Energy Policy 78 (2015) 78–90

Contents lists available at ScienceDirect

Energy Policy

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

Optimal allocation of energy sources for sustainable development in South Korea: Focus on the electric power generation industry

Joongha Ahn [a,1], JongRoul Woo [b,2], Jongsu Lee [b,*]

[a] Samsung Economic Research Institute, 29th Floor, Samsung Life Seocho Tower, Seocho 2-dong, Seocho-gu, Seoul 137-955, South Korea
[b] Technology Management, Economics, and Policy Program, College of Engineering, Seoul National University, San 56-1, Sillim-Dong, Kwanak-Gu, Seoul 151-742, South Korea

HIGHLIGHTS

- Optimal least-cost/cost-risk energy mix for sustainable development in Korea.
- We account for CO_2 and external costs of generation from each energy source.
- Externalities and physical/policy constraints in Korea produce realistic energy mix.
- Nuclear and renewables should replace coal and gas for sustainability in Korea.
- Least-cost approach limits uptake of renewables and produces high-risk energy mix.

ARTICLE INFO

Article history:
Received 22 July 2014
Received in revised form
12 November 2014
Accepted 19 December 2014
Available online 30 December 2014

Keywords:
Energy planning
Sustainable development
Optimization model

ABSTRACT

National energy planning has become increasingly complex owing to a pressing need to incorporate sustainability considerations. In this context, we applied least-cost and cost-risk optimization models to allocate energy sources for sustainable development in the Korean electric power generation industry. The least-cost model determined an electricity generation mix from 2012 to 2030 that incurs minimum generation cost to meet electricity demand. The cost-risk model determined electricity generation mixes in 2030 considering the risks associated with each energy source in order to lessen external risks. In deriving these optimal electricity generation mixes, we considered both conventional and renewable energy sources in conjunction with physical and policy constraints that realistically reflect Korean circumstances. Moreover, we accounted for CO_2 and external costs within the electricity generation costs for each energy source. For sustainable development in Korea, we conclude that a portion of the coal and gas in the electricity generation mix must be substituted with nuclear and renewable energy. Furthermore, we found that least-cost allocation is sub-optimal from cost-risk perspective and that it limits the adoption of renewables. Finally, we also discuss the implications of decisions taken by the Korean government regarding the electricity generation mix for next-generation energy planning to achieve sustainability.

1. Introduction

Energy is an essential input for economic development and energy demand increases with economic growth (Stern, 1997). At present, most energy is derived from conventional sources such as fossil fuels (oil, coal, and gas) and nuclear fuel. Although these conventional energy sources are economical, increased fossil fuel consumption has exacerbated emissions of greenhouse gases (GHGs) and the depletion of natural resources. Moreover, increasing GHG emissions have resulted in adverse environmental effects and global climate change (Baños et al., 2011). Climate change has been a global issue since the late 20th century, particularly because it has increased the frequency of natural disasters, inducing both financial and non-monetary losses. Stern (2007) estimated that, without action to mitigate climate change, the associated costs would be equivalent to 5–20% of annual global gross domestic product (GDP). Nuclear energy has been considered as a major alternative energy source to fossil fuels. However, after the Fukushima nuclear accident in 2011, there has been considerable international debate regarding the risks and future of

* Corresponding author. Fax: +82 2 880 8389.
E-mail addresses: joongha.ahn@samsung.com (J. Ahn), jroul86@snu.ac.kr (J. Woo), jxlee@snu.ac.kr (J. Lee).
[1] Fax: +82 2 3780 8006.
[2] Fax: +82 2 873 7229.

http://dx.doi.org/10.1016/j.enpol.2014.12.023
0301-4215/

nuclear energy[3] (Hartmann et al., 2013; Hong et al., 2013; Srinivasan and Gopi Rethinaraj, 2013; Wittneben, 2012). In this context, sustainable development has emerged as a new economic development paradigm.

According to the report entitled "Our Common Future" by the Brundtland Commission (Brundtland, 1987), sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Under the principles of the United Nations, The United Nations Millennium Declaration (United Nations General Assembly, 2000) identified principles and proposed treaties on sustainable economic development, social development, and environmental protection. Specifically, in the energy sector, the two most important challenges for sustainable development have been identified as controlling the contribution of energy to climate change and securing the energy supply (Abbasi and Abbasi, 2010). Thus, governments worldwide have attempted to move toward more sustainable economic development in response to climate change, the depletion of natural resources, the need to ensure energy security, and public opposition to nuclear energy. In particular, most OECD countries, including Korea, have established policies to supply new renewable energy and to restrict GHG emissions to ensure sustainable development (OECD, 2007). Furthermore, post-Fukushima, OECD governments have considered external costs not included in the current energy system and have attempted to create new energy plans that consider the externalities of each energy source (Rabl and Rabl, 2013). Accordingly, energy planning can no longer simply seek to satisfy energy demands at the lowest total generation cost.

Globally, in 2012, Korea was the eighth largest energy consumer and the seventh largest emitter of CO_2 and it imported 97% of its energy needs (Enerdata, 2013). To address this, Korea has been making efforts to achieve sustainable development. In 2008, the Korean government declared low-carbon green growth as a policy goal, and it aimed to reduce its CO_2 emissions by 30% below the business-as-usual (BAU) baseline by 2020. Moreover, the Korean government actively promotes renewable energy diffusion because such policies would not only reduce Korea's CO_2 emissions and its dependence on overseas energy sources, but would also create new markets for renewable energy (Shin et al., 2014). Furthermore, post-Fukushima, the Korean government has considered the externalities of energy sources and attempted to reflect these in its energy policy.

Many types of optimization models have been used for national energy planning and such models are based primarily on linear programming, which refers to a problem whereby the optimal value of a linear function is determined subject to linear constraints. Policy makers and researchers have used different optimization models to establish an appropriate framework with which to guide energy investments in a desirable direction. Optimization models in energy planning can be distinguished according to the objective function they adopt. Of these, the least-cost optimization model establishes an objective function to minimize generation costs for a cost-efficient energy mix. However, because sustainable development has gained importance in energy planning, the least-cost model has incorporated renewable energy sources (which emit less GHGs than fossil fuels) and also included the CO_2 price of energy sources within the generation costs (Cai et al., 2009; Cormio et al., 2003; Kim et al., 2012; Koo et al., 2011a, 2011b). Meanwhile, increased attention has been given to the substitution by renewables to help reduce exposure to fossil fuel price volatility. In such scenarios, the use of the cost-risk optimization model, based on portfolio theory, minimizes both the cost and the uncertainty or risk associated with the long-term cost flow of energy sources (Awerbuch and Berger, 2003). The cost-risk optimization model has been modified from the efficient diversification model or mean-variance efficient portfolio model presented by Markowitz (1952), which is used widely in the field of finance as an asset allocation method. For example, Awerbuch and Berger (2003) applied the portfolio theory to the electric power generation sector to obtain an optimal energy mix for the EU by considering both the cost and risk of energy sources.

Previous energy planning studies have included renewables, but have predicted an unrealistic energy mix as an optimal solution (Kim et al., 2012). However, such studies have not considered realistic constraints on renewable energy sources. For example, renewable energy policy and the feasible construction capacity for renewable energy sources, which differ yearly between renewable energy sources, must be considered. Moreover, fluctuations in energy costs are important for initiating sustainable development for countries that rely on imports for most of their energy (e.g., Korea) (Kim et al., 2011). However, few previous studies have applied a cost-risk optimization model for energy planning and none have examined the Korean context (Bhattacharya and Kojima, 2012; Huang and Wu, 2008). To address this, the present study examined scenarios that can be considered more realistic for sustainable energy planning in the Korean electric power generation industry via two methodologies: least-cost and cost-risk optimization, and combined both methodologies. Through the least-cost optimization model, we determined an energy mix for electricity generation from 2012 to 2030 to meet electricity demand with a stable energy supply, based on minimum cost—including CO_2 costs and external costs—within the present environmental and regulatory framework of Korea. We extended this to cost-risk optimization and determined electricity generation mixes for 2030 that consider the risks associated with each energy source. Given Korea's status as a net energy importer, risk assessment is an important component of energy planning that can lessen the external risks to the country's energy security. Based on the results, we propose electricity generation mixes to guide energy investment toward sustainable development in Korea.

This remainder of this paper is organized as follows. Section 2 describes the method proposed and the data used in this paper. Section 3 presents the results of the least-cost and cost-risk optimization models and Section 4 discusses the findings. Finally, Section 5 presents the conclusions and implications for energy policy.

2. Methods

2.1. Optimization method

Optimization is a process of identifying the best overall solution to a problem (Intrilligator, 2002). Generally, it can be expressed in the form of an objective function that must be optimized and a set of constraints that impose limitations on decision variables. Linear programming is a classical tool and the most popular optimization method whereby the objective function is assumed and the constraints expressed in linear functions. However, practical problems in the real world are typically too complex to be expressed as linear functions, although they may be solved using simulation-

[3] Before the Fukushima nuclear accident, Korea and Japan had very similar energy mixes for electricity generation. However, since the accident in 2011, the Japanese public has been strongly opposed to nuclear energy; as a result, the Japanese government has reviewed its previous energy plan. Accordingly, the Japanese government announced an outline to reduce Japan's nuclear power dependency and replace nuclear power with a combination of renewable and fossil-fuel-generated energy (Hong et al., 2013). Consequently, in Japan, the shares in the mix of electricity generated by nuclear, fossil fuels, and renewables have changed from 29% to 10%, 62% to 78%, and 10% to 13%, respectively, from 2010 to 2011 (Ministry of Trade, Industry, and Energy, 2014).