Flexible Best Generation Mix for Korea Power System Considering CO_2 Constraint – Vision 2030

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Abstract -- This paper proposes a fuzzy linear programming based solution approach for the long-term generation mix with multi-stages (years) considering air pollution constraints on CO_2 emissions, under uncertain circumstances as like as ambiguities of budget and reliability criterion level. This paper approaches to generation mix problem for 2030 year in Korea eventually. The proposed approach may give more flexible solution rather than too robust plan. The effectiveness of the proposed approach is demonstrated by applying it to solve the multi-years best generation mix problem on the Korea power system which contains nuclear, coal, LNG, oil and pumped-storage hydro plants.

Index Terms **— fuzzy linear programming, best generation mix, air pollution**

I. INTRODUCTION

There is a global trend towards liberalization and privatization of the electricity supply industry. This is coupled with growing environmental awareness and increasing prospects ratification of the Kyoto Protocol.[1] Electricity is the indispensable form of energy in modern societies. In this paper, a new approach for the long-term generation mix with multi-criteria considering air pollution constraints, which are not only SO_2 and NO_X but also CO_2 emission limitations, under the uncertain circumstances is proposed using linear programming. The effectiveness of the proposed approach is demonstrated by applying to the best generation mix problem of Korea power system, which contains nuclear, coal, LNG, oil and pumped-storage hydro plant in multi-years. This case study in this paper is mainly focused on CO_2 emission limitation effect in the best generation mix. The method can accommodate the operation of the pumped-storage generator which has a relationship with operation of nuclear power plant with some strict for load following.[2-7]

This paper approaches to flexible generation mix problem for 2030 year in Korea eventually, which is called vision 2030. The proposed approach may give more flexible solution rather than too robust plan.

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II. THE CONCEPT OF FLEXIBLE PLANNING

In recently, the uncertainties of external conditions for power system scheduling problem, demand growth, primary energy resource circumstances, reliability of energy supply system and energy security are becoming more and more unmanageable. The uncertainties require more flexible system for preventing power system from the unmanageable collapse. Fig.1 means that the flexible planning and operation for power system is one which,

"Although not necessarily gives the optimum solution for the basic forecasted conditions, yet can keep the reasonable scheduling solution from being significantly worsened by any assumed changes in the surrounding situations" [8,9].

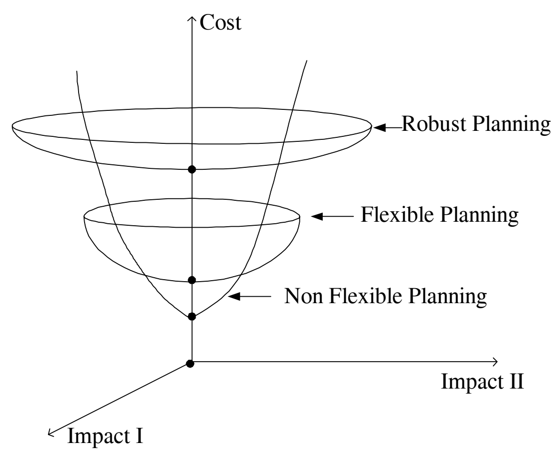


Fig. 1. Concept of flexibility

The useful methods for flexible generators mix problem and generators maintenance flexible scheduling problem using fuzzy LP, DP, IP and search method have been developed by the authors [3-23]. Some cases of application of fuzzy set theory for the flexible planning and operation of power systems are introduced in this seminar. It is expected that more flexible solution can be obtained with the proposed methods because the fuzzy set theory that can reflect the subjective decision of decision-maker is used in these studies. This paper uses fuzzy set theory in order to get a flexible long-term generation mix solution in Korea power system considering CO_2 emission constraint.

III. The LP Formulation of Best Generation Mix

A. Problem statement

This problem can be defined as to determine the generation mix under the following assumptions:

(1) The annual loads are given.
(2) The number of generator is not that of units but that of types.
(3) Nuclear power plants are able to perform load following.

The system for the proposed method can be modeled as shown in Fig. 2.

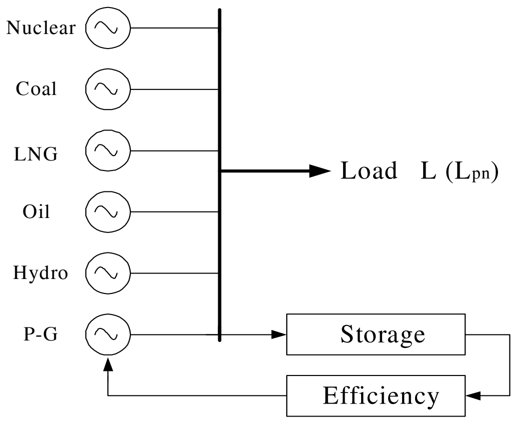


Fig. 2. A system model for the proposed method

In this study, it is assumed that the hydro generator construction is separately planned from that of the other kinds of generation units. In actual system, the basic resources, which are reserves, of the hydro power plants have limitation in the country. Therefore, the choice of hydro plant construction is not much and non-flexible. Under the assumption, the best generation mix problem is formulated as followings.

B. Objective functions

The economic criterion:

The economic criterion in the best generation mix is minimization of the sum of the construction cost and the fuel cost as

$$\text{Minimize } Z = \sum_{n=1}^{N}\sum_{i=1}^{NG} K_{cin}\, d_{in}\alpha_i\, \Delta x_{in} + \sum_{n=1}^{N}\sum_{i=1}^{NG} K_{fin}\, f_{in}\, y_{in}$$

$$= F(\Delta x_{in}, y_{in})$$

where, i: unit type number (1 for nuclear, 2 for coal, 3 for LNG, 4 for oil, and 5 for pumped-storage generators are specified in this paper)

N: number of total study stage year

NG: number of unit type

$K_{cin} = ((1+e_{ci})/(1+r))^{n\,Tn}$

$K_{fin} = ((1+e_{fi})/(1+r))^{n\,Tn}$

e_{ci}: apparent escalation rate of construction materials of i-unit

e_{fi}: apparent escalation rate of fuel of i-unit

r: discount rate

$\Delta T_{k,k-1}$: step size years of study years from k to k-1

d_{in}: construction cost of the i-unit in n year

f_{in}: marginal fuel cost of the i-unit in n year [Won/MWh]

α_i: annual expenses rate of the i-unit

Δx_{in}: construction capacity of the i-unit in n year [MW]

y_{in}: generation capacity of the i-unit in n year [MWh]

C. Constraints

1) Installed capacity constraint

$$\sum_{i=1}^{NG} (x_{in-1} + \Delta x_{in}) + \mathrm{HYD}_n \geq \mathrm{L}_{Pn}(1+\mathrm{R}_n) \quad n=1 \sim N$$

where, R_n: supply reserve rate in n year. [p.u]

HYD_n: capacity of hydro generator in n year. It is assumed that the HYD_n is given in this study.

2) Energy constraint of demand

$$\sum_{i=1}^{NG} y_{in} \geq (\mathrm{L}_{Pn} + \mathrm{L}_{Bn}) \times 8760/2 + V_n - \mathrm{HYD}_n \times 8760 \times \mathrm{CF_H}$$

where, L_{Pn}: peak load at n year

L_{Bn}: base load at n year

V_n: the added demand energy is caused by pumped-storage generator

$\mathrm{CF_H}$: average capacity factor of hydro generator

3) Production energy constraint of generation system

$$y_{in} \leq (x_{in-1} + \Delta x_{in}) \times 8760 \times \mathrm{CF}_i \qquad i=1 \sim NG,\quad n=1 \sim N$$

where, CF_i: average capacity factor of the i-unit

4) Capacity constraint in initial year

$$x_{i0} = \mathrm{EX}_i \qquad i=1 \sim NG$$

where, EX_i: capacity of the i- existing unit

5) Constraint of mutual relationship between existing generator capacity and new generator capacity (state equation)

$$x_{in} = x_{in-1} + \Delta x_{in} \qquad i=1 \sim NG,\quad n=1 \sim N$$

6) Energy constraint of LNG thermal plant

$$y_{3n} \geq \mathrm{LEP}_{\min n} / \rho_3 \qquad n=1 \sim N$$

where, LEPmin_n *:* LNG thermal generator production energy for LNG minimum due to consumption in n year

7) Constraints of reservoir capacity of pumped-storage generator

$$y_{5n} = \eta_g \times Vn$$

where, η_g: efficiency of pumped-storage generator

8) No load following power constraints of nuclear power plant

$(x_{1n}- x_{5n}) \leq L_{Bn}$ $n=1 \sim N$

9) Upper-lower constraints of new unit capacity

$\Delta x_{in} \leq \Delta X_{\max\, in}$ $i=1 \sim NG,\ n=1 \sim N$

where, $X_{\min\, in}$ and $X_{\max\, in}$ are minimum and maximum capacity of new unit at n years(period) respectively.

10) CO_2 air pollution constraint

$$\sum_{i=1}^{NG} \xi_i y_i \leq CO_{2MAXn}$$

where, CO_{2MAXn} : maximum quantity of CO_2 permitted in n year [Ton/yr]

ξ_i : fuel consumption rate of the i- unit [Ton/MWh]

11) SO_X air pollution constraint

$$\sum_{i=1}^{NG} SO_{Xin}\, \xi_i\, y_n \leq SO_{XMAXn}$$

where, SO_{Xin} : SO_X density of the i- unit in n year [ppm/Ton]

SO_{XMAXn} : maximum quantity of SO_X permitted in n year [Ton/yr]

12) NO_X air pollution constrain

$$\sum_{i=1}^{NG} NO_{Xin}\, \xi_i\, y_n \leq NOX_{MAXn}$$

where, $NO_{Xi,n}$: NO_X density of the i- unit in n year [ppm/Ton]

NO_{XMAXn} : maximum quantity of NO_X permitted in n year [Ton/yr]

IV. The Fuzzy LP Formulation of Flexible Generation Mix

A. The Optimal Decision Theory by Fuzzy Set Theory

The fuzzy decision D resulting from q fuzzy goals $G_1,\ldots,G_q$ and p fuzzy constraints $C_1,\ldots,C_p$ is the intersection of them;

$$D = \left(\bigcap_{i=1}^{q} G_i\right) \cap \left(\bigcap_{j=1}^{p} C_j\right) \quad (1)$$

and also its membership function μ_D resulting from fuzzy goals and constraints is defined by

$$\mu_D(\mathbf{x}) = \min\left[\min_{i=1\sim p} \mu_{Gi},\ \min_{j=1\sim q} \mu_{Cj}\right] \quad (2)$$

Where, min is an abbreviation of minimum. The fuzzy mathematical programming problem consists of finding the maximum of the fuzzy decision D.

$$\mu_D(\mathbf{x}^*) = \max\ \mu_D(\mathbf{x}) \quad (3)$$

where $\mathbf{x}^*$ is the optimal decision solution max is an abbreviation of maximum. The vector eq.(3) can be rewritten as the eq.(4) .

$$\mu_D(x_1^*,x_2^*,\ldots,x_N^*) = \max_{x_1 \ldots x_N} \mu_D(x_1,x_2,\ldots,x_N) \quad (4)$$

Fig. 3 shows the concept for optimal decision on fuzzy sets, which is proposed by Bellman Zadeh[6].

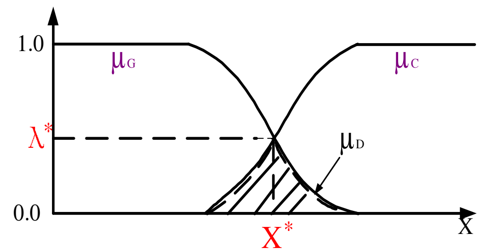


Fig. 3. Concept for optimal decision on fuzzy sets

B. The function of Fuzzy linear programming

Fuzziness of Cost : $Z \lesssim Z_0$

The Satisfaction Level in the best generation mix is flexible because the total cost is unjustly.

Fuzziness of Reliability criterion : $R_n \gtrsim R_{0n}$

The reliability criterion in the long term based best generation mix may be flexible criterion than entirely strict.

Using parameter ▯, therefore, which means satisfaction level physically, best generation mix problem can be formulated as following.

***Objective functions**: Maximize λ*

***Constraints** : Subject to* $F(\Delta x_{in}, y_{in}) + \Delta Z_0 \lambda = Z_0 + \Delta Z_0$

$$\left(\left(\sum_{i=1}^{NG} (x_{in-1} + \Delta x_{in}) + HYD_n\right) - L_{Pn}\right)/L_{Pn} - \Delta R_0 \lambda = R_0 - \Delta R_0$$

$$\sum_{i=1}^{NG} y_{in} \geq (L_{Pn} + L_{Bn}) \times 8760/2 + V_n - HYD_n \times 8760 \times CF_H$$

$y_{in} \leq (x_{in-1} + \Delta x_{in}) \times 8760 \times CF_i$

$x_{i0} = EX_i$

$x_{in} = x_{in-1} + \Delta x_{in}$

$y_{3n} \geq LEP_{minn} / \rho_3$

$y_{5n} = \eta_g \times Vn$

$(x_{1n}- x_{5n}) \leq L_{Bn}$

$\Delta x_{in} \leq \Delta X_{\max\, in}$

$$\sum_{i=1}^{NG} \xi_i y_i \leq CO_{2MAXn}$$

$$\sum_{i=1}^{NG} SO_{Xin}\, \xi_i\, y_n \leq SO_{XMAXn}$$

$$\sum_{i=1}^{NG} NO_{Xin}\, \xi_i\, y_n \leq NOX_{MAXn}$$

V. Case Studies

In order to demonstrate the effectiveness of the proposed method the generation mix is performed on Korea power system, which consists of 6 types generators over 25 years (2006-2030). It is assumed that the initial year is 2006. The step size of planning year is assumed as five years ($\Delta T=5$). The maximum, minimum load and hydro capacity in standard years are listed in table I. The characteristics and economic data are summarized in table II and table III, respectively. [11]

TABLE I
MAXIMUM LOAD, MINIMUM LOAD, AND HYDRO PLANT AT STANDARD YEARS

Years	Peak load L_P [MW]	Base load L_B [MW]	Hydro [MW]	LEP (10^3Ton)
2006	58,990	35,394	1,800	--
2011	65,940	39,564	2,000	4,500
2016	70,050	42,030	2,200	5,500
2021	74,000	44,400	2,400	6,500
2026	77,000	46,200	2,600	7,500
2030	80,000	48,000	2,600	7,500

TABLE II
MAXIMUM LOAD, MINIMUM LOAD, AND HYDRO PLANT AT STANDARD YEARS

Gen. Type	Initial capacity [MW]	Fixed charge [10^5won/kW]	A_{ER} of fixed charge [%]	Marginal fuel cost [Won/kW]	A_{ER} of fuel cost [%]	Annual cost rate [%]	Capacity factor [%]	Fuel consumption rate [Ton/MWh]	Density [ppm/Ton] CO_2, SO_2, NOx
Nucl.	17,716	144.4	3.5	4	1	19	90	--	
Coal	18,465	79.7	3.4	17	1	17	90	0.2300	700 450 500
LNG	17,437	61.4	3.3	67	1	17	60	0.1100	450 200 300
Oil	4,686	153.2	3.3	87	4	17	55	0.2000	600 200 100
P-G	3,300	63.4	3.5	0	0	13	30	--	

(where: A_{ER} means the apparent escalation rate and the discount rate is assumed as 7.5%)

Maximum new construction capacity is limited by limitation of human and equipment resources, etc. It is assumed, as shown in Table III, that the maximum and minimum capacities per a stage year of new generator are same for all stage/year in this study.

TABLE III
MAXIMUM AND MINIMUM OF CAPACITY PER A STAGE YEAR OF NEW GENERATORS ([MW])

Gen. Type	ΔX_{max}	X_{max}
Nuclear	5,000	30,000
Coal	5,000	30,000
LNG	5,000	30,000
Oil	500	2,500
P-G	1,000	5,000

TABLE IV
MAXIMUM PERMISSIBLE LIMITATION OF AIR POLLUTION EMISSION (10^3 [TON/YR])

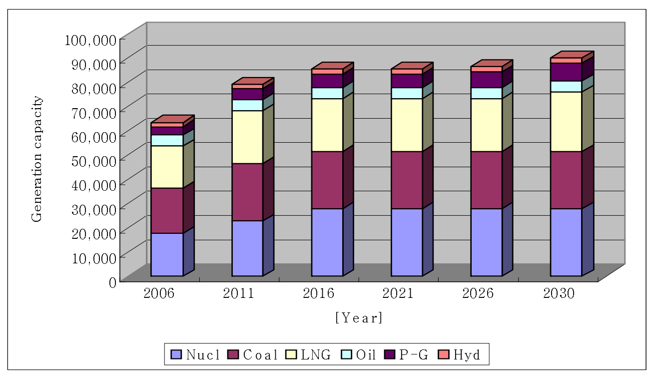
Air pollution	2011	2016	2021	2026	2030
CO_2	40	40	40	40	40
SO_2	40	40	40	40	40
NO_X	40	40	40	40	40

A. Results by Non-Fuzzy model

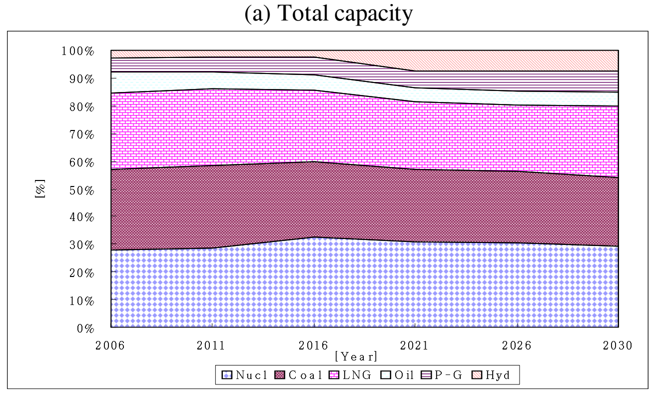
The simulated results in the cases; base case not considering air pollution criterion and case1 considering air pollution criterion, are shown in Table V and Table VI. The proposed fuzzy set theory based on best generation mixes, which are simulated under considering air pollution criterion are different from the generation mix using conventional method. The results yield that the mix of nuclear power plants is increasing and that of coal power plants is decreasing. Fig. 4 and Fig. 5 shows total capacity and percent ratio results for conventional method and proposed method considering air pollution constraints.

TABLE V
BEST GENERATION MIX FOR THE CONVENTIONAL METHODS. [%]

Gen. type	Conventional method (Base Case: Case 0)					
	2006	2011	2016	2021	2026	2030
Nucl	27.94	28.71	32.48	35.51	35.05	33.74
Coal	29.12	29.65	27.50	25.73	25.40	24.44
LNG	27.50	27.75	25.74	24.08	23.77	25.58
Oil	7.39	5.92	5.49	5.14	5.07	4.88
P-G	5.20	5.43	6.21	6.91	7.90	8.65
Hyd	28.4	2.53	2.58	2.63	2.81	2.71



(a) Total capacity



(b) Percent ratio

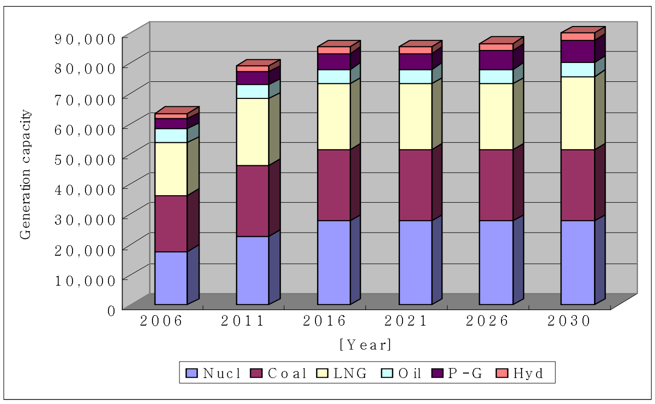
Fig. 4. Best generation mix by Conventional method (case 0)

Table VII and Fig. 6 show the results of sensitivity analysis of permissible maximum for CO_2 constraint. As the air pollution constraints are considered, the mix of nuclear power plant is growing up and the total cost is increasing.

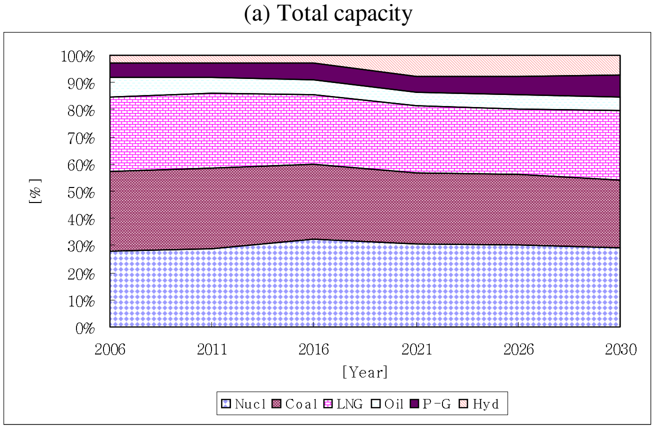
TABLE VI
BEST GENERATION MIX FOR THE PROPOSED METHODS. [%]

Gen. type	Proposed method - APC reinforcement mix (Case 1)					
	2006	2011	2016	2021	2026	2030
Nucl	27.94	28.71	32.47	35.62	35.16	33.91
Coal	29.12	29.65	27.53	25.71	25.38	24.48
LNG	27.50	27.75	25.73	24.03	23.71	25.37
Oil	7.39	5.92	5.49	5.13	5.06	4.88
P-G	5.20	5.43	6.21	6.89	7.88	8.65
Hyd	28.4	2.53	2.58	2.63	2.81	2.71

(where, APC means the air pollution(CO_2, SO_2 and NO_X) constraints)



(a) Total capacity



(b) Percent ratio

Fig. 5. Best generation mix by proposed method with CO_2 air pollution constraint (case 1)

B. Results in Fuzzy model

The proposed fuzzy set theory based best generation mixes which are simulated under considering air pollution criterion are different from the generation mix using conventional method. The results are shown in Table VIII. Where, satisfaction level (Z_0) is 16.5×10^3[billion won] and ΔZ_0 is 10[%] of Z_0. Table IX shows the comparison of costs and satisfaction levels of best generation mix in three cases.

TABLE VII
COST VARIATION ACCORDING TO CHANGING OF THE CO_2 GAS AIR POLLUTION CONSTRAINTS. [BILLION WON]

	Permissible maximum For CO_2 constraint x 10^6 [Ton/yr]	Construction Cost	Operating Cost	Total Cost
Case 0	-	4,475.10	11,238.99	15,714.09
Case 1	40	4,498.82	12,018.50	16,517.32
Case 2	35	4,531.21	12,468.79	17,000.00
Case 3	30	4,563.62	12,919.07	17,482.69
Case 4	25	4,596.02	13,369.35	17,965.37
Case 5	20	4,638.19	13,826.55	18,464.74

[Billion won]

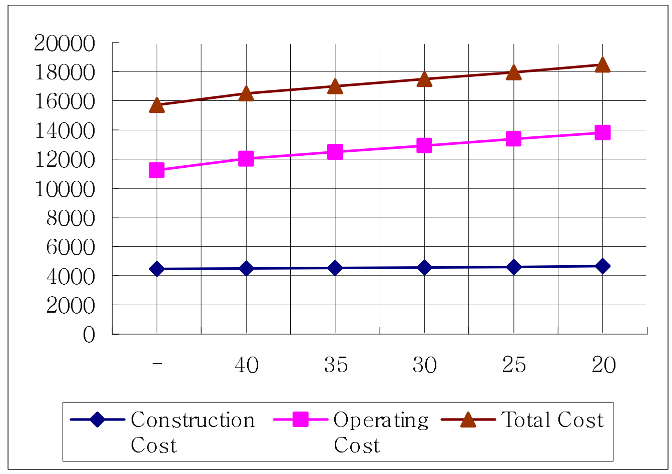


Fig. 6. Construction, fuel and total costs variation according to gas emission constraints.

TABLE VIII
BEST GENERATION MIX FOR APC REINFORCEMENT MIX USING FUZZY SET THEORY [%]

Gen. type	Proposed method - APC reinforcement mix					
	2006	2011	2016	2021	2026	2030
Nucl	27.94	28.71	32.47	35.62	35.16	33.91
Coal	29.12	29.65	27.53	25.71	25.38	24.48
LNG	27.50	27.75	25.73	24.03	23.71	25.37
Oil	7.39	5.92	5.49	5.13	5.06	4.88
P-G	5.20	5.43	6.21	6.89	7.88	8.65
Hyd	28.4	2.53	2.58	2.63	2.81	2.71

TABLE IX
TOTAL COST EVALUATION OF BEST GENERATION MIX IN THE THREE CASES. [Billion Won]

	Construction Cost	Operation Cost	Total Cost	Satisfaction Level
Conventional method (Case 1)	4,498.82	12,018.50	16,517.32	-
Mix without APC (Case FA1)	4,475.10	11,238.99	15,714.09	0.98
Mix with APC (Case FB4)	4,498.82	12,018.50	16,517.32	0.49

Table X and Fig 7 show the relationship between Z_0 and satisfaction level for various aspiration targets using fuzzy set theory. As satisfaction level of 0.1 point increases, the total cost increases about 150 billion [Won]. Where, the abbreviation, APC means air pollution constraint of CO_2, SO_X and NO_X. The result recommends informs about the incremental rate value of cost in order to make one unit of satisfaction level higher.

TABLE X
SATISFACTION LEVEL VARIATION ACCORDING TO CHANGING OF COST ASPIRATION LEVEL

	Cases	Aspiration level z_0 [10^3Billion won]	Satisfaction level λ
APC not considered Cases	Fuzzy A1	16.5	0.98
	Fuzzy A2	16.4	0.92
	Fuzzy A3	16.3	0.86
	Fuzzy A4	16.2	0.80
APC considered Cases	Fuzzy B1	17.4	1.00
	Fuzzy B2	17.1	0.84
	Fuzzy B3	16.8	0.67
	Fuzzy B4	16.5	0.49

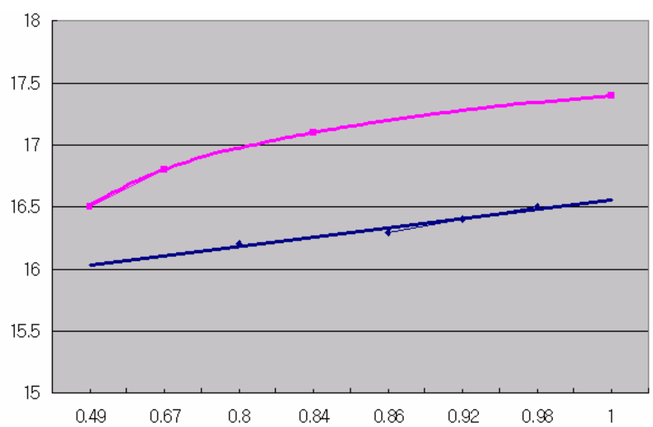


Fig. 7 Satisfaction level variation according to changing of cost aspiration level

VI. CONCLUSIONS

In this paper, an alternative approach for the long-term generation mix with multi-criteria considering air pollution constraints, which are not only SO_2 and NO_X but also CO_2 emission limitations is proposed using linear programming. The effectiveness of the proposed approach is demonstrated by applying to the best generation mix problem of Korea power system, which contains nuclear, coal, LNG, oil and pumped-storage hydro plant in multi-years. This paper approaches to generation mix problem for 2030 year in Korea eventually. The result is nuclear 33.9[%], coal 24.5[%], LNG 25.4[%], and pumped-storage generator 8.7[%]. The method can accommodate the operation of the pumped-storage generator which has a relationship with operation of nuclear power plant with some strict for load following. This case study in this paper is mainly focused on CO_2 emission limitation effect in the best generation mix. The CO_2 air pollution constraint is more strict, the nuclear or LNG power plant construction is recommended as shown in the case study although the total cost is increasing. So the increasing cost is called the cost for air pollution constraints. The cost for air pollution constraints is [0.82Won/kWh]. Although it is just an example, it is will basic date of carbon dioxide emission trading market. From sensitivity analysis between satisfaction level and cost, decision makers can obtain informs of the incremental rate value of cost in order to make one unit of satisfaction level higher.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES

[1] Hisham Khatib, *Economic Evaluation of Projects in the Electricity Supply Industry*, IEE Power & Energy Series 44., MPG Books Limited, Bodmin. Cornwall, 2003

[2] Hongsik Kim, Seungpil Moon, Jaeseok Choi, Soonyoung Lee, Daeho Do, and Madan M. Gupta. Generator Maintenance Scheduling Considering Air Pollution Based on the Fuzzy Theory, *IEEE International Fuzzy Systems Conference Proceedings*, August, Vol. III, pp. 1759~1764, 1999.

[3] Ministry of Commerce, Industry & Energy, The 3rd basic plan for long term electricity supply and demand (2006~2020), December 2006.

[4] Hongsik Kim, Seungpil Moon, Jaeseok Choi, Soonyoung Lee, Daeho Do, and Madan M. Gupta, “Generator Maintenance Scheduling Considering Air Pollution Based on the Fuzzy Theory”, IEEE International Fuzzy Systems Conference Proceedings, Vol. III, pp. 1759~1764, August, 1999.

[5] W.J.M. Kikert, Fuzzy theories on decision-making, Martinus Nihoff, 1978.

[6] H.J. Zimmermann, Fuzzy Set Theory and Its Applications, Kluwer-Nijhohh Boston, pp.220-234, 1986.

[7] Jaeseok Choi, TrungTinh Tran, Jungji Kwon, A(Rahim) A. El-Keib and Junzo Watada, "Emissions Constrained Multi-Criteria-Best Generation Mix Using Fuzzy Dynamic Programming" IJICIC(International Journal of Innovative Computing, Information and Control), Vol.3 No.1, pp.41-52, Feb., 2007.

[8] Fumio Arakawa et al., Energy Security Assessment Quantitative Analysis for Flexible System Planning, *CIGRE SC-37*, Florence, Oct., 17-20, 1989

[9] K. Takahadshi et al., Power Systems Flexibility Principles and Means, Available Methods at the Planning Stage, *CIGRE SC-37*, Brussels, Feb.5, 1988.