Generation Expansion Planning Model Supporting Diverse Environmental Policies for Reduction of Greenhouse Gases

Jeong-In Lee, Il-Woo Lee, and Bal-Ho Kim

The purpose of this paper is to a develop model for generation expansion planning that can support diverse environmental policies for the reduction of greenhouse gases (GHGs) of South Korea. South Korea is required to reduce its GHG emissions by 30% from the BAU level by 2020. The Wien Automatic System Planning Package currently used in South Korea has limitations in terms of the application of renewable energy policies and GHG targets; this paper proposes the use of an equipment planning model named generation and transmission expansion program , which has been developed to resolve such limitations. For verification of the model, a case study on the 6th Basic Plan of Long-Term Electricity Supply and Demand has been conducted. The results show that for the year 2020 South Korea's annual GHG emissions will be 36.6% more than the GHG Target Management System (GHG TMS) target set for the same year (30%). To achieve the GHG TMS target, the costs involved amount to about 72 trillion KRW (70 billion USD). Consequently, the South Korean government needs to review the performability of this target.

Keywords: Generation expansion planning, renewable energy, greenhouse gas emission, environmental policies.

Manuscript received Aug. 10, 2014; accepted Feb. 11, 2015.

This work was supported by the Electronics and Telecommunications Research Institute (ETRI) grant funded by the Korea government (15ZC1600, Development of key technologies for energy sharing networking to realize the zero energy community).

Jeong-In Lee (corresponding author, jilee@etri.re.kr) and Il-Woo Lee (ilwoo@etri.re.kr) are with the IT Convergence Technology Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Bal-Ho Kim (bhkim@wow.hongik.ac.kr) is with the Department of Electronic and Electrical Engineering, Hongik University, Seoul, Rep. of Korea.

I. Introduction

The increase of greenhouse gases (GHGs) due to human activities has led to serious environmental challenges across the world. In response to such challenges, many various efforts for reducing GHG emissions have been exerted on a global scale in accordance with the Climate Change Convention and the Kyoto Protocol. With the continuing trends of rising energy demands from emerging markets (fossil fuel–oriented energy consumption) and the growing world economy, the most powerful solution to global warming is to reduce our dependency on fossil fuels.

South Korea has been endeavoring to address issues related to global warming and energy crises. Following the government announcement of a national vision of low-carbon green growth in 2008, the Committee on Green Growth was launched in February 2009, and the Framework Act on Low Carbon, Green Growth came into force on April 14, 2010 in South Korea [1]. The Framework Act on Low Carbon, Green Growth sets out a target of reducing South Korea's GHG emissions by 30% from the business-as-usual (BAU) level by 2020. Furthermore, the Renewable Portfolio Standard (RPS) has been implemented since 2012, and the government's Emissions Trading Scheme (ETS), which is modelled on the European Union Emissions Trading System, is set to be adopted in 2015.

Around 80% of South Korea's total GHG emissions are caused by the energy industry, of which 37% is from the power generation sector [2]. The South Korean government initially planned to expand nuclear power plants to achieve its GHG

Target Management System (GHG TMS) target [3]. Recently, however, the 6th Basic Plan of Long-Term Electricity Supply and Demand (6th BPE) [4], which is prepared and announced biennially by the Minister of Knowledge Economy, outlines plans for increasing the use of liquefied natural gas (LNG) and renewable energy sources while substantially reducing the capacity of nuclear power facilities, taking note of growing resistance to nuclear energy among the public in the aftermath of the nuclear accident in Fukushima in Japan and nuclear power plant failures in South Korea. However, with the continuing rise in GHG emissions in South Korea, the plan for reducing the capacity of nuclear power facilities should be reconsidered carefully. Determining an appropriate mix of various generation sources is critical to industrial development and efficiency enhancement from a long-term point of view.

The computation model currently used for the establishment of generation expansion planning (GEP) in South Korea is Wien Automatic System Planning Package (WASP) [5], where the minimization of cost is used as an objective function and the probabilistic production simulation (PPS) is applied for calculation of the operational cost of the combinations of candidate facilities by year [6]. Also, in this model, a load duration curve (LDC) used. An LDC is arrangement of all hourly load data in a descending order of magnitude regardless of chronological sequence. It can be used to determine how the mix of available power plants, operating at minimum cost, should be used to meet the load. Since solar photovoltaic power plants generate electric energy only during the day and wind power plants generate electric energy based on the variation features of wind, these RE power plants have higher operating costs compared to others. Hence, there is a limit to how far one can accurately calculate the minimum hourly operation costs of all power plants. The cost of carbon emissions is considered in the WASP-IV model, which is the latest version, but this model still requires further improvement [7] and causes difficulties in reflecting environmental policies such as the carbon emission allowance system [8]–[9].

This paper proposes the equipment planning model generation and transmission expansion program (GATE-PRO), which has been developed for application to diverse energy policies under the GHG TMS reduction target and for accurate calculation of operational costs [10]. GATE-PRO offers various advantages, such as the ability to change the objective function either to cost minimization from a national perspective or to profit maximization from a utility perspective [11]; the hourly operation costs of all types of power plants; more accurate simulation than WASP by applying linear programming (LP) to the calculation of the cost for operation and environmental policy implementation; addition of constraint conditions; and so on. Based on this model, this paper reviews the necessity for expanding nuclear power facilities from a national perspective and analyzes an optimal generation mix for 2027 by assuming various environmental policy scenarios. In addition, the impact of GHG TMS on the generation mix is analyzed along with the associated costs involved.

II. GEP Model for National Energy Policy

1. Overview of GEP

GEP is traditionally perceived as the determination of the minimum-cost capacity addition plan that meets forecasted demand within a pre-specified reliability criterion over a planning horizon (typically 20 years) [12]. Electric utility companies consider GEP to be one of the most important factors when considering whether to construct a new power plant [13]–[14]. GEP is the problem of finding the optimal strategy to plan the construction of new generation plants while satisfying technical and economic constraints [15]. Solving an optimal GEP problem is equivalent to finding a set of optimal decision vectors that minimize an objective function under several constraints. The installation of generation facilities based on accurate prediction of electricity demand is critical [16], as was illustrated by the large-scale rolling blackouts that took place due to the failure of demand prediction in South Korea in 2011. As such, GEP is considered to be one of the most important policy issues in the country.

The following are examples of computation models used for the optimization of GEP: WASP, model of national investment (MNI), electric generation expansion analysis system (EGEAS), dynamic programming (DP), optimal control theory, and generalized Benders decomposition method [17]. The computation model used in the 1980 GEP plan of South Korea was WASP-II. WASP is designed to find the economically optimal GEP within constrains given by the planner. The result of WASP is an output that illustrates the number of power plants, by type, required to be built over the plan period and has the advantage of field application in power systems [18]. However, in spite of the fact that WASP has many advantages, it also has some disadvantages.

First, to reflect the energy policies of South Korea, it should be possible to add related constraints to the model and to calculate the resulting associated costs. WASP is capable of reflecting renewable energy policies such as GHG TMS and ETS in its computations [19]–[26]. However, WASP is not capable of considering RPS due to the intermittent nature of RE sources and high RE power plants investment costs that are economically infeasible.

http://dx.doi.org/10.4218/etrij.15.2314.0059

Second, WASP uses PPS for calculation of the operational cost of the combinations of candidate facilities by year and applies LDC expressed as a fifth-order polynomial for load, not hourly load data. In more detail, LDC is used to work out the generation amount and fuel cost by power source and to predict probabilistic fail stop by power source, reducing the use of PPS for calculation [27]. WASP supports a fast calculation convergence rate, but its reliability for operational cost evaluation tends to decrease with time due to errors [28]–[29]. Therefore, a new approach based on a model for GEP is required to overcome the limitations of WASP. This paper proposes GATE-PRO to reflect various energy policies in GEP through a mathematical formulation.

2. Development of GATE-PRO

The improvement of the computation speed of central processing units has helped to solve the problem of slow convergence speed of previous mathematical programming. Therefore, this paper adopts LP, which was previously not considered as a mathematical programming approach for an operation cost simulation due to its slow convergence speed. GATE-PRO has been adopted due to its advantages, such as the processing of chronological loads and easy addition of various constraint conditions.

Figure 1 shows an outline of GATE-PRO. Unlike the existing models, GATE-PRO is capable of reflecting diverse factors such as electricity market information, the investment plans of utility owners, and environmental policies. When GATE-PRO is applied, it is possible to use economic dispatch (ED), which distributes the output of a power plant in a way that minimizes the total fuel cost and transmission loss by properly responding to electricity demand. GATE-PRO has the flexibility to change its own software processes and can handle a wider range of policies, which is a significant improvement over previous models. Furthermore, GATE-PRO offers a more accurate calculation of operational costs by using hourly load data, thereby making it possible to consider a diverse range of load patterns in terms of season, day, time, area, and so on.

When GATE-PRO is used to calculate GEP, the total capacity of all types of power plants (that is, those that already exist and those that are due to be built) in a given year can be calculated; this is not possible in the case of WASP because RE sources are not considered. Since the operational costs of facilities differ depending on which operation method is applied, the minimum operational costs for the given facilities should be computed for each year.

Figure 2 shows a computation model of GATE-PRO. As shown in Fig. 2(a), the computation model consists of four modules excluding input/output data. The four modules are

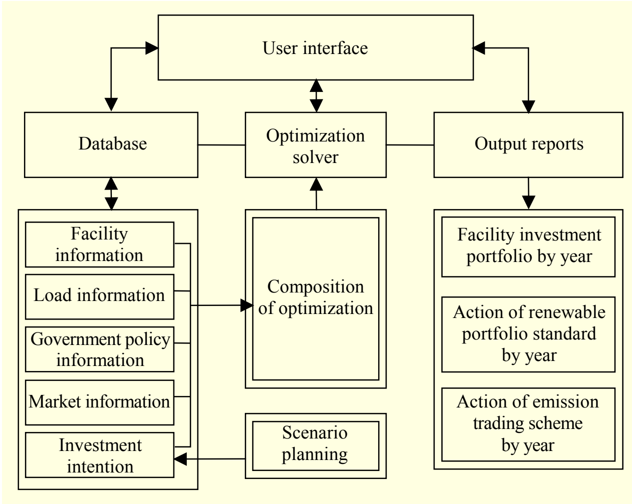

Fig. 1. Outline of GATE-PRO.

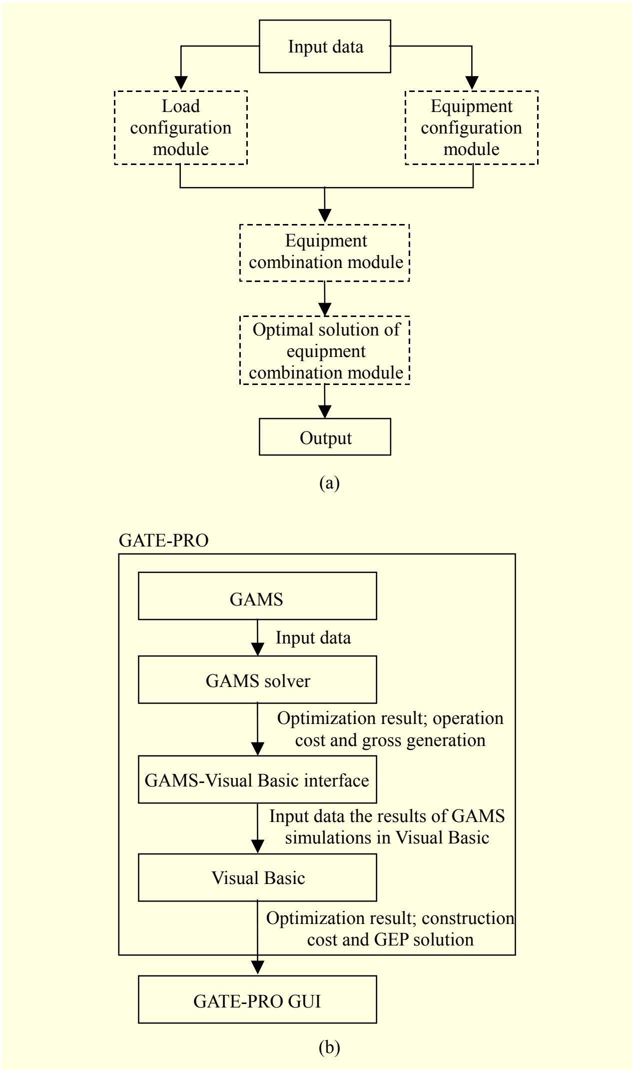

Fig. 2. GATE-PRO: (a) architecture of GATE-PRO and (b) GATE-PRO simulation tool.

operated independently from each other, but each module produces its own execution result file, which is then offered to the other modules as input for consistent performance between them.

As shown in Fig. 2(b), GATE-PRO is designed to calculate GEP using software tools such as General Algebraic Modeling System (GAMS) and Visual Basic. GAMS has the flexibility of implementing a wide variety of optimization problems, such as LP and nonlinear programming applications. However, GAMS has some problems applying DP. Visual Basic is made available to DP and uses the calculated total annual operation costs of all power plants for a given year in the plan period to estimate the total construction cost of all power plants to be built in the following year. GATE-PRO has an interface for GAMS and Visual Basic.

GATE-PRO has a similar configuration to WASP, but it differs from WASP in that it is equipped with an optimization model and an equipment configuration module, as shown in Fig. 2(a). Constraint conditions according to different environmental conditions can be formulated and input into the equipment configuration module, and objective functions can be modified in the optimization model depending on the user of the model (government or utility owner).

Referring to Fig. 2(a), the load configuration module is used to predict the maximum demand and generation capacity during a target period of the future. For the prediction of hourly gross generation for a given time, (1) is used, where the hourly generation information and maximum demand of a certain year before the plan period are compared to obtain the ratio

$$C_{\mathrm{ft}}^{\mathrm{gen.h}} = \frac{D_t^{\mathrm{avg.h}}}{D_t^{\max}} \times D_{\mathrm{ft}}^{\max}, \tag{1}$$

where $C_{\mathrm{ft}}^{\mathrm{gen.h}}$ is the predicted hourly gross generation capacity of the nation's energy sources in a given future year (ft) (MWh), $D_t^{\mathrm{avg.h}}$ is the nation's average hourly demand for electric energy in year t — a given year before the beginning of the plan period (MWh), $D_t^{\max}$ is the maximum demand value for electric energy in year t — a given year before the beginning of the plan period (MWh), and $D_{\mathrm{ft}}^{\max}$ is the predicted maximum demand value for electric energy in year ft (MWh).

The equipment configuration module produces data concerning information on the existing power plants during the initial stage of the plan period and input data for a candidate generator. The load and equipment configuration modules classify power plants based on generation type and input data — such as generation capacity; number of facilities; fuel cost; maintenance and operation cost; utilization rate; CO_2 emission coefficient; and so on — into the equipment combination module. The equipment combination module divides the plan period into several stages (unit of stage: year). Each stage can be divided into different states depending on the number of power plant combinations that can be constructed for each year of a stage. For each state, a generator operation simulation is performed. The power plant combination means the possible configurations of power sources of the future, and a given combination of power plants is defined as an "expansion state." The upper limit (maximum number of power plants by power source) and lower limit (minimum number of power plants by power source) of a combination can be set, and the range is called a *tunnel*.

The optimal solution of the equipment combination module exists within the designated equipment combinations. By applying scenarios for responding to environmental policies by power plant combinations, calculations can be made for operational cost, RPS target, GHG emissions, emissions permit trading volume, emission permit trading cost, and so on. While WASP uses LDC to calculate loss-of-load probability, GATE-PRO uses the reserve margin of 6th BPE for the supply reliability calculation. The optimization module develops a plan to minimize the sum of the operational cost and investment cost for each year by using the result values of the equipment combination module as input.

3. Objective Function of GATE-PRO

Mathematically, solving an optimal GEP problem is equivalent to finding a set of optimal decision vectors that minimize an objective function under several constraints. An objective function for minimizing total costs during a plan period is presented in (2). The function includes the computations for generation costs, ETS implementation costs, and construction costs.

$$\mathrm{Min} \sum \left(C^{\mathrm{G}} + C^{\mathrm{ETS}} + C^{\mathrm{C}} \right), \tag{2}$$

where C^{G} is the generation cost of all power plants in a given year of the plan period, y (\$), C^{ETS} is the total ETS implementation cost for the plan period (\$), C^{C} is the total construction cost of all power plants constructed for the plan period (\$).

As shown in (3) below, the generation costs by year can be calculated by deducting the costs of fuel and maintenance and operation from the generation cost.

$$\begin{aligned} C^G = & \sum_F \sum_y \sum_t [X_{F,y,t} \times C_F] \\ & + \sum_y [(I_{\mathrm{Cap\_}F} + (\mathrm{Add}_{F,y} \times \mathrm{PU}_F)) \times \mathrm{OM}_F] \\ & + \sum_y [(I_{\mathrm{Cap\_}R} + (\mathrm{Add}_{R,y} \times \mathrm{PU}_R)) \times \mathrm{OM}_R] \\ & + \sum_y [(I_{\mathrm{Cap\_}S} + (\mathrm{Add}_{S,y} \times \mathrm{PU}_S)) \times \mathrm{OM}_S], \end{aligned} \tag{3}$$

where, F is a type of fuel for power generation (excluding RE sources and solar photovoltaic), t a given time instance in the plan period, R is a type of renewable energy source (excluding photovoltaic renewable energy), S is a type of solar photovoltaic power plant, $X_{F,y,t}$ is the total accumulated amount of electric energy produced from power plants belonging to fuel type F during the plan period in year y at time t, C_F is the operating cost (fuel cost) of power plants belonging to fuel type F (\$/MWh), I_{Cap} is the total capacity of the currently installed power plants (MW), Add is the number of additional new power plants to be built, PU is per unit of capacity, and OM is the cost of operation and maintenance (\$/MW).

As shown in (4) below, the total ETS implementation cost for the plan period from the annual trading volume of emissions permits is

$$C^{\text{ETS}} = \sum_{y} (\text{TCER}_y \times \text{CER}_{\text{P}_y}), \quad (4)$$

where TCER_y is the total amount of trading certified emissions reduction for the plan period (tCO_2) and CER_{P_y} is the price of certified emissions reduction for the plan period (\$/tCO_2).

The calculation of the construction costs by year is made based on the unit construction cost of each facility, determined by (5) below where K is the construction cost of each power plant (\$/MW).

$$C^{\text{C}} = \sum_{y} [\sum_{F} (K_F \times \text{Add}_{F,y} \times \text{PU}_F) + \sum_{R} (K_R \times \text{Add}_{R,y} \times \text{PU}_R) + \sum_{S} (K_S \times \text{Add}_{S,y} \times \text{PU}_S)]. \quad (5)$$

4. Constraints of GATE-PRO

GATE-PRO computes an optimal solution for minimizing an objective function under diverse constraint conditions. The constraint conditions applied in the model include the following: the balance between supply and demand of electricity by year and by hour; carbon emission allowance assigned to the generation sector: expansion of new generation facilities by facility type; facility characteristics, and so on. The constraint condition for the balance between supply and demand of electricity is that the gross generation of facilities should be greater than or equal to the sum of hourly electricity demand and installed reserve for a target year, as shown in (6) below. In (6), $D_{y,t}$ is the hourly electricity demand (MWh) and $R_{y,t}$ is the hourly reserve capacity of power plants (MWh).

$$\sum_{F} X_{F,y,t} + \sum_{R} X_{R,y,t} + \sum_{S} X_{S,y,t} \geq D_{y,t} + R_{y,t}. \quad (6)$$

The hourly generations of thermal power facilities are always positive numbers due to the consideration for GHG emissions; thus, we have

$$0 \leq X_{F,y,t} \leq \text{I}_{\text{Cap\_}F} + (\text{Add}_{F,t} \times \text{PU}_F). \quad (7)$$

As shown below in (8), the value gained by applying a capacity factor to the sum of the installed capacities of the existing renewable energy facilities and those to be installed in the future should be greater than or equal to the gross generation of renewable energies (excluding solar energy). In (8) below, CF is such a capacity factor for power plants.

$$X_{R,y,t} \leq (I_{\text{Cap\_}R} + \text{Add}_{R,t} \times \text{PU}_R) \times \text{CF}_R. \quad (8)$$

The constraint condition in (9) is that the generation capacity of all solar power plants in South Korea should be greater than or equal to the amount of generated solar energy.

$$X_{S,y,t} \leq (I_{\text{Cap\_}S} + \text{Add}_{S,t} \times \text{PU}_S) \times \text{CF}_S. \quad (9)$$

The constraint on GHG emissions by year, in (10), is that the trading volume of emissions permits is set to be the difference between the total amount of GHG emissions for a given year and the GHG allowances for the same year. When the trading volume is a positive number, it means that the purchase of emissions permits has been made since the amount of actual GHG emissions exceeded the GHG allowances. A negative number for the trading volume indicates the opposite case. In (10), $\text{ET}_y^{\text{Emission}}$ is the total GHG emissions amount for the plan period (tCO_2), EA_y is the emissions allowance during the plan period (tCO_2).

$$\text{ET}_y^{\text{Emission}} = \text{EA}_y + \text{TCER}_y. \quad (10)$$

As shown in (11), the total annual amount of GHG emissions is calculated by multiplying the annual amount of power generation by the GHG emission coefficient, where Coef is the emission coefficient type of all power plants (tCO_2/MWh).

$$\text{ET}_y^{\text{Emission}} = \sum_{F} \sum_{y} \sum_{t} X_{F,y,t} \times \text{Coef}. \quad (11)$$

III. Case Study for GEP

1. Key Factors for GEP Scenario

To develop a rational alternative national plan capable of satisfying the optimum target of GHG reduction, diverse scenarios have been considered and analyzed in this paper. Table 1 shows some major factors and their variable characteristics to be considered in the proposed scenarios, which are required to analyze their effects on GEP. The proposed scenarios are based on the fact that the 6th BPE will continue to be published periodically as the principal energy policy in South Korea.

The 6th BPE holds information on the current status of the

Table 1. List of considerations.

Energy policy	Assumption and baseline
Nuclear	· 6th basic plan for long-term electricity supply and demand plan (6th BPE) · Disuse of nuclear power plants after their lifespan (disuse) · Stoppage of nuclear power plants currently in operation (stoppage)
Renewable energy (RE)	· Renewable Portfolio Standard (RPS)
GHG reduction	· GHG Target Management System (TMS) · Emissions trading between countries (ETS)

generation mix outlook and constraints applied to power plants. For example, in the 5th BPE, it was stated that from 2007 onwards further constructions of pumped storage power plants (PSPPs) is prohibited. The 6th BPE continues to uphold this constraint because of the limiting nature of South Korea's geography. Therefore, scenarios assume no additional construction of such power plants in GEP simulations when using the input data from the 6th BPE.

The South Korean government has been driving the national energy policy based on a consideration of energy security and the need to minimize dependency on current imports of energy resources. Nuclear power has become a major energy source for South Korea. The first nuclear power plant in South Korea, Kori 1, began commercial operation in 1978 and is due to be decommissioned in 2017. Like Kori 1, nuclear power plants have limited lifespans and require regular maintenance throughout their lifetime (stoppage times). Therefore, in the case of nuclear energy, disuse after fulfillment of lifespan and stoppage times is to be considered in the proposed scenarios.

RPS sets an obligatory amount to be supplied by RE sources on generator business companies in South Korea; additionally, an obligatory supply ratio for each supplier is imposed in a separate obligation. In this paper, in the case of the RE scenario, GATE-PRO considers the total amount of energy generated from RE sources for a given year of the plan period. To achieve the GHG TMS reduction target and promote mitigation capabilities, GHG TMS is adopted, and ETS is scheduled to begin in 2015. To achieve the GHG TMS reduction target, this paper predicts a change in GHG emissions targets from power generation, as shown in Table 3.

Currently the South Korean government is considering the use of shale gas to help reduce its annual GHG emissions. Our model predicts for the course of the plan period that the price of shale gas will remain cheaper than that of any renewable energy source but higher than that of coal. Thus, our model shows that shale gas can be taken seriously by the South

Table 2. Baseline scenarios.

Classification	Nuclear	RE	GHG TMS	ETS	Note
Scenario 1	6th BPE	RPS	Not	Not	Current state
Scenario 2	6th BPE	RPS	Achieved	Achieved	—
Scenario 3	6th BPE	RPS	Achieved	Not	—

Table 3. Changes in GHG TMS emission allowances scenarios.

Classification	Nuclear	RE	GHG TMS	ETS	Note
Scenario 3	6th BPE	RPS	Achieved	Not	BAU 30%
Scenario 4	6th BPE	RPS	Achieved	Not	BAU 20%
Scenario 5	6th BPE	RPS	Achieved	Not	BAU 10%

Table 4. LNG price change scenarios.

Classification	Nuclear	RE	GHG TMS	ETS	Note
Scenario 3	6th BPE	RPS	Achieved	Not	—
Scenario 6	6th BPE	RPS	Achieved	Not	LNG[1)] 10%
Scenario 7	6th BPE	RPS	Achieved	Not	LNG[1)] 30%
Scenario 8	6th BPE	RPS	Achieved	Not	LNG[1)] 50%

1) LNG price marked down

Table 5. Scenarios based on nuclear policies.

Classification	Nuclear	RE	GHG TMS	ETS	Note
Scenario 1	6th BPE	RPS	Not	Not	—
Scenario 9	Disuse	RPS	Not	Not	—
Scenario 10	Stoppage	RPS	Not	Not	—

Korean government as a viable RE source.

2. Scenarios for Analyzing Effects of Key Factors on GEP

Table 2 shows various scenarios designed to test whether the GHG TMS under current government policy is achievable or not. In addition, simulations have been performed to estimate the additional costs related to GHG TMS and emissions trading between countries. Scenario 1 is a BAU scenario based on the 6th BPE and does not consider a GHG reduction or RE policy. Scenario 2 is based on the 6th BPE, RE, and GHG reduction polices.

Table 3 shows various scenarios designed to review the performability of the emissions reduction target of South Korea (that is, an emissions reduction of 30% from the BAU level by 2020). The nation's annual carbon emissions have been rising steadily due to increasing energy demand. Scenarios 3 to 6 predict a change in the GHG TMS reduction target from 30% to 10%.

Given that shale gas is now hailed as an alternative energy source to LNG, various scenarios (see Table 4) are designed to reflect the effects of potential changes in LNG prices. Such changes are likely to occur as a result of an advancement of shale gas technologies and the subsequent enhancement of its price competitiveness. The LNG price scenario considered here predicts a 10% to 50% fall in the price of LNG by 2027. Table 5 shows various scenarios that are based on nuclear policies.

IV. Results and Discussion

1. Result of Implementing GHG TMS and ETS Policies

A simulation has been conducted based on Table 2. Table 6 shows the result of implementing GHG TMS and ETS policies by scenario for the plan period 2012–2027. Figures 3 through 5 show the GHG emissions by year of each of the scenarios featured in Table 2.

If the current 6th BPE is followed, then South Korea's annual volume of carbon emissions is expected to be 36.6% over the GHG TMS target in 2027 (scenario 1); therefore, achievement of this target is unlikely. If GHG TMS is implemented at the beginning of the plan period and electricity demand is met throughout the duration of this period (scenario 3), then the total accumulated cost of all energy sources will amount to about 419 trillion KRW (408 billion USD). This means there will be an additional cost of about 72 trillion KRW (70 billion USD) for implementation of GHG TMS compared to scenario 1. Meanwhile, the cost required when the GHG TMS and cross-border emissions trading (scenario 2) are permitted is smaller than the cost when the cross-border emissions trading alone is not permitted (scenario 3). For instance, the price of carbon emissions permits has fallen to an all-time low in the European permit market. Thus, from a national perspective, it is advantageous to buy emissions permits from this market rather than seek capacity expansion. Therefore, it is necessary for the government to make efforts to secure emissions allowances.

2. Result of Changing GHG TMS Reduction Target

Table 7 shows the changes in the total accumulated costs for scenario 3 assuming that the reduction target of 26.7% assigned to the generation sector is fulfilled by reducing the national greenhouse reduction target to 20% (scenario 4) and 10% (scenario 5) based on scenario 3, respectively.

Figures 6 through 8 show the generation composition during the plan period and indicate that nuclear power and LNG

Table 6. Total accumulated costs of power plants for the plan period 2012–2027; unit: trillion KRW (billion USD).

Classification	Total cost	Construction cost	Generation cost	Emissions trading cost	Rate of change (%)
Scenario 1	346.986 (338)	106.857 (104)	240.129 (233)	—	—
Scenario 2	351.907 (342)	106.857 (104)	240.129 (233)	4.921 (4)	1.42
Scenario 3	419.365 (408)	114.433 (111)	304.932 (297)	—	20.86

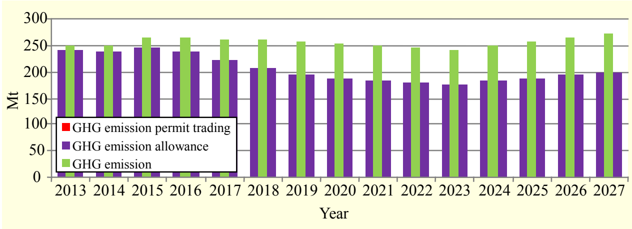

Fig. 3. GHG emissions by year (scenario 1).

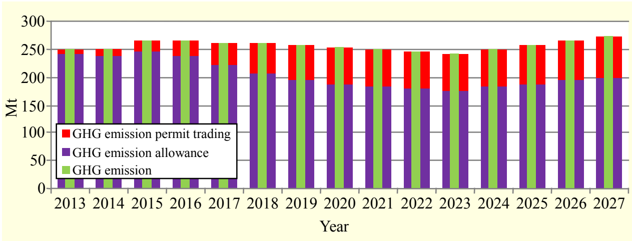

Fig. 4. GHG emissions by year (scenario 2).

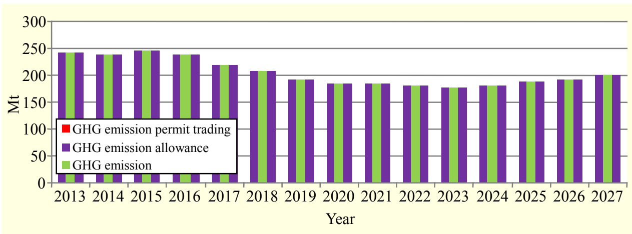

Fig. 5. GHG emissions by year (scenario 3).

Table 7. Total accumulated costs of power plants for the plan period 2012–2027; unit: trillion KRW (billion USD).

Classification	Total cost	Construction cost	Generation cost	Rate of change (%)
Scenario 3	419.365 (408)	114.433 (110)	304.932 (297)	—
Scenario 4	386.061 (376)	114.239 (110)	271.823 (264)	–7.94
Scenario 5	353.852 (344)	110.927 (108)	242.925 (236)	–15.62

generation are essential to the fulfillment of the reduction target as long as cross-border emissions trading is not realized. Meanwhile, an analysis of the impact of the national GHG TMS reduction target changes shows that when the target is lowered, nuclear energy still accounts for nearly fifty percent of consumed energy. The GEP model predicts that the South Korean government will have to continue to use coal and LNG throughout the period plan rather than renewable energy sources. LNG has a lower carbon content per unit of energy than coal does and is less expensive than renewable energy. The government has planned to expand upon its use of renewable energy sources, but has not yet done so due to a lack of available sites, seasonal variations in South Korea's weather, and the fact that such energy sources are more expensive than non-renewable ones. Therefore, it is necessary for the government to invest in additional installations of renewable energy sources to preserve the environment, as well as supporting subsidies for the expansion of renewable energy.

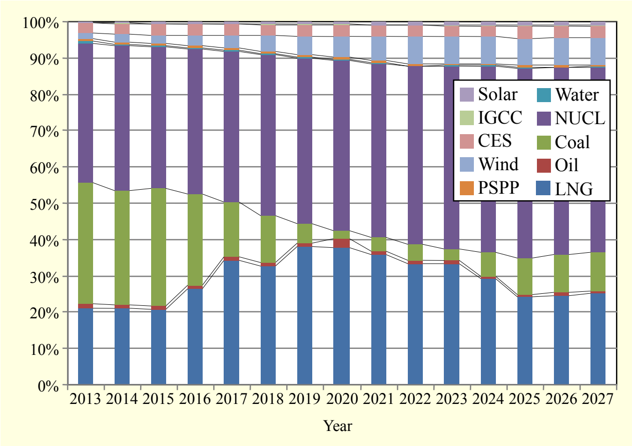

Fig. 6. Generation mix outlook (scenario 3).

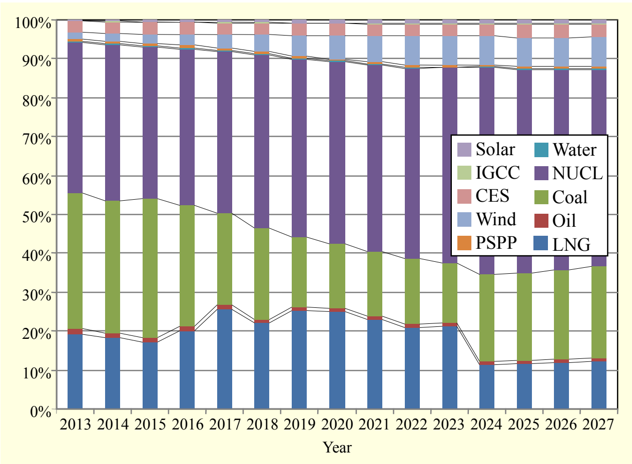

Fig. 7. Generation mix outlook (scenario 4).

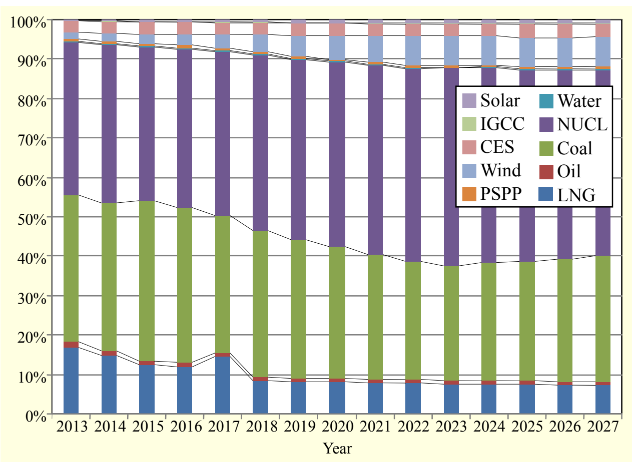

Fig. 8. Generation mix outlook (scenario 5).

3. Result of Changing LNG Price (Introduction of Shale Gas)

Tables 8 shows, by power source, the total accumulated generation capacities for scenarios that reflect the effects of potential changes in LNG price for the plan period. Table 9 shows the total accumulated costs of all energy sources for scenarios 3, 6, 7, and 8. Even if we were to assume that the price of LNG were to drop by 50% (scenario 8) from the current level, there would be no change in the generation capacity of LNG power plants.

The total accumulated cost for scenario 8 during the plan period (2013–2017) is reduced by about 19% supported by the lower fuel costs of LNG facilities, but the construction costs of LNG facilities remains the same. This means that the price competitiveness of LNG will still be low compared to other

Table 8. Generation mix outlook in 2027 (unit: MW).

Classification	Scenario 3	Scenario 6	Scenario 7	Scenario 8
LNG	30,378	30,378	30,378	30,378
Oil	3,833	3,833	3,833	3,833
Coal	40,534	40,534	40,534	40,534
Nuclear	40,316	40,316	40,316	40,316
Water	1,592	1,592	1,592	1,592
PSPP	4,700	4,700	4,700	4,700
Wind	22,676	22,676	22,676	22,676
CES[1)]	5,770	5,770	5,770	5,770
IGCC[2)]	150	150	150	150
Solar	3,790	3,790	3,790	3,790
Total	153,739	153,739	153,739	153,739

1) Community Energy System (CES)
2) Integrated Gasfication Combined Cycle (IGCC)

http://dx.doi.org/10.4218/etrij.15.2314.0059

Table 9. Total accumulated costs of all energy sources for the plan period; unit: trillion KRW (billion USD).

Classification	Total cost	Cost fluctuation	Rate of change (%)
Scenario 3	419.365 (408)	—	—
Scenario 6	403.338 (393)	–16.027 (16)	–3.82
Scenario 7	372.761 (363)	–46.464 (45)	–11.11
Scenario 8	338.977 (330)	–80.388 (78)	–19.17

power sources even when the LNG price is reduced by 50%. The total cost of implementing GHG TMS and ETS for the plan period (scenario 2) is greater than that of scenario 8.

The South Korean government has specified three phases for the implementation of ETS. For the first phase, ETS participants (South Korea's largest emitters) will be allowed to allocate 100% of the allowances free of charge. And, in the second and third phases, ETS participants will be allowed to allocate 97% and 90% of the allowances free of charge, respectively. As a result, at least 3% of allowances will be auctioned in Phase II and at least 10% will be auctioned in Phase III. Therefore, the government needs to prepare for the provision of financial assistance in relation to LNG prices in the initial stages of the introduction of ETS.

4. Result of Implementing Nuclear Policies

This paper has analyzed the changes in generation facilities and total accumulated cost under the nuclear and renewable energy policies — both of which are based on scenario 1, taking note of the concern regarding the expansion of nuclear power facilities in South Korea. Tables 10 and 11 show the total accumulated generation capacities and total accumulated costs for the plan period, respectively, by power source, according to considerations of nuclear policies.

As for the disuse of nuclear power plants after their lifespan (scenario 9), an analysis of changes in the generation mix and total cost has been conducted based on an application of the RPS policy and the assumption that the current generation capacity of nuclear power is maintained and that there is no plan for nuclear power plant construction during the target period. As for the stoppage of nuclear power plants currently in operation (scenario 10), an analysis of changes in the generation mix and total cost during the plan period has been conducted based on an application of the RPS policy and the assumption that the nuclear power facilities that are now in operation will be stopped. As for the disuse of nuclear power plants after their lifespan and operation of the current nuclear power plants without further expansion during the plan period,

Table 10. Generation mix outlook in 2027 (unit: MW).

Classification	Scenario 1	Scenario 9	Scenario 10
LNG	29,978	35,578	34,778
Oil	3,833	3,833	3,833
Coal	40,534	51,534	73,034
Nuclear	36,116	20,716	0
Water	1,592	1,592	1,592
PSPP	4,700	4,700	4,700
Wind	22,676	22,676	22,676
CES	5,770	5,770	5,770
IGCC	150	150	150
Solar	3,790	3,790	3,790
Total	149,139	150,339	150,323

Table 11. Total accumulated costs for the plan period 2012–2027; unit: trillion KRW (billion USD).

Classification	Total cost	Construction cost	Generation cost	Rate of change (%)
Scenario 1	346.986 (338)	106.857 (104)	240.129 (234)	—
Scenario 9	351.808 (342)	96.137 (93)	255.671 (249)	1.39
Scenario 10	422.838 (412)	125.471 (122)	297.367 (289)	21.86

it is expected that an expansion of thermal power facilities will take place to meet the rising energy demand, and the total accumulated cost for scenario 9 will increase by 1.39% compared to the baseline scenario due to the fact that such facilities have a poorer economic efficiency compared to nuclear power facilities. Compared to scenario 9, in the case of scenario 10, more thermal power facilities will be built; additionally, the total accumulated cost for scenario 10 will increase significantly. When the generation share of nuclear power facilities is lowered, the installation of thermal power facilities will grow to make up for the reduction in power supply, but this may conflict with any plans to achieve the GHG TMS reduction target. In addition, in this case, to reduce the emission of GHGs, an expansion of renewable energy facilities may be required, resulting in higher costs.

V. Conclusion

The results of the scenario analyses show that, with the current 6th BPE only, the generation amount from coal and thermal power will not be reduced and the GHG emissions will exceed the level expected for the GHG TMS generation sector. Therefore, in the future, changes to the generation mix are inevitable. To achieve the GHG TMS reduction target for the generation sector, the generation share of coal and thermal power must be reduced while continuously increasing the share of nuclear power and renewable energy sources. Due to the recent Fukushima Daiichi nuclear disaster (Japan) and nuclear power plant failures in South Korea, the South Korean government is considering reducing its capacity of nuclear power plants. Thus, if this were to happen, then coal and LNG will come to play a bigger role based on their price competitiveness, leading to additional GHG TMS implementation costs. In this case, the target will have to be modified. As for the introduction of shale gas to replace coal and nuclear power, the concern here is that the price competitiveness of nuclear power will still be higher than that of LNG, even after the price of LNG falls.

The reality is that continuous expansion of nuclear power plants is required, and if nuclear power plants are disused after their lifespan, then the consumption of LNG and coal will inevitably rise. In this respect, the existing reduction target of 26.7% for the generation sector needs to be reviewed for its performability. In addition, a reduction of between 10% and 20% in the GHG TMS reduction target should be considered so as to avoid extreme cost burdens associated with target fulfillment and abandonment of nuclear power.

In this study, a simulation has been conducted assuming a fixed price of carbon emission allowances, failing to reflect the current market conditions where the price of carbon emission allowances is decreasing. This market environment makes it more complicated to develop mid- and long-term plans for generation mix change and to reflect the target properly under GHG TMS. Based on this recognition, in the future, more research will be done on the methodology for the analysis of the global emission trading market trend so as to allow for the development of mid- and long-term plans for generation mix change and for an optimal approach to ensure cost-effectiveness of emissions trading.

References

[1] Ministry of Government Legislation, *Enforcement Decree of the Framework Act on Low Carbon, Green Growth*, Ministry of Government Legislation, Rep. of Korea, 2010. Accessed Feb. 12, 2012. http://www.moleg.go.kr/english/korLawEng?pstSeq=54792

[2] IETA (International Emissions Trading Association), *The World's Carbon Markets: A Case Study Guide to Emissions Trading*, Discussion Paper, European Development Fund, 2013.

[3] Greenhouse Gas Inventory & Research center of Korea, "National Greenhouse Gas Inventory Report," Greenhouse Gas Inventory & Research center of Korea, Seoul, Rep. of Korea, Tech. Rep. 11-1480745-000003-10, Feb. 2013.

[4] Korea Power Exchange, *6th Basic Plan for Long-Term Electricity Supply & Demand of Electric Power*, Korea Power Exchange, 2012. Accessed Aug. 12, 2013. http://www.motie.go.kr/motie/in/ay/policynotify/announce/bbs/bbsView.do?bbs_seq_n=61532 &bbs_cd_n=6

[5] International Atomic Energy Agency, "*Wien Automatic System Planning (WASP) Package: A Computer Code for Power Generating System Expansion Planning – User's Manual*," Vienna, Austria: IAEA, 2000, pp. 19–251.

[6] R.T. Jenkins and D.S. Joy, "*Wien Automatic System Planning Package (WASP): An Electric Utility Optimal Generation Expansion Planning Computer Code*," Virginia, USA: Oak Ridge National Laboratory, 1974, pp. 197–222.

[7] A. Rouhani, G. Varamimi, and M. Nikkaha, "Generation Expansion Planning Considering Renewable Energies," *American J. Eng. Res.*, vol. 2, no. 11, Feb. 2013, pp. 276–286.

[8] Y.-M. Park et al., "Generation Expansion Planning Based on an Advanced Evolutionary Programming," *IEEE Trans. Power Syst.*, vol. 14, no. 1, Aug. 1999. pp. 299–305.

[9] Y. Fujii and K. Akimoto, "Optimal Power System Expansion Planning under Uncertain CO_2 Emissions Control Policies," *Electr. Eng. Japan*, vol. 117, no. 5, Feb. 1996, pp. 1–13.

[10] J.-I. Lee, S-H. Han, and B.H. Kim, "A Study of the Long-Term Fuel Mix with the Introduction of Renewable Portfolio Standard," *Trans. Korea Institute Electr. Eng.*, vol. 58, no. 3, Mar. 2009, pp. 467–477.

[11] S. Hwang and B.H. Kim, "A Study on the Generation Expansion Planning Model Reflecting Environmental Policies," *Adv. Mater. Res.*, vol. 962, no. 1, June 2014, pp. 2210–2219.

[12] J. Zhu and M.-Y. Chow, "A Review of Emerging Techniques on Generation Expansion Planning," *IEEE Trans. Power Syst.*, vol. 12, no. 4, Nov. 1997, pp. 1722–1728.

[13] K.H. Chung, B.H. Kim, and D. Hur, "A New Approach to Generation Scheduling in Interconnected Power Systems Using Predictor-Corrector Proximal Multiplier Method," *Electr. Eng.*, vol. 94, no. 3, Aug. 2012, pp. 177–186.

[14] S. Porkar et al., "Distribution System Planning Considering Integration of Distributed Generation and Load Curtailment Options in a Competitive Electricity Market," *Electr. Eng.*, vol. 93, no. 1, Mar. 2011, pp. 23–32.

[15] Y.M Park, J.B. Park, and J.R. Won, "A Hybrid Genetic Algorithm/Dynamic Programming Approach to Optimal Long-Term Generation Expansion Planning," *Int. J. Electr. Power Energy Syst.*, vol. 20, no. 4, May 1998, pp. 295–303.

[16] Z. Zhao et al., "An Optimal Power Scheduling Method Applied in Home Energy Management System Based on Demand Response," *ETRI J.*, vol. 35, no. 4, Aug. 2013, pp. 677–686.

[17] Y.-C. Kim and B.H. Ahu, "Multicriteria Generation-Expansion Planning with Global Environmental Considerations," *IEEE Trans. Eng. Manag.*, vol. 40, no. 2, May 1993, pp. 154–161.

[18] J.-B. Park et al., "An Improved Genetic Algorithm for Generation Expansion Planning," *IEEE Trans. Power Syst.*, vol. 15, no. 3, Aug. 2000, pp. 916–922.

[19] Y.M. Park, "Long-Term Generation Expansion Planning with Consideration of CO_2 Emission," *Trans. Korean Institute Electr. Eng.*, vol. 43, no. 3, Nov. 1998, pp. 263–268.

[20] Y. Park, and S. Kim, "Bargaining-Based Smart Grid Pricing Model for Demand Side Management Scheduling," *ETRI J.*, vol. 37, no. 1, Feb. 2015, pp. 197–202.

[21] S. Kim, "An Adaptive Smart Grid Management Scheme Based on the Coopetition Game Model," *ETRI J.*, vol. 36, no. 1, Feb. 2014, pp. 80–88.

[22] G. Byun et al., "Analysis of the RPS System in Korea Based on SCP Framework," *Int. Conf., FutureTech*, Loutraki, Greece, June 28–30, 2011, pp. 288–295.

[23] J.W. Shin et al., "Analyzing Public Preferences and Increasing Acceptability for the Renewable Portfolio Standard in Korea," *Energy Economics*, vol. 42, no. 2, Mar. 2014, pp. 17–26.

[24] Korea Energy Management Corporation, *Overview of New and Renewable Energy in Korea 2013*, KEMCO, 2013. Accessed Feb. 2014. http://www.kemco.or.kr/new_eng/pg02/pg02040300.asp

[25] United Nations Environment Programme, *Overview of the Republic of Korea's Nation Strategy for Green Growth*, UNEP, 2010. Accessed Apr. 2013. http://www.unep.org/PDF/PressReleases/201004_unep_national_strategy.pdf

[26] J.A. Bloom, "Long-Range Generation Planning Using Decomposition and Probabilistic Simulation," *IEEE Trans. Power Apparatus Syst.*, vol. 4, no. 4, Apr. 1982, pp. 797–802.

[27] S.-M. Han, K.-H. Chung, and B.H. Kim, "ISO Coordination of Generator Maintenance Scheduling in Competitive Electricity Markets Using Simulated Annealing," *J. Electr. Eng. Technol.*, vol. 6, no. 4, Oct. 2011, pp. 431–438.

[28] R.W. Jefferson and R.N. Boisvert, "*A Guide to Using the General Algebraic Modelling System (GAMS) for Applications in Agricultural Economics*," New York, NY, USA: Dept. of Agricultural Economics, Cornell University, 1989, pp. 58–66.

[29] International Emissions Trading Association, "*Wien Automatic System Planning (WASP) Package: A Computer Code for Power Generating System Expansion Planning Version WASP-IV with User Interface User's Manual*," Vienna, Austria: IAEA, 2006, pp. 13–150.

Jeong-In Lee received her BS and MS degrees in electrical engineering from Hongik University, Seoul, Rep. of Korea, in 2007 and 2009, respectively. In 2009, she worked as a researcher for the Korea Electric Power Research Institute, Daejeon, Rep. of Korea. In 2010, she joined the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, as a researcher. Her research interests include energy management systems, renewable energy, and smart grids.

Il-Woo Lee received his BS and MS degrees in computer science from Kyunghee University, Seoul, Rep. of Korea, in 1992 and 1994, respectively and his PhD degree in computer science from Chungnam National University, Daejeon, Rep. of Korea, in 2007. In 1994, he joined the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, where he has been engaged in the research and development of ATM-based networks, high-speed routing systems, and home network systems. Currently, he is a senior fellow of smart grid technology, and his research interests are green home/buildings and smart grids.

Bal-Ho Kim received his BS degree in electrical engineering from Seoul National University, Rep. of Korea, in 1984 and his MS and PhD degrees in power system economics from the University of Texas at Austin, CA, USA, in 1992 and 1996, respectively. From 1984 to 1990, he was with the Korea Electric Power Corporation. In 1997, he joined Hongik University, Seoul, Rep. of Korea, where he is currently working as an associate professor of electrical engineering. His research fields include distributed optimal power flow, public pricing, B/C analysis, and power system planning and operation.