Analysis of the Economic and Environmental Effects of Renewable Portfolio Standards with DECADES

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Abstract - This paper analyzes the environmental impact and economic effect of introducing the Renewable Portfolio Standard (RPS) into the Korean electricity market using the DECADES (Database and Methodologies for Comparative Assessment of Different Energy Sources for Electricity Generation) model, a comparative assessment tool developed by IAEA. A bottom up approach is adopted for the evaluation of air pollutant emission and its impact of several RPS scenarios. The environmental damage costs of RPS scenarios are evaluated based on the Extern-E results and the Thailand externality study carried out by EGAT. The results of this study can be applied in determining or analyzing the national electricity policy and energy policy.

Keywords: DECADES, environmental impact assessment, renewable energy, renewable portfolio standard

1. Introduction

The global electricity industry is rapidly being transformed into a market framework. The introduction of competition seems to be making a huge impact on the energy market. In particular, the penetration of environmentally friendly renewable energies and technologies into the market are much swifter thanks to the introduction of competition in the electricity industry. This phenomenon is already been observed in many countries that have adopted the market mechanism. These countries have vigorously developed and studied new systems, energy policies and economic assessment techniques to promote the technologies using alternative energies. In this study, a brief introduction of the DECADES model, which is designed to comprehensively analyze the generating technologies in economic and environmental aspects, is made, and the emission factors and costs of various generating technologies are derived by use of DECADES. With these and the various study results on quantification of environmental impacts, the economic and environmental effects of RPS, while it is introduced in Korean, is analyzed.

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2. DECADES Program

2.1 Structure of DECADES

The DECADES program was developed by the International Atomic Energy Agency (IAEA). It consists of DBs, the optimization module and several assistant sub-modules for long term resource planning. It uses the Energy-Chain concept and has advantages over prevalent power planning models such as WASP and EGEAS in environmental impact assessment. Therefore, this model could be useful in building technology DBs including renewable energy technologies and dynamic analysis of generation technologies. On the basis of this program, deeper economic analysis of generation technologies following the ESI deregulation and environmental regulation could be possible [3].

DECADES' DB consists of Country Specific DB (CSDB) and Reference Technology DB (RTDB). The information in RTDB could be used as a reference [2]. CSDB basic data such as energy resources, their constitution and technologies are core elements of CSDB and they are used to formulate the energy chain.

2.2 Economic and Environmental Impact Analysis using DECADES

Plant level analysis, Energy chain analysis and System level analysis could be performed by way of DECADES. In order to accurately analyze the generation alternatives, the assessment should be based on the entire energy chain. With the generation alternatives for system capacity expansion having been selected, each alternative's annual energy production costs, levelized generation costs, amount of pollutant emission, land use and wastes could be assessed. However, plant level analysis is insufficient for the complete consideration of environmental impacts.

The major step of CO2 emission in the energy chain is the incineration of fossil fuel. However, CO2 emission during construction and abolition is also significant in comparing the alternatives. In fuel chain analysis of the alternatives, the entire energy chain related to electricity generation from mining and extraction to waste disposal is analyzed. In this analysis, the fuel's transportation path, amount of fuel production, costs and environmental impacting materials such as air pollutant emission, green house gas emission, liquid waste production, solid waste production and land use are quantitatively assessed at each step. In addition, the environmental impact caused by auxiliary inputs such as electricity, other fuel and materials for construction and abolition are also considered.

System level analysis could be used for minimum cost generation expansion planning with consideration of environmental impacts or for the assessment of long term projects. For optimization of the expansion plan, investment costs, O&M costs, fuel costs, fuel inventory costs and unserved energy costs are considered. DECADES's system level analysis function also enables a screening test and the comparison of energy chain mixes.

3. Analysis of Renewable Portfolio Standards

In this study, an algorithm for the quantitative assessment of economics and environmental benefits (such as reduction of CO2 emission) of the Renewable Portfolio Standards mechanism using DECADES is suggested and it is applied to the Korean electricity system. Several RPS scenarios, in other words, the obligatory percentage, are considered. The amount of pollutant emission, environmental costs and total costs were assessed for each RPS scenario.

3.1 DB Construction and Load Preparation

In order to analyze the economic and environmental impacts using DECADES, firstly the CSDB must be formulated. The CSDB consists of characteristics of fuels or energies used for electricity generation and those of technology chains. Fuel characteristics were derived from 'The draft of the 1st Basic Plan of Long Term Electricity Supply and Demand, KPX 2002', 'Fuel and Combustion Manual, KEPCO 1998' and 'Environment management and chemical works records, KEPCO 1997'. Technology (or Energy) chain information was based on 'Generating Facility Statistics, KPX 2001' and 'The draft of the 1st Basic Plan of Long Term Electricity Supply and Demand, KPX 2002'. For the complete life cycle analysis, information on every step of the energy chain, for example, mining, extraction, transportation, electricity generation and waste extraction and waste disposal are required. However, because the air pollutant emission at other steps is relatively insignificant compared with that from electricity generation and because currently it is difficult to obtain detailed data, only electricity generation technology data is used for this study. Thus, only the air pollutant emission by electricity generation is considered. Fig. 1 indicates the air pollutant emission at each step in the coal fired electricity generation technology chain. It can be found that the emission at step VI, the electricity generation step, is dominant.

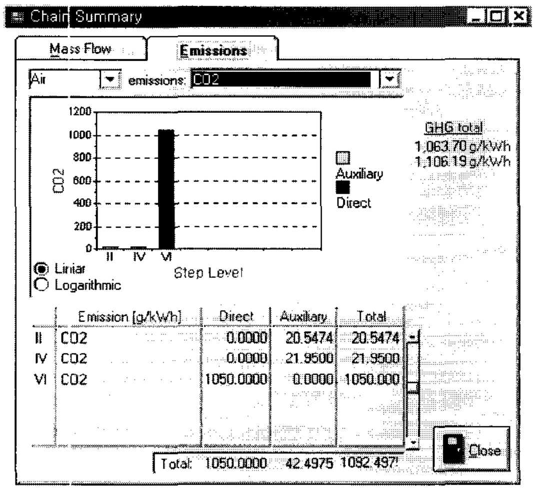

Fig. 1 CO2 emission of coal fired electricity generation at each step

RPS is generally defined as a mechanism to promote renewable energy use by enforcing utilities or load serving entities to supply a certain percentage (determined by government) of their electricity sales produced by renewable energies. One of the problems in analyzing renewable energies is that non-dispatchable renewable energies like wind power and solar power cannot be modeled in DECADES. Thus, in order to consider renewable energies, external load adjusting could be utilized. In this study, annual energy adjusting is utilized instead of the huge time and data demanding hourly load adjusting. To adjust load reflecting renewable energies, 'LOADSYS automatic generation package' developed by Dr. Jong Bae Park is used.

3.2 Optimal Expansion Plans and Pollutant Emissions

Optimal expansion plans are elicited for the case with no RPS and that with RPS of 0.1%, 0.5%, 1%, 2%, 3%

Table 1 Electricity generation of RPS scenarios by fuel type

Unit: GWh

Obligatory Percentage	Hydro	Nuclear	Bituminous	Anthracite	Oil	LNG	Renewable	Sum
RPS 0%	130,920	2,012,247	1,564,932	447,298	228,783	863,485	0	5,247,665
RPS 0.1%	130,920	2,012,117	1,562,653	446,240	228,750	861,650	5,250	5,247,580
RPS 0.5%	130,920	2,010,769	1,553,067	445,477	228,166	852,748	26,248	5,247,395
RPS 1%	130,920	2,008,949	1,540,607	444,034	227,589	842,375	52,495	5,246,969
RPS 2%	130,920	2,004,737	1,515,186	442,681	225,937	821,553	104,990	5,246,004
RPS 3%	130,920	2,02,7123	1,484,774	423,883	222,951	797,701	157,485	5,244,837
RPS 5%	130,920	1,990,750	1,446,894	418,125	219,862	772,624	262,475	5,241,650

Table 2 Amount of pollutant emission by RPS scenario

Unit : Thousand Ton

Scenario	SOx	NOx	Particulae	CO_2
RPS 0%	9,835	492,642	100,528	1,751,159
RPS 0.1%	9,831	491,640	100,056	1,749,248
RPS 0.5%	9,793	488,425	99,865	1,739,275
RPS 1%	9,743	484,472	99,041	1,727,253
RPS 2%	9,619	477,151	98,041	1,701,979
RPS 3%	9,399	461,860	95,636	1,668,197
RPS 5%	9,159	451,274	93,642	1,630,760

Table 3 Environmental costs applying Extern-E result

Unit : 100Billion Won

Scenario	Lower value			Sum	Upper value			Sum
의무비율	SOx	NOx	Part	합계	Sox	Nox	Part	합계
RPS 0%	467	27,136	8,285	35,888	800	44,541	16,600	61,941
RPS 0.1%	467	27,080	8,246	35,794	800	44,451	16,522	61,773
RPS 0.5%	465	26,903	8,231	35,599	797	44,160	16,490	61,447
RPS 1%	463	26,686	8,163	35,311	793	43,803	16,354	60,950
RPS 2%	457	26,282	8,080	34,819	783	43,141	16,189	60,112
RPS 3%	446	25,440	7,882	33,768	765	41,758	15,792	58,315
RPS 5%	435	24,857	7,718	33,010	745	40,801	15,463	57,009

and 5%. To acquire the optimal expansion plans, the ELECSAM module of DECADES was used. The ELECSAM module is a modified model of WASP to enable the use of DECADES DB. The ELECSAM module uses dynamic programming for optimization and it can consider reserve margin constraint, LOLP constraint and spinning reserve constraint. Table 1 shows the electricity production of each scenario by fuel type and Table 2 presents each scenario's amount of emission of SOx, NOx, particulate and CO2. It can be easily found that the amount of pollutant emission decreases with a higher RPS rate. With these results, it can be identified that DECADES works properly.

3.3 Environmental Costs and Total Costs

For calculating social costs incurred by pollutant emission, the two methods of Top-down approach and Bottom-up approach can be used. Generally, the pathway approach (bottom-up approach) is the most ideal. However, to apply this approach, huge amounts of information including metrological data, population distribution, geological data and etc. are required. In the case of European countries, they have invested an enormous budget into the Extern-E project and constructed a database of this information. In the case of developing countries like Korea, recognition of the importance of the environment is insufficient and it is also difficult to obtain funds for this type of study. Therefore, it could be meaningful to utilize other countries' study results for the calculation of environmental costs. Moreover, the Korea Electric Power Corporation performed the study project entitled 'The Study on the Social Costs of the Electricity Industry' in 1997 and calculated the costs of environmental impacts by

Table 4 Environmental costs applying Thailand's results

Scenario	Lower value			Sum	Upper Value			Sum
	Sox	NOx	Part		Sox	NOx	Part	
RPS 0%	15	0	1,922	1,937	81	0	14,173	14,254
RPS 0.1%	15	0	1,913	1,928	81	0	14,107	14,188
RPS 0.5%	15	0	1,910	1,925	81	0	14,080	14,160
RPS 1%	15	0	1,894	1,909	80	0	13,964	14,044
RPS 2%	15	0	1,875	1,889	79	0	13,822	13,902
RPS 3%	14	0	1,829	1,843	77	0	13,483	13,561
RPS 5%	14	0	1,791	1,805	75	0	13,202	13,278

pollutants from power plants. Since the KEPCO's results are within the range of Extern-E project results and Thailand's study results, these values are not considered in this study [8]. In this study, environmental costs per ton of pollutant emission are calculated by use of the Extern-E result and the Electricity Generation Authority of Thailand's study result. If human impacts by pollutants are assumed to be equal, the values from Extern-E and EGAT could be directly adopted.

Table 5 Environmental cost of Korea

Environmental costs applying Extern E results		
	low	high
Sox	4,750	8,136
Nox	5,508	9,041
Part	8,242	16,513
Environmental costs applying EGAT results		
Korea	low	high
Sox	153	823
Part	1,912	14,099

However, in this study, the willingness to pay for the avoidance of the impacts is assumed to be different in each country and the environmental costs per ton of pollutant emission are assumed to be proportional to Purchasing Power Parity GDP (PPPGDP). The income elasticity index is the coefficient used to express the possibility of non proportional cost increase with increased income due to the rapid rise in the willingness to pay with income increase above a certain level or to prevent the gap between advanced countries and under developed countries in regards to environmental costs. Of course, it is extremely difficult to obtain this index. In this study, it is assumed to be one, in other words, environmental costs are proportional to PPPGDP. Table 3 illustrates the environmental costs of Korea calculated on the basis of Extern E and Thailand's environmental costs. The total environmental costs of each scenario were calculated based on environmental costs in Table 3 and the amount of pollutant emission by each scenario. Table 4 and Table 5 show the results.

The total cost of each scenario was elicited by adding the system costs or objective function of ELECSAM, externally calculated renewable energy capital as well as variable costs and environmental costs. Table 6 shows each scenario's total cost while Extern E's upper and lower limit values were applied. It was found that the total cost of the higher RPS rate is lower. This is the result of much greater environmental costs compared with the costs of renewable energies. Table 7 presents the results of applying Thailand's upper and lower values of environmental costs. While the lower value of Thailand's study was applied, RPS 0.1% scenario had the lowest total cost. The reason the higher RPS rate scenario has higher total costs different from the results applying other environmental costs is that the investment cost increase following the RPS rate increase is higher than the environmental cost increase. From these, it can be known that the relative merits among scenarios depend on the cost per ton of pollutant emission. To analyze this relationship more closely, merits of RPS scenarios are reviewed by use of the decision aiding tool, DAM equipped in DECADES.

Table 6 Total cost of RPS scenarios applying Extern-E results

Scenario	Applying lower value					Applying upper value				
	Traditional energy cost①	Ren. Energy cost②	Internal cost ①+②	Env. cost③ (External)	Total cost ①+②+③	Traditional energy cost①	Ren. Energy cost②	Internal cost ①+②	Env. cost③ (External)	Total cost ①+②+③
RPS 0%	841	-	841	35,888	36,729	841	-	841	61,941	62,782
RPS 0.1%	842	4	846	35,794	36,640	842	4	846	61,773	62,619
RPS 0.5%	842	21	863	35,599	36,462	842	21	863	61,447	62,310
RPS 1%	846	42	888	35,311	36,199	846	42	888	60,950	61,838
RPS 2%	854	85	939	34,819	35,758	854	85	939	60,112	61,051
RPS 3%	867	127	994	33,768	34,762	867	127	994	58,315	59,309
RPS 5%	841	212	1,054	33,010	34,063	841	212	1,054	57,009	58,063

Table 7 Total cost of RPS scenarios applying Thailand's result

Scenario	Applying lower value					Applying upper value				
	Traditional energy cost①	Ren. Energy cost②	Internal cost ①+②	Env. cost③ (External)	Total cost ①+②+③	Traditional energy cost①	Ren. Energy cost②	Internal cost ①+②	Env. cost③ (External)	Total cost ①+②+③
RPS 0%	841	-	841	1,937	2,778	841	-	841	14,254	15,095
RPS 0.1%	842	4	846	1,928	2,774	842	4	846	14,188	15,034
RPS 0.5%	842	21	863	1,925	2,787	842	21	863	14,160	15,023
RPS 1%	846	42	888	1,909	2,797	846	42	888	14,044	14,932
RPS 2%	854	85	939	1,889	2,828	854	85	939	13,902	14,840
RPS 3%	867	127	994	1,843	2,837	867	127	994	13,561	14,555
RPS 5%	841	212	1,054	1,805	2,858	841	212	1,054	13,278	14,331

3.4 Comparison between RPS Scenarios

To make comparative assessment of RPS scenarios, benefit/cost analysis and trade-off analysis by use of the DAM model were performed. The DAM model utilizes the interval decision methodology to solve multi attribute decision-making problems. Contrary to general trade-off analysis tools that require exact value for the trade-off, the DAM model can perform 'Imprecise trade-off' analysis. In imprecise trade-off analysis, the traditional definition of optimality cannot be applied. Therefore, the definition is modified. Following are the definitions used in the DAM model.

Definition 1. If alternative A has the highest score within a given boundary, alternative A is the Optimal Alternative.

Definition 2. If alternative A1 satisfies the following two conditions, alternative A1 dominates alternative A2 Pareto Optimally;

A1 is not lower than A2 in every attribute,

A1 is superior to A2 in at least one attribute.

Definition 3. If no other alternative dominates alternative A in the Pareto aspect, alternative A is the efficient alternative.

Definition 4. If the total score of alternative A1 is higher than that of alternative A2 within the given bounds, alternative A1 outperforms alternative A2.

Definition 5. If any alternative outperforms A1, A1 is called the outperformed alternative and if no alternative outperforms A1, A1 is called the non-outperformed alternative.

Definition 6. With given sets of bounds, if the total score of alternative A1 is highest, alternative A1 is the potential optimal.

The DAM module has the following four functions.

① Pareto Dominance Test: The information required for this test is the values of alternatives' attributes. This test performs examination based on definition 2. The result is expressed in three colors. If the alternative in the row dominates the alternative in the column, the color of the

Table 8 Result of B/C analysis

Scenario	Applying Extern-E Environmental Costs					
	Lower			Upper		
	Cost	Benefit	B/C	Lower	Upper	Lower
RPS-0.1%	5	94	17.30	5	169	30.98
RPS-0.5%	22	267	12.09	22	494	22.38
RPS-1%	47	530	11.19	47	992	20.94
RPS-2%	98	971	9.93	98	1829	18.70
RPS-3%	153	1966	12.84	153	3626	23.68
RPS-5%	213	2665	12.53	213	4932	23.18
Scenario	Applying Thailand's Environmental Costs					
	Lower			Upper		
	Cost	Benefit	Cost	Benefit	Cost	Benefit
RPS-0.1%	5	9	1.66	5	67	12.21
RPS-0.5%	22	13	0.58	22	94	4.25
RPS-1%	47	29	0.60	47	210	4.44
RPS-2%	98	48	0.49	98	352	3.60
RPS-3%	153	94	0.62	153	693	4.53
RPS-5%	213	133	0.62	213	976	4.59

cell is red, if dominated, blue and if no decision can be made, yellow.

② Outperformance Test: This test is based on definitions 4 and 5. For this test, users provide weighting values required for trade-off. Like the dominance test, the result is expressed in colors. If the alternative in the row outperforms the alternative in the column, the color of the cell is red, if outperformed, blue and if no decision can be made, yellow.

③ What-If Test: This test checks the outperformance among alternatives alternating the weighting factor for trade-off. For example, we can find the outperformance of the alternative depending on the unit cost of SOx emission. The expression of the result is identical to the above two tests.

④ Potential Optimality Test: This test is based on definition 6. The results are different from other tests. It provides whether each alternative can be optimal or not and the set of weighting values where each alternative can be optimal.

Table 8 shows the benefit/cost analysis results. Benefit is assumed as the difference between the environmental costs of the reference plan without RPS and the expansion plan with RPS. Cost is defined as the difference between the internal cost of the reference plan without RPS and that of the plan with RPS. In B/C analysis, the RPS 0.1% has the highest B/C ration regardless of unit environmental cost. Only the RPS 0.1% scenario has a B/C ratio bigger than that one when the lower unit environmental cost of Thailand is applied. With B/C analysis, the most cost effective option can be found, but the least cost option cannot be found.

As told, the DAM model has 4 analysis functions, Pareto Dominance Test, Outperformance Test, Optimality Test and What-If Test. For the comparative assessment of RPS scenarios, system costs, the investment and O&M costs of renewable energies, the amount of SOx emission, the amount of NOx emission and the amount of particulate emission were inputted as attributes of alternatives. For the trade-off among attributes, unit costs of pollutants were used.

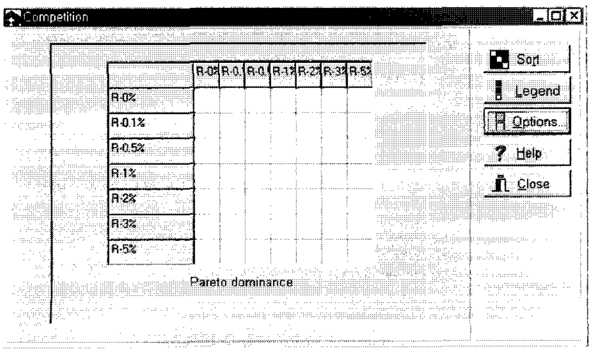

Fig. 2 Pareto Dominance Test Result

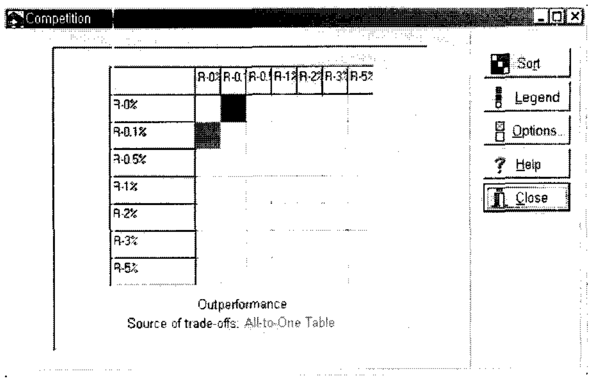

Fig. 3 Outperformance Test Result

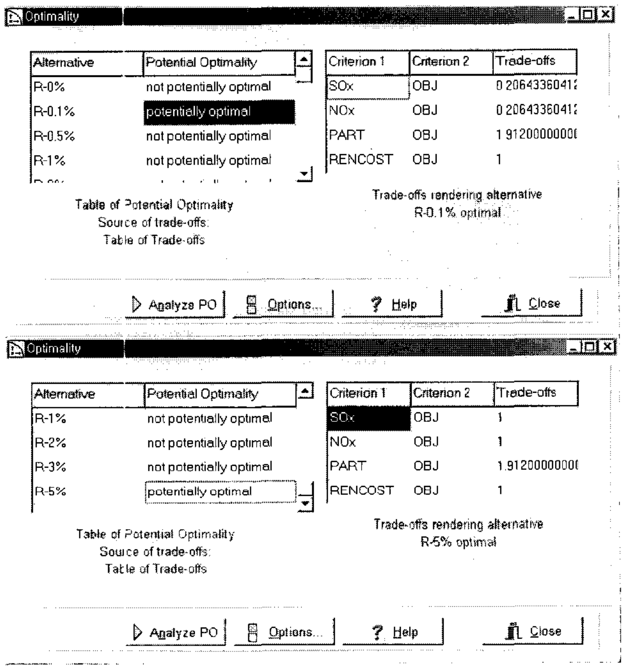

Fig. 4 Optimality Test Result

Fig. 2 indicates the result of the Pareto Dominance Test. The definition of Pareto Dominance is that one alternative is not worse than the other alternative in every attribute and is better than the other alternative in at least one attribute. It is shown that no alternative is Pareto Dominant. This is a natural result, because with higher RPS rate, the system cost decreases and the pollutant emission decreases.

Fig. 4 presents the result of the outperformance test. Outperformance is defined as the case in which the total score of a certain alternative is higher than that of the other within the given bounds. It was discovered that RPS 0.1% alternative outperforms RPS 0% alternative, i.e. the expansion plan without RPS. Therefore, once the weighting factor bounds are proper, it can be concluded that RPS should be adopted.

Fig. 4 shows the result of the optimality test. It was found that RPS 0.1% and RPS 5% could be potentially optimal alternatives. The right hand side table shows the weighting values (unit cost of pollutant emission) at which each alternative became the optimal. The RPS 0.1$ alternative can be an optimal when the unit emission costs of SOx and NOx are 206.4 thousand won/ton and that of the particulate is 1,912 thousand won/ton. On the contrary, the RPS 5% alternative can be optimal when SOx and NOx costs are 1,000 thousand won/ton.

Figs. 5, 6 and 7 indicate the results of the What-If tests. Fig. 5 shows the outperformance among alternatives following the change of unit cost of SOx emission. The RPS 0.1% alternative outperforms the RPS 0% alternative regardless of SOx cost. RPS 3% outperforms RPS 2% once the unit cost of SOx emission is higher than 4,304 thousand won/ton. If the SOx cost is higher than 6,778 thousand won/ton, RPS 5% outperforms RPS 2%. No additional outperformance among alternatives was discovered even when the SOx cost was higher.

Fig. 6 provides the outperformance among alternatives following the change of unit cost of NOx emission. The merit among alternatives was found to be very sensitive to this cost. This is because the amount of NOx emission calculated is greater than other pollutants. Once the unit cost of NOx emission is higher than 271.2 thousand won/ton, the RPS 5% alternative, having the highest renewable energy share, is optimal.

Fig. 7 shows the outperformance among alternatives following the change of unit cost of particulate emission. While the unit cost of particulate emission is higher than 3,226 thousand won/ton, the RPS 5% alternative outperforms other alternatives.

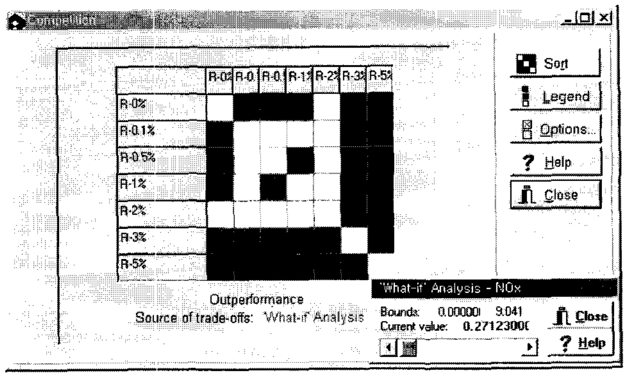

Fig. 6 What-If Test Result Varying Unit NOx cost

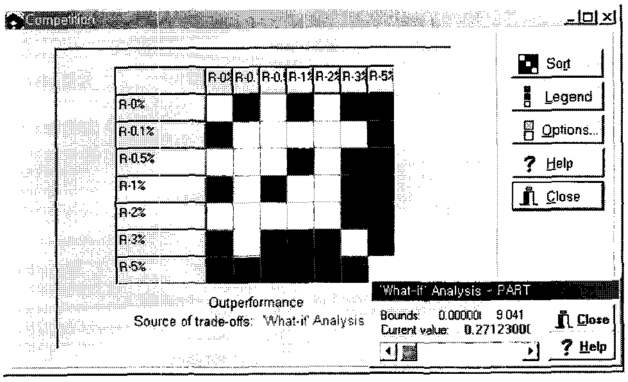

Fig. 7 What-If Test Result Varying Unit Particulate cost

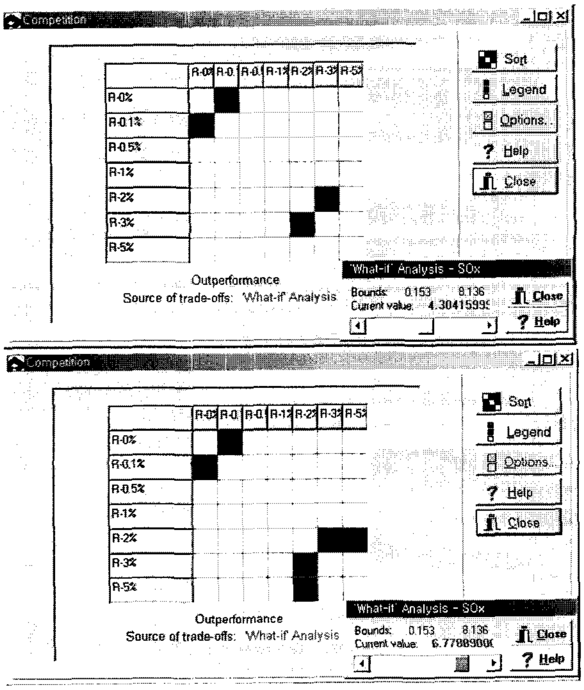

Fig. 5 What-If Test Result Varying Unit SOx cost

Taking advantage of the emission factors and costs of various generating technologies from DECADES and the various study results on quantification of environmental impacts, the economic and environmental effects of RPS, while introduced in Korean, is analyzed. The change of pollutant emission amount, environmental costs and total costs for each RPS scenario were calculated. And, by use of these values as attributes, comparative assessment among scenarios was made. At the benefit/cost analysis, the RPS 0.1% scenario was found to be most efficient. However, because benefit/cost analysis cannot find the least social cost RPS percentage, the comparative assessment among RPS scenarios was made with varying unit emission costs by use of the DAM model.

In the Pareto Dominance test, no alternative was Pareto Dominant. In the Outperformance test, it was found that the RPS 0.1% alternative outperforms the expansion plan without RPS. Through the Optimality test, it was determined that RPS 0.1% and RPS 5% are potentially optimal. The RPS 0.1% scenario could be optimal when the unit cost of SOx and NOx emission are 206.4 thousand won/ton respectively and the unit cost of particulate emission is 1,912.0 thousand won/ton. The RPS 5% scenario could be optimal when the unit costs of SOx and NOx emission are 1,000 thousand won/ton.

Through the What-If test, the outperformance among alternatives following the change of unit cost of emissions and the merits among alternatives was found to be very sensitive to the unit cost of NOx emission. The reason for this phenomenon seems to be that the amount of NOx emission calculated is much greater than other pollutants. Once the unit cost of NOx emission is higher than 271.2 thousand won/ton, the RPS 5% alternative, having the highest renewable energy share, was found to be optimal.

On the basis of the above tests, we can conclude as follows.

① The RPS 0% option should not be selected. It is based on the observation that if given emission costs are in the reasonable region, the RPS 0% option is always inferior to the RPS 0.1% option.

② The RPS 1%, RPS 2%, RPS 3% and RPS 4% options are not inferior to a certain option. With the given range of unit emission cost, it is not confident that these options are inferior to RPS 0.1% or RPS 5%. However, if unit emission costs are fixed in the given range, the total costs of these options are always bigger than RPS 0.1% or RPS 5%. Therefore, it is a better decision not to select one of them.

③ It seems most beneficial to make a final decision between RPS 0.1% and RPS 5%. The unit cost of NOx emission and that of particulate emissions are two major factors for making the final decision. The unit cost of SOx emission is the less important factor. Further study on whether the NOx cost is higher than 271.2 thousand won/ton and whether the particulate cost is higher than 3,226 thousand won/ton is required in order to formulate a decision between the two options of RPS 0.1% and RPS 5%.

4. Conclusion

In this study, an introduction to the DECADES model was made, and the economic and environmental effects of RPS, while it is introduced in Korean, is analyzed. Using the emission factors and costs of various generating technologies derived by DECADES combined with the study results of other countries, we elicited environmental damage costs of pollutants by power plants. The result of this study could be utilized in formulating national energy or electricity industry policies related to renewable energies and could also be useful for long term direction for the promotion of renewable energies. Due to the absence of national data, we utilized the Extern-E and Thailand's study results. In order to obtain better and localized results and to complete pathway analysis not performed in this study, further studies on dose-response curve, estimation of environmental costs and construction of DB are greatly needed. Because this kind of study requires such huge funding, it seems advantageous to make a cooperative study among northeastern Asian countries.

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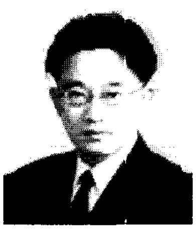

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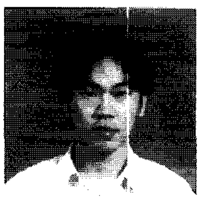

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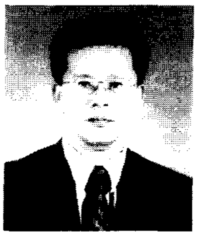

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