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Diffusion of renewable energy technologies in South Korea on incorporating their competitive interrelationships

Sung-Yoon Huh [a,1], Chul-Yong Lee [b,*]

[a] Technology Management Economics and Policy Program, College of Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea
[b] Korea Energy Economics Institute (KEEI), 132 Naesonsunhwan-ro, Uiwang-si 437-713, Gyeonggi-do, South Korea

HIGHLIGHTS

- We develop a diffusion model incorporating the competition among renewables.
- A price function and a diffusion model are used in 2-step forecasting procedure.
- The annual demand through 2035 for five renewables in South Korea is forecasted.
- Wind power will maintain the largest market share in the electric power sector.
- The supply of geothermal energy will be larger than that of solar thermal energy.

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ABSTRACT

Renewable energy technologies (RETs) have attracted significant public attention for several reasons, the most important being that they are clean alternative energy sources that help reduce greenhouse gas emissions. To increase the probability that RETs will be successful, it is essential to reduce the uncertainty about its adoption with accurate long-term demand forecasting. This study develops a diffusion model that incorporates the effect of competitive interrelationships among renewable sources to forecast the growth pattern of five RETs: solar photovoltaic, wind power, and fuel cell in the electric power sector, and solar thermal and geothermal energy in the heating sector. The 2-step forecasting procedure is based on the Bayus, (1993. Manage. Sci. 39, 11, 1319–1333) price function and a diffusion model suggested by Hahn et al. (1994. Marketing Sci. 13, 3, 224–247). In an empirical analysis, the model is applied to the South Korean renewable energy market.

1. Introduction

There has been a great deal of experimentation and research regarding renewable energy technologies (RETs) since the first oil crisis in 1973 (Jacobsson and Johnson, 2000). Through the socio-economic changes such as the Kyoto Protocol of 1997, renewable energy sources (RESs) have received global attention because they have been regarded as a solution for oil depletion as well as for climate change. Renewable energy (RE) has also been given much emphasis owing to its potential of being a key industry that can lead national economic growth. RESs accounted for 16.7% of global final energy consumption in 2010. RE capacities showed high annual growth rates during 2006–2011; solar photovoltaic (SPV) power grew at 58%, wind power, 26%, and concentrating solar thermal power, 37% (REN21, 2012).

In general, RE uses lower technology levels and is less price competitive as compared to conventional fossil fuels. It is essential, therefore, to reduce the uncertainty regarding RE adoption, thereby enhancing its market value and success probability. Accurate forecasting of long-term demand for individual RESs takes precedence over other tasks in order to reduce this uncertainty. On establishing the future trend of individual RESs, the technology that would succeed in the market could be identified and, thus, become a strategic target. In addition, policies and strategies suitable to the RESs' life cycle can be designed on the basis of an accurate forecast.

Recently, several studies that forecast future growth patterns of RET have been published. Despite the fact that RE has distinctive features compared to conventional energy sources, in terms of innovation diffusion theory, most existing studies have not considered

* Corresponding author. Tel.: +82 31 420 2289; fax: +82 31 420 2162.
E-mail addresses: hsy1@snu.ac.kr (S.-Y. Huh), cylee@keei.re.kr (C.-Y. Lee).
[1] Tel.: +82 2 880 8386; fax: +82 2 873 7229.

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this issue; many types of RESs available lead to the existence of an innovation interrelationship among the various RESs, and finally, this interrelationship has an effect on the diffusion of individual RESs. As indicated by Mahajan and Peterson (1985), innovations do not exist in isolation, and one innovation in the social system may have an influence – either positive or negative – on the other. In the RE context, energy suppliers consider various factors – such as unit energy price, stability of supply, and geographical constraints – to choose the specific RES that gives them the highest utility. In this selection process, several RE alternatives are compared to one another, and hence, interaction occurs among them. That is, because some RESs such as SPV, wind power, and fuel cell diffuse through mutual competition, a diffusion model considering such competition should be used rather than estimating individual diffusion independently.

This study develops a diffusion model reflecting competition among RESs to forecast the growth pattern of an individual source more accurately. It is assumed that SPV, wind power, and fuel cell technologies compete against one another in electric power sector and that solar thermal and geothermal energy compete against each other in heating sector. The levelized cost of energy (LCOE) is considered to be a key variable that has a major effect on the competition process. The suggested model is composed of two steps. In step 1, the Bayus (1993) price function of individual RESs is estimated, followed by forecasting the LCOE of each source. In step 2, the diffusion model suggested by Hahn et al. (1994) – generally abbreviated as the HPKZ (Hahn, Park, Krishnamurthi, and Zoltners) model – is modified to reflect the competition among RESs. In step 2, the LCOE forecasted in step 1 is inserted into the model as a variable.

The proposed model is applied to the South Korean RE market for an empirical analysis. The current Korean RE market is in its initial stage, making accurate forecasting very meaningful. Besides, the Korean market's RE data are more accessible than that of other countries, thus making it suitable to use and, hence, verify the model.

The remainder of this paper is organized as follows. The next section provides a brief summary of existing RE literature, in which diffusion models were the main tools for analysis: their strengths, weaknesses, and limitations are indicated and the differentiation from our model is suggested. Section 3 introduces the two main estimation models used – the Bayus price function and HPKZ model – and explain the detailed procedure for integrating as well as applying them to RE diffusion forecasting. Section 4 discusses data collection, presents the empirical results, and suggests future diffusion trends along with related interpretations. The last section presents concluding remarks with policy implications, and provides the limitations of our approach as well as directions for future research.

2. Literature review: Applications of diffusion models to renewable energy analysis

In this study, an innovation diffusion model is used to forecast demand for RESs. Innovation diffusion models have been widely used in the field of social sciences to analyze the growth pattern of new technologies/products and to estimate their market potential. They have shown good representations of real market dynamics and their usefulness was proven in several business and academic fields.[2]

[2] Readers interested in an extensive review on the history, mathematical formulation, and applications of innovation diffusion models are advised to refer to existing review papers such as Mahajan et al. (1995), Geroski (2000), and Meade and Islam (2006).

Among the many diffusion models, the seminal Bass (1969) model has been used in diverse field of studies. Although the Bass model shows good data fitness and forecasting accuracy, it has some limitations owing to several underlying assumptions which are established for model parsimony. To overcome its limitations, several extensions have been developed. Typical examples of such extensions are the models considering price as an influence on internal factors (Jain and Rao, 1990; Horsky, 1990; Bass et al., 1994), incorporating competition among technologies into the model (Peterson and Mahajan, 1978; Eliashberg and Jeuland, 1986; Hahn et al., 1994), reflecting the effect of contemporary economic circumstances (Frank, 2004), considering repurchase and multiple purchases (Olson and Choi, 1985; Bayus et al., 1989; Hahn et al., 1994; Danaher et al., 2001), and examining the effect of supply constraints on diffusion patterns (Jain et al., 1991; Ho et al., 2002).

Applications of such diffusion models to RETs are limited, both quantitatively and qualitatively. However, as RESs gained increasing public attention, many studies applied diffusion models to forecast their future growth patterns. Rao and Kishore (2010) reviewed different diffusion models and their applicability to RET diffusion analysis. They classified existing literature into four categories: (i) economies of scale, experience and learning curve approaches to establish cost reductions, (ii) economic analysis of RETs for their viability as compared to the given alternatives, (iii) stakeholders' perspectives, barrier analysis frameworks, and barrier mitigation approaches, and (iv) policy analysis and influences on RET adoption. They concluded that existing diffusion models could be useful tools to analyze diffusion mechanisms as well as to assess the effectiveness of different RET diffusion strategies.

In addition to Rao and Kishore's (2010) classification, research studies related with RET diffusions can be classified into four categories: (i) application of typical epidemic diffusion models to RETs, (ii) identifying factors promoting or impeding RET diffusion by qualitative analysis, including case studies (Jacobsson and Johnson, 2000; Tsoutsos and Stamboulis, 2005; Dinica, 2006; Jacobsson and Lauber, 2006), (iii) forecasting future trends of individual RES by a simulation technique such as an agent-based model (Sopha et al., 2011), and (iv) diffusion studies using other econometric methodologies (Isoard and Soria, 2001; Ibenholt, 2002; Söderholm and Klaassen, 2007; Kumbaroğlu et al., 2008). In this section, we introduce studies belonging to the first of the aforementioned categories, owing to the modeling similarity to our model, and describe our novel contributions as compared to them.

Purohit and Kandpal (2005) analyzed diffusion trends of four RETs (SPV, windmill, biogas, and producer gas-driven dual fuel engine) for irrigation water pumping and presented their future dissemination levels using the Bass, Gompertz, Logistic, and Pearl models. They showed that RET potential is achieved fastest in the case of the Logistic model, whereas the diffusion following the Gompertz model is the slowest; the remaining two models represent an intermediate diffusion trend as compared to the first two. The authors concluded that, in India, the dissemination of RETs for irrigation water pumping would not reach its maximum potential in another 25 years.

Rao and Kishore (2009) investigated growth patterns of wind power technology in several Indian states using the Bass model. The state-level data of cumulative wind power installed capacity is used to rank the diffusion in four states. On the basis of the difference in each state's wind power promotion policies, the composite policy index (CPI) of each state is calculated to prove the existence of a general correlation between CPI and the diffusion parameters. It was found that the diffusion model provides a good basis not only for the study of consumer markets but also for the study of capital intensive equipment such as wind power generators.

Guidolin and Mortarino (2010) examined the effect of institutional intervention that can interact with RESs' diffusion using the Generalized Bass model (GBM). The authors modelled the intervention function of the GBM through two types of shock function: a drastic perturbation was described by an exponential function while a more stable perturbation by a rectangular function. They analyzed adoption patterns of SPV for eleven countries to select a model suitable to each country, among the several Bass variants. As they pointed out, however, their analysis focused only on the domestic SPV markets, without taking into account competitive dynamics with other RESs.

Valle and Furlan (2011), using a similar model as Guidolin and Mortarino (2010), introduced incentive effects as exogenous dynamics in the GBM to explain the lifecycles of wind power in the US and some European countries. External interventions represented by two different shock functions were incorporated into the GBM. With such modified GBM, the authors could identify the policies corresponding to the individual shock and its impact on wind power technology diffusion. They also founded that, among several diffusion models, GBM had the best performance in terms of forecast accuracy.

Harijan et al. (2011) forecasted the market penetration of wind power in Pakistan until about 2050 using the Logistic model and an analogous approach to the experiences in India. Three policy scenarios – standard, moderate, and optimistic – were assumed to forecast the corresponding diffusion trends. They showed that about 42%, 58% and 73% of the country's potential for wind power generation could be exploited by 2030 according to each scenario.

Davies and Diaz-Rainey (2011) analyzed the diffusion of wind energy in 25 OECD countries by testing several propositions related to the Logistic and Bass models. The authors examined the difference between induced diffusion patterns when policy tools or interventions exist and conventional diffusion patterns with no intervention. They showed how the effects of induced diffusion could be modeled through a series of analyses and suggested several policy implications for inducing the diffusion of wind energy. They emphasized that, in more detailed country-specific case studies, it would be desirable to incorporate factors such as the relative factor prices and competing technologies.

In addition to the aforementioned papers, it is necessary to briefly summarize other researches on RET diffusion. Chen et al. (2010) analyzed the technological lifecycle of hydrogen energy and fuel cell technologies by integrating bibliometric and patent analyses into the Logistic model. Purohit and Michaelowa (2007), Purohit (2008), and Purohit (2009) used the Logistic model to estimate clean development mechanism potential of bagasse cogeneration, small hydro power projects, and biomass gasification projects, respectively. Lund (2006) analyzed market penetration rates of eleven different new energy technologies by the internal influence model. All of these articles are good examples of research on RETs using innovation diffusion models, and hence, motivate our research. Table 1 summarizes previous literature on diffusion models for RETs.

Existing studies made certain contributions because they provided policy implications according to estimation results or model improvements. For example, many studies recognized the importance of policy intervention on RET diffusion, and hence, they tried to reflect this effect somehow in their analyses. As indicated in Section 1, however, they overlooked the competitive nature among individual RESs, and thus, did not reflect this unique characteristic in their models. In addition, most studies focused on the diffusion pattern of individual RESs; even if the forecasts covered several RESs, the interrelationships among them were not considered. Thus, the novel contribution of our approach is to consider competition among various RESs with a 2-step methodology that is different from those in existing literature. Detailed model formulation is presented in Section 3.

3. The model

Accurate demand forecasting for a technology is very important not only for finalizing a firm's management strategy but also for drawing up a national policy. In this study, a methodology that forecasts the future demand and growth pattern of RESs is developed on the basis of an innovation diffusion model. Fig. 1 summarizes the two steps of demand forecasting procedures. Step 1 is an estimation of the levelized cost of energy (LCOE) of individual RESs, which is considered as a key factor in their competition. The Bayus (1993) price function is used for the estimation and forecasting of the LCOE of five RESs: SPV, wind power, and fuel cell, which are expected to compete against one another in the electric power sector, and solar thermal and geothermal energy in the heating sector. Step 2 forecasts the growth patterns of five individual RESs with the modified Hahn et al. (1994) diffusion model that uses forecasted LCOEs as a variable. The detailed model formulation of each step is as follows.

3.1. Estimation of individual RESs' price function: An exponential time trend

The price of individual RESs is a key factor among various factors for RESs' diffusion. Although different cost measures are useful in different situations, the LCOE[3] of RETs is a widely used measure by which RETs can be evaluated for modeling or policy development (International Renewable Energy Agency (IRENA), 2012). LCOE can be thought of as the price at which energy must be sold to break even over the lifetime of the technology. It is the fairest comparison between energy supply technologies, which takes into account the lifetime energy production and lifetime costs associated with a system (Darling et al., 2011). Thus, we estimate the LCOE of individual RESs in step 1 as a preliminary work. There are two methods for estimating price trends, among others: estimating the price function, which includes time as an explanatory variable (Bayus, 1993), or considering the learning rate (Bhandari and Stadler, 2009). In this article, we use the former owing to its simplicity and excellent forecasting ability.

In addition to the demand and supply, many factors can affect the prices of new technologies and products including the degree of technological progress, government policy, costs, and distribution structure. However, Bayus (1993) assumed that time t reflects all these factors, and hence, a price trend can be represented by a decreasing function of time, as expressed in Eq. (1). If the price trend of a new technology corresponds with this exponential function, price rigidity in the downward direction can be easily described. Also, this declining price pattern is a good representation of optimal dynamic pricing policies (Bayus, 1993). Owing to these advantages, it has been applied in several studies including on high-tech products (Lee et al., 2006; Cho and Koo, 2012). Hence, we too use the Bayus (1993) price function to estimate the LCOE of individual RESs.

$$p_{jt} = p_{jo} \times \exp(-\phi_j t) + \varepsilon_t, \quad j = 1, 2, 3, 4, 5 \tag{1}$$

In Eq. (1), p_{jt} represents the LCOE of renewables at time t. Both p_{jo} and ϕ_j are parameters to be estimated; p_{jo} stands for initial price of j, and ϕ_j for price trend, which is the degree of price decline. Once the price function is estimated with the past LCOE data of five RESs, future price patterns can also be forecasted. Nonlinear least square (NLS) is used as an estimation technique.

[3] $\mathrm{LCOE} = \frac{\sum_{t=1}^{n} I_t + M_t + F_t/(1+r)^t}{\sum_{t=1}^{n} E_t/(1+r)^t}$ where I_t, M_t, F_t, and E_t are investment expenditures, operations and maintenance expenditures, fuel expenditures and electricity generation in time t, respectively. r and n are discount rate and economic life of the system.

Table 1
Use of innovation diffusion models for RETs.

Author and year	Country/region	Type of RET (REs)	Model used
Purohit and Kandpal (2005)	India	– SPV – Windmill – Biogas driven dual fuel engine – Producer gas driven dual fuel engine	– Bass model – Gompertz model – Logistic model – Pearl model
Rao and Kishore (2009)	India (State level)	Wind power technology	- Mixed influence diffusion model (Bass model)
Guidolin and Mortarino (2010)	Eleven countries including USA, UK, Japan	Photovoltaic installed capacity	– Bass model – Generalized Bass model (GBM)
Valle and Furlan (2011)	US, Europe, and some leading European countries	Wind power technology	- GBM
Harijan et al. (2011)	Pakistan	Wind power	- Logistic model
Davies and Diaz-Rainey (2011)	25 OECD countries	Wind energy	– Bass model – Davies type B (logistic) models

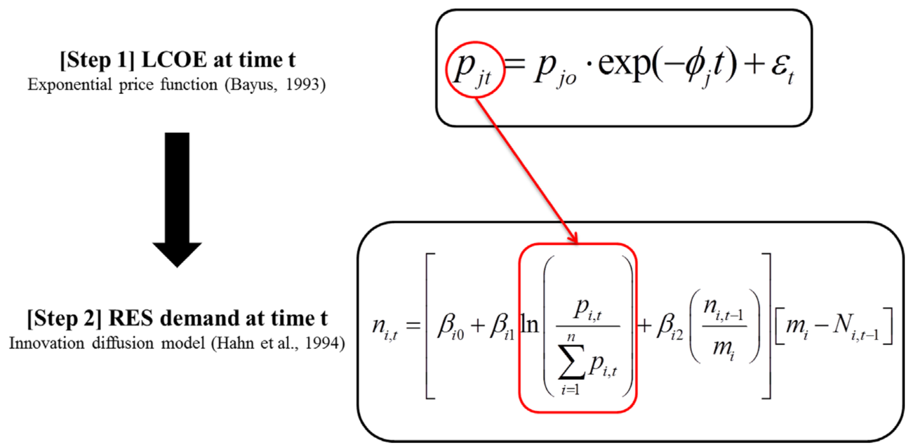

Fig. 1. Methodological framework of demand forecasting.

3.2. *Forecasting demand for individual RESs: Diffusion model incorporating competition*

We describe a demand forecasting model using both the LCOE forecasted in step 1 and the cumulative/noncumulative supply data of individual RESs over time. As RESs such as SPV, wind power, and fuel cell (in electric power sector), and solar thermal and geothermal energy (in heating sector) grow through competition against one another, it is more desirable to establish a diffusion model incorporating such competition than estimating diffusion of individual sources separately. We use the HPKZ model suggested by Hahn et al. (1994). Originally, the HPKZ model was suggested to reflect consumers' repeat purchases of new products in duopolistic markets, and it is a useful tool for analyzing the effect of a firm's launch strategy. In addition, the HPKZ model can represent a competitive situation very well with its simple formulation.[4] In the HPKZ model, the sales of new technology are represented by Eq. (2).

$$n_{i,t} = \alpha_t (m_i - q_{i,t-1}) + \beta_{3,t} q_{i,t-1} \quad (2)$$

In Eq. (2), $n_{i,t}$ represents technology i's sales at time t; m_i is market potential; $q_{i,t-1}$ represents cumulative adopters up to $t-1$. α_t is the trial-rate, that is, the fraction of non-triers in period $t-1$ who try the new product in t. $\beta_{3,t}$ is the repeat rate, that is, the fraction of post-trial buyers who repurchase the new product in t. Thus, Eq. (2) is composed of two parts: the former represents the new purchase of the non-adopters at $t-1$ and the latter represents the repeat purchase of previous adopters at $t-1$. The trial-rate α_t is affected by the competing products' prices as well as word-of-mouth communication from previous purchasers, which is summarized in Eq. (3).

$$\alpha_t = \beta_0 + \beta_1 \ln(x_{i,t} / \textstyle\sum_i x_{i,t}) + \beta_2 (n_{i,t-1}/m_i) \quad (3)$$

here, $x_{i,t}$ represents the marketing effort variable such as price of product i at time t; β_i is a parameter to be estimated. Combining Eqs. (2) and (3), and assuming that the repeat rate is constant ($\beta_{3,t} = \beta_3$) for modeling parsimony, we obtain the following HPKZ model of Eq. (4).

$$n_{i,t} = [\beta_0 + \beta_1 \ln(x_{i,t} / \textstyle\sum_i x_{i,t}) + \beta_2 (n_{i,t-1}/m_i)][m_i - q_{i,t-1}] + \beta_3 q_{i,t-1} \quad (4)$$

The HPKZ model is very suitable to consider the interrelationships among RESs because it emphasizes the competitive aspect in new technology diffusion. As explained earlier, the original HPKZ model considers consumers' repeat purchases in model designing. In case of RET, however, the technology life span is about 20 years, and hence, we modify the original HPKZ model to neglect the repeat purchases effect. For this reason, the last term $\beta_3 q_{i,t-1}$ of Eq. (4) is removed to develop a modified HPKZ model as shown in

[4] The HPKZ model has two forms. One emphasizes the competitive aspect of marketing communication, whereas the other emphasizes its informative nature. In this study, we adopt the competitive aspect of the HPKZ model to our model because it is consistent with our formulation, which reflects the competitive nature of different renewable sources. For more details, see Hahn et al. (1994).

Table 2
Possible utilization of RET in major Korean sectors[a].

Sector	Electric power	Heating	Transportation
Types of RET	**SPV, wind power, fuel cell**, hydropower, ocean energy, bio energy, waste, coal IGCC (solar thermal, geothermal)	**Solar thermal, geothermal,** bio energy, waste	Bio energy (fuel cell)

[a] The word in the parenthesis is an energy source having an unclear prospect of market success or being expected to have very low spread levels in South Korea.

Eq. (5).

$$n_{i,t} = \left[\beta_{i0} + \beta_{i1} \ln\left(\frac{p_{i,t}}{\sum_{i=1}^{n} p_{i,t}}\right) + \beta_{i2}\left(\frac{n_{i,t-1}}{m_i}\right)\right][m_i - N_{i,t-1}] \quad (5)$$

In Eq. (5), $n_{i,t}$, $N_{i,t}$, and $p_{i,t}$ denote new production, cumulative production, and price (LCOE) of ith RESs at time t, respectively. This equation can be understood as an extension of the Bass (1969) diffusion model considering competitive environment; parameter β_{i0} can be understood as an innovation coefficient, whereas β_{i2}, as an imitation coefficient. That is, β_{i0} explains the newly diffused quantity from potential $[m_i - N_{i,t-1}]$ by external influences, while β_{i2} explains the diffusion by the infectious influences of previous supply $n_{i,t-1}$. β_{i1} is a parameter that explains the diffusion by price competition and represents the interrelationship among RESs. The model is estimated using the NLS method.

Table 3
Estimates and standard errors (in brackets) of the Bayus price function for five sources[b].

Sector	Type of REs	p_{jo}	ϕ_j
Electric power	SPV	**774.9**[a] (30.1)	**0.05105**[a] (0.00772)
	Wind power	**109.0**[a] (0.7)	**0.00545**[a] (0.00109)
	Fuel cell	**369.1**[a] (0.0)	**0.01980**[a] (0.00000)
Heating	Solar thermal	**1477.8**[a] (26.0)	**0.01647**[a] (0.00312)
	Geothermal	**2449.9**[a] (39.1)	**0.04825**[a] (0.00314)

[a] Significant at 1% level.
[b] Suggested parameters are estimated with the original Korean won (KRW) data.

4. Results and discussion

4.1. Status of Korean RE market and selection of competing sources

In this section, we demonstrate empirically the suggested diffusion model in the renewables market of South Korea. For this analysis, we examine the RE industry, policy tools, and classification and types of RESs in Korea in order to select the sources expected to have competitive relationships in each of the electric power and heating sectors. From this point of view, we briefly summarize the status of the RE market in Korea and select appropriate sources expected to have competitive relationships.

The Korean government defines New and Renewable Energy as "energy converted from conventional fossil fuel (New Energy) or energy from natural resources including sunlight, water, and terrestrial heat (Renewable Energy)" and adopts eleven types of RET: SPV, solar thermal, wind power, geothermal, hydropower, ocean energy, bioenergy, waste-to-energy, fuel cell, coal integrated gasification combined cycle (IGCC), and hydrogen energy.[5] These eleven types of RES can be utilized in the electric power, heating, and transport sectors in Korea, as summarized in Table 2. As shown, most of the RETs can be utilized in the electric power sector. Solar thermal, geothermal, bioenergy, and waste sources can be utilized in the heating sector, whereas bioenergy and fuel cell can be utilized in the transportation sector. However, in the Korean market, the probability of success in electricity generation from solar thermal and geothermal is unclear, and the spread of vehicles with fuel cell technology is expected to be difficult in the short run.

In the electric power sector, hydropower, ocean energy, and coal IGCC, whose growth is driven by large-scale projects, are generally diffused by the government's long-term planning, and thus, their diffusion is not directly affected by interaction with other sources. In the case of waste energy, most sources have been utilized by the heating sector until now, but the possibility of diverting a considerable amount of such sources to electric power seems to be high, according to the Renewable Portfolio Standard (RPS) implementation in Korea. The supply of waste energy in the electric power sector, therefore, seems to be controlled by the plan of electric power producers; a similar situation exists in the case of bioenergy. In future Korean electric power sector, therefore, only SPV, wind power, and fuel cell are likely to have competitive interrelationships with one another. That is, these three are the only RESs that diffuse spontaneously through competition, not by long-term planning of government. The competitive interrelationships among these three sources also can be inferred from the fact that technologies related to them have similar market shares in RESs' supply (2.60%, 2.45%, and 0.84% in 2011, respectively), as compared to other sources (Korea Energy Management Corporation (KEMCO), 2012).[6]

Selection of competitive RESs in the heating sector is as follows. Because most of the waste energy's potential seems to be saturated in Korea (accounting for 67.54% of total RESs' supply in 2011), it is difficult to apply an ordinary diffusion model to forecast its future growth pattern (Korea Energy Management Corporation (KEMCO), 2012). In addition, bioenergy in the heating sector tends to diffuse autonomously rather than by competing against other sources. Therefore, in the future, the remaining solar thermal and geothermal energy are likely to compete against each other in the heating sector in Korea. Solar thermal and geothermal account for 0.36% and 0.63%, respectively, of total RESs' supply in Korea in 2011 (Korea Energy Management Corporation (KEMCO), 2012). We highlight these five sources expected to have competitive relationships in each sector in bold letters in Table 2.

4.2. Price function estimation and forecasting LCOE of individual RESs

Although the price of RE is still less competitive owing to its higher LCOE as compared to conventional fossil fuel, there has

[5] Under current legislation of South Korea, RET are classified into two categories: One is New Energy and the other is Renewable Energy. The eight types of Renewable Energy include SPV, solar thermal, wind power, geothermal, hydropower, ocean energy, bioenergy, and waste-to-energy while the three types of New Energy include fuel cell, IGCC, and hydrogen energy. For the consistency of the terminologies, in this research, all these eleven sources are expressed as RET and/or RES without classification hereafter.

[6] Other RES has relatively much higher market share (supply) in 2011 of Korea. For example, waste energy, hydropower, and bioenergy accounts for 67.54, 12.73, and 12.70%, respectively (Korea Energy Management Corporation (KEMCO), 2012).

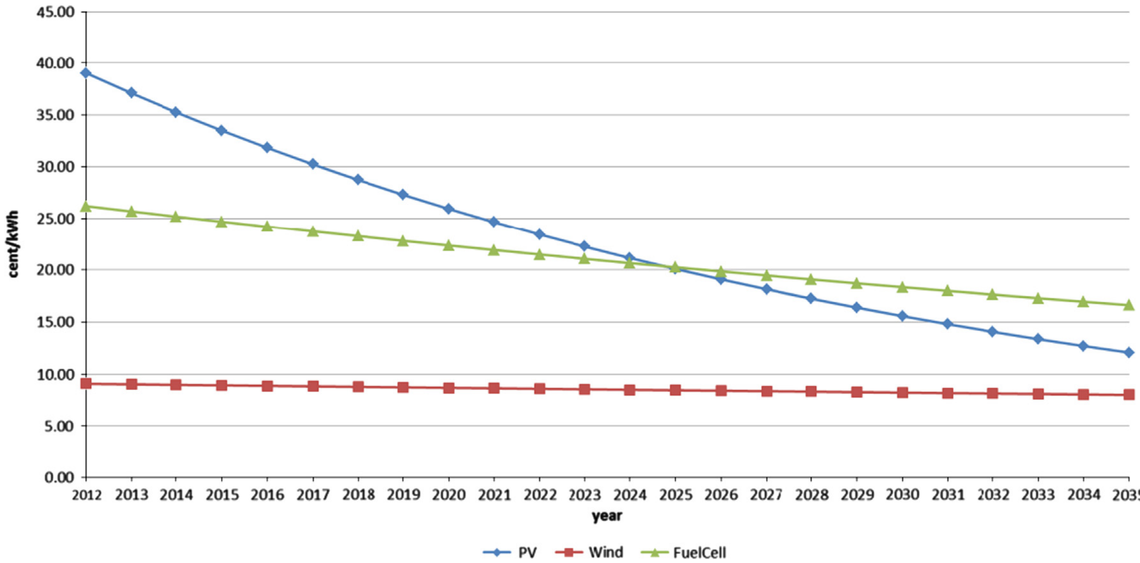

Fig. 2. Forecasting LCOE of individual RESs in the electric power sector.

been a continuous drop in RE prices induced by technological progress and manufacturing facility expansion. As individual RESs have their own characteristics, the rates of decrease in their LCOE are different. Thus, we estimate each source's price function and forecast its LCOE until 2035, according to the estimated parameters.

LCOE data of five RESs, from 2001 to 2011, are obtained from a government-affiliated organization in Korea (New & Renewable Energy Center, KEMCO), which is nominal value. Table 3 summarizes the estimation results of the Bayus price function for the five sources along with the data; both parameter p_{jo} and ϕ_j are represented.

As shown in Table 3, all parameters are significant at the 1% level. p_{jo} denotes the initial price (LCOE) of jth RES and coefficient ϕ_j is the degree to which the price (LCOE) of RES j is decreasing over time. That is, the value of p_{jo} represents the LCOE estimate of RES j in 2011, the first year of our data. The unit of p_{jo} is Korean Won (KRW)/kW h for RESs in the electric power sector and is thousand KRW/TOE for RESs in the heating sector. ϕ_j shows the relative degree of LCOE decrease, so LCOE will drop more rapidly when the absolute value of ϕ_j is higher. A declining price trend over time is observed for all five RESs because ϕ_j is positive. For the electric power sector, SPV has the highest initial LCOE (p_{jo}) followed by fuel cell and wind power, while the decreasing rate (ϕ_j) is high in the order of SPV, fuel cell, and wind power. Therefore, the relative price competitiveness of SPV and fuel cell will be enhanced over time in line with technological developments as well as production facility expansion. For the heating sector, because geothermal has not only a higher initial LCOE but also a higher decreasing rate than solar thermal, price competition between these two sources will intensify.

Coinciding with our expectation from the estimated parameters, in the electric power sector (see Fig. 2), the LCOE of SPV drops most rapidly as compared to the other two sources. Between 2024 and 2025, the LCOE of SPV will reach a lower level than that of fuel cell technology. This rapid drop will be caused by various factors including the government's policy support, expansion of production scale owing to increase in global demand, decrease in the price of related components and material, and development and application of new technology. As a result, the LCOE of fuel cell (16.62 cent/kW h) is forecasted to be the highest in 2035, followed by that of SPV (12.07 cent/kW h) and wind power (8.00 cent/kW h). Further, the gap in the LCOE among these RESs will also reduce significantly. To sum up, as the relative price competitiveness of SPV and fuel cell as compared to wind power improves rapidly, competition among the three sources in the electric power sector will intensify in due course.

Referring to the heating sector (see Fig. 3), it is forecast that the LCOE of geothermal energy would drop more rapidly than that of solar thermal energy. There will be a price reversal between 2016 and 2017, and the ultimate LCOE per tons of oil equivalent (TOE) of solar thermal and geothermal energy is expected to reach 746 USD and 420 USD in 2035, respectively. Geothermal energy has a large amount of reserves though the estimates of potential reserves are different according to the evaluation methods (Fridleifsson, 2001; Bertani, 2003). Geothermal heat also has the advantage over other RESs of being available all day and in all seasons (Hurter and Schellschmidt, 2003). Moreover, shallow geothermal energy has few limitations as regards geographical conditions (Haehnlein et al., 2010). If these advantages and the LCOE decline forecasted by our model have a synergetic effect, then geothermal energy will receive great attention as one of the major RES in Korea.

4.3. Forecasting future diffusion patterns of renewable energy in South Korea

On the basis of the estimated LCOE and HPKZ model, we forecast the demand for five RESs in the electric power and heating sectors by 2035. As described in Section 3.2, the modified HPKZ model is used to estimate parameters β_{i0}, β_{i1}, and β_{i2} of individual sources.

When focusing on the availability of RESs, it is important to define the type of potential that is considered (Hoogwijk and Graus, 2008). Various types of utilization potential of each RES can be used as m_i in Eq. (5): Theoretical, geographical, technical, and market potential.[7] Among them, we use the market potential which is the total amount of RE that can be implementation in the market taking into account the demand for energy, the

[7] The theoretical potential, which is the highest level of potential, only takes into account restrictions with respect to natural and climatic parameters. The geographical potential is the theoretical potential limited by the resources at geographical locations that are suitable. This geographical potential is further reduced due to technical limitations as conversion efficiencies, resulting in the technical potential (Hoogwijk and Graus, 2008). The market potential is explained in the main text.

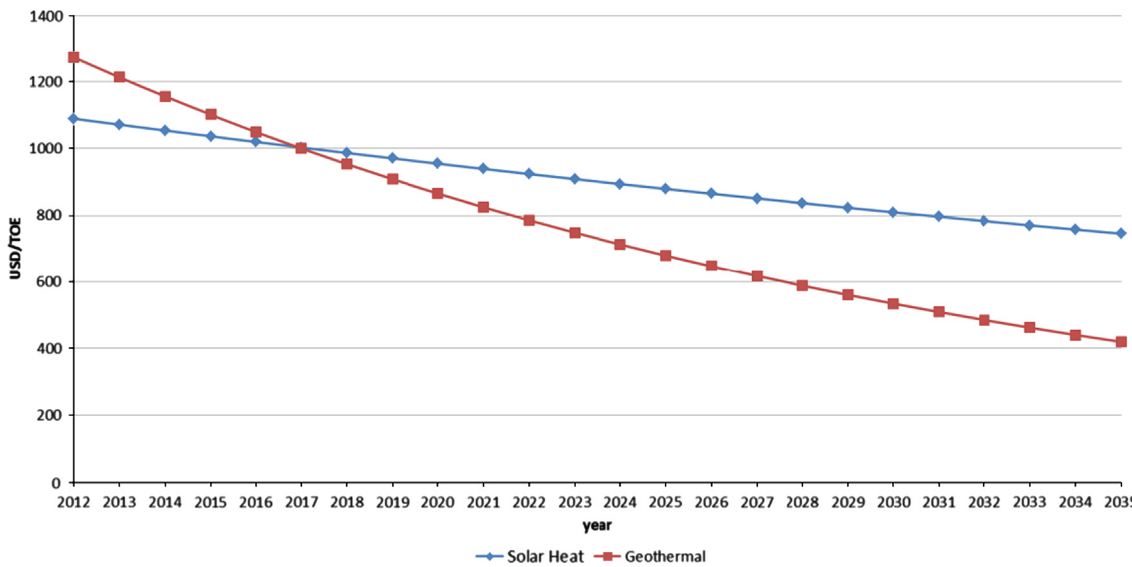

Fig. 3. Forecasting LCOE of individual RESs in the heating sector.

competing technologies, the costs and subsidies of renewable energy sources, and the barriers (Hoogwijk and Graus, 2008). The market potentials of each source in Korea are ascertained as 15 million, 15.3 million, and 12 million TOE for SPV, wind power, and fuel cell, respectively, in the electric power sector and 20.9 million and 27.9 million TOE for solar thermal and geothermal, respectively, in the heating sector (Korea Energy Economics Institute (KEEI), 2008).

The results of diffusion trends in the electric power sector are as follows. The estimates of parameters in the modified HPKZ model are represented in Table 4. Fig. 4 shows cumulative diffusion patterns of SPV, wind power, and fuel cell, on the basis of these estimates. As can be seen in Table 4, all parameters in the case of SPV and fuel cell are statistically significant at the 1% or 10% levels, while β_{i0} and β_{i1} of wind power are not.

As shown in Fig. 4, the supply of wind power will be the largest at all times through 2035 in the electric power sector of Korea. Therefore, wind power will maintain the largest market share in the electric power sector through 2035. This result can be explained by the fundamental characteristics of wind power: it can generate electricity on a relatively large scale, and it has a higher capacity factor than other sources. In addition, this forecasting result is supported by the fact that wind power will maintain the smallest LCOE until 2035, although the absolute gaps of the three sources' LCOE will decrease over time.

In relation to the individual diffusion pattern, however, the supply from SPV and fuel cell will show a steady increase through 2035. Therefore, these two sources are expected to be still at their growth stage in the product life cycle (launch, growth, maturity, and decline). By contrast, wind power will reach its maximum utilization potential relatively earlier and approach its maturity stage. This is confirmed by the declining slope for wind power as shown in Fig. 4, which gets smaller from around 2025 to 2026. This trend may result from the fact that current strong price competitiveness of wind power weakens as the LCOE of SPV and fuel cell drops much more rapidly over time than that of wind power. Through the competitive diffusion model, the ultimate supplies of these three sources in the electric power sector are expected to be about 18 million (SPV), 29.1 million (wind power), and 10.4 million (fuel cell) MW h in 2035.

Demand forecasting results of the heating sector are as follows. The estimates of parameters in the modified HPKZ model and the forecasted diffusion pattern of the two sources through 2035 are represented in Table 5 and Fig. 5, respectively.

Table 4
Estimates and standard errors (in brackets) of the modified HPKZ model: Electric power sector.

REs	Parameter	Estimate
SPV (i=1)	β_{i0}	$-$**0.00448**[a] (0.00218)
	β_{i1}	$-$**0.00946**[a] (0.00432)
	β_{i2}	**0.82485**[b] (0.15345)
Wind power (i=2)	β_{i0}	0.00240 (0.00252)
	β_{i1}	0.00098 (0.00106)
	β_{i2}	**1.24939**[b] (0.04389)
Fuel cell (i=3)	β_{i0}	**0.01455**[b] (0.00518)
	β_{i1}	**0.01168**[b] (0.00433)
	β_{i2}	**0.55908**[b] (0.16830)

[a] Significant at 10% level.
[b] Significant at 1% level.

The supply of geothermal energy is expected to be larger than that of solar thermal energy in all periods through 2035. As confirmed in Section 4.2, geothermal energy will have stronger price competitiveness than solar thermal energy, and hence, it may have continuous superiority over solar thermal. The supply of both sources will grow steadily through 2035, showing stable diffusion patterns. The model forecasts that the ultimate supplies of these two sources in the heating sector will be about 1.63 million (solar thermal) and 3.07 million (geothermal) TOE in 2035. Compared to the electric sector, RESs utilized for heating are currently in more initial stages, and thus, the heating sector is expected to have a wider range of fluctuation in future supply; there seems to be relatively more room for governmental policy intervention to control these RESs' supplies.

In 2008, South Korea announced 'The third basic plan for technology development, application, and deployment of new and renewable energy (2009–2030)' (MKE, 2008) which not only formulated the total RE supply target but also shaped major governmental policies for it. According to this master plan, annual RE supply target was set to be 4.3% of total primary energy consumption in 2015, 6.1% in 2020, and finally 11.0% in 2030 which amount to about 33.03 million TOE. The growth rates of ocean, geothermal, wind power energy were set relatively higher

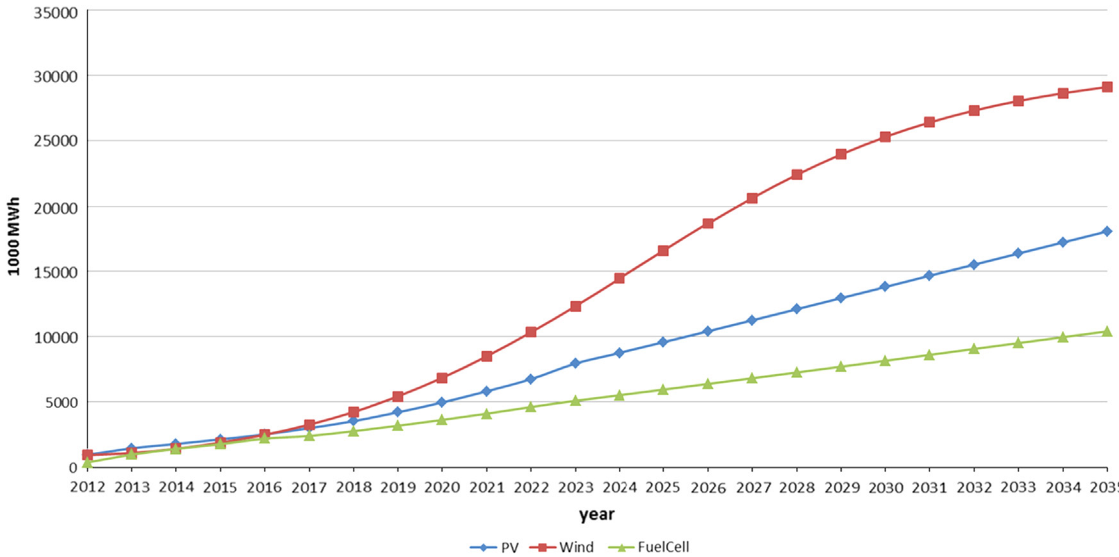

Fig. 4. Diffusion of individual RESs incorporating competition: electric power sector.

Table 5
Estimates and standard errors (in brackets) of modified HPKZ model: Heating sector.

REs	Parameter	Estimate
Solar thermal (i=4)	β_{i0}	**0.00311**[a] (0.00162)
	β_{i1}	**0.00318**[a] (0.00182)
	β_{i2}	**0.66417**[b] (0.16396)
Geothermal (i=5)	β_{i0}	−0.00086 (0.00054)
	β_{i1}	−**0.00181**[a] (0.00104)
	β_{i2}	**0.98591**[b] (0.11199)

[a] Significant at 10% level.
[b] Significant at 1% level.

while those of waste and hydropower which have accounted for major part of renewables in Korea were lower.

The diffusion patterns of five RE sources forecasted by this research can examine whether their future supply target will be met or not, and enables the stakeholders to select relatively more promising sources. Table 6 compares the supply target of each source announced by Korean government with the forecasting results of our model.

As presented in Table 6, all sources except solar thermal energy will be able to meet the 2030 supply target. The achievement rates of RES in the electric sector are forecasted to generally be very high while those of other two in the heating sector will be relatively low. This proves that Korean government has put much emphasis on the electric sector while it has been somewhat indifferent to heating and transport sector when promoting RES. If we compare the 2030 governmental target with the forecasting results by our model, it seems that RE promotion policies of Korean government have been proceeded favorably. On the other hand, however, it also can be presumed that the RE supply target set by Korean government in 2008 was underestimated. Thus, it is recommended for Korean government to set up a more challenging supply target of these five RESs than the target established in 2008.

We also examined the compound annual growth rate (CAGR) of five RESs from 2012 to 2035 (Table 6). The CAGR can show each source's relative rate of market expansion, which is valuable information not only for implementing governmental policies but also for establishing business strategies of RE-related enterprises. Wind power and geothermal energy is expected to have the highest annual growth rate in electric power and heating sector, respectively.

5. Conclusions and policy implications

This study developed a two-step procedure based on the Bayus price function and the HPKZ diffusion model to reflect competition among various RESs. The suggested model was applied to the Korean RE market to forecast annual demand for five sources that are expected to have competitive interrelationships in the electric power and heating sectors. The analysis results forecast that the LCOE of SPV and geothermal energy in each of the electric power and heating sectors will decrease more rapidly than those of the others. The ultimate LCOE of five RESs in 2035 will drop to 16.62 cent/kW h, 12.07 cent/kW h, and 8.00 cent/kW h for fuel cell, SPV, and wind power, respectively, in the electric power sector, and 746 USD/TOE and 420 USD/TOE for solar thermal and geothermal in the heating sector. The ultimate supplies of five RESs in 2035 are forecasted to be about 18 million, 29.1 million, and 10.4 million MW h for SPV, wind power, and fuel cell, respectively, in the electric power sector and 1.63 million and 3.07 million TOE for solar thermal and geothermal, respectively, in the heating sector.

Although South Korea has made various efforts to promote RE through governmental policies since 2008, there have been several limitations. Above all, the total RE share in 2011 was 2.75% of primary energy consumption, which failed to reach the governmental goal of 3.24%. This failure is caused by the excessive increase in primary energy consumption beyond the government's prospect and the delayed introduction of large scale onshore wind farm due to site regulations. Another problem is that the increase in RE supply and related industrial growth are focused only on specific sector. Government has laid much emphasis on the policies for market vitalization of electric sector, such as FIT (Feed in Tariff) and RPS, while the promotion in the heating and transport sector are relatively neglected. Also, major construction projects which are delayed by some inappropriate regulations and strong public oppositions, have to be progressed.

To support the RE diffusion pattern forecasted in this research as well as to overcome aforementioned policy limitations, Korean government is recommended to take strategic actions as follows. First, new policy for the creation of RE market should be

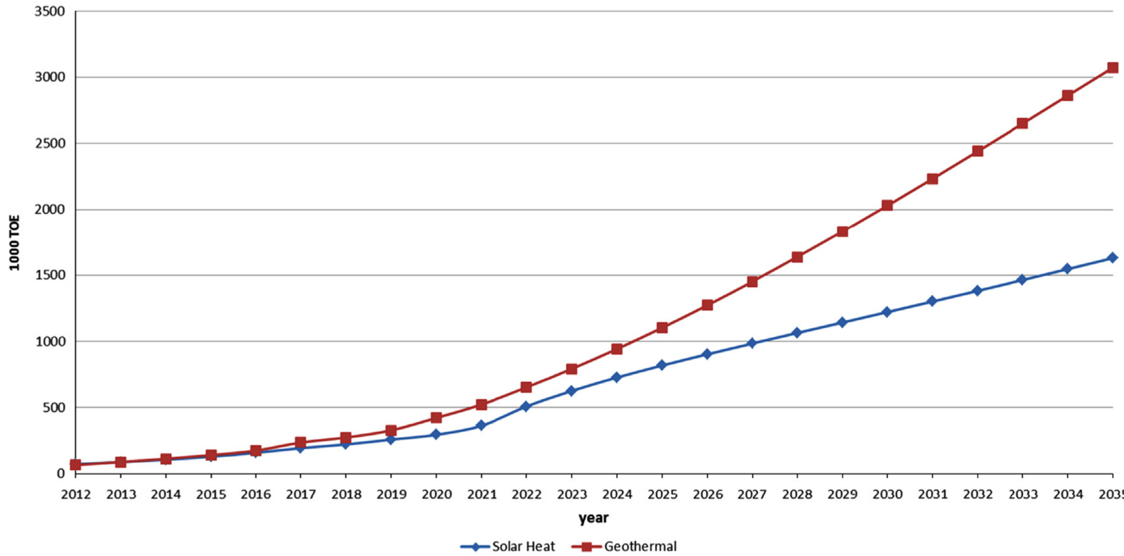

Fig. 5. Diffusion of individual RESs incorporating competition: heating sector.

Table 6
Renewable energy supply: comparison of the governmental target with the forecasts.

Sector	Type of REs	2011 Supply[a]	2030 Target[b]	Forecasts by model		Attainability	CAGR (2012–2035) (%)
				2030	2035		
Electric power (GW h)	SPV	917	**5,457**	**13,799**	18,042	**Positive**	13.5
	Wind power	863	**16,620**	**25,303**	29,122	**Positive**	16
	Fuel cell	295	**2,793**	**8,160**	10,411	**Positive**	15.2
Heating (1000 TOE)	Solar thermal	27	**1,882**	**1,222**	1,630	**Negative**	17.8
	Geothermal	48	**1,261**	**2,031**	3,074	**Positive**	18.7

[a] Korea Energy Economics Institute (KEEI) (2012).
[b] MKE (2008).

continuously introduced. To enforce RHO (Renewable Heat Obligation) and RFS (Renewable Fuel Standard) of which enactments are delayed, should take precedence over the other tasks. RHO and RFS force energy suppliers to supply assigned quota of RE in the heating and the transport sector, respectively. These two policies were originally planned to be enforced from 2016, 2015 respectively, but their implementations are still unclear because there exist severe debates among stakeholders. Especially, the heating sector has much potential for supplying RE because it is responsible for a large share of final energy demand.

Second, the government has to work out a differentiated scheme for each individual source as their diffusion patterns are clearly different. As shown in Section 4.3, even the annual growth stages of individual five sources in this research are different. The government should, therefore, not only try to vitalize overall RE market but also prepare individual strategy for each source. In case of SPV, it is important to preoccupy promising technology that creates high added value as there exist various technological alternatives. For wind power, deregulation of several inappropriate legislations is necessary because site selection and the delayed construction permit have been acted as barriers to diffusion. The importance of permitting procedure for wind power development was highlighted in several researches (Söderholm et al., 2007; Dinica, 2008; Han et al., 2009; Pettersson et al., 2010). European Wind Energy Association (EWEA) (2009) also suggested that both the clear process for registration and the planning/construction consents are key elements for site approval of wind power. Nevertheless, in Korea, a new wind power project should be approved by several different bills, which made the application for wind power projects very complex and time consuming (Greendaily, 2013). The supply chain centering around the manufacturers should be completed for fuel cell while providing higher technological reliability and securing the larger market to induce private investments are urgent for solar thermal energy. Lastly, in case of geothermal energy, detailed incentive program should be designed to compensate high initial investment costs by private enterprises.

The limitations of this study and future research directions are as follows. Above all, this study did not consider policy interventions that can affect the supply of RESs, because it emphasized the suggestion of conceptual methodology and modeling parsimony. However, government policy strongly affects renewables' diffusion. It is recommended, therefore, to forecast the demand according to a future environment by assuming several policy scenarios, as suggested in Harijan et al. (2011). In addition, in relation to the competitive factor, the suggested diffusion model considered only the LCOE as a key variable. If other factors that can affect the competition among RESs are incorporated into the model, more varied policy implications could be suggested.

Despite these limitations, this study contributes to the existing literature by suggesting a model that incorporates interrelationships among RESs, especially their competitive relationships; to the best of our knowledge, it is the first competitive diffusion model that applies to RET forecasting. This model is also a general method that can be utilized for forecasting RESs' diffusion patterns for individual countries. Therefore, after some modifications and by considering the appropriate factors of a target market, such as the classification system and policies of RESs, the suggested model can be applied to countries other than Korea. Thus, the more accurate the future RET diffusion pattern we obtain, the more appropriate will be the government policies and firms' strategies established.

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