# RELIABLE ROLE OF NUCLEAR POWER GENERATION UNDER $CO_2$ EMISSION CONSTRAINTS

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*Received January10, 2007*
*Accepted for Publication July 30, 2007*

Most decision makers in the electricity industry plan their electric power expansion program by considering only a least cost operation, even when circumstances change with differing complexities. It is necessary, however, to analyze a long-term power expansion plan from various points of view, such as environmental friendliness, benefit of a carbon reduction, and system reliability, as well as least cost operation. The objective and approach of this study is to analyze the proper role of nuclear power in a long-term expansion plan by comparing different scenarios in terms of the system cost changes, $CO_2$ emission reduction, and system reliability in relation to the Business-As-Usual (BAU). The conclusion of this paper makes it clear that the Korean government cannot but expand the nationwide nuclear power program, because an increased energy demand is inevitable and other energy resources will not provide an adequate solution from an economic and sustainability point of view. The results of this analysis will help the Korean government in its long-term resource planning of what kinds of role each electric resource can play in terms of a triangular dilemma involving economics, environmental friendliness, and a stable supply of electricity.

KEYWORDS : Nuclear Power, Long-Term Expansion Planning, Least Cost, $CO_2$ Reduction, Energy Policy

## 1. BACKGROUND

There are many important issues involved in the sustainable development of the electricity industry in Korea, such as electricity market restructuring, climate changes regime, increasing demand for renewable energy, and difficulties of nuclear power program expansion. Additionally, public acceptance in looking for a site for a nuclear facility is an issue being faced by the Korean nuclear industry [1].

The Korean government has relied on nuclear and fossil fuel power generation for more than 70% of Korea's total generation capacity due to limited domestic resources. According to a rigid environmental regulation like a climate change regime expected in the near future, fossil power generation may shrink to meet $CO_2$ emission constraints. Thus, other power generation resources will have to make up the deficiency of fossil fuel power generation to meet the future electricity demand.

Even though nuclear power has contributed over 30 % of the total power generation capacity and has enabled a stable electricity supply in Korea, many of Korea's citizens do not readily accept the expansion of nuclear power. Some NGO environmentalists have insisted that the Korean energy plan should get away from a policy depending only on nuclear power and adopt a distributed energy system using renewable or combined heat power generation [2].

Therefore, it is necessary to investigate the possibility of a steady supply of a natural resource, such as wind or solar power, and the economics and environmental benefits of different resources should also be reviewed for a sustainable power supply before fixing the optimal long term fuel mix. In addition, the national long term power expansion program thus far has focused on optimization only in terms of system operation with least cost. It is necessary, however, to co-optimize the best mix of electric resources considering which combination of power plants is economically and environmentally advantageous. Most research on long term capacity expansion or resource planning carried out in the 1980's and 1990's considered general methods of generation cost or long term power expansion. It is hard to determine whether these previous studies used analytical methodologies or various computational simulations, thus references of this study are very limited.

This study analyzes the reliable role and portion of nuclear power in a fuel mix for power generation systems under $CO_2$ emission constraints, which is a similar concept to limiting the allowance of carbon emission from the power generation system. First, the computational method used in the analysis is introduced, and the sustainable and proper role of nuclear power is analyzed. Then, the reference and alternative scenarios are compared from cost and $CO_2$ emission credit points of view. The role of nuclear power refers to the number of new nuclear power plants needed to meet the increased electricity demand, in relation to different emission targets, while the $CO_2$ and cost credits explain the changes of the total system cost and $CO_2$ savings due to an increase in nuclear power generation.

## 2. TECHNICAL BASIS OF THE COMPUTATIONAL MODEL

To estimate the system cost changes, $CO_2$ emission reduction and system reliability, the methodological tool used in the study is the WASP-IV (Wien Automatic System Planning Package) for system cost and $CO_2$ emission [3,4,5].

WASP-IV code establishes the optimal expansion plan for a power generation system over a period of up to thirty years, within constraints given by the planner. The optimum is evaluated in terms of minimum discounted total system costs. A simplified description of the model follows. Each possible sequence of power units added to the system (expansion plan or expansion policy) meeting the constraints is evaluated by means of a cost function (the objective function), which is composed of the following:

- Depreciable capital investment cost: equipment and site installation costs (I)
- Salvage value of investment costs (S)
- Non-depreciable capital investment costs: fuel inventory, initial stock of spare parts, etc. (L)
- Fuel cost (F)
- Non-fuel operation and maintenance costs (M)
- Costs of the energy not served (O)

The cost function to be evaluated by WASP-IV can be represented by the following expression:
The optimal expansion plan is defined as a minimization of the objective function (B), as follows.

$$B_j = \sum_{t=1}^{T} [I_{j,t} - S_{j,t} + L_{j,t} + F_{j,t} + M_{j,t} + O_{j,t}]$$

where
- Bj is the objective function attached to the expansion plan j,
- t is the time in years
- T is the length of the study period (total number of years) and all values are discounted values to a reference data at a given discount rate, i.

The WASP-IV analysis requires as a starting point the determination of alternative expansion policies for the power system. If $[K_t]$ is a vector containing the number of all generating units in operation in year t for a given expansion plan, then $[K_t]$ must satisfy the following relationship.

$$[K_t] = [K_{t-1}] + [A_t] - [R_t] + [U_t],$$

where $[A_t]$ is a vector of committed additions of units in year t
$[R_t]$ is a vector of committed retirements in year t
$[U_t]$ is a vector of candidate generating units added to the system in year t

$[A_t]$ and $[R_t]$ are given data in the 'FIXSYS' module, and $[U_t]$ is the unknown variable (in the 'VARSYS' module) to be determined; the latter is called the system configuration vector or, simply, the system configuration (generated by the 'CONGEN' module). Concepts and contents of each module in the WASP-IV are explained in detail below.

To establish the optimal expansion plan meeting the Minimum Bj, WASP-IV needs inputs about the characteristics of the load forecast in the LAODSYS module and various kinds of plants in the FIXSYS and VARSYS modules. The CONGEN module generates all the possible year-to-year combinations of the expansion candidate additions, and the MERSIM module calculates the production costs, energy not served (ENS), and system reliability represented by LOLP for each configuration. Then, the DYNPRO module determines the optimum expansion plan based on previously derived operating costs along with input information on the capital costs, energy not served cost, and economic parameters and reliability criteria (in the Korea power system case, the LOLP value must be under 0.5days/year). Figure 1 shows a simplified flow chart of the process to establish the optimal expansion plan through the WASP-IV modules.

## 3. SCENARIO APPROACH

This study uses three scenarios to analyze a long-term power expansion plan from the perspectives of carbon reduction benefit and system reliability, as well as least cost operation, which shows a trade-off between the incremental system cost and the benefit of a $CO_2$ reduction.

First, a Business-As-Usual (BAU) case is selected only as a least system cost point of view, which means the optimal fuel mix to meet the given electricity demand is determined at the minimized system cost. Each scenario is compared to the BAU case in terms of the incremental system cost and $CO_2$ emission amounts.

Second, a $CO_2$ regulation scenario is selected. This model can simulate the system cost changes and $CO_2$ emission projection according to the different limits of

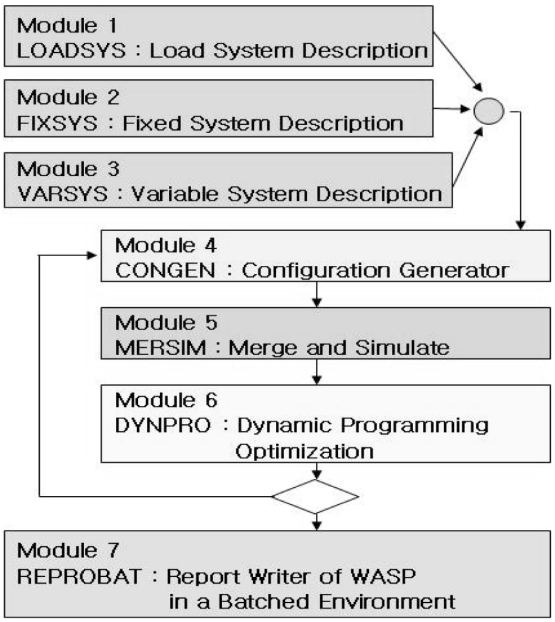


Fig. 1. Simplified Flow Chart of the WASP IV

$CO_2$ emission. If a stricter $CO_2$ constraint is applied, a higher system cost can be expected, because a power generation using bituminous coal is restricted and less $CO_2$ and a more expensive fuel, like an LNG, must be used if a nuclear power plant cannot be added. Step-by-step emission targets of $CO_2$ are getting stricter 0.20 kg-c/kWh through 0.11 kg-c/kWh. Different carbon emission limits [kg-c/kWh] are applied, such as 0.11, 0.12, 0.13, 0.15, and 0.20. Additionally a 0.15 limit is kept through 2011, while after 2011, a more stringent target of 0.11 is applied (0.20 $\longrightarrow$0.11).

## 4. PREPARATION OF THE INPUT DATA

### 4.1 Load Profile

Two common scenarios are analyzed for the period from 2005 to 2020, and the discount rate is set at 7%. The constraint for system reliability uses the Loss of Load Probability (LOLP) of less than 0.5 day/yr. The reserve margin is assumed to be between 10 ~ 45 %, and the optimal reserve margin allowing for the minimum system cost is fixed in the Business As Usual (BAU) scenario [6].

The expansion model needs the electricity demand during the planning period, and its forecast depends on an economic parameter, such as the population growth rate. The projection of the electricity demand is beyond the scope of this study, which uses the data produced by the Korea Power Exchange (KPX) in 2001 for the second Electricity Supply and Demand Basic Plan of the government. Demand data is specified from January 1, 2005 to December 31, 2017, and the model extrapolates the three years of demand from 2018 through 2020, as shown Fig. 2. The different colored lines refer to the different loads over 24 hours a day.

Because WASP-IV LOADSY includes the annual and period peak loads and shapes of period load duration curves (LDCs), input data on the LDCs are prepared

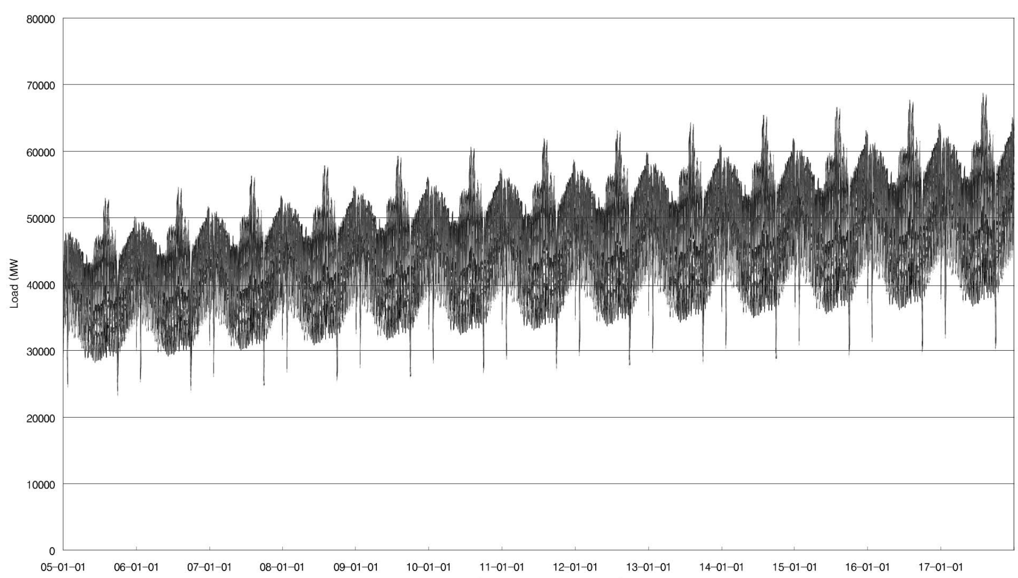


Fig. 2. Hourly Load Profile

using the normalized load duration curve of the period, for which the load magnitudes are expressed as fractions of the peak load of the period and the respective load duration values are expressed as fractions of the total hours of the period. LDCs show the consumer patterns for electricity demand, as well as load shapes, and this is the basic information needed to estimate the magnitude of the new generators to be added. For convenient calculation of system reliability and plant generation performed using a probabilistic simulation, the LOADSY module internally reverses the axis of each LDC to generate a normalized load duration curve, whose vertical axis shows the ratio of an hourly load to a maximum load in a year. Furthermore, as shown in Fig. 3, this inverted LDC is expressed in terms of a Fourier series to approximate the shape of the curve and, in this format, the information on a system load is transferred to the subsequent model [7].

To estimate the LDC, the model needs the annual peak load data and Fourier series coefficients by periods calculated from the hourly load. The quantities of the capacity and number of plants, as well as fuel type, are determined based on the LDC. To decide how many inputs the LDC model needs and whether every year has a similar load pattern or not, the model needs the load factor expressed as the annual peak load during 8,760 hours divided by a generation in GWh. If every year has a similar load profile, it means the load factor of each year will be almost the same, which allows for considering only one year LDC. Calculation of every year's load factor revealed an identical load factor of 0.7522. Finally, the annual peak load and LDC of 2005 only were used to estimate the additional capacities, as shown in Fig. 4.

## 4.2 Characteristics of Existing Plants

General information of the existing plants by fuel types charged from the current demand include capacity, heat rate of fuel, fuel cost, operation and maintenance cost, forced outage rate, and heat value. Fuel types such thermal plants as nuclear, bituminous coal, domestic coal, oil, and LNG are selected, and a total of 235 generators and 12 combined cycles are imported into the model. Hydro plants and pumped storage are also included in the model; however, a community energy system and miscellaneous energy sources, like renewable energy, are excluded, because their contribution to the total installed capacity is below 2%. Their characteristics from a technical point of view also come from the data produced by the Korea Power Exchange (KPX) in 2001 for the second Electricity Demand and Supply Basic Plan.

To verify how accurate the model estimates a real power system and whether the specifications of the current plants are reliable, model estimation results need to be compared to the actual data based on 2004 [8]. Table 1 shows the comparison of the model estimation and the actual data for the existing plants. First of all, how well a model reflects a real power system and how close it is to the actual Korean system have to be checked, because an exact calculation of the capacity and generation should be the basis for estimating the $CO_2$ emission as well as the system cost.

## 4.3 Selection of Candidates

In this study, the term "candidates" refers to the new plants to be added into the grid to meet the increased

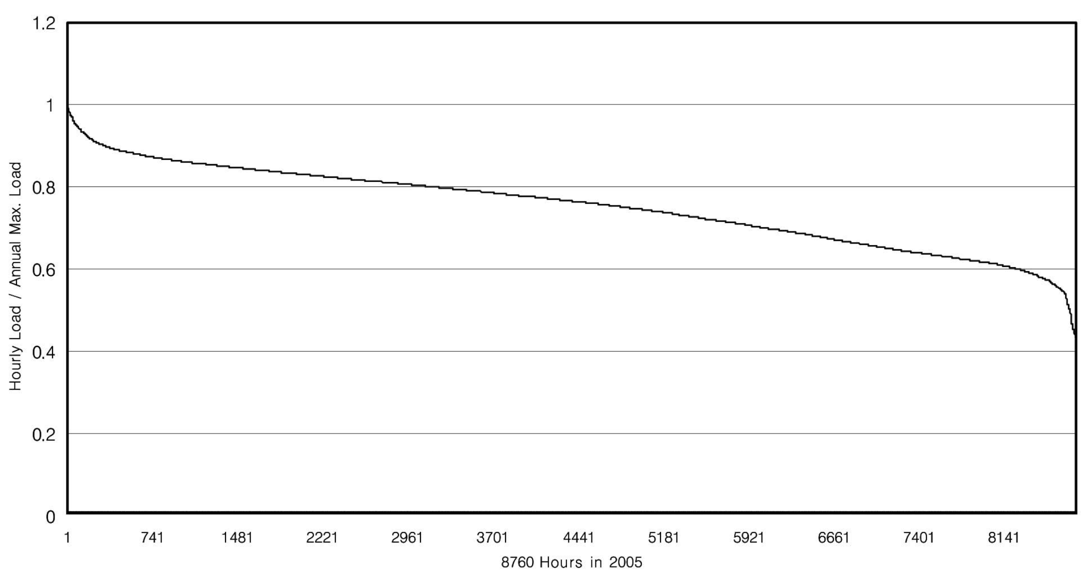


Fig.3. Load Duration Curve

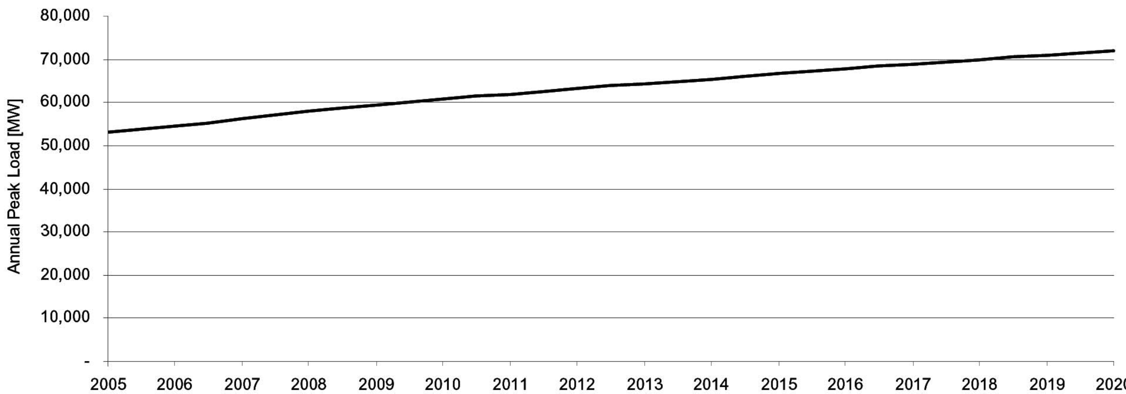


Fig.4. Annual Peak Load in 2005

**Table 1**. Comparison of the Model Estimation and Actual Data for Existing Plants

| | Actual data [end of 2004] | | | | Model Estimation | | | |
|---|---|---|---|---|---|---|---|---|
| Fuel Name | Install Capa [MW] | Net Generation [GWh] | Capacity Factor | NO. of Plants | Install Capa [MW] | Energy Generation [GWh] | Capacity Factor | NO. of Plants |
| Nuclear | 16,716 | 123,970 | 0.85 | 19 | 16,800 | 129,032 | 0.88 | 20 |
| Antracite | 1,125 | 5,131 | 0.52 | 6 | 1,166 | 8,366 | 0.82 | 7 |
| Bituminous | 16,340 | 117,137 | 0.82 | 32 | 16,960 | 115,591 | 0.78 | 32 |
| LNG | 1,538 | 687 | 0.05 | 6 | 1,545 | 65,910 | 4.87 | 6 |
| Oil | 4,309 | 14,972 | 0.40 | 19 | 4,380 | 25,661 | 0.67 | 17 |
| CC | 14,313 | 54,441 | 0.43 | 14 | 13,955 | | - | 14 |
| Thermal Total | 54,340 | 316,339 | 0.66 | 96 | 54,806 | 344,560 | 0.72 | 96 |
| Hydro - Small Other company | 1,043 | 2,776 | | | 1,047 | | | |
| Hydro - General GenCo. | 536 | 1,486 | | | 535 | | | |
| Hydro Total | 1,579 | 4 | | | 1,582 | | | |
| PS GenCo. | 2,300 | 1,541 | | 8 | 2,300 | | | 6 |
| **TOTAL** | **58,219** | **317,884** | | | **58,688** | | | |

future demand. The model selected nuclear plants of 1000MW and 1400MW, bituminous plants of 500MW and 800MW, an LNG of 450 MW, an Oil plant of 500MW, and domestic a coal plant of 200MW. Their levelized costs according to the capacity factor are divided into two groups by the screening curve method: one is the low cost fuel group being charge with a base load, including coal and nuclear energy; the other is the high cost fuel of a peak load. As the capacity factor becomes higher, nuclear energy becomes more competitive, and the plants with large installed capacity are more economical, as shown Fig. 5.

## 5. REFERENCE CASE SCENARIO

The system cost is the sum of the investment cost, fuel cost, O&M cost, and energy not served cost. It needs to be defined with respect to the reference case scenario BAU to compare it with alternative scenarios in terms of the $CO_2$ emission amounts and system cost.

Capacity and generation by fuel types have the same trend as the reference of the 2$^{nd}$ expansion plan by the government shown in Fig.6. The slight difference of the comparison by fuel type is because the renewable and

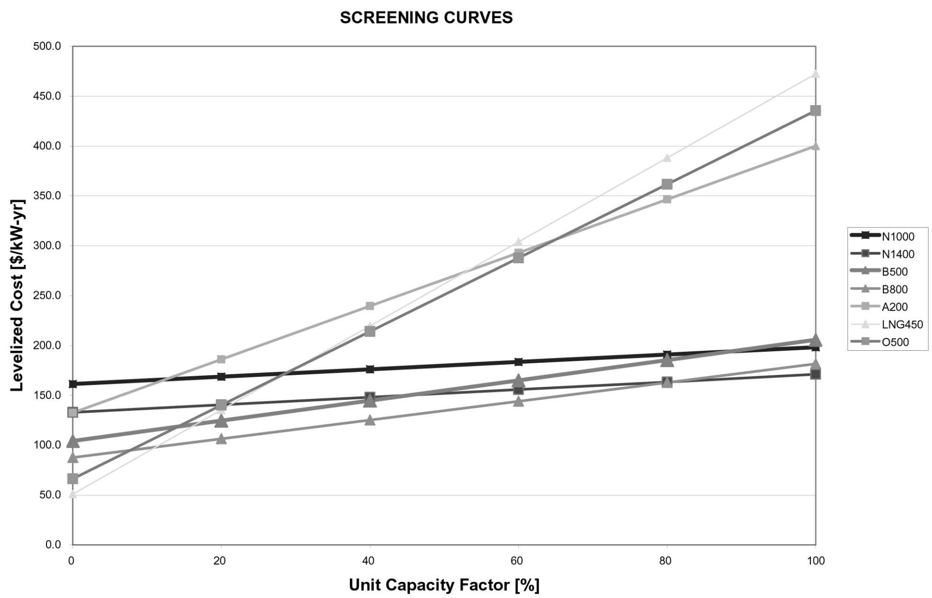


Fig.5. Screening Curves of the Candidates

community energy systems are included in the government estimation only, while the present model doesn't consider them.

The reference case is a scenario without any constraints. The reserve margin (RM) as the indicator of system reliability is the surplus capacity over the peak load, and it is optimized to minimize the total system cost [9]. Usually, a lower RM is preferred over a higher RM, because extra capacity due to a higher RM can be non-economical. In Korea, however, a lower RM causes a higher system cost, which means that nuclear and coal plants with a large capacity as the base load can have major roles for an optimized system.

Additionally, as shown in Fig. 7, the operation of nuclear and coal plants, even though they create a higher RM, is better than the operation of LNG or oil plants with a lower RM in terms of the system reliability. The reference case of this study is a 103,512,848 k$ system cost with a 45% RM .

## 6. $CO_2$ REGULATION CASE SCENARIO

The $CO_2$ regulation scenario simulates the system cost changes and $CO_2$ emission projection according to the different limits of a $CO_2$ emission. Step-by-step emission targets of $CO_2$ are becoming stricter: 0.20 kg-c/kWh through 0.11 kg-c/kWh. Different carbon emission limits [kg-c/kWh] are applied, as follows: 0.11, 0.12, 0.13, 0.15, and 0.20. Additionally a 0.15 limit is kept through 2011, while after 2011, a more stringent target of 0.11 is applied (0.20 → 0.11)

A stricter $CO_2$ constraint is applied, as depicted in

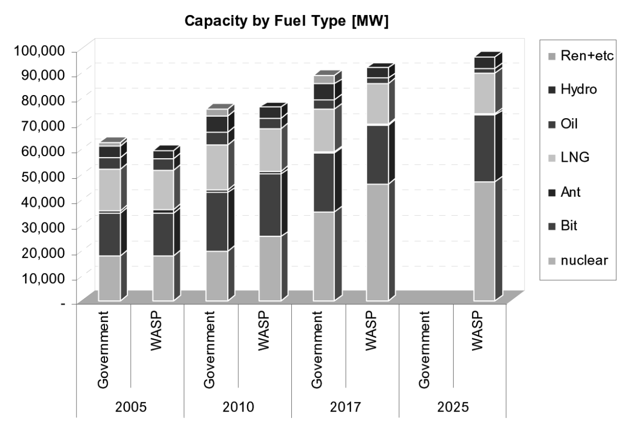


Fig.6. Comparison of Expansion Capacity Between Government Plan and Present Model

Fig. 8. A higher system cost can be expected, because power generation using bituminous coal is restricted, and less $CO_2$ emitting and a more expensive fuel like a LNG must be used if a nuclear power plant cannot be added. After all, a higher system cost can be expected when a stricter $CO_2$ emission target of 0.20 kg-c/kWh to 0.11 kg-c/kWh is applied. In this situation, a nuclear power can have a major role as a system stabilizer from an economics point of view and can abate $CO_2$ emission from an environmental point of view. Conventional nuclear power plants are a more cost effective GHG mitigation option than coal fired power plants with a carbon capture and storage [10].

Change of a fuel mix, i.e., number of plants in Fig.9 shows that a stricter carbon emission limit introduces the

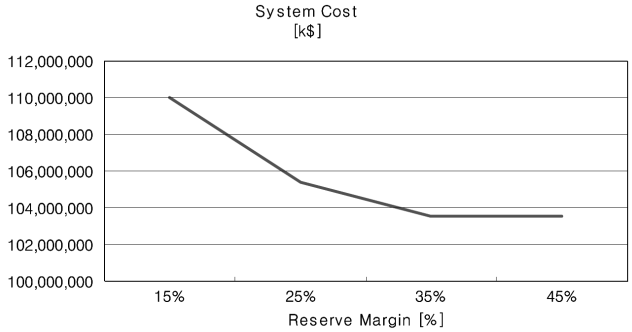


Fig.7. Comparison of the System Cost According to the Reserve Margin [%]

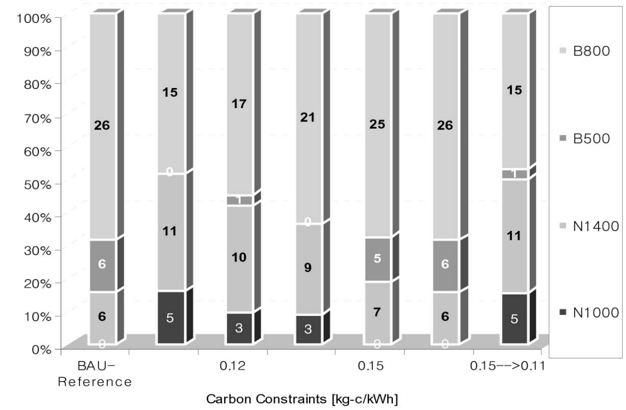


Fig.9. Fuel Mix Changes with Respect to Various $CO_2$ Limits

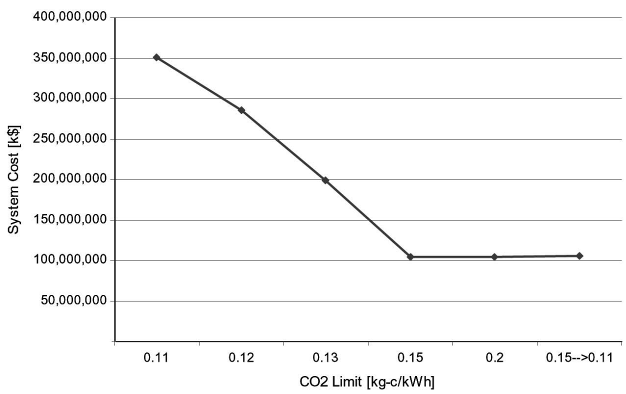


Fig.8. System Cost Changes with Respect to Various $CO_2$ Limits

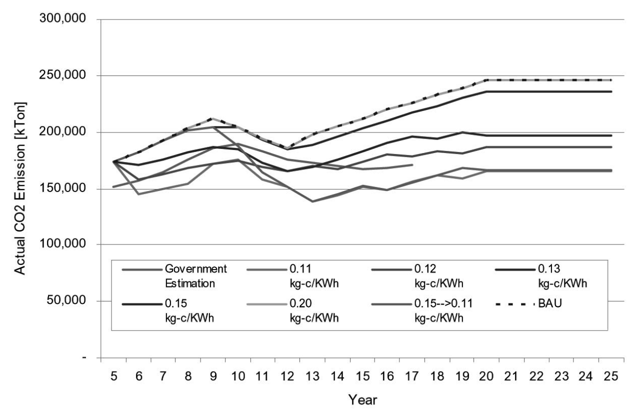


Fig.10. Changes of the $CO_2$ Emission with Respect to Various Emission Limits

more nuclear plants to mitigate the carbon level and the number of nuclear plants is added at as much as the decrease of the coal plants to meet the demand. From this result, it can be expected that a plant with a large capacity is preferred over a plant with a small capacity.

Figure 10 shows a comparison of the estimation of the actual $CO_2$ emission with respect to the different carbon emission limits derived from the present model and government estimations from 2005 to 2017. As the emission limit becomes stricter, less $CO_2$ is emitted. $CO_2$ emission decreases until 2010, and after that it decreases rapidly. This result indicates that many fossil power plants in the current system will play a major role before 2010 and, as economical and non-carbon source plants, such as nuclear plants, are connected to the system, total $CO_2$ emissions will decreased.

From 2005 to 2010, no new coal power plants are planned for construction, and the $CO_2$ emission of this period is predicted to decline. After completion of a new coal plant, the $CO_2$ emission is predicted to increase again. The Korean government expects that the $CO_2$ emission will be between 0.12 and 0.13kg-c/kWh; however, the present model predicts that the $CO_2$ emission will be much higher than the government expectation. The reason for the discrepancy between the models is that the present model considers the different fuel efficiencies of the plants, while the government model uses only the IPCC emission factor multiplied by fuel consumption. To consider the different fuel characteristics, a more detailed heat rate, heat value, and $CO_2$ weight % of a fuel can be included, which increases the model's accuracy, even when considering the same fuel.

The ratio of actual $CO_2$ emission to its limit, as depicted in Fig.11, shows how close the actual emission amounts are to the limit and how much the margin of an emission limit is available. At the beginning of the regulation, the emission is near the margin; however, over time, new nuclear power plant begins operation and a greater margin is available. This is due to the new connection of a nuclear power plant and not to a phase out of a coal power plant. Because an emission is almost settled down approximately 10 years later, Korean government is requested that Korea have a rigid and strict

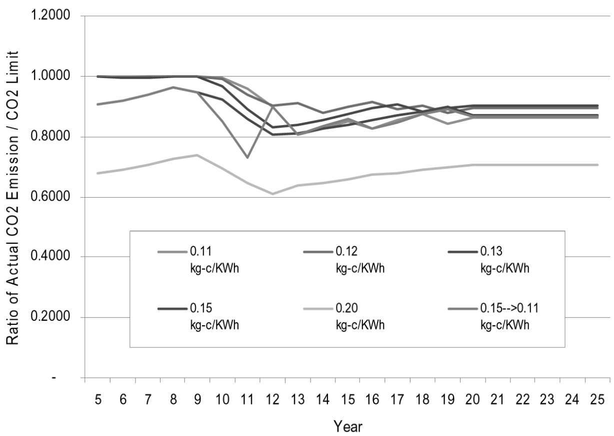


Fig.11. Changes of $CO_2$ Emission Margin

emission limit after 2012, when new nuclear plants come into the system, in terms of least cost system operation and $CO_2$ constraints. Therefore, to reach the low emission target at an early stage would not be the unique solution and the possibility of new construction of carbon free power plants and a long term fuel mix should be accounted for to set the target.

## 7. CONCLUSION

Until now, a power expansion planning by Korean government has focused on the least cost point of view. However, with increasing concerns about the $CO_2$ problem and domestic resource availability in Korea, it is necessary to analyze the fuel mix by combining the emission credit as well as the least cost option. This study has analyzed the proper role of nuclear power generation resources in a long-term expansion plan by comparing different scenarios in terms of the system cost changes, a $CO_2$ emission reduction, and system reliability with a reference case. As a result, operation of cheap and large nuclear and coal plants with relatively higher RM can be more economical than the operation of LNG or oil with a lower RM. Coal is an important resource to keep the system cost low; however, it cannot be a sustainable fuel under the situation of a stricter $CO_2$ regulation.

This paper makes it clear that Korea has no option in terms of economics and stricter $CO_2$ emission requirements but to use nuclear energy. The Korean government cannot but expand the nationwide nuclear power program, because increased energy demand is inevitable, and other resources will be inadequate from economic and sustainability points of view. It is well known that growth of nuclear power in Korea has been limited in the past due to lack of public acceptance, which may well persist. However, the main purpose of this paper is to suggest that no other major electric resource remains except nuclear power with the coming limits on carbon emissions. Thus, it is for the public benefit that citizens be apprised of the situation using these quantitative simulation results. Other issues, such as fossil fuel price volatility and stable uranium supply will be considered in a future work. The input data from 2001 used in the model, such as the actual generation cost, maintenance schedule, and fuel heat value should be updated for further study.

It is unrealistic to think that a specific electric resource will be a unique solution from the economic and sustainability points of view. The results from the present analysis are useful for the Korean government in long-term resource planning to determine how each electric resource can be used with respect to a triangular dilemma involving economics, environmental friendliness, and a stable supply of electricity.

## ACKNOWLEDGEMENT

This study in progress is supported by the R&D fund of Korea Hydro and Nuclear Power Company.

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