and amount of supply electricity are defined market behavior.

In the field of energy system modeling and planning, market behavior is considered through merging two extreme modeling paradigms, i.e., top-down and bottom-up approaches. Top-down is named the "pessimistic" economic paradigm, while the bottom-up approach is associated with —but not exclusively restricted to— the "optimistic" engineering paradigm (Grubb et al., 1993). In economic paradigm, technology is considered as a set of techniques by which inputs such as capital, labor, and energy can be converted into useful outputs and the "best" or most optimal techniques are provided by efficient markets. However, in engineering paradigm the developed model is independent of the observed market behavior (Beek, 1999). In this regard, integrated models try to bridge the gap between top-down and bottom-up by including elements of both approaches. They attempt to combine the benefits of top-down and bottom-up modeling schemes using either systematic vision or modular structure to integrate the disparate systems. The existing integrated models can be generally categorized as:

(1) models which try to endogenous market price i.e., game theoretic based and real option models;

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(2) System Dynamics and Computable General Equilibrium (CGE) models that incorporate price dynamics of demand and supply into the models without involving inaccurate parameters; and
(3) multi-agent based models that consider not only inter-temporal dynamics of energy system but also interactions within heterogeneous participating entities and their adaptive behavior.

Hence, multi-agent based models are suitable tools for dealing with uncertainties related to problem parameters and for capturing dynamics of energy systems.

The approach developed by Botterud and Korpås (2007) is a real options approach dealing with uncertainty in load growth, and its influence on future electricity prices, which is taken into account in the GEP problem. This approach addresses an electricity price model, where the spot price is a function of load level and installed generation capacity, as well as short-term uncertainties and temporal fluctuations in the market (Botterud and Korpås, 2007). References Cunningham et al. (2002); Jing-Yuan and Smeers (1999); Murphy and Smeers (2005); Roh et al. (2007) detail a game theory based (Cournot) model with an exclusive behavior for the purpose of mathematical composition and expression of an integrated GEP problem model incorporating endogenous market prices. For describing the game of GEP problem, the Cournot equilibrium is obtained through iterative methods. Several approaches explicitly recognize price dynamics of demand and supply in certain problem environments. In the case of (Pereira and Saraiva, 2011) a System Dynamics approach is used to capture the long-run behavior of electricity markets and to characterize the evolution of the electricity prices and the demand. This addresses a feedback mechanism between the individual expansion planning problems and the long-term System Dynamics model. Blumberga et al. (2014) also showed that system dynamics has a high potential to be used for sustainable end-use energy system planning at both national and sub-sectoral levels. In the case of Zhou et al. (n.d.) energy system parameters are assumed as fuzzy sets and a fractile-based interval mixed-integer programming (FIMP) method is developed for sustainable municipal-scale energy system planning and management.

Several authors linked bottom-up energy models to top-down ones to be capable of simulating the macro-level economy and micro-level technology details of the energy systems. Generally, there are two main solution approaches used in these studies. The first approach, a combination of LP and econometric demand equation is used to determine the equilibrium price and quantities of fuels. This approach demonstrates perfect foresight and is proved to be non-realistic and unsuitable for the resulting year by year analysis. The second approach, namely modular approach, is developed in order to compute the equilibrium price and quantities by iterative interactions between various modules (e.g., Andreas Schafer et al., 2006; Chen et al., 2009; Ehrenmann and Smeers, 2011; Wing, 2006). The studies of Botterud et al. (2007), Gnansounou et al. (2007) and also Logenthiran et al. (2011) are precedent works using agent technologies for modeling and simulating the market of power systems in the GEP problem. However, these multi-agent frameworks either aim at short-term operational planning or merely cope with one-sided market mechanism, and ignore the interactions of demand side agents and their effects on supply level accordingly.

The GEP problem is a complex one with a set of dependencies between its parameters and variables such as long-term evolution of demand, fuel prices, investment and maintenance prices and also behavior of generating entities. Moreover, they are often uncertain in terms of problem environment. A good example of this situation in energy planning tasks is the case of Iran. Uncertain economic conditions, changing electricity demand pattern due to heavy removal of subsidies on fuel, sociopolitical threats and needs for independency, as well as economic and technological sanctions against Iran which lead to an uncertain (vague) environment for the GEP problem. To do this, it requires an integrated modeling framework that not only considers the market behavior in the modeling but also decreases the uncertainties of the model parameters in order to identify a sustainable generation expansion plan.

The main purposes of this paper are to illustrate:

(1) How incorporating market dynamics into the GEP problem leads to a sustainable generation expansion plan, according to the sustainable development definition (Glavič and Lukman, 2007);
(2) How a modified game theory is applicable to the GEP problem with multi-type generating units in Pool markets under some constraints;
(3) How a novel two-sided multi-agent based framework incorporating demand side dynamics and interactions into the GEP model leads to a cleaner and more economical, reliable generation plan; and
(4) How the two approaches of system integration (the modified game theory based and the multi-agent based modeling approaches) behave differently in uncertain (vague) problem environments? What different philosophies underlying them and which of them are suitable for different contexts?

To do this, we first outline three kinds of modeling practices for energy systems planning, namely, traditional optimization, game theoretic and multi-agent based models and for transparency and simplicity of comparison, all the three models are reformulated in terms of the intended case data and conditions. Afterwards, the results obtained by using these three models will be analyzed and compared.

The rest of this paper is organized as follows. Section 2 is devoted to the description of the main GEP problem modeling approaches. The comparison of the results obtained by using these three models is presented in Section 3. Section 4 addresses conclusions and final remarks.

2. Modeling approaches

In this section the main modeling approaches which include a traditional optimization model, pseudo game theoretic model, and a two-sided multi-agent based model are described. The notations used in the main (traditional) CEP problem formulation are as follows:

Indices

j	Input fuel, $j = 1,2, \ldots, J$
t	Stage in the planning horizon (year), $t = 1,2, \ldots, T$
T	Number of stages in the planning horizon
g	Time period from t-f to t where f is technical life
d	Time period from 0 to t, $d = 0,1, \ldots, t$
h	Time period from t to, T, $h = t, t+1,..,T$
J	Number of input fuels
f	Technical life (Year)
n	Consumer number, $n = 1,2,3, \ldots ., N$
m	Supplier (technology) number, $m = 1,2,3, \ldots ., M$
N	Number of consumers
M	Number of suppliers