Optimization for the operation of electric power generation taking account of distributed regional demand in Japan

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Abstract

The purpose of this study is to analyze impacts of distributed regional demand on the operational characteristics. Many energy models for the operation of electric power generation tended to regard Japan as a single demand node. However, the power generation plants and electricity demand are distributed throughout the nation. There is still unknown about the impacts of distributed electricity demand on the operation of electric utilities. We have designed two types of model to estimate the impacts of distributed regional demand on the operation characteristics. The first model regards Japan as a single area for electricity consumption, and the second model considers the distributed consumption of electricity. In conclusion, we should note that it is important to consider the distributed regional demand in order to estimate operation characteristics appropriately.

1. Introduction

In 1998, the Government of Japan adopted a plan of partial liberalization of its Electricity Supply Industry (ESI). Large consumers, which use more than 2MW and take power at 20,000 volts or above, have been eligible to choose their supplier. These consumers account for 30% of total electricity demand. In addition, there is negotiated third party access to the grid. The partial reform was implemented in March 2000 and will be reviewed in three years. Under the deregulation of ESI, it is necessary for each utility to operate their power plants with cost-effective way.

In addition, the ESI in Japan plays an important role in stabilizing an atmospheric concentration of greenhouse gas emissions. Table 1 shows the quantity of CO_2 emissions by each sector, such as the electricity sector, the industrial sector, the residential and commercial sector and the transportation sector in Japan in the year 1999. The electricity sector exhausts 32% of CO_2 emissions in Japan. There is a large possibility of decreasing CO_2 emissions in the electricity sector. It is necessary for the ESI to operate the utilities with less impact on the global environment.

For these purposes, it is important to develop an analytical model that can estimate the operation characteristics of power stations.

In the past, many energy models have been proposed for the issue of operation and the planning of electric power generation (Bowen et al. 1999, Cardell et al. 1997, Chen et al. 1993,

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Dismukes et al. 1998, Hsu 1997, Larivière and Lafrance 1999, Parikh 1995, Ramos et al. 1998, Rosekrans et al. 1998, Wu et al. 2000). These models tended to regard Japan as a single demand node, and simulated its operation performance without constraints of transmission capacities. However, the electricity demand is unevenly distributed throughout the nation. Power generation plants, which are distributed nationwide, are not always placed in order to operate cost-effective way. In the conventional model, most of the results show incorrect solution for siting and operating power plants. The results mislead the ESI to inefficient management, such as excess investments and the bottleneck of transmission. Therefore, it is necessary to develop an analytical model that can consider distributed demand, capacity of power plants and constraints of transmission capacities.

The purpose of this study is to develop an analytical model considering distributed regional demand. Then, by introducing designed models into Japan's condition, we analyze the impacts of distributed demand on the operation characteristics and clarify optimal operation conditions to reduce annual costs.

2. Optimization model

In this study, we have designed two types of model to estimate the impact of distributed regional demand on the operation characteristics. The first model regards Japan as a single demand node, and the second model considers the distributed demand of electricity.

2.1 Single Node Model (SNM)

The structure of this model is shown in Figure 1. The model has one demand node of electricity that represents overall consumption of electricity in Japan. Power generation plants are located around the demand node. In terms of fuel price and current costs for the ESI, averaged data are used for running this model. The constraint of transmission capacity is not considered in this model.

2.2 Multi Node Model (MNM)

Figure 2 shows the structure of multi node model (MNM). The model has sixty regions expressing the size of prefecture, in particular the size of subprefecture at Hokkaidoh, and considers regional electricity demand. Each prefecture has one node of electricity demand. The demand node represents the consumption of electricity at each prefecture. There are at most seven types of power generation plant nodes at each prefecture, which represents the generation of electricity there. For example, Fukushima prefecture has three nodes of power generation plants. One node represents nuclear and thermal power generation plants owned by Tohoku Electric Power Company. Another node represents hydropower generation plants owned by Tohoku Electric Power Company. The other node represents nuclear power generation plants owned by Tokyo Electric Power Company. Transmission grids are modeled to connect neighboring region based on the actual transmission network in Japan.

3. Methodology of the analysis

3.1 Objective function

In order to achieve economical operation of power plants, both SNM and MNM use the following objective function, where *TC* is a total cost, *P* is a demand pattern (1-7), *T* is time (hour, 1-24), *R* is region (SNM: 1, MNM: 1-60), and *V(P,T,R)* is a variable cost.

$$TC = \sum_{P,T,R} \left(V(P,T,R) \right) \tag{1}$$

SNM and MNM are calculated to minimize the objective function.

3.2 Constraints

3.2.1 Constraint of capacity of power plants

A constraint of capacity of power plants determines an output range for each power plants, where *RP* is a site of power plant in region *R*, *POW(P,T,RP)* is an output of each power plant, *CAPLO(P,T,RP)* is a lower limit of output, and *CAPUP(P,T,RP)* is an upper limit of output.

$$CAPLO(P,T,RP) \le POW(P,T,RP) \le CAPUP(P,T,RP) \qquad (2)$$

3.2.2 Constraint of supply of electricity

A constraint of supply of electricity determines a balance between demand and supply of electricity including nationwide daily-load. The constraint is expressed as following, where *X(P,T,R)* is a supply of electricity to region *R*, *S(P,T,R)* is a supply to the pumped hydropower plant in region *R*, and *D(P,T,R)* is an electricity demand at region *R*.

$$\sum_R \left(X(P,T,R) - S(P,T,R) \right) = \sum_R D(P,T,R) \qquad (3)$$

3.2.3 Constraint of load-following capability

A constraint of load-following capability determines a range of capability of changing its load per 1 hour at each power plant. This constraint is expressed as follows, where *FUP(RP)* is an upper limit of load-following capability and *FLO(RP)* is a lower limit of load-following capability. *FUP(RP)* and *FLO(RP)* are shown in Table 6.

$$\begin{aligned} POW(P,T,RP) &\le FUP(RP) \times POW(P,T-1,RP) \\ POW(P,T,RP) &\ge FLO(RP) \times POW(P,T-1,RP) \end{aligned} \qquad (4)$$

In addition to these constraint conditions, MNM has the following transmission constraint.

3.2.4 Constraint of transmission capacity

A constraint of transmission capacity determines a capacity of transmission line. This constraint is expressed as the following inequality, where *TRANS*(P,T,R_1,R_2) is a transmission power from region R_1 to R_2, and *TRUP*(R_1,R_2) is an upper limit of transmission capacity from region R_1 to R_2.

$$TRANS(P,T,R_1,R_2) \le TRUP(R_1,R_2) \qquad (5)$$

3.3 Assumptions for the analysis

In this model, annual characteristics of electricity demand are categorized into seven patterns. These patterns are shown in Table 2. Power generation plants in this model include nuclear, thermal power (coal-fired boiler, LNG-fired boiler, LNG combined cycle, oil-fired boiler) and hydropower (conventional hydropower, pumped hydropower). In order to analyze the operation characteristics, we consider two conditions with or without distributed regional demand.

The data of these utilities derives from the data in the year 1998 (Table 3). Fuel price and thermal efficiency in each power plant are shown in Table 4 and Table 5, respectively. These parameters take an average among nationwide.

Electricity transmission loses 1% per 100km in MNM based on the actual data given by Tokyo Electric Fukushima Nuclear Power Station. Reserve power ratio is set at 8%. In this analysis, there are no constraints on CO_2 emissions.

4. Result of the analysis

We can see the following results by the analysis. In the first place, we will discuss the impact of distributed regional demand on the operation characteristics.

Figure 3 shows the result of annual electric generation in the year 1998, and Table 7 shows the power generation cost per unit output. From the figure, it is clearly shows that there is a large difference in thermal power generation. The result of single node model (SNM) shows that power generation of coal-fired boiler is large part of generation and that of oil-fired boiler is small part. On the other hand, the result of multi node model (MNM) shows that coal-fired boiler and oil-fired boiler have similar proportion of annual electric generation. This is because the difference between the sites of coal-fired boiler and that of oil-fired boiler.

Most coal-fired plants are located far from the large consumption node, such as Tokyo, Nagoya and Osaka. On the other hand, there are large capacities of oil-fired plant near big cities. In the analysis by using single node model (SNM) without transmission constraint, it is possible to supply all the power produced by coal-fired plant to the large consumption node. However, in the analysis by using multi node model (MNM) with transmission constraints, it is difficult to transmit the power produced by coal-fired plant because it causes bottleneck of transmission. For this reason, it is necessary to operate oil-fired plants in spite of higher cost in MNM.

Figure 3 also shows the comparison between the results and actual electric generation in the year 1998. We see from the figure that the pumped hydropower plants are not much operated to supply the electricity in the analytical results because the pumped hydropower takes high operational cost (see Table 7). The pumped hydropower plays as a reservoir of over produced electricity by nuclear power at nighttime, and plays as a power sources for peak load at daytime. However, the thermal power generation has an enough load-following capability to supply the electricity stably. Therefore, under the condition of economical operation, the pumped hydropower is not always attractive.

Figure 4 shows the comparison between actual generation and the result of MNM in each ESI. As the diagram indicates, the results in the ESI, such as Hokkaidoh Electric, Hokuriku Electric, Chugoku Electric, Shikoku Electric, Kyushu Electric, are similar to the actual data. This is the reason that these ESIs are located far from the big cities. Therefore, it is possible for these ESIs to supply electricity without the bottleneck of transmission. However, the result in the other ESI, such as Tohoku Electric, Tokyo Electric, Chubu Electric, Kansai Electric, are different from the actual data regarding the electric generation share of both nuclear generation and thermal generation.

In the actual data, more nuclear plants generate electricity, resulting in higher annual generation cost, because it is necessary to operate the pumped hydropower plant in order to storage over-produced electricity at nighttime. On the other hand, in the results derived by MNM, nuclear plants generate less electricity rather than the actual data, resulting in low load for the pumped hydro power plants. The latter ESIs supply electricity generated by thermal power generation, in particular LNG-fired and LNG combined cycle.

Figure 5 shows the annual cost in the year 1998 in Japan. In the figure, it clearly shows that the LNG-fired generation plants run at high load, resulting in higher share of annual cost. The annual cost derived by SNM shows the lowest, because SNM has no transmission constraint as mentioned above. Therefore, it is possible for SNM to operate utilities in the order of lower cost. On the other hand, actual cost in the year 1998 and annual cost derived by the MNM show the similar one. It is difficult for MNM to operate utilities in the order of lower cost because of bottleneck of transmission.

Figure 6 shows the CO_2 characteristics from the electricity sector in Japan. This diagram tells us that annual cost derived by SNM shows the lowest (see Figure 5). However, the annual CO_2 emission increases in the result of SNM. The coal-fired plants exhaust more CO_2 per unit output than the gas-fired plants. Therefore, the great dependence on coal-fired plants results in the reduction of annual cost, as well as the increase of CO_2 emissions. On the contrary, CO_2 emissions derived by the MNM shows the similar characteristics of actual CO_2 emissions.

5. Conclusions

In order to analyze the impacts of regional electricity demand on the operation characteristics of ESI in Japan, we have designed the analytical model considering distributed regional demand. The following description is derived from our analysis.

Under the condition of economical operation, regardless of taking consideration into distributed regional demand of electricity, the pumped hydropower plants are not always attractive, and the LNG-fired generation plants run at high load, resulting in higher share of annual cost.

In the analysis by using single node model (SNM) without considering regional demand, the coal-fired plant has an important role on electric generation. This is because that SNM has no constraint of transmission capacity. Therefore, power generation plants operate in the order of lower cost in SNM. The great dependence on coal-fired plants results in the reduction of annual generation cost, as well as the increase of CO_2 emissions. On the other hand, in the analysis by using multi node model (MNM) with distributed regional demand, the coal-fired plant and the oil-fired plant have a similar role in annual electric generation. The composition of electricity supply in each ESI is different by the distance from the large consumption node. The result of the ESI, which is far from the big cities, is similar to the actual generation. In addition, both annual cost and CO_2 emissions derived by the MNM are similar to actual data. The reason is that MNM considers distributed demand and constraints of transmission capacity.

From what has been discussed above, we can conclude that it is necessary to consider the distributed regional demand in order to analyze operation characteristics of electric utilities appropriately.

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Table 1 CO_2 emission in Japan in the year 1999 (mmTC)

Electricity	Industrial	Residential and Commercial	Transportation	Own use	Total
102.2 (32%)	90.3 (29%)	37.2 (12%)	69.2 (22%)	14.6 (5%)	313.6 (100%)

Source: The Energy Data and Modeling Center 2002

Table 2 Demand patterns

	Pattern	Days
1	Maximum demand days in Summer	3
2	Weekday in Summer	98
3	Weekday in Winter	95
4	Weekday in Spring and Autumn	97
5	Holiday in Summer	21
6	Holiday in Winter	26
7	Holiday in Spring and Autumn	25

Table 3 Installed capacity in the year 1998

Type	Installed capacity (MW)
Nuclear	45,083
Coal	31,030
LNG	37,482
Combined LNG	24,913
Oil	51,960
Pumped hydropower	21,034
Conventional hydropower	16,877
Total	228,379

Source: MITI. Agency of Natural Resources and Energy 1999

Table 4 Fuel price

Type	Fuel price (JPY/kg)
Nuclear	1.51 JPY/kWh*
Coal	7.16
LNG	36.36
Combined LNG	36.36
Oil	28.20
Pumped hydropower	None
Conventional hydropower	None

* This includes thermal efficiency of nuclear.

Table 5 Thermal efficiency

Type	Thermal efficiency (%)
Coal	38.98
LNG	38.13
Combined LNG	43.27
Oil	37.04

Table 6 Load-following capability

Type	Upper limit (%/hr.)	Lower limit (%/hr.)
Nuclear	108.0	75.1
Coal	126.2	69.1
LNG	141.2	53.5
Combined LNG	129.7	8.2
Oil	144.8	69.0
Pumped hydropower	None	None
Conventional hydropower	None	None

Table 7 Power generation cost

Type	Cost(JPY/kWh)
Nuclear	1.58
Coal	2.50
LNG	6.58
Combined LNG	5.67
Oil	7.05
Pumped hydropower	10.00
Conventional hydropower	3.00

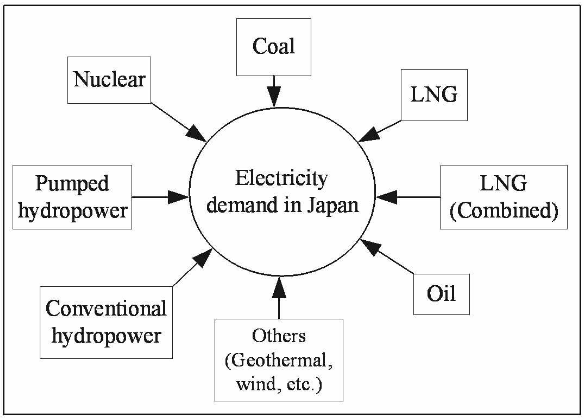


Figure 1 Structure of Single Node Model (SNM)

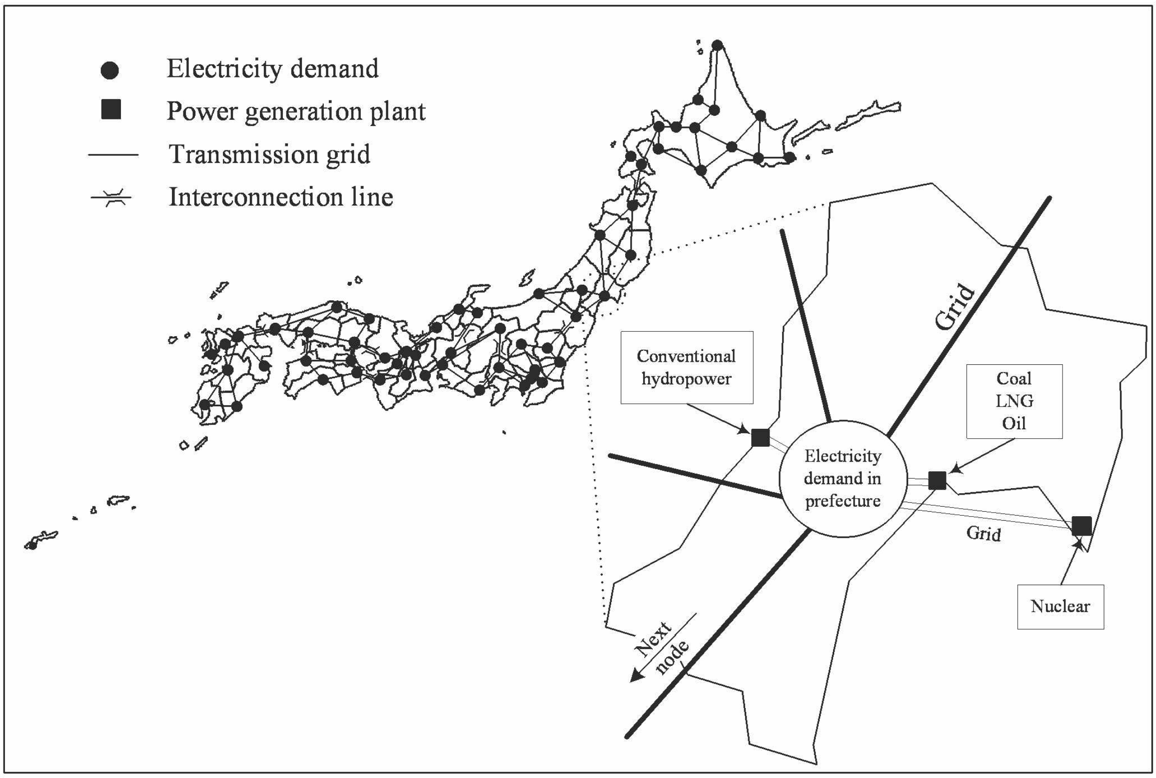
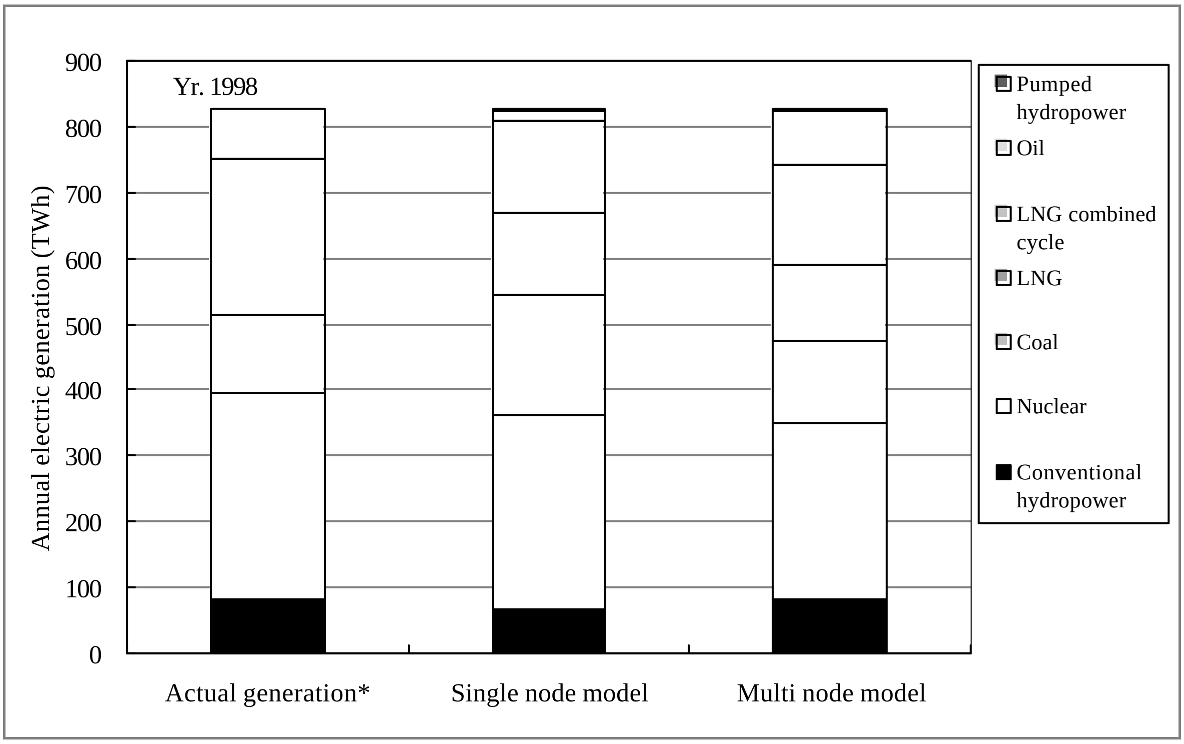


Figure 2 Structure of Multi Node Model (MNM)



* LNG includes both LNG-fired and LNG combined cycle.

Figure 3 Annual electric generations by using SNM and MNM

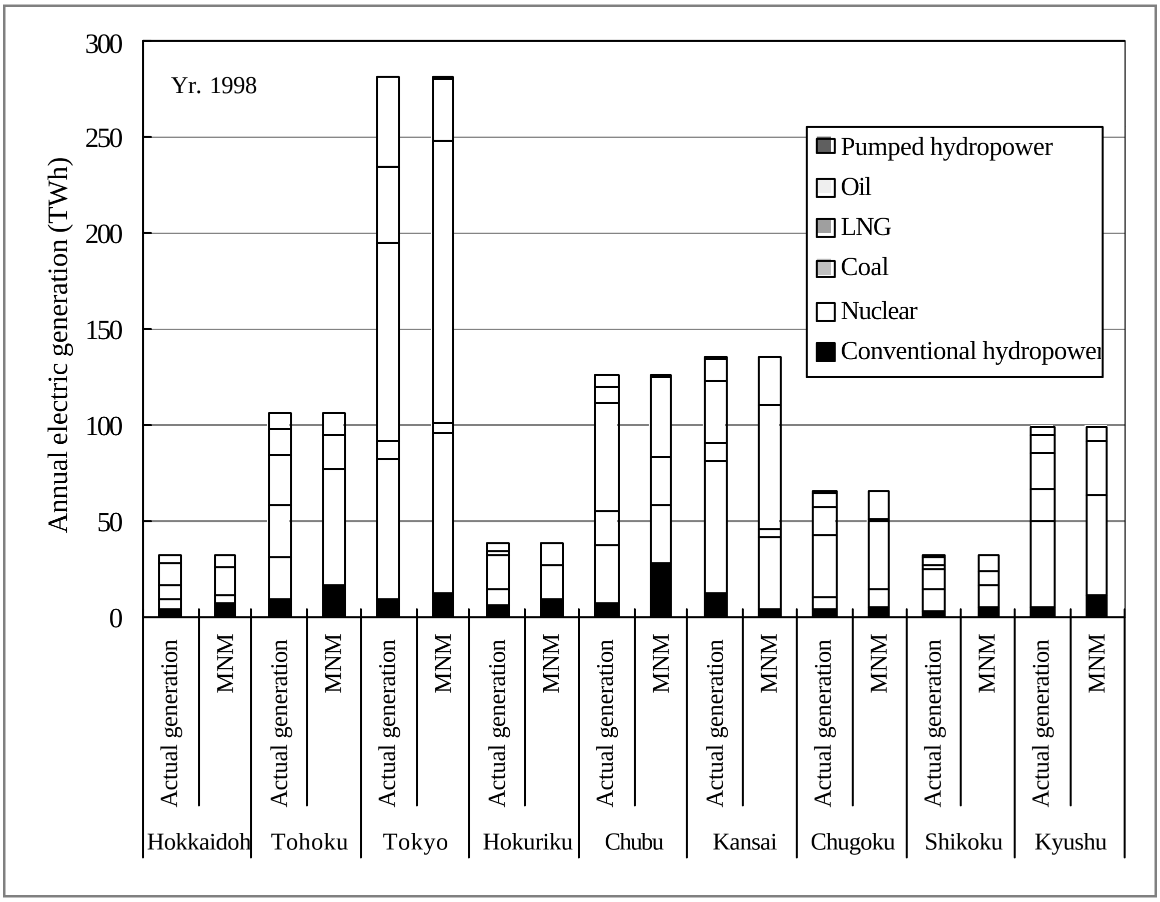


Figure 4 Annual electric generations by nine electric utilities

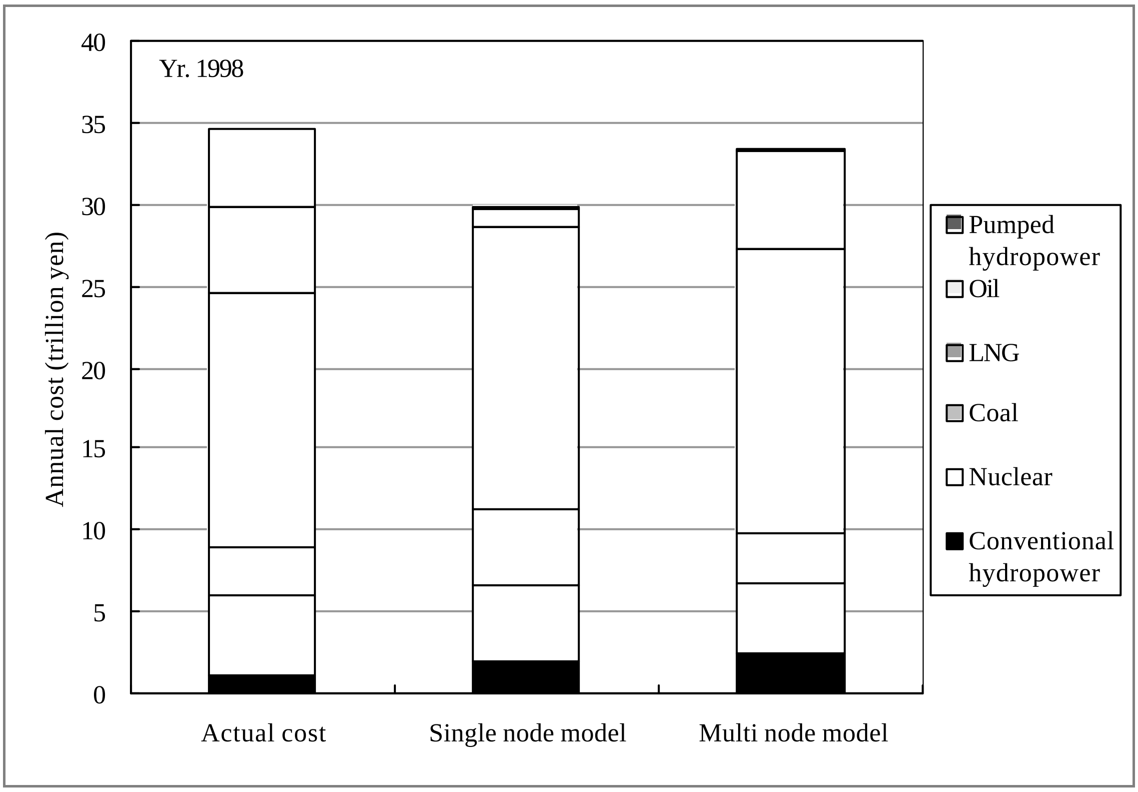


Figure 5 Annual costs

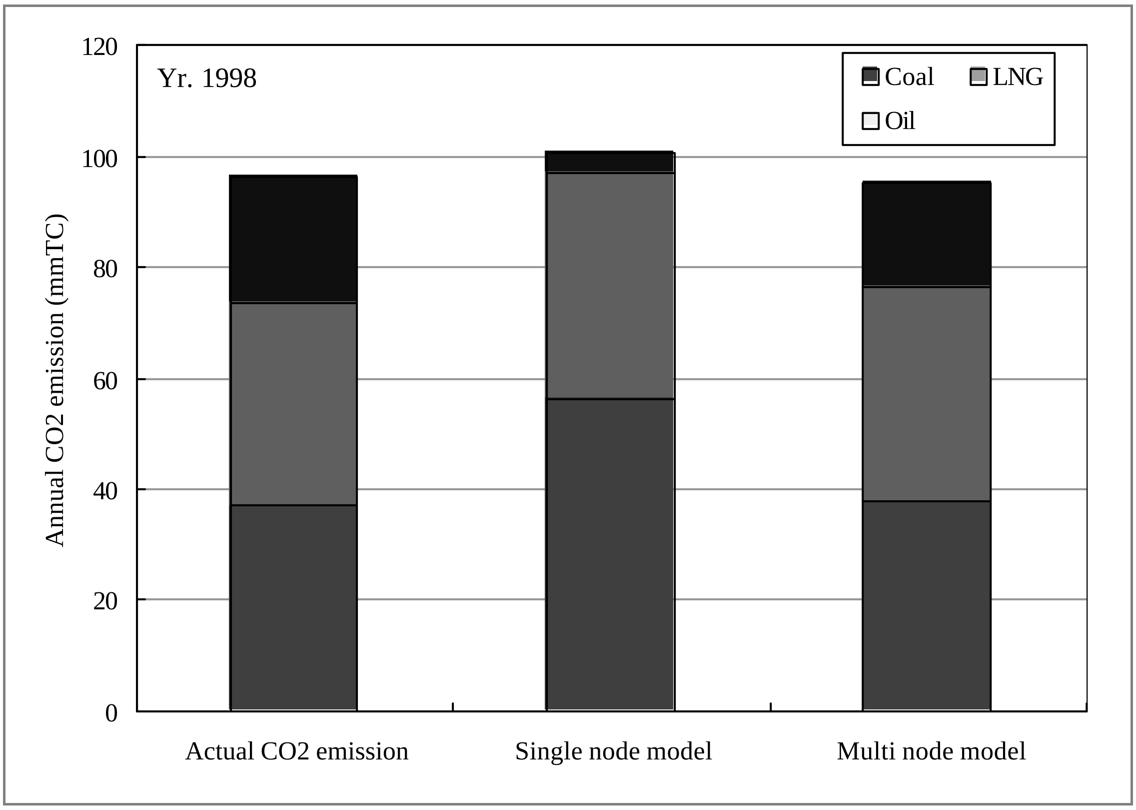


Figure 6 CO_2 emission from the electricity sector in Japan