Simulation Model for Evaluation of Deregulation Effects in Electric Power System

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Abstract: Deregulation in a power-supply system which includes photovoltaic power generation systems and/or co-generation systems, is indispensable for making the system more efficient and robust. Effectiveness of deregulation measures have been analysed from the viewpoint of micro-economics and game theory which are normative approaches based on rather simplified models of the real system. However, long-term and short-term stability of the system, for example, cannot be evaluated without more detailed model structure. This paper discusses effectiveness of a simulation-model approach for evaluating the behaviour of the deregulated market.

Keywords: electric power system; deregulation; power market; dispersed generation system; autonomous decentralized system; industrial organization.

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1 Introduction

Recently technological development in dispersed generation systems (DGS), e.g. co-generation system, photovoltaic power generation system, power storage, has been remarkable. Therefore, appropriately activating introduction of such technology into electric power system will improve its efficiency and robustness.

The power market in Japan is composed of ten power-supply areas in each of which an electric power company monopolizes the market. The reason for the natural monopoly is the existence of scale economies in the power-supply system. It is obvious that the power transmitting and distributing system becomes more advantageous on a competitive market as its scale grows. As for the power generation plants, however, some recent researches asserted that scale economies could not be observed [1].

On the other hand, it is important to lower a barrier to the rapid change in the power system in order not only to improve the efficiency of the system but also to deal with uncertainty in future energy supply and demand. From this viewpoint the monopolized market is not the best solution for a future power system.

As understood from the above discussion, there is large possibility for the power system to be improved by changing its regulation. Some deregulation policies have already been enforced to tempt consumers to install efficient power systems such as DGSs. For example, in Japan the consumers who have photovoltaic power generation systems, are permitted to sell the surplus power to the electric power company. But the possibility of the system change would be much larger than expected under the current regulations. Therefore, it is necessary to investigate the effective deregulation policies in the future power system.

An autonomous decentralized system has been attracting much attention in a variety of research fields. And the deregulation policies, that means to introduce "autonomous decentralized decision making process" into the power system, are also considered to be effective [2]. It is so because the decision making related to energy utilization depends much on local information, such as the infrastructure planning for energy supply and demand, energy load characteristics, the balance of heat and power and so on.

In enforcing the deregulation policies, however, some additional regulations will also be needed in order to keep the short-term and long-term stability of the system.

Normative approaches based on microeconomics and/or game theory have usually been used for this sort of problems. But these approaches require drastically simplified models of the large-scale power system, and cannot take the practical decision making in the companies and the consumers into consideration. This paper proposes the way how to build a simulation model of the power system with "autonomous decentralized decision making process" and shows that the complementary utilization of the simulation model to the normative one offers an effective way of analyzing the deregulated power system.

The contents of this paper is as follows: in the next section the features of the deregulated power system investigated in this study, are outlined. The structure of the simulation model developed here to evaluate the behaviour of the deregulated power market, is shown in Section 3. Representation of the decision making process of the participants in the market is also explained. In Section 4 we present some interesting results obtained through the model simulation. Interactive ways of model utilization are also illustrated. In the end of this paper some possible future development of the approach based on the simulation model is discussed briefly.

2 Outline of Deregulated Power System

A rough image of the deregulated power system considered in this study is given in Figure 1. It is composed of generators, consumers and a transmitting and distributing company (TDC). As explained in the previous section, only deregulation in the power generation sector is considered in this study. On the other hand the transmitting and distributing sectors are assumed to be monopolized by a non-commercial company, TDC.

The consumers can buy electric power from the generators directly (**a**) and/or from a power pool which is managed by the TDC (**c**). Any companies are allowed to participate in the market and sell power to the consumers and/or the power pool (**b**). This structure resembles that of the U.K. [3]. But the U.K.'s is in oligopolistic state and the group of small-scale generators has not had much influence on the market conduct yet. One of the features of the model proposed in this paper is that the variety of small-scale DGSs can be taken into account and that it aims to evaluate the effectiveness of the regulation policies necessary for stabilizing and improving the power system.

Dealing procedures are as follows. The generator offers dealing information, e.g. providable maximum power, the selling price and the period during which the generator can provide power, to TDC or to the consumers. It will be possible that the information is transmitted to a lot of consumers through such information network as Ethernet or FDDI. The selection of the contracts to TDC and to consumers depends on the preference of the decision- makers, that is, generators and consumers.

The supply-demand balance is now kept by the power company that is responsible for it in Japan. It is because the company is permitted to monopolize the market locally. But after the market being deregulated, the generators would no longer have the responsibility for the balance. In this study the spot-pricing mechanism is assumed to be introduced in the market as a load-management measure to compensate for the lack of supply-responsibility in the power system [4].

The TDC is a public utility, which makes efforts to keep the balance of the generators' output and the consumers' demand under contract. For this purpose the TDC adjusts the spot price of electric power at each time-period. It is also necessary for the consumers to respond to the change of price rapidly. This will be possible in the near future by the prevalence of load schedulers which control the electric equipments of the consumers.

3 Simulation Model of Deregulated Power System

In this Section the simulation model developed in this study is outlined. The purpose of the model development here is to show the availability of the simulation model in evaluating the behaviour of the deregulated power market. Therefore, the model structure is rather simple. The model development for investigating the behaviour of more realistic power market in detail is now under way.

3.1 Long-term Simulation Model

The long-term simulation model is for decision-making about facility investment and disposal. In this study some assumptions are made, for simplifying the discussion, as follows:

- Each generator has only one kind of plants.
- The decisions on the investments of all generators are made simultaneously at the beginning of every year.

It should be noted that these assumptions will not restrict the model behaviour so much.

The outline of the long-term model is shown in Figure 2. In this Figure dotted lines denote the flow of investment-related information and solid lines denote the sequence of the procedures. The availability of the information in deciding investment planning influences the model behaviour. In the simulations of this study, the information about the growth rate of the demand in the future is provided by the TDC to all generators. The way of investment planning is explained in the latter part of this section.

3.2 Short-term Simulation Model

The short-term simulation model represents the decision-making process of the participants in the market on the hourly dealing of electric power (see Figure 3). Currently this model does not include for the moment direct dealing between the generators and the consumers . Therefore, the supply-demand balance is realized by the TDC by using the spot-pricing mechanism.

The outline of the daily dealing is as follows: a generator decides a supply function of tomorrow, which defines the relation between the amount of the power output and its price, and informs the TDC of the function. The TDC is assumed to have enough information as to estimate a demand function of all consumers. When the TDC gets the supply function of the generators which want to sell the power to the TDC, it will dispatch the hourly loads of tomorrow economically. This procedure is also necessary for short-term direct dealing with consumers, to be considered in this study. And on the day of dealing, the TDC announces the power price to the consumers every hour. The power price is determined to balance the supply and demand at each time. The consumers decide the amounts of electric power to be used based on the informed price. It is also assumed in this study that there are some contracts between TDC and generators related to spinning reserve, which are necessary for keeping the balance of supply and demand.

3.3 Supply Function

The investment cost for plant construction is hardly recovered in the competitive market without appropriate price regulations. In this study the fixed cost included in the power price of each generator is determined automatically according to the characteristics of its plant. The supply function of each generator is assumed to be a step function which is based on the fixed cost, as shown in (1). The assumption of using the step function means that the fuel consumption rate does not depend on the load factor of the plant.

$$s(p) = \begin{cases} 0 & (p < p_0) \\ P & (p \geq p_0) \end{cases} \quad (1)$$

$$p_0 = f + \left(e \cdot \frac{c}{r} + u \cdot m \right) /8760wu \quad (2)$$

where

- $s(p)$: supply function(kWh)
- p : power price (Yen/kWh)
- p_0 : expected minimum price (Yen/kWh)
- P : capacity (kW)
- f : fuel cost (Yen/kWh)
- w : expected load factor
- c : capital cost (Yen/kW)
- r : expected pay back time (year)
- u : capacity of available facility (kW)
- m : maintenance cost (Yen/kW/year)
- e : capacity whose capital cost is included in price (kW)

There would be some other choices of regulations to be treated in the model for recovering the investment cost. In the U.K., for example, the increment of the sales due to an extra price added for balancing supply and demand, is divided among generators and used to recover their investment cost.

3.4 Decision-making Process for Facility Investment and Disposal

The optimal investment problem is usually solved by using the dynamic programming method and so on. To include these procedures into the simulation model needs much calculation time in executing the model simulation. However, the participants are not considered to make strictly optimal plans in practical situations, because of the existence of the uncertainty in future power load and energy price and also because of the lack of information about the decision-making of the other participants in the market. Therefore, it is not so unrealistic to incorporate simple algorithms of the investment planning into the model.

In this study the capacity of plants to be disposed, ξ, is determined every year by each generator so as to maximize the profit of the year. In order that the capacity of plants should be constructed, η, is also decided every year by each generator so as to maximize the sum of profit during the pay-back time after the plant construction.

In the following there are explained the algorithms of the decisions that a generator makes at the beginning of one year. Their objective functions are shown in (3) and (4).

- Objective function for disposing facility

$$\underset{\xi}{\text{maximize}}\ w = profit_1(0,\xi) \quad (3)$$

where the suffix '1' means that the value is of the current year when the decision is made.

- Objective function for constructing facility

$$\underset{\eta,\xi}{\text{maximize}}\ z = \sum_i profit_i(\eta,\xi) \quad (4)$$

where the summation is during the payback time of the plant to be constructed and the suffix i means that the value is of the ith year.

The profit of the ith year, $profit_i$, is defined as the difference between the sales amount, $sales_i$, and the total cost, $cost_i$, of the ith year.

$$profit_i = sales_i - cost_i \quad (5)$$

where $sales_i$ depends on the expected minimum price, $p_i(t)$, and the output, $x(t)$, at each time t of the ith year. The price, $p_i(t)$, is calculated by adding the facility cost, the maintenance cost and the fuel cost. The rate of return is assumed to be 0.

$$\begin{aligned} sales_i &= \sum p_i(t)\cdot x_i(t) \\ &= p_i \cdot X_i \end{aligned} \quad (6)$$

$$p_i(t) = p_i = f + \left(e_i \cdot \frac{c}{r} + u_i \cdot m\right) / 8760wu_i \quad (7)$$

where e_i means the capacity of the ith year whose capital cost will not have been recovered by the i year. The capacity, e_i, is decomposed into that of the facilities to be constructed, η, and that of the facilities which have been constructed but not recovered there capital cost yet, a_i. The facilities to be disposed of are not included in e_i. In (8), l is the time (year) required for the plant construction.

$$e_i = \begin{cases} a_i & (i < l) \\ a_i + \eta & (i \geq l) \end{cases} \quad (8)$$

In (7), u_i is the capacity which is available at the ith year, and depends on that of the facilities to be constructed, η, on that of the facilities to be disposed of, ξ, and on that of the facilities which have been constructed and will be available at the ith year, s_i.

$$u_i = \begin{cases} s_i - \xi & (i < l) \\ s_i + \eta - \xi & (i \geq l) \end{cases} \quad (9)$$

The total cost, $cost_i$, is the sum of fuel cost, maintenance cost and facility cost. In the following equation, X_i is the estimated yearly output of the ith year.

$$cost_i = f \cdot X_i + e_i \cdot \frac{c}{r} + u_i \cdot m \quad (10)$$

It should be noted that each generator has to estimate the future power load which it will be able to provide power to, in order to make decisions about facility. The maximum amount of such load has to be estimated by using information about the growth rate of power load, the past investment of the other generators and the economic characteristics of their plants. But future investment planning of the others, is of course unknown. It means that there is much uncertainty in deciding the future load that each generator will be able to get. The enterprising spirit of each generator, which is an essential factor in analysing the behaviour of the deregulated market, differs with that of other generators.

For this problem two parameters related to the enterprising spirit, α and β, are introduced into the simulation model. And $ratio_i$ obtained by (11) represents the degree of the spirit, that is, a generator considers that it will be able to get $ratio_i \times$(the estimated maximum load), at the ith year.

$$ratio_i = \begin{cases} \beta & (i < l) \\ \beta - \alpha(i - l) & (i \geq l) \end{cases} \tag{11}$$

The larger the value of $ratio_i$ is, the more the generator is considered to be risk-prone. The maximum load is estimated by using the information about the past investments of other generators, their power prices and the total load in the future. For this estimation it is assumed that other generators will neither construct nor dispose plants.

Although the assumptions used in this study simplifies the representation of the decision process, the model can produce meaningful results for the evaluation of the real behaviour of the market.

4 Simulation Results and Some Comments

The results of three cases of simulations are taken up in this section. The characteristics of the generators used in Case 1 are shown in Table 1. For simplifying the discussion the scale of the market is set rather small. The size of the unit that each generator can construct or dispose is fixed. The plant No.1 is for base load and No.4 is for peak load. The number of units in Table 1 is the initial value for the simulation.

The characteristics of the power demand are summarized as follows: four sets of hourly power loads of a typical day, that is, the daily loads of four seasons, spring, summer, fall and winter, and their price elasticities are assumed in the model. The growth rate of the power demand is set to be 5% a year, and small perturbation is added. These values are decided to show some typical behaviour

Table 1: Characteristics of Generators

Plant No.	1	2	3	4
(1)	65000	45000	35000	25000
(2)	5	8	15	40
(3)	30000	20000	15000	10000
(4)	10	4	5	3
(5)	100	100	100	30
(6)	15	9	5	4
(7)	15	9	5	4
(8)	0.9	0.5	0.5	0.3
(9)	0.5	0.5	1.0	1.0
(10)	0.5	0.5	1.0	1.0

(1):Facility cost (Yen/kW), (2):Fuel cost (Yen/kWh), (3):Maintenance cost(Yen/kW/Year), (4):Number of units, (5):Capacity of unit (MW), (6):Time for construction (Year), (7):Pay-back time (Year), (8):Load factor, (9),(10): Parameters of the enterprising spirit, α and β.

of the simulation model developed in this study. Therefore, for more realistic evaluation of the market, these data need be re-examined.

Figure 4 shows the change of the daily average prices in Case 1. The small perturbation of the price is mainly due to seasonal change of demand . On the other hand the big fluctuation in the early years is due to undesirable initial values of the number of the generation units. The change of the capacity of the base plant (No.1) is shown in Figure 5. According to this figure the generator, the owner of the base plant, considers that the base plant is too much at the beginning, and therefore, some units are disposed in the first year. These results signify that a big disturbance, such as drastic change of demand or a jump in oil price, possibly causes serious transient problems on the market. It is also observed in Figure 4 that price modification is stabilized in about 10 years even if the growth of demand exists. The time required for the stabilization depends on the time for plant constructions.

Case 2 is the scenario where the unit sizes of the plants No.1 and No.2 are modified to be 500 and 200 MW respectively. The initial numbers of units are adjusted according to the modification. The effect of larger unit size is that the plant investment becomes later (compare Figure 5 with Figure 7) and the power price gets higher when the supply capacity becomes insufficient (see Figure 6). The fluctuation of the price which is mainly caused by the plant construction of large unit size, that is, of No.1 and No.2, is also serious (see Figure 6 and Figure 7).

In Case 3, only the time for construction of plant No.4 is modified from 4 to 2 years when compared with Case 1. This modification results in a lower and more stable price as shown in Figure 8. This is because the capacity of plant No.4 increases largely (see Figure 9) and there is no sharp need for managing the power load in order to balance with the supply. From Figure 10 it is understood that the plant capacity is insufficient in the daytime of summer in Case 1. Less time for construction means that the generator can invest more easily under some uncertainty in a future situation. Similar results are obtained by increasing the enterprising spirit of generators. This result shows that positive actions of participants under risk in the future is indispensable for the deregulated market.

5 Concluding Remarks

The availability and usefulness of the simulation model in analyzing the deregulated power market has been discussed in this paper. Although the model shown here still remains a simple one, its simulation has produced some interesting results. Decision making processes of generators and consumers can be realized in the model as independent function modules, and therefore various decision criteria and algorithms can easily be installed in the model. It is the most salient feature of this simulation model, and more detailed evaluation of deregulation policies is expected to be possible than in the case where only macroscopic normative approaches are used.

The simulation model is also effective when used in discussions of a group composed of specialists in various fields. Ideas and questions proposed in the discussion can easily be put into the model and then the obtained simulation results can be exploited in the discussion. For this purpose the interactive utilization of the model becomes another important factor for the model development.

There was an unexpected aspect of CAI in building the simulation model. The students who worked for the model development learned the theory of industrial organization and the game theory through interpreting the simulation results.

The authors are developing a detailed model structure to investigate a more realistic deregulated market and also the effective way for regulating the autonomous decentralized power system by combining the simulation model with the normative model which is obtained by reducing the former.

The authors wish to thank Mr M. Okamoto, who was a graduate student of Kyoto University, for his collaborative work in developing the models.

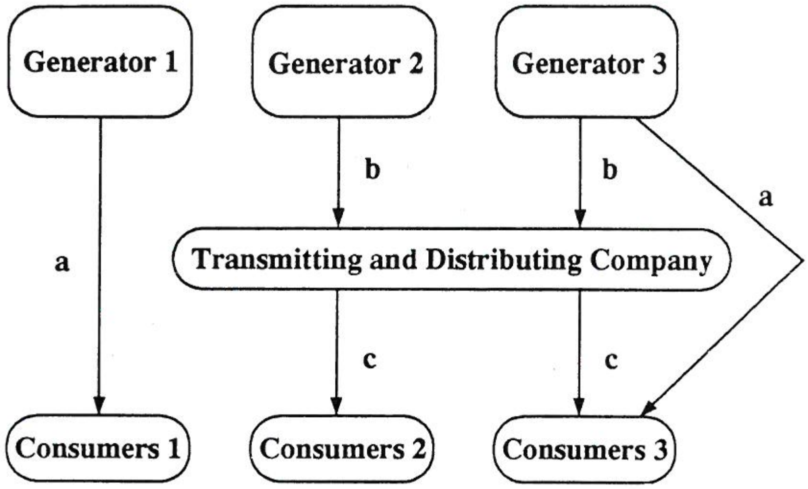

Figure 1: Structure of the Deregulated Power System

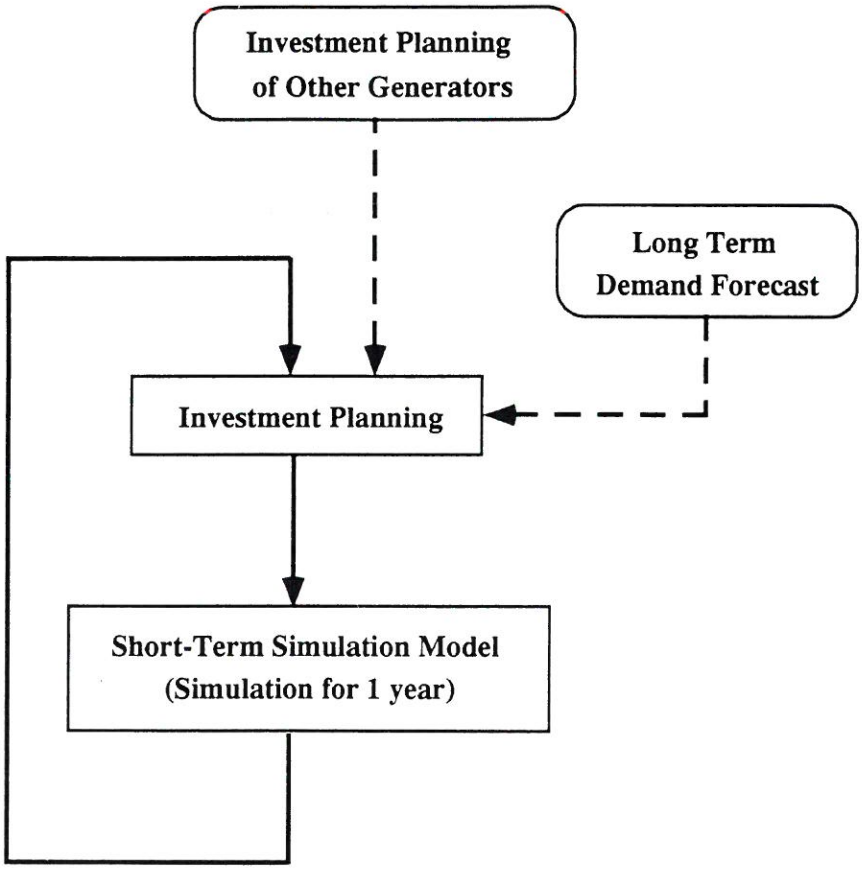

Figure 2: Long-term Simulation Model

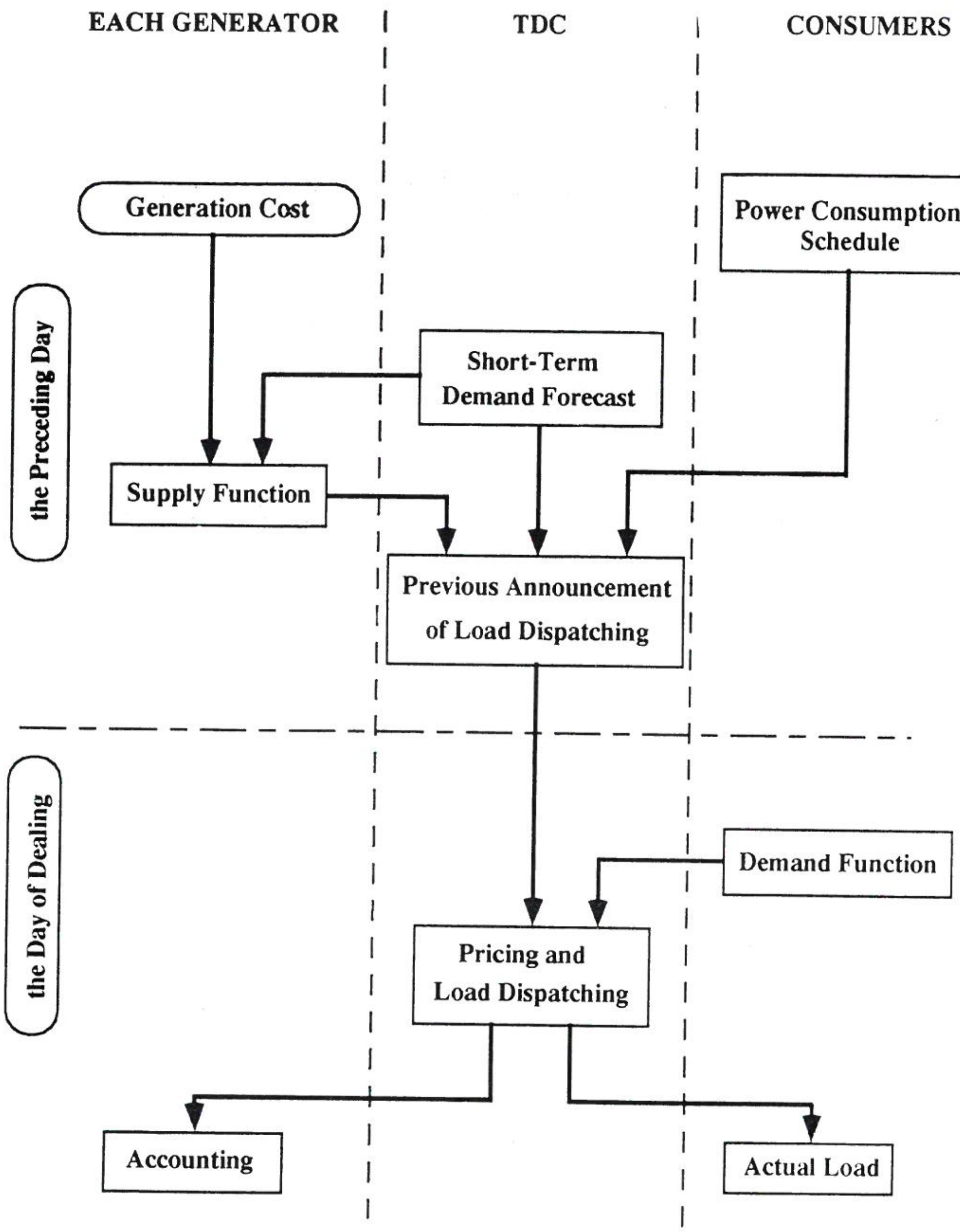

Figure 3: Short-term Simulation Model

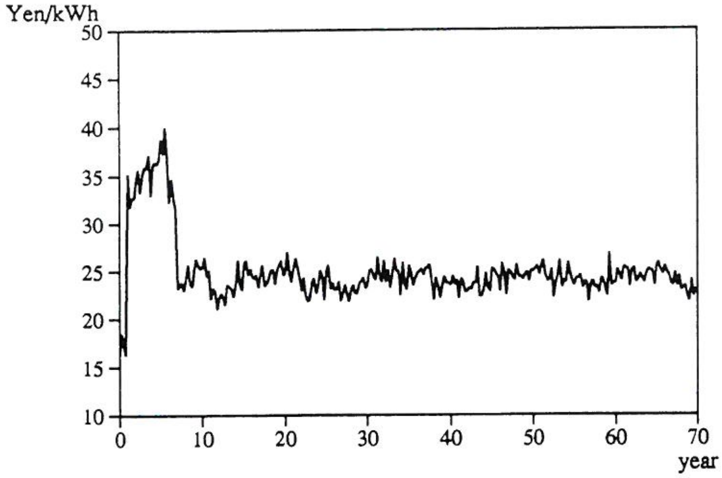

Figure 4: Simulation Result of Case 1 - Daily Average Price -

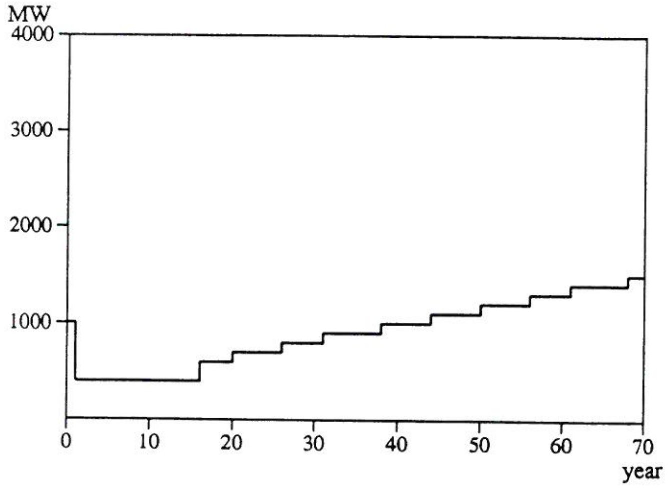

Figure 5: Simulation Result of Case 1 - Capacity of Base Plant -

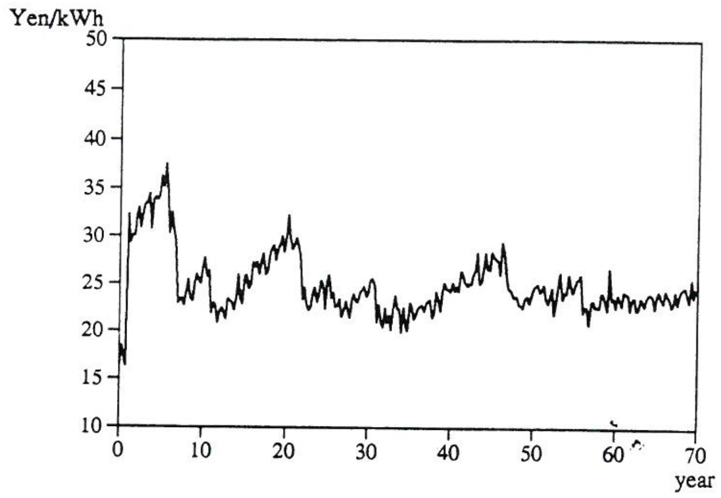

Figure 6: Simulation Result of Case 2 - Daily Average Price -

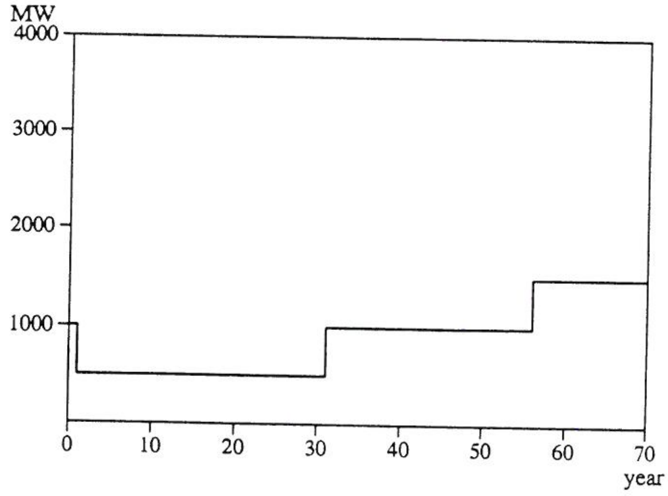

Figure 7: Simulation Result of Case 2 - Capacity of Base Plant -

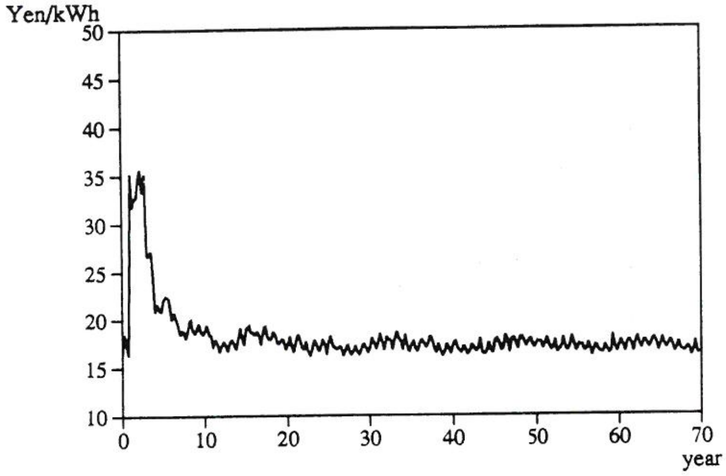

Figure 8: Simulation Result of Case 3 - Daily Average Price -

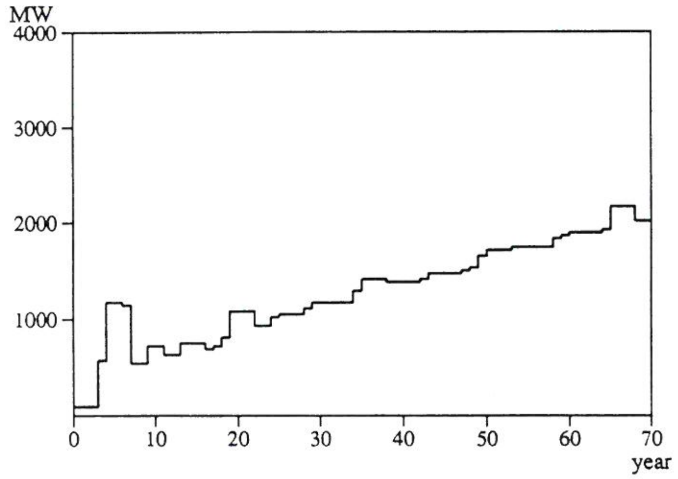

Figure 9: Simulation Result of Case 3 - Capacity of Peak Plant -

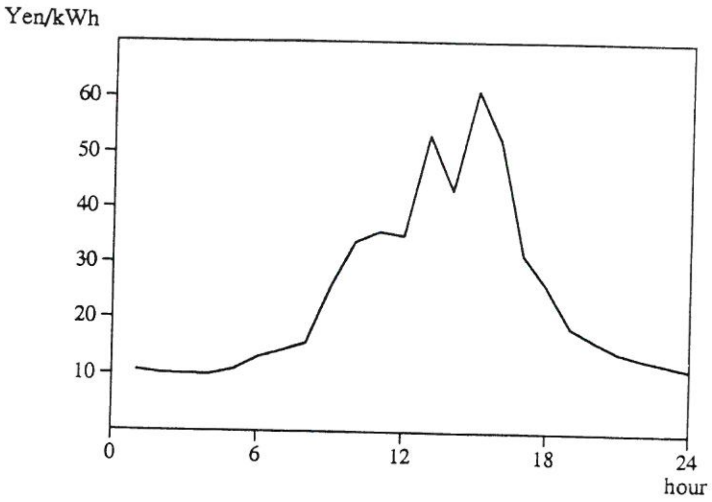

Figure 10: Simulation Result of Case 1 - An Example of Hourly Power Prices in Summer -

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