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An Analytical Method of Constructing Best-mixed Power Generation Systems Reflecting Public Preference

by

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Abstract

An investigation of energy consumer's preference for the power generation was performed. It was found that most consumers gave their preference to a value 'social acceptability' and to 'environmental effect' in constructing the energy system. An analytical method to evaluate the best-mixed power generation system to meet the consumer's preference was developed. It was applied to evaluate each best-mixed system meeting with a preference of each consumer. The resulting best-mixed system was largely composed of the natural gas fired system and the hydraulic power generation system. And the other powers with disadvantages in terms of the 'social acceptability' and/or 'environmental effect' were hardly introduced. The duality theorem allowed us to evaluate the marginal cost of consumers' preference. The 'social acceptability' yielded the highest marginal cost, and the 'environmental effect' was the next.

Keywords : Best-mix, Analytical Hierarchy Process, Linear programming method, Duality theorem, Marginal cost

1. Introduction

There are many controversial issues in terms of energy problem. Energy suppliers are now forced to take into account the environmental effects and the safety at the cost of less commercial profit. Although they intend to build more nuclear plants, sometimes it is difficult facing to the opposing people who fear the risk of severe accident or the waste disposal from the nuclear plants. On the other hand, energy consumers expect alternative natural energy resources such as the solar energy as the main energy resources in the near future. However, at this moment, it is presumed that the natural energy resources are rather expensive and their technologies are yet immature. Unfortunately, three participants of the

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energy society: suppliers, consumers and the government hardly evaluate uncountable values of energy resources, or the energy externalities because of complexity and variety. Under this situation, arguments on the future energy system among the participants are often confused.

Recently, especially after 1980, in the field of nuclear engineering many subjects about the best-mixed power generation system, or simply the 'best-mix' have been discussed recognizing the externality of nuclear power. In Japan, Mankin et al.[1] estimated a gain on investment for small- or middle-scale nuclear reactor in the future, and predicted that it would be compatible with that for large-scale reactor. Ohkubo et al.[2] produced a new model to simulate the future energy best-mix, and using their model they showed an advisability of the nuclear power for the Japanese policy. The authors also evaluated the roles of nuclear energy in terms of energy security of this country [3]. In other countries, Afanasiev[4] revealed an economical advantage of Russian nuclear power over other types of power generation using an idea of marginal cost.

After the agreement of the Kyoto Protocol, marginal cost estimations for the reduction of greenhouse gas emissions have been focused in the field of environmental engineering. Kainuma[5] reviewed several economic models to achieve the Kyoto Protocol Standard, and pointed out that Japan had higher marginal cost to reduce the CO_2 emissions than other countries. Yoshida et al.[6] proposed new energy model minimizing the power generation cost, and predicted that the marginal cost to reduce the CO_2 emissions would become higher dramatically when the growth of nuclear power generation approached to its saturation. Jackson[7] compared some technologies for the reduction of greenhouse gas emissions based on their marginal costs.

However, few discussions have focused on constructing energy system reflecting consumers' preference. Thus we have developed a method to know the public preference for values by questionnaire[8], and to establish the best-mix which reflects the preference[9,10]. In this study, applying this method, a survey on energy consumers' preference was conducted, and the best-mix which reflects the preference was evaluated. In the analysis, the linear programming algorithm was applied; with the duality theorem, marginal costs for various external values were also evaluated.

2. Analytical Method

2.1 Investigation of energy consumer's preference

A questionnaire shown in **Fig. 1** examines consumers' preference for the following five values: economical efficiency, convenience, energy security, environmental effect and social acceptability, which are classified by the factor analysis as the essential values regarding the energy related problems. Except for the economical efficiency, all of the remaining four values might be regarded as the external values. The questionnaire is composed of ten questions based on the AHP (Analytical Hierarchy Process), a multivalues decision support method designed to make overall ranking table of preference for values; e.g., "Which value do you regard more important in constructing the power generation system, economical efficiency or environmental effect? " All of preferences for each value are normalized to be between 0 and 1.

Please choose one suitable for your idea.
(a) more important than (b) a little more important than (c) as important as
(d) a little less important than (e) less important than

Q1. Economical efficiency is ___________ convenience.
Q2. Economical efficiency is ___________ energy security.
Q3. Economical efficiency is ___________ environmental effect.
Q4. Economical efficiency is ___________ social acceptability.
Q5. Convenience is ___________ energy security.
Q6. Convenience is ___________ environmental effect.
Q7. Convenience is ___________ social acceptability.
Q8. Energy security is ___________ environmental effect.
Q9. Energy security is ___________ social acceptability.
Q10. Environmental effect is ___________ social acceptability.

Fig. 1 Questionnaire to investigate a consumer's preference for values

2.2 Performance of power generation system

In constructing the best-mixed power generation, the following eight systems are employed: oil fired (OIL), coal fired (COA), natural gas fired (LNG), hydraulic (HYD), photovoltaic (SOL), light water reactor (LWR), high temperature gas cooling reactor (HTGR), and fast breeder reactor (FBR) power generation systems. An assessment of these systems is performed in terms of five values described above, and the performance scores of each system for each value are evaluated.

As shown in **Table 1**, several specifications related to each value are selected; e.g., capital cost, maintenance cost and fuel cost are taken to assess the value 'economical efficiency'. Similarly, emissions of CO_2, SO_x, NO_x and radioactive waste are chosen for assessment of the value 'environmental effect'. The quantitative specifications such as costs or amount of emissions of exhaust are available from literatures. These are carefully determined referring the latest publications. However, some qualitative specifications, such as 'technological maturity', contained in **Table 1** are difficult to evaluate. To do this, the AHP is applied.

All specifications thus evaluated are weight averaged and summed up to give the performance score of values. The weights are also determined by the AHP. The performance scores of each system are tabulated in **Table 2**. These are reduced to the standard deviation scores, where zero indicates an average. If a score is positive, it is superior to the average performance, and if negative, it has less performance.

2.3 Linear Programming

Figure 2 illustrates the process to find the best-mix applying the linear programming method (LP)[9,10]. The preferences of five values, which vary depending on examinees, are the input to LP. The LP searches the solution that minimizes the total cost to construct the best-mix. The problem is formulated as follows:

Table 1 Values and Specifications to evaluate the performance of power generation systems

Value	Specification
Economical efficiency	Capital cost
	Maintenance cost
	Fuel cost
Convenience	Technological maturity
	Energy density
	Easiness to handle the waste
Energy security	Amount of resource
	Distribution of resource
	Easiness of fuel storing or self-supplying
Environmental effect	CO_2 emission
	SO_x emission
	NO_x emission
	Radioactive waste
Social acceptability	Human damage
	System risk
	Local agreement
	Possibility of large-scale accident

Table 2 Performance scores of eight systems

	OIL	COA	LNG	HYD	SOL	LWR	HTGR	FBR
Economical efficiency	0.388	0.388	0.460	0.191	-2.464	0.465	0.286	0.268
Convenience	0.241	-0.339	0.285	0.576	-0.501	-0.279	0.037	-0.020
Energy security	-0.861	-0.729	-0.843	1.254	1.254	-0.352	-0.352	0.629
Environmental effect	-0.542	-1.247	-0.114	0.693	0.478	0.242	0.242	0.242
Social acceptability	-0.054	-1.065	0.296	0.035	1.274	-0.140	-0.140	-0.207

$$\text{Minimize} \quad z = \sum_{i=1}^{8} c_i x_i, \tag{1}$$

$$\text{subject to} \quad \sum_{i=1}^{8} S_{ij} x_i \geq b_j \quad (j = 1, \cdots, 5) \tag{2}$$

$$\sum_{i=1}^{8} x_i = 1 \tag{3}$$

$$x_i \geq 0 \quad (i = 1, \cdots, 8) \tag{4}$$

where x_i and c_i are the composition and power generation cost of the system i, respectively. b_j is the preference for the value j, S_{ij} the performance score of the system i for value j. Only x_i is unknown and c_i, b_j, and S_{ij} are fixed during minimization. The right hand side of **Eq.(1)** is the total cost to be minimized. **Equation(2)** imposes a requirement that a sum of the product to the performance score S_{ij} and the composition x_i with respect to all power generation system should exceed the preference b_j of the value j. Each value of c_i is tabulated in **Table 3**. To solve the LP, the simplex algorithm is adopted.

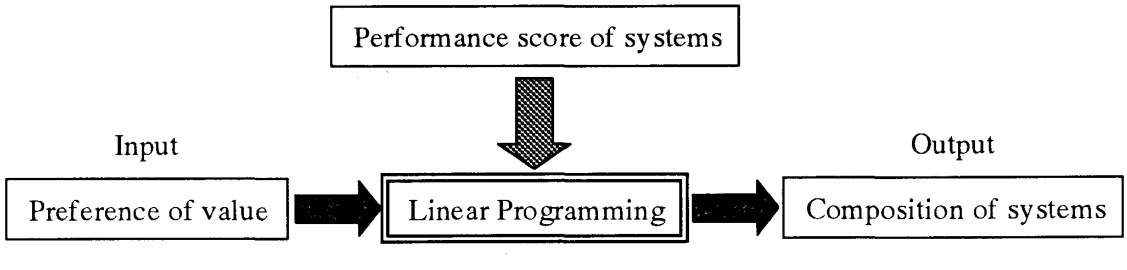


Fig. 2 Process to find the best-mixed power generation

Table 3 Power generation costs of eight systems

	OIL	COA	LNG	HYD	SOL	LWR	HTGR	FBR
Power generation cost [yen/kWh]	10.96	10.96	10.23	12.96	40.00	10.17	12.00	12.00

2.4 Dual problem

The duality theorem belongs at the center of the underlying concept of the LP, which gives the dual problem formulated as follows:

$$\text{Maximize} \quad w = \sum_{j=1}^{5} b_j y_j + y_6, \tag{5}$$

$$\text{subject to} \quad \sum_{j=1}^{5} S_{ij} y_j + y_6 \leq c_i \quad (i = 1, \cdots, 8) \tag{6}$$

$$y_j \geq 0 \quad (j = 1, \cdots, 5) \tag{7}$$

where y_j, the variable in the problem, gives the marginal costs of the constraint conditions of the primal problem.

The implication of the marginal cost (or the shadow price) is very important. Taking the emission trading as an example, the interpretations of the primal problem and its dual are presented below.

Suppose a situation: A new law for the power generation is enacted. To assess the power generating system i, the law defines their performance scores for values j to yield the score table S_{ij}, and also defines the regulation of each value b_j. All of energy suppliers must keep the guideline written in **Eq.(2)**. However, a supplier failing to the regulation is allowed to buy a surplus score from other suppliers. A price of the score traded can be decided through a negotiation between them, and the price is determined from demand and supply.

Suppliers will face the primal problem when they try to minimize the total cost for constructing the power generation system, however they have to do this with guideline. When a supplier can afford to sell his surplus score, the dual problem is arise. With a price y_i per unit score of value j his total benefit is given by **Eq.(5)**. Although he shall wish to be the benefit as high as possible, **Equation(6)** determines its upper limit. To let other suppliers buy his score, the price charged to the performance of a system should not exceed the power generation cost of the system. Otherwise, other suppliers never buy his score.

According to the duality theorem, the minimized total cost for power generation of a buyer is the same to the maximized total benefit of a seller. Therefore, even though a supplier decides either to meet all regulations by himself or to buy scores from other suppliers, both costs are equal.

Furthermore, the complementary slackness condition in the theorem tells us that if a buyer had score over the regulation for a value, the price of the value yields zero. In other words, if a buyer has just met the regulation for a value, that value is priced.

3. Results and Discussions

3.1 Preference

A survey was conducted from October to December in 1999. **Figure 3(a)** shows the result of individual preference for values obtained from the survey. The abscissa and the ordinate are the percentage of examinees and their preference, respectively. **Figure 3(b)** shows the result of the averaged preference. A preference 0.2 indicates an average. If an examinee regards that a certain value is more important than the average, its preference is above 0.2,

About 90% of the examinees thought that the value 'social acceptability' was above the average importance, and the 'environmental effect' and 'energy security' were the next. Few examinees put their preference on the 'economical efficiency' and 'convenience'.

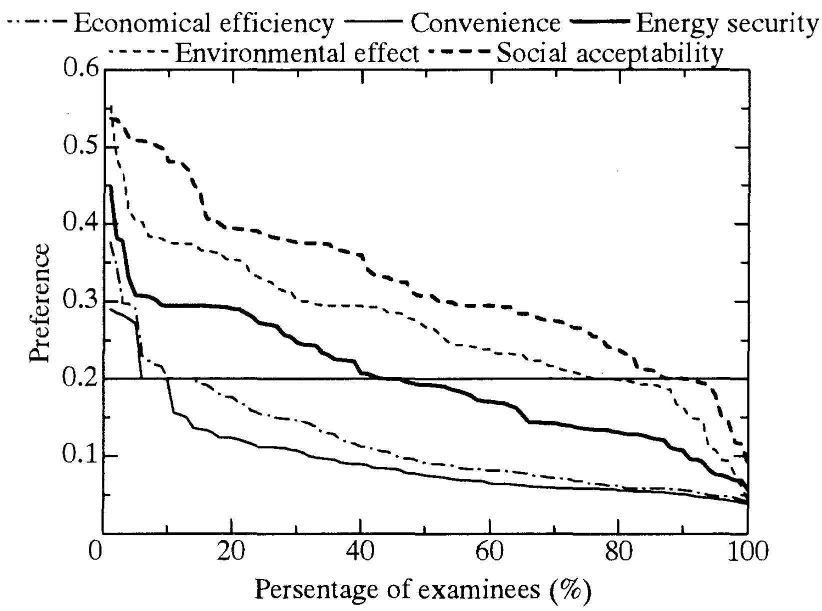
3.2 Best-mixed power generation system

Figure 4(a) shows the best-mix to accord with examinees' preference evaluated individually by the procedure described above. The abscissa and the ordinate are the percentage of examinees and the composition of each power generation system in the best-mix, respectively. **Figure 4(b)** shows the best-mix averaged.

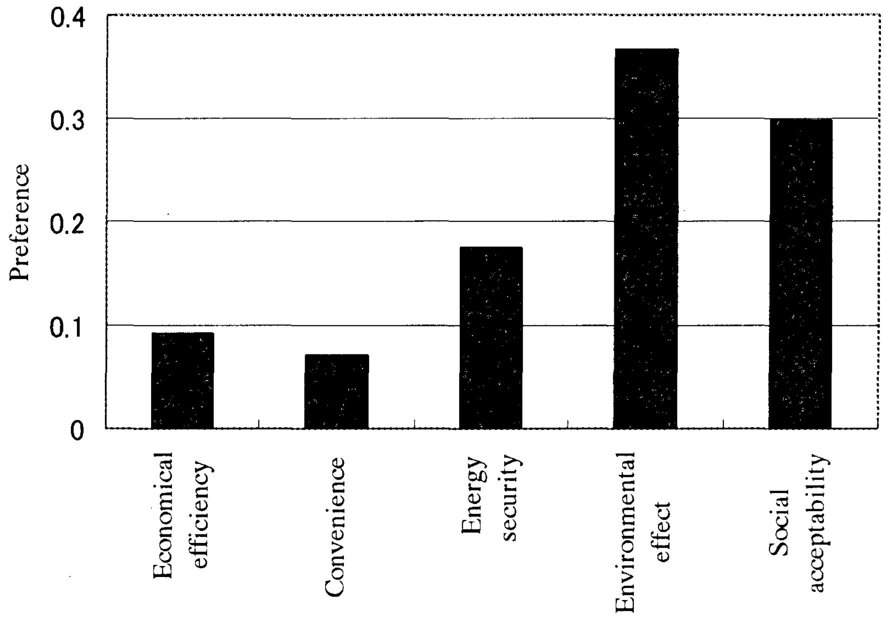
LNG and HYD comprised large part in most of the best-mix evaluated for all examinees' preference. This was reasonable because these power generation systems have relatively higher performance scores for the social acceptability as tabulated in **Table 2**.

Some best-mixes contained small compositions of SOL and LWR. Although SOL had the best score for the social acceptability in all systems, its economical score was considerably lesser than the others. Therefore, it was involved only in the best-mix of an examinee who regarded the social acceptability as extremely important. The reason for including LWR was that it had the average performance for all values.

The best-mix that contained OIL, COA, HTGR and FBR hardly appeared. OIL and COA had few advantages except for economical efficiency and convenience, which were not thought important much. HTGR and FBR had average performances almost the same as LWR, but the lower economical performances were disadvantage.

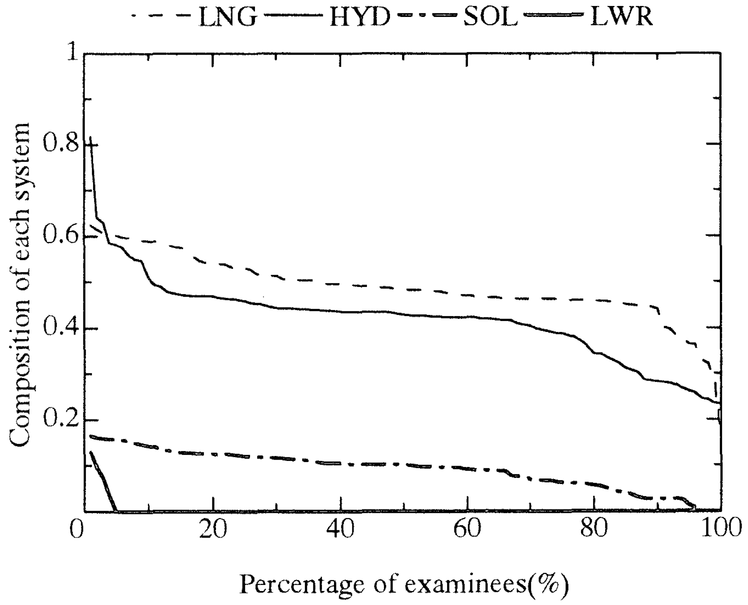


(a)

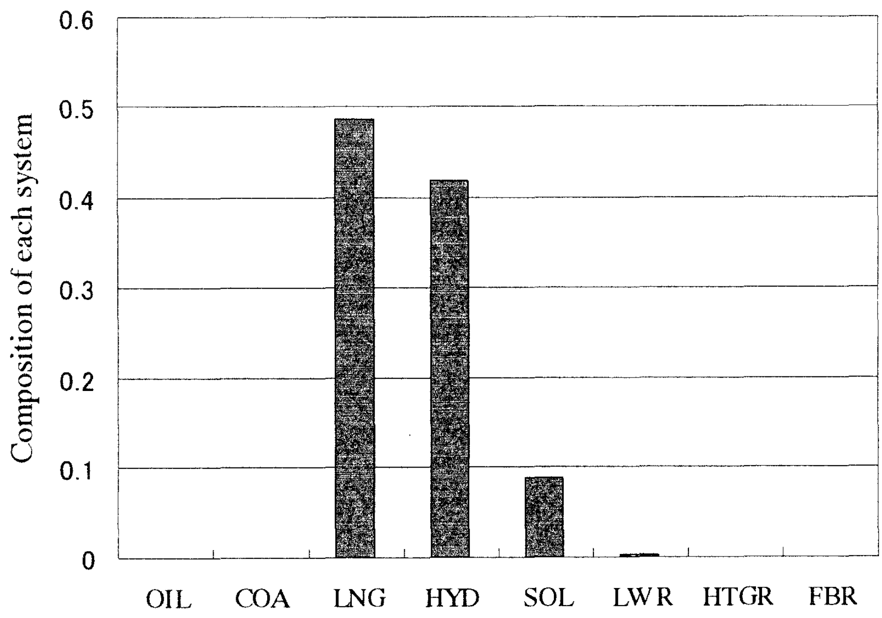


(b)

Fig. 3 Preference of each value (a)individual (b)averaged



(a)



(b)

Fig. 4 Composition of each system in the best-mix (a)individual (b)averaged

3.3 Marginal costs

Figure 5(a) shows the marginal costs of values calculated individually for all examinees' preferences. The abscissa and the ordinate are the percentage of examinees and the marginal cost of each value, respectively. **Figure 5(b)** shows the marginal costs averaged. The highest marginal cost of the social acceptability meant that most examinees approved the highest level of expense for the social acceptability. It made this result agreeable that the marginal costs of environmental effect and energy security follows. As mentioned above, these values were regarded as important next to the social acceptability. The fact that the marginal costs of economical efficiency and convenience were consistently zero was also remarkable. This was interpreted that all examinees were going to spend no expense for these values since their requirements for these values had been already satisfied.

In addition, the term $b_j y_j$ in **Eq.(5)** represents an examinee's willingness to pay for the value j, since y_j is the price of the value j while b_j the amount of the value, which the examinee demands. And $S_{ij} y_j$ in **Eq.(6)** is a monetary value of the value j of the system i in terms of the price of electricity.

Figure 6 shows the price of willingness to pay for values averaged. The price for the social acceptability is the most expensive. **Figure 7** shows the monetary value of values of the systems averaged. LNG and HYD took part in the best-mix since high score for social acceptability of LNG, energy security and environmental effect of HYD got high appraisals, respectively. The monetary value of SOL for social acceptability was the highest. But SOL took only a part of the best-mixed power generation system for the reason that the power generation cost of SOL was more prohibitive than its value. There were the cases that SOL took in the best-mix and the other cases LWR did.

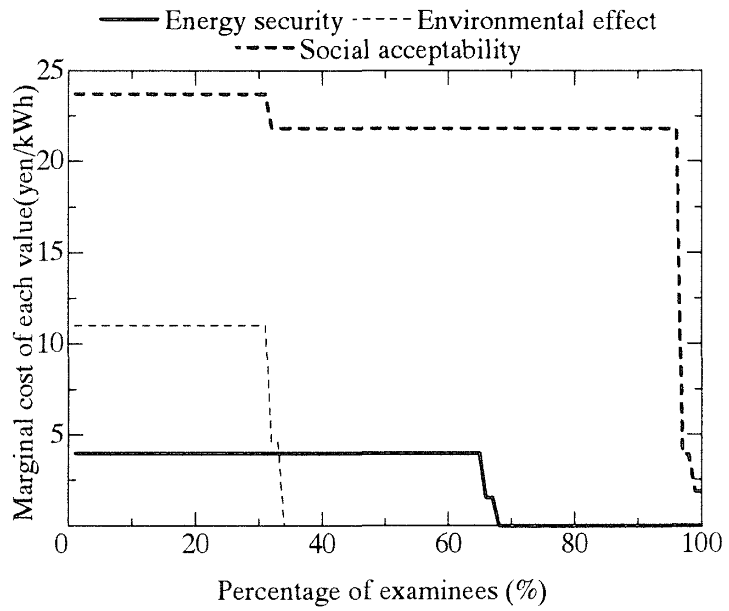
Figure 8 and **9** show the preference of an examinee A and his best-mix, respectively. **Figure 10** shows his willingness to pay for values. He was willing to pay only for the social acceptability and the energy security. **Figure 11** shows the monetary value of each power generation system for value. The energy security of HYD, the social acceptability and the energy security of SOL were highly evaluated. The SOL, however, did not take part in his best-mix, since the power generation cost of SOL was more expensive than his appraisal of that.

Figure 12 and **13** show the preference of an examinee B and his best-mix, respectively. **Figure 14** and **15** show his willingness to pay for values and the monetary value of each power generation system. He was willing to pay only for the social acceptability and the environmental effect with very high appraisal of the high score of the social acceptability of SOL. By the merit, SOL was called in the best-mix.

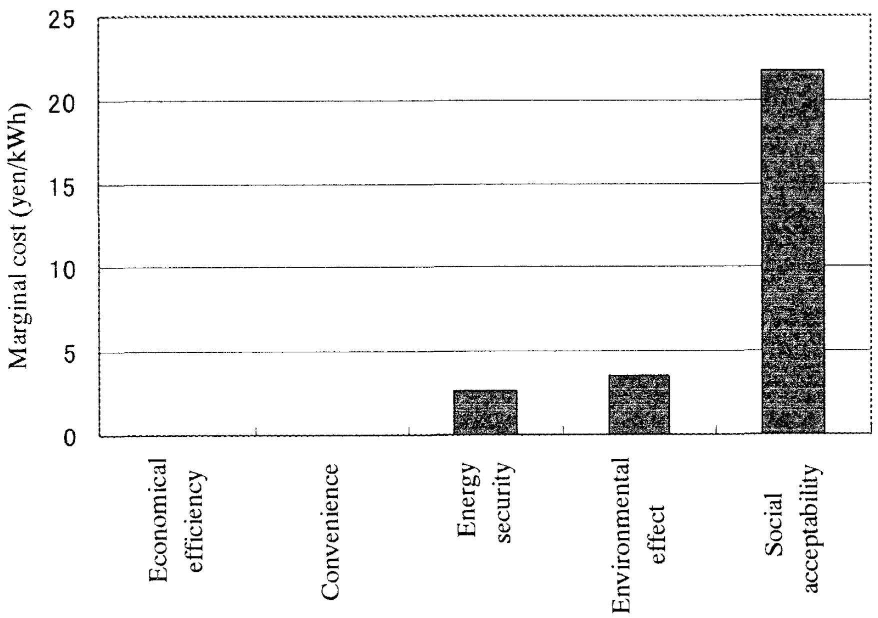
4. Conclusions

The primal problem to find the best-mixed power generation system for energy consumers was discussed. The linear programming approach could solve the problem, and the best-mix was evaluated individually according to the preference of each consumer. The dual problem that the duality theorem derived from the primal problem was discussed. A solution of the dual problem gave the marginal costs of values for consumers' preference.

The survey of energy consumers' preference told us that the examinees tended to attach most importance to the social acceptability, and in their best-mixes the LNG and HYD took larger part than the others. It was understood from the resulted marginal costs that most examinees approved the highest expense for the social acceptability. It is regarded that the prices representing the 'willingness to pay' for values in constructing the best-mix are obtained by the marginal cost.



(a)



(b)

Fig. 5 Marginal cost for each value (a)individual (b)averaged

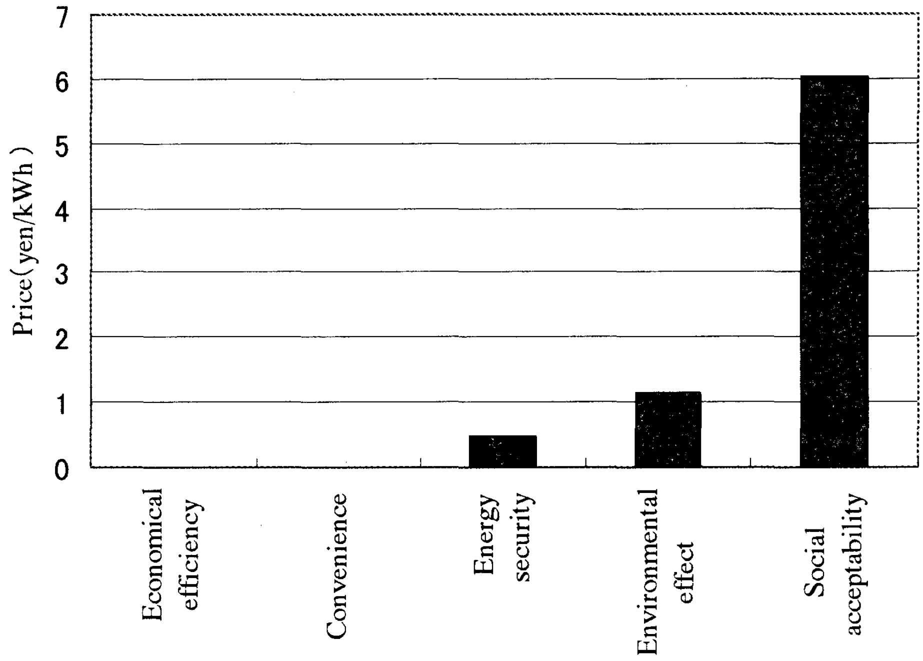


Fig. 6 Willingness to pay for each value averaged

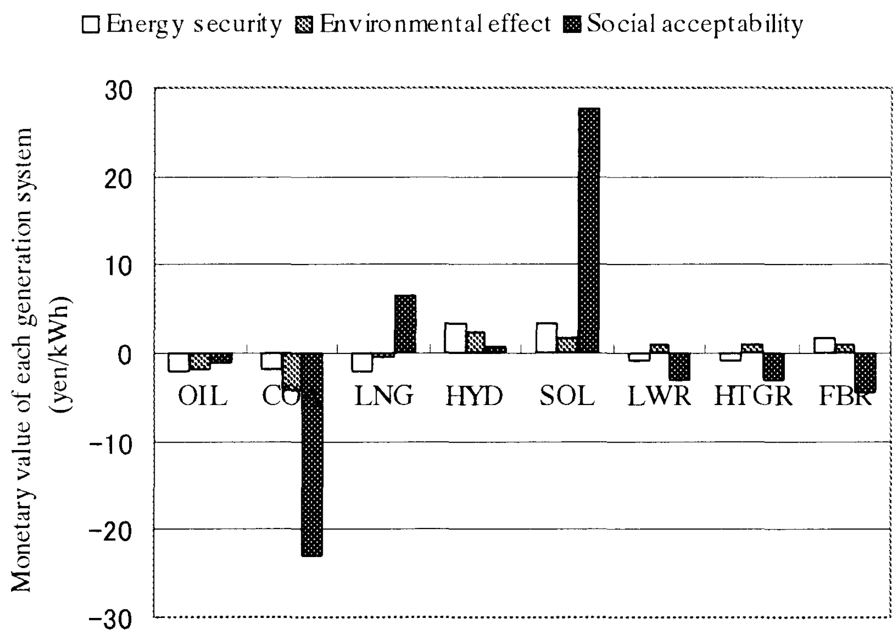


Fig. 7 Monetary value of each system averaged

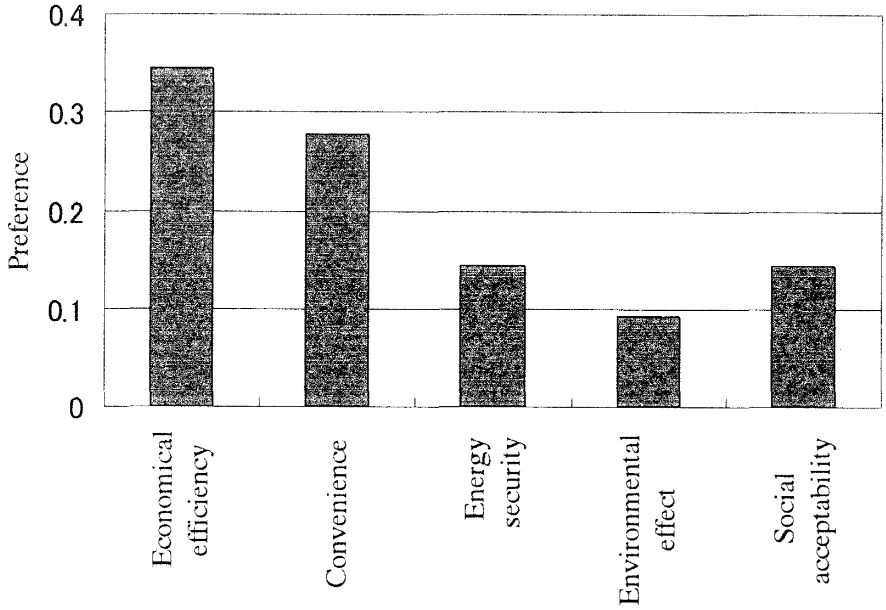


Fig. 8 Preference of each value (Examinee A)

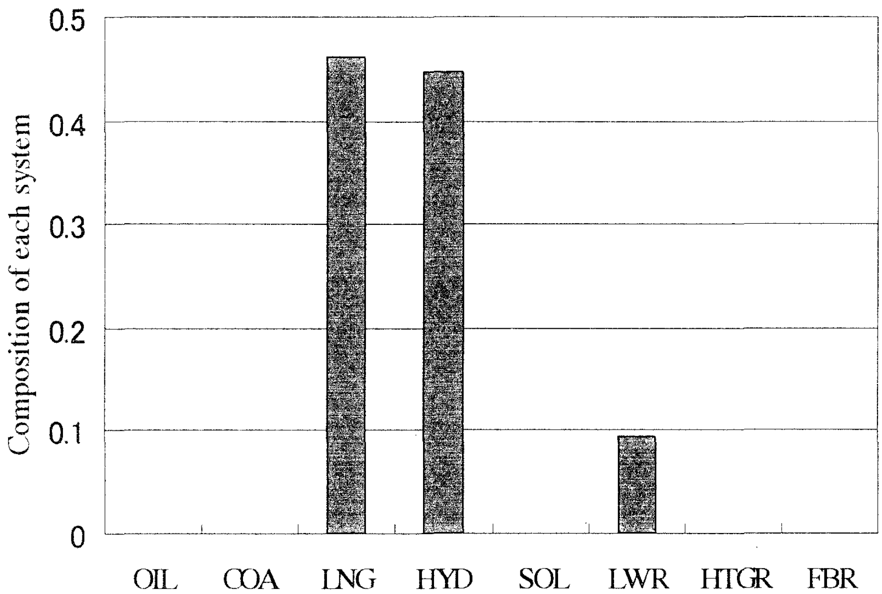


Fig. 9 Composition of each system in the best-mix (Examinee A)

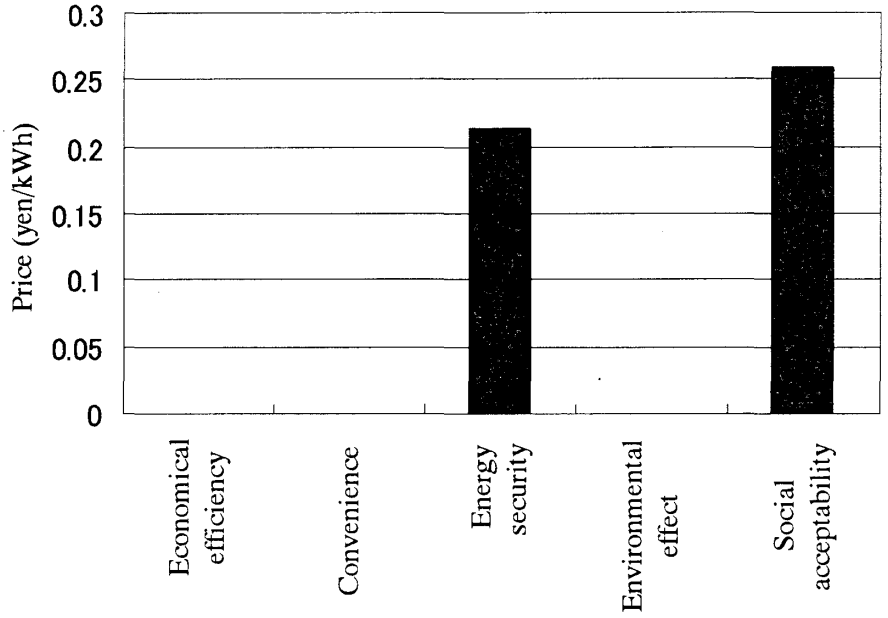


Fig. 10 Willingness to pay for each value (Examinee A)

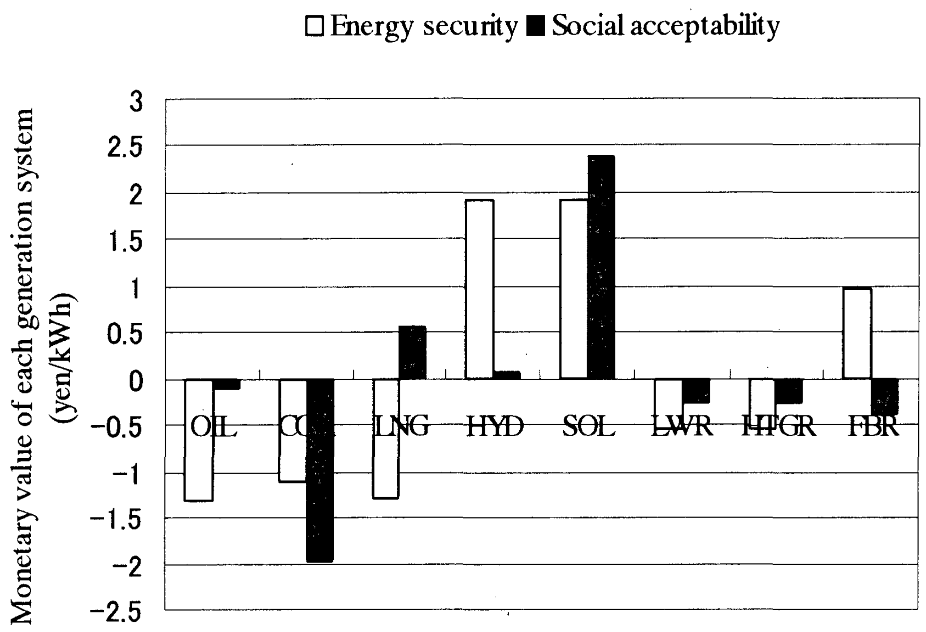


Fig. 11 Monetary value of each system (Examinee A)

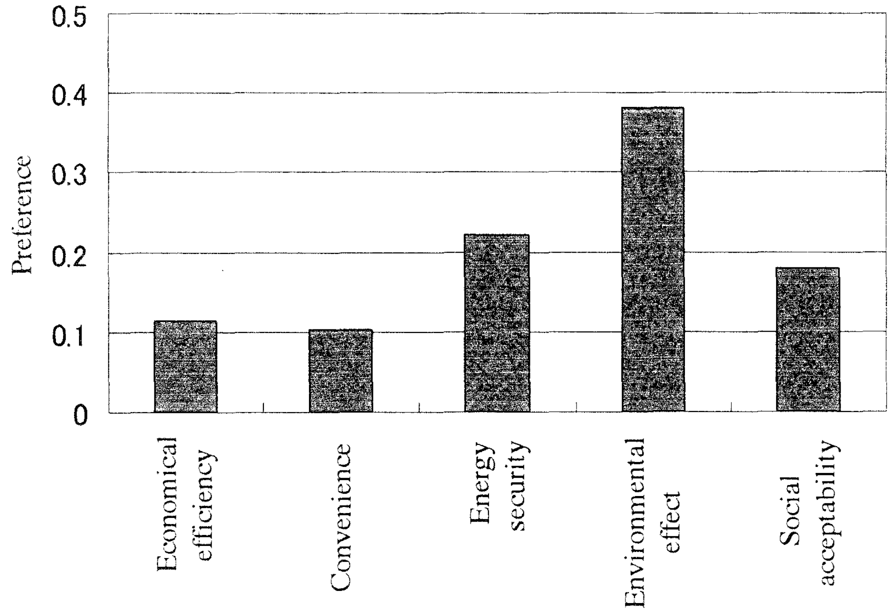


Fig. 12 Preference of each value (Examinee B)

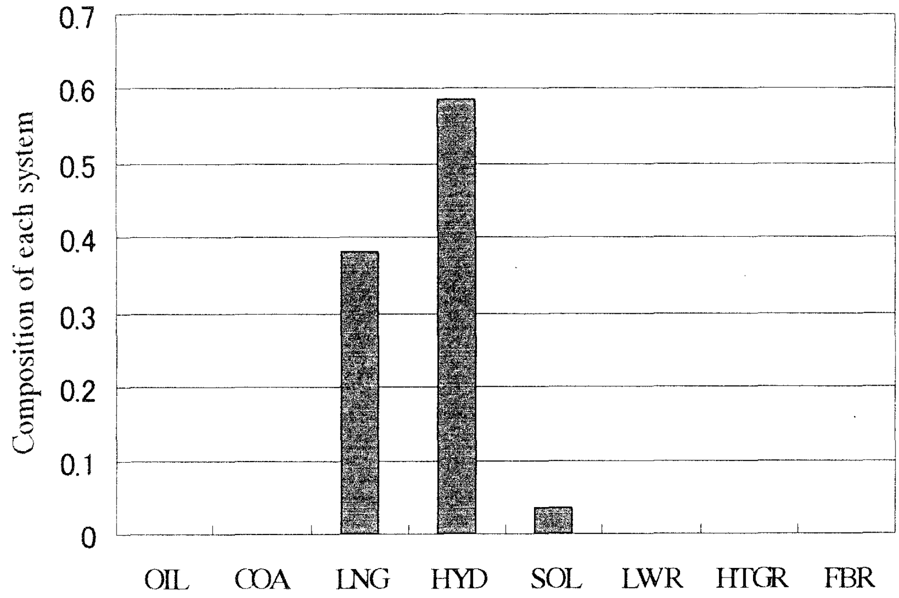


Fig. 13 Composition of each system in the best-mix (Examinee B)

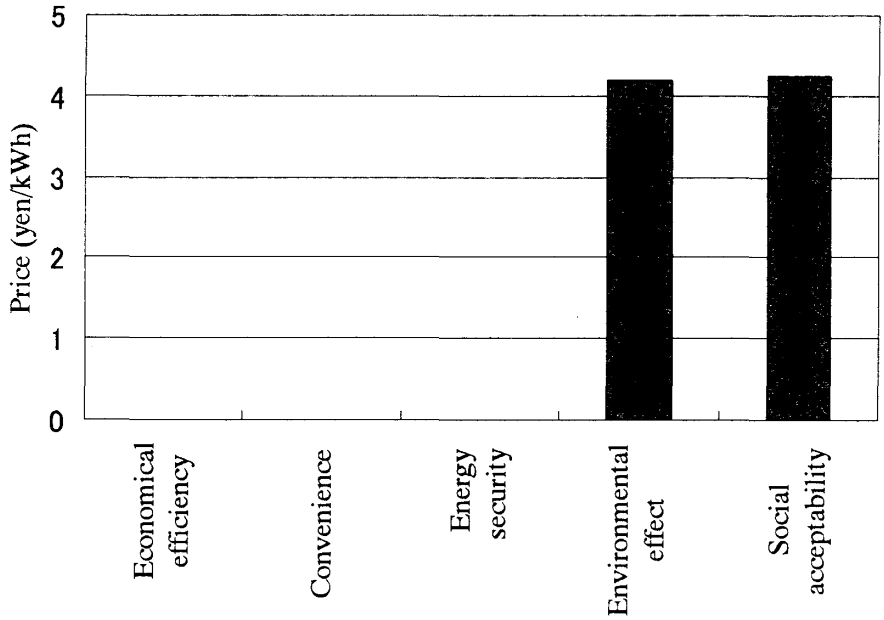


Fig. 14 Willingness to pay for each value (Examinee B)

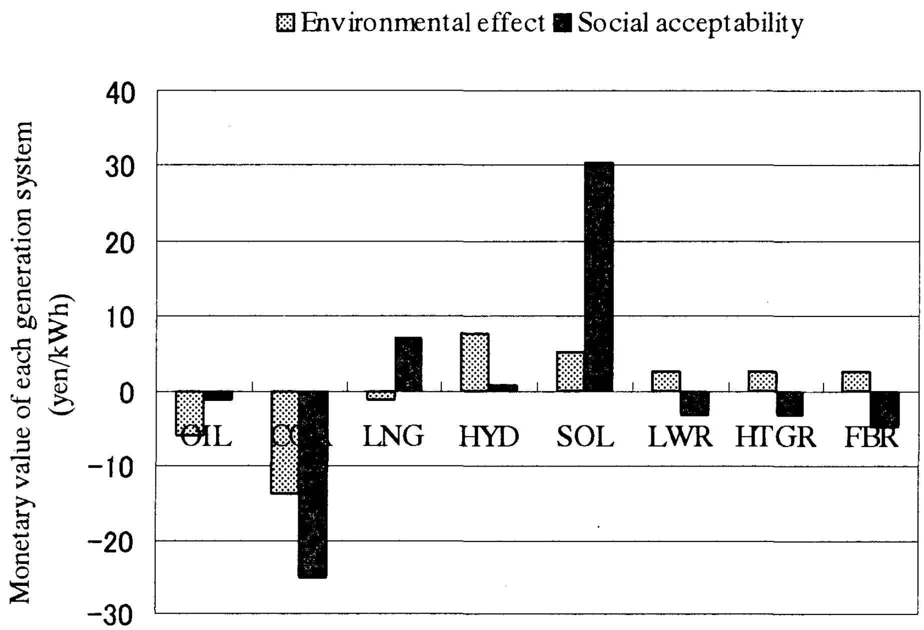


Fig. 15 Monetary value of each system (Examinee B)

References

1) Mankin,S.,Sato,O.,Yasukawa,S.and Hayashi,T., Economic Perspective of SMSNRs in the Energy Market of Japan, *Nuclear Engineering and Design*, **109**,355-363, (1988).
2) Ohkubo,H.,Suzuki,A.and Kiyose,R., The Mathematical Analysis on an Efficient Use Of Energy, *Journal of Faculty of Engineering, The University of Tokyo, Series B*, **36**,4,787-826, (1982).
3) Fujimoto,N.,and Fukuda,K. *Trans. Japan Soc. Energy Resouces*, 21,5,438,(2000)
4) Afanasiev,A.A.,Bolshov,L.A.and Karkhov, A.N, Economic Competitiveness of the New Generation of NPPs with NP-500 Units in Russia, *Nuclear Engineering and Design*, **173**, 219-227, (1997).
5) Kainuma,M., `http://www-cger.nies.go.jp/cger-j/c-news/vol10-4/vol10-4-2.html`
6) Yoshida,Y.,Ishitani,H.and Matsuhara,R., A Study of Systematic Measures for Reducing CO_2 Emissions, *J. Jpn. Soc. Simul. Technol.*, **14**, 1, 52-57, (1995).
7) Jackson,T., Least-cost Greenhouse Planning: Supply Curves for Global Warming, *Energy Policy*, **19**, 1,35-46, (1991).
8) Harada,Y., et. al., *Eng. Sci. Rep. Kyushu Univ.*, **18**,4,289,(1997)
9) Fukuda, K.,Fujimoto,N.,et. al., *ibid*, **20**,1,19
10) Fujimoto,N.,et. al., *Technol. Rep.Kyushu Univ.,*, **74**,3,221