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Multi-period energy planning model under uncertainty in market prices and demands of energy resources: A case study of Korea power system

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ABSTRACT

This paper presents a mathematical framework for planning an energy supply system. The proposed model takes into account important factors affecting the total cost of supplying commercial energy such as market prices and waste disposal costs. Forecasting models are employed to predict future prices and demand levels. Given the renewable energy portfolio standard that promotes energy generation from renewable sources, a large-scale nonlinear planning problem is decomposed into a mixed integer linear program and a nonlinear program for traditional and renewable energy sectors, respectively. Nonlinearity arises from the learning curve that describes cost changes through future advances in technologies for exploiting renewable energy sources. The suggested approach can provide insights for crafting long-term policies, which can then be revised with updated information. The modeling framework is illustrated using public data from South Korea, interpreted in light of country's policies. Results based on various scenarios indicate that uncertainty and the cost of waste disposal facilities significantly affect the optimal policy choice.

1. Introduction

Over the last few decades, satisfying the ever-growing demand for energy in a sustainable way has become a major challenge worldwide. Increasing usage of conventional resources has severe environmental and economic consequences. Combustion of fossil fuels generates various noxious substances, and carbon dioxide (CO_2) emissions are known to be a major cause of global warming. In the case of nuclear power plants, wastes disposal is costly and may incur environmental problems and catastrophic disaster.

Renewable energy resources are a suggested alternative to these conventional resources. These stem from natural resources that are spontaneously replenished on a human time scale such as wind, sunlight, biomass and tides. They have advantages in addressing some of the above-mentioned environmental problems of conventional resources. Many renewable energy sources emit little or no CO_2 or toxic materials when generating electricity. Although the cost of electricity generation from renewable energy sources is not greatly affected by the price of raw materials, they are not generally yet cost-competitive compared to traditional resources. In 2013, the U.S. Energy Information Administration (EIA) reported that the total cost of renewable energy for the constant electricity generation can be 2–3 times that of the traditional energy resources (U.E.I. Administration, 2013).

Another problem with renewable energy is its intermittency, i.e., inherent discontinuities in power generation. Since the fluctuating availabilities of resources such as wind and sunlight cannot ensure a stable power supply, additional capacity for intermittent storage is required. For these reasons, renewable energy cannot currently replace conventional resources completely. Nevertheless, many countries still promote the use of renewable resources because of the increasing interest in environmental issues and the possibility of gradually reducing capital and operating costs through technological improvement.

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Devising a proper energy supply policy is a difficult task: many complex factors must be considered, including current reserves of energy resources, market prices, environmental issues, and expected cost reduction through technological improvement. To tackle this problem, various mathematical models have been proposed (Hobbs, 1995). The process of formulating such models and obtaining their optimal solution is referred to as energy planning, of which there are various types depending on the model, objective function and energy resources considered. In terms of the decision time-scale, energy planning varies in temporal and spatial granularity including long-term generation expansion planning (GEP) as well as short-term electricity generation dispatch. Various criteria can be used to determine the optimal policy, but the total cost of supplying energy to meet demand is often chosen as an objective.

How to formulate an energy-planning model mathematically is related to the desired reliability and applicability of the resulting solutions. Many researchers have studied long-term GEP and resource supply network. MARKet ALlocation (MARKAL) is one of the representative models (Fishbone and Abilock, 1981). Its modified forms are still popularly used. Among them are assessment of availability for bioenergy production in UK (McDowall et al., 2012) and policy making for renewable fuels in US (Sarica and Tyner, 2013). MARKAL is a linear programming-based model and minimizes the total cost of the flow of energy resource to the demand sectors considering depreciation and security. The Time-stepped Energy System Optimization Model (TESOM) is another early model that includes energy balances optimized over a single time period (Kydes and Rabinowitz, 1981). TESOM uses sequential linear programming to manage multiple time periods: a sequence of linear programs and the solutions derived for earlier periods are incorporated into subsequent problems. These long-term GEP problems are recently studied for reflecting situation of each state or evaluating specific parameters. Amirnekooei et al. develop a reference energy system and forecast of energy consumption (EC) for a 25-year period for Iran and examine the effects of several demand and supply side management strategies on resource depletion and environmental emissions (Amirnekooei et al., 2012). Koltsaklis et al. present mixed integer linear programming combined with Monte Carlo simulations and demand responses to determine optimal power capacity addition and power generation for 15-year time period (Koltsaklis et al., 2015). Daily constraints at the hourly level are also considered in GEP such as start-up and shut-down related decisions using Greek power system (Koltsaklis and Georgiadis, 2015). Viana et al. consider a standard thermal unit commitment problem in power generation planning and use quadratic programming in an iterative manner (Viana and Pedroso, 2013).

Since the 1990s, growing interest in clean energy resources has led researchers to expand these models and achieve additional environmental goals such as using renewable energy resources, reducing CO_2, or purifying flue gases. Studies on the optimization of renewable energy generation mainly focus on financial aspects, technology adoption, supportive policies and comprehensive utilization (Zhang et al., 2010). Sampio et al. study sustainable energy planning for the city of Guratingueta, Brazil. They use goal programming for a multi-objective model including environmental constraints and energy production (Sampaio et al., 2013). A modified multi-dimensional model with renewable energy as a dominant contributor has been suggested for the electricity and heat sectors in Germany (Henning and Palzer, 2014). Walmsley et al. investigate possible scenarios that can achieve 33% generation using renewable energy resources by 2020 in California, US (Walmsley et al., 2015). The issues related to CO_2 reduction have also been discussed by many researchers. Muis et al. develop optimal planning of electricity generation at a national level to meet a specified CO_2 emission in Malaysia (Muis et al., 2010). Zhang et al. present a decision making model that calculates optimal pathways of power sectors in China (Zhang et al., 2013). In this study, two cases are compared by varying the prediction performance of carbon tax. Mirzaesmaeeli et al. propose an optimization model to determine an optimal mix of energy sources including pollutant migration, CO_2 emission and several time-dependent parameters (Mirzaesmaeeli et al., 2010).

Previous studies have been focused on a single problem formulation to construct an expansion planning model of all types of resources. The resulting formulation includes all the factors related to the total cost in a single problem, which is complex to solve and analyze. On the other hand, previous studies also specify plant capacity of renewable energy resources given a standard portfolio of renewable energy resources. This portfolio includes government requirement for the minimum percentage of power generation using renewable energy resources (Kim et al., 2012; Koo et al., 2011b). In light of this, we propose a manageable energy planning optimization model that separates the problem into two problems for the renewable energy and traditional energy, respectively. This will facilitate the analysis of important factors on each type of resources in solving multi-region, multi-period GEP.

Cost factors and their relative weights in the objective function depend on the types of energy resource used for electricity generation. For operating power plant using traditional energy resource, maintenance cost including purchase of raw material accounts for 40–60%, even 70% of total cost according to the report (U.E.I. Administration, 2014). Since the cost of raw materials takes a high proportion in the total cost, various techniques are applied to predict resource prices. Shafiee et al. present a mean reverting jump diffusion model (MRJD) to extrapolate historical trends in fossil fuel prices (Shafiee and Topal, 2010). Feedforward neural networks are combined with slope-based method to forecast crude oil prices (Liu and Wan, 2012). It is also shown that the energy price trend is not well represented by the single positive or negative trend of the existing models (Ghoshray and Johnson, 2010). A time-series model is suggested to find stochastic properties in a database of 11 non-renewable resource prices (Presno et al., 2014).

Moreover, additional wastes produced in generating electricity from the conventional energy resources are another cost factor. For reduction of CO_2 emission, technical and institutional measures are necessary although they incur additional costs. In case of nuclear power plant, most of the radioactive wastes are stored in power plant intermediately and the cost of waste disposal is often ignored. However, gradual decrease in the available storage capacity can be a major cost factor, especially for the high-level radioactive wastes.

As for the renewable energy planning, capacity cost is crucial because the fuel cost of electricity production using renewable sources is almost negligible. The capacity cost can be further reduced through advances in technology; many on-going studies are focused on improving the efficiency of renewable energy via capacity expansion. The cost reductions achieved through trial-and-error processes can be represented by learning curve (Söderholm and Sundqvist, 2007). It can quantify the impact of experience on cost reduction via technology and relate future cost changes to the current investments on new technologies. Koo et al. evaluate the economics of renewable energy resources in South Korea using learning curve-based iterations (Koo et al., 2011a). Similarly, Cong studies optimization of the total cost of China's renewable energy system by considering a learning effect (Cong, 2013).

This paper presents a modeling and optimization framework for temporal and spatial energy planning considering future advances in renewable energy technologies and uncertainty in demands and resource prices. Implementing such an integrated model is difficult due to the challenge of forecasting uncertain variables and technological improvement which involves a large number of variables and nonlinearity. However, this complex, large-scale problem can be decomposed into two separate problems given an obligation to use renewables or an incentive program. We show that the resulting problems are formulated as MILP for traditional energy resources with price forecasting and nonlinear programming (NLP) for renewable energy resources considering technological improvements. A MRJD model modified with a geometric Brownian motion (Ball and Torous, 1983) is employed to predict resource prices. Given a small number of data, the suggested framework can also predict demands for energy resources and electricity using a grey model proposed by Guo et al. (2005). In addition, the cost of waste disposal is included as a way of evaluating energy policies supporting traditional energy resources.

The proposed work presents an optimization approach and formulation that divides the total energy resource optimization problem into two separate, manageable ones: the traditional and renewable