

# **Study of Scenarios after the Great East Japan Earthquake to Create a Secure, Affluent and Low-Carbon society**

Ryuji Matsuhashi, Kae Takase, Koichi Yamada and Yoshikuni Yoshida

Ryuji Matsuhashi, Professor, Department of Electrical Engineering and Information Systems, Graduate School of Engineering, The University of Tokyo and Research Director, Center for Low Carbon Society Strategy, Japan Science and Technology Agency

Kae Takase, Department of Environment Systems, The University of Tokyo and Center for Low Carbon Society Strategy, Japan Science and Technology Agency

Koichi Yamada, Center for Low Carbon Society Strategy, Japan Science and Technology Agency

Yoshikuni Yoshida, Department of Environment Systems, The University of Tokyo and Center for Low Carbon Society Strategy, Japan Science and Technology Agency

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## **Abstract**

The Great East Japan Earthquake in March 2011 devastated the eastern region of Japan. Due to the resulting nuclear accident, Japanese Cabinet decided to revise its energy policies. This article investigates whether a secure, affluent and low-carbon energy system can be established taking into account the serious situation after the earthquake. We first develop three models: a power planning model, final energy demand model and computable general equilibrium model. Then we integrate these models to depict energy scenarios in 2030. Finally, we investigate whether a secure, affluent and low-carbon energy system can be established based on the energy scenarios.

## **1. INTRODUCTION**

The basis of a sound energy policy is to support a secure, affluent and environmentally sound society. In the Basic Energy Plan authorized by Japanese Cabinet in 2010, nuclear energy was expected to play a significant role in ensuring a stable supply of energy and reducing CO<sub>2</sub> emissions in Japan. The Plan proposed building 14 new nuclear power plants, and to increase the average operating rates of those plants to 90% by 2030. However, on March 11, 2011, the Great East Japan Earthquake devastated the eastern region of Japan. This earthquake, and the subsequent tsunami, cut off all power, including emergency backup power, to Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plants, causing severe accidents. The situation remains uncertain, and we can only hope for a speedy resolution and recovery. This nuclear accident, the most serious in Japan's history, will inevitably affect the country's future plans for nuclear energy, and the government may have to revise the Basic Energy Plan itself. This paper quantitatively investigates future energy scenarios and CO<sub>2</sub> emissions.

## **2. FRAMEWORK OF THE ANALYSIS**

### **2.1 General framework**

Overall framework of our analysis is as follows. We developed a computable general equilibrium (CGE) model for Japan, a multi-regional power planning model and a final energy demand model for envisioning energy scenarios in 2030. The results estimated by the multi-regional power planning model and final energy demand model are input to the computable general equilibrium model to

obtain overall results for the energy scenarios. The details of each model are described below.

## 2.2 Computable general equilibrium model

We developed a computable general equilibrium (CGE) model for Japan on the basis of Ichioka's analysis<sup>[1],[2]</sup>. We used this model to evaluate the effects of various scenarios on the national economy. In this CGE model, households choose between present consumption and savings to maximize their utility. The goods and services available for present consumption are grouped into 19 categories, as shown in Figure 1. The utility of consuming these 19 types of goods and services is expressed by using the Cobb-Douglas function given in Equation (1). The present utility, consisting of present consumption and leisure, is expressed by a constant elasticity of substitution (CES) function given in Equation (2). Finally, the utility integrating the present and future consumption is expressed by another CES function given in Equation (3).

$$X_i = \prod_{j=1}^{19} X_{ij}^{\lambda_{ij}} . \quad (1)$$

where,

$X_i$ : Composite consumption of goods and services by the  $i$ -th income bracket

$X_{ij}$ : Consumption of the  $j$ -th good or service by the  $i$ -th income bracket

$$H_i = \left\{ \beta_i^{1/\sigma_{2i}} l_i^{\phi_i} + (1 - \beta_i)^{1/\sigma_{2i}} X_i^{\phi_i} \right\}^{1/\phi_i} . \quad (2)$$

where,

$H_i$ : Present consumption by the  $i$ -th income bracket

$l_i$ : Consumption of leisure by the  $i$ -th income bracket

$$U_i = \left\{ \alpha_i^{1/\sigma_{2i}} H_i^{\nu_i} + (1 - \alpha_i)^{1/\sigma_{2i}} C_{Fi}^{\nu_i} \right\}^{1/\nu_i} . \quad (3)$$

where,

$U_i$ : Utility of the  $i$ -th income bracket

$C_{Fi}$ : Future consumption by the  $i$ -th income bracket

Households are classified into 18 brackets according to their annual income, from the lowest bracket receiving less than 2 million yen per year to the highest bracket earning more than 15 million yen per year. This classification is important in the current analysis for evaluating the economic impact on each income bracket. Since renewable energy and products with improved efficiency tend to be more expensive than ordinary products, households in higher income brackets can more easily afford these products than households in lower income brackets. Consequently, the impact on a household depends on its annual income, and it is important to minimize the economic impact on lower income households.

On the other hand, firms determine the factors of production, labor and capital inputs in order to maximize their profit, as shown by Equation (4). At the same time, intermediate demand in each industry is determined from the Leontief production function given in Equation (5), in which the relations between 39 types of goods and services are expressed in an input-output table (Figure 1).

$$VA_j(L_j, K_j) = A_j L_j^\alpha K_j^{1-\alpha} \quad (4)$$

where,

$L_j$ : Labor input of the  $j$ -th industry

$K_j$ : Capital input of the  $j$ -th industry

$VA_j$ : Value-added production of the  $j$ -th industry

$\alpha$ : Optimal share of labor cost in the factors of production

$$Q_j = \min\{VA_j(L_j, K_j)/a_{0j}, X_{1j}/a_{1j}, \dots, X_{nj}/a_{nj}\} \quad (5)$$

where,

$Q_j$ : Production of the  $j$ -th industry

$a_{ij}$ : Input coefficient from the  $i$ -th to the  $j$ -th industry

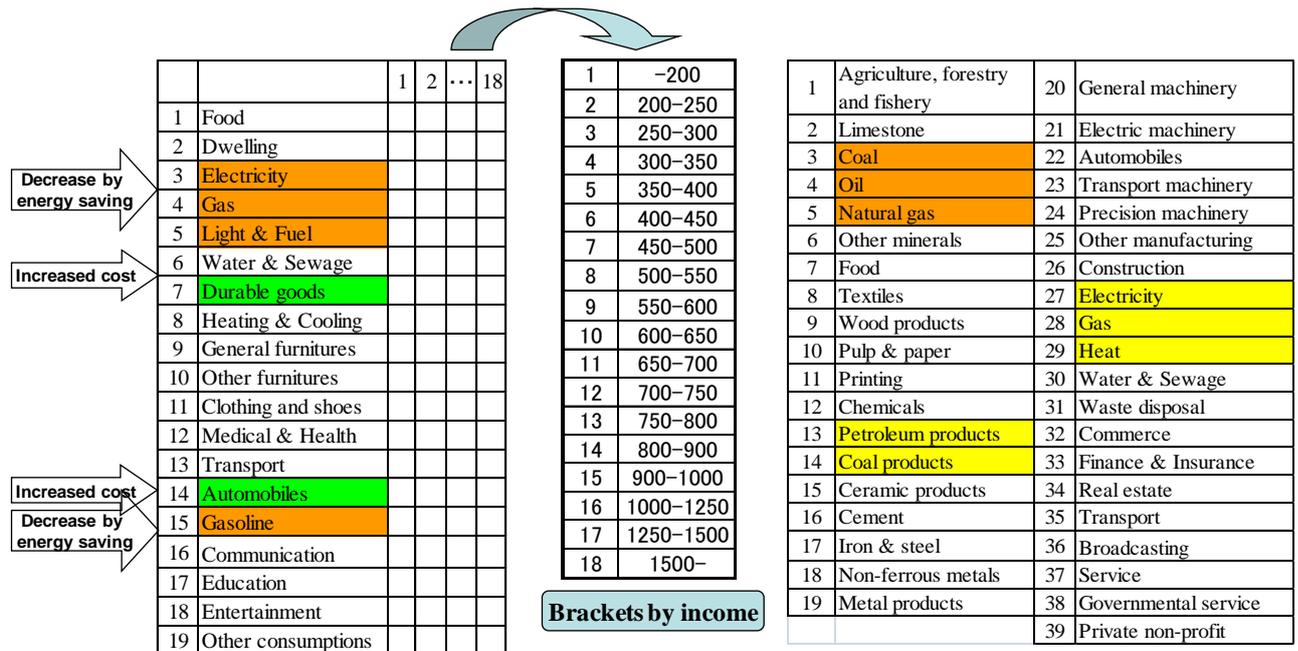


Figure 1. Consumption and production sectors in the CGE model.

For the case where an industrial sector is deploying energy-saving and renewable products for

households, production values increase in electric machinery, precision machinery, transportation and the like. In contrast, households consume less electricity and gasoline as a result of efficiency improvements, and thus the production values in the industrial sectors of electricity and petroleum products decrease. Consequently, complicated repercussion effects are observed in many industrial sectors. An additional consideration is that governments will impose various taxes in order to meet targets for final demand and public investment.

Finally, we compute the equilibrium points, at which the supply and demand of all goods and services, and of factors of production, are equal.

### 2.3 Power planning model and influence of introducing large amounts of photovoltaics

Figure 2 shows the overall framework of the power planning model used in this framework, while the electric power demand in each time period is shown in Figure 3. This mathematical model determines variables for power generation, consumption of each fuel, newly built capacity and so on to minimize total costs as discounted present values. In order to calculate the optimal power mix, we assume specific parameters on the fuel cost, initial cost, operation & maintenance cost and efficiency of each power generation technology. We also set parameters on present capacities and on future demolition capacities. On the other hand, we adopt constraints on satisfying the demand in each time period and region, response to fluctuating demand, upper and lower limits of operational rates and so on. The total numbers of variables and constraints are 841,826 and 482,761, respectively. We used the GAMS mathematical software to determine these variables in the optimal power mix.

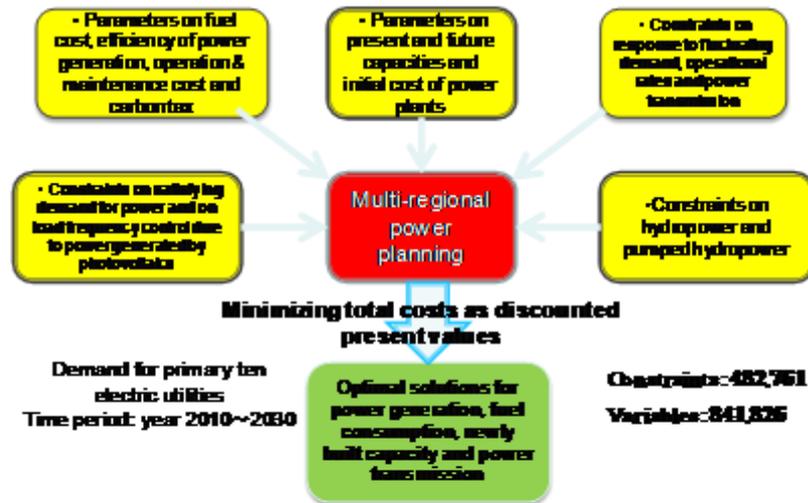
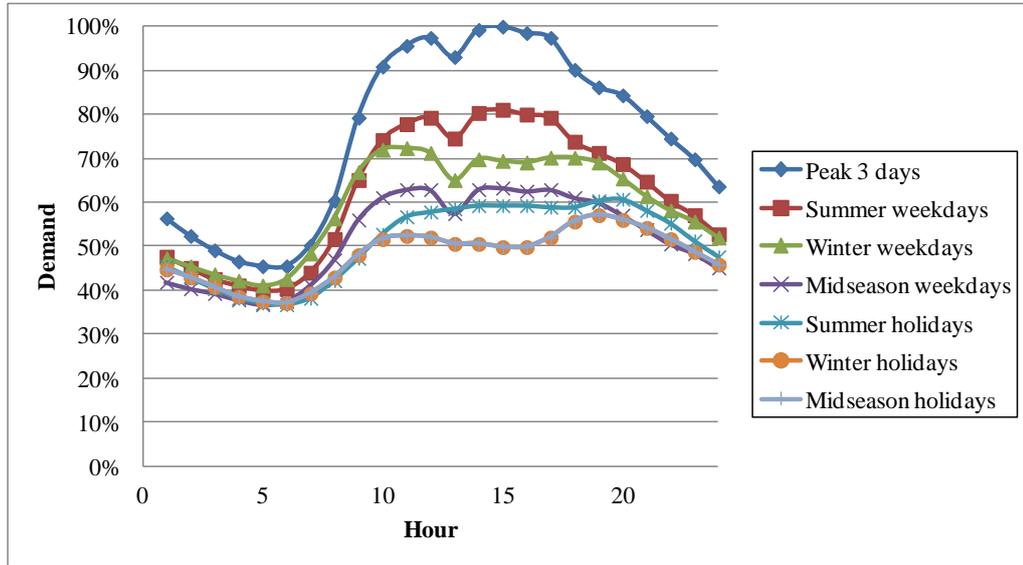
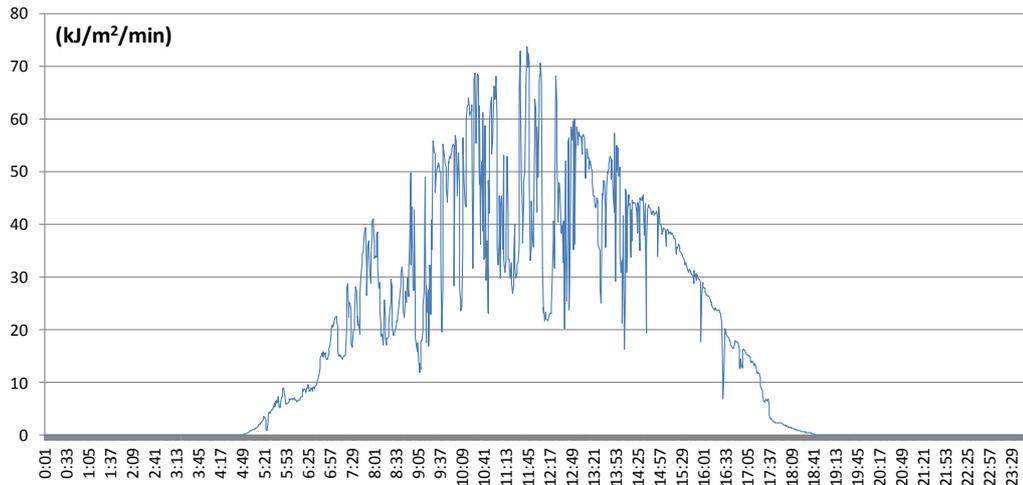


Figure 2. Multi-regional power planning model.



**Figure 3. Electricity demand in the multi-regional power planning model.**

Next, we explain how we deal with the fluctuating power generated by photovoltaics. Figure 4 shows the fluctuation of solar radiation by minute in a meteorological station in Tokyo on July 25, 2009. As shown, solar radiation at any point fluctuates greatly, and so the electricity generated by PV will also fluctuate.

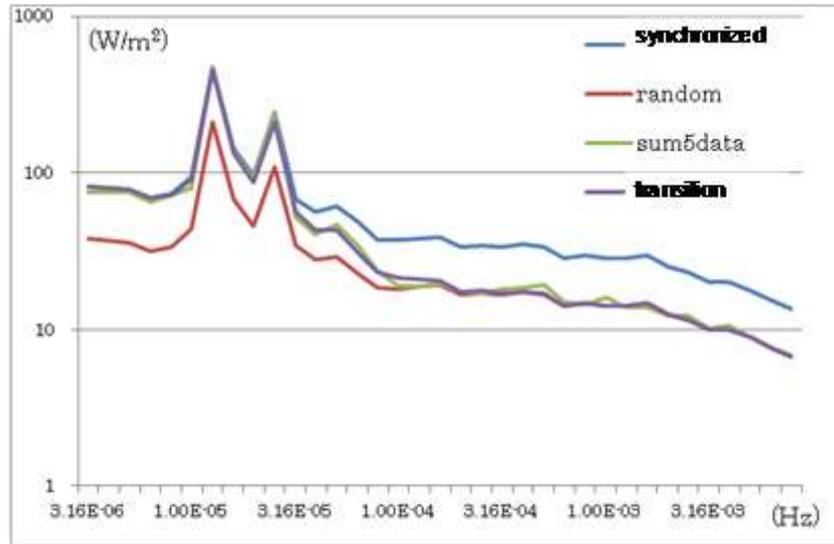


**Figure 4. Estimation of fluctuation of PV output**

Next, we investigate smoothing effects utilizing the transfer hypothesis<sup>[3]</sup> as follows. The transfer hypothesis proposed by Nagoya et al.<sup>[3]</sup> is as follows. PV systems are distributed over wide regions, so the output fluctuation is less than individual fluctuations. This smoothing effect is estimated by the

transfer hypothesis. Below we explain how to estimate the effect according to Nagoya et. al.<sup>[3]</sup>. By applying fast Fourier transformation (FFT) to the data in Figure 4, the frequency spectrum is acquired as shown in Figure 5. In the figure, the frequency spectra with long periods such as 24 and 12 hours are naturally synchronized even among different regions. However, the frequency spectra with short periods such as several minutes are random among different regions. Namely, the frequency spectrum for the sum of PV output is transferred from the long periods with synchronized fluctuation to the short periods with random fluctuation. The green line in Figure 5 shows the frequency spectrum for the total of five regions, while the purple line shows the estimated frequency spectrum of the transfer hypothesis according to Equation (6). The purple line well coincides with the green line, and hence the transfer hypothesis for the actual PV output is true.

$$S_{tra}(f) = \left| \frac{S_{syn}(f) + j \cdot T_x \cdot f \cdot S_{ran}(f)}{1 + j \cdot T_x \cdot f} \right| \quad (6)$$



**Figure 5. Frequency spectrum of fluctuation in solar radiation.**

To evaluate the fluctuation in PV output throughout Japan, we divided the whole of Japan into 10-kilometer square meshes. Then we estimated the fluctuation rate utilizing the transfer hypothesis, assuming the PV capacity in each mesh to be proportional to the roof area of houses.

As a result, the rates of fluctuation to PV output are estimated to be 0.144 in Hokkaido, but only 0.076 in Tohoku. Thus, the rates of fluctuation differ depending on the fluctuation of solar radiation and distribution of PV. Figure 6 shows an example of the estimated smoothing effect.

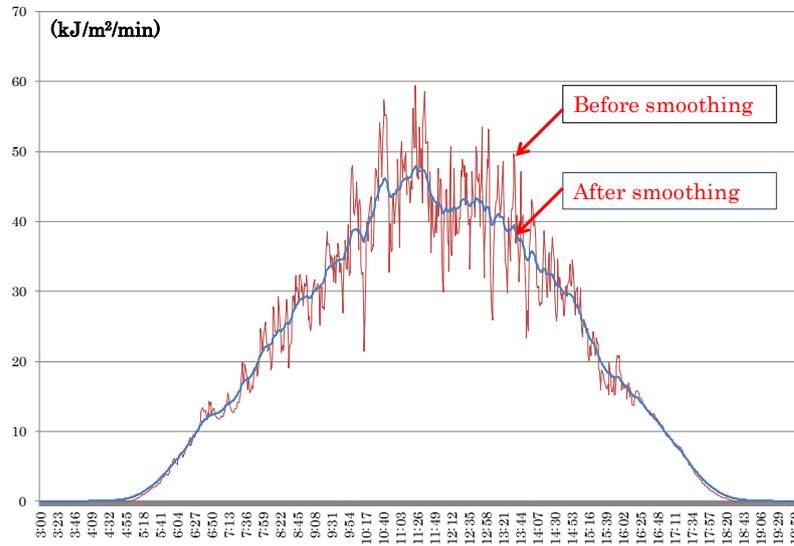


Figure 6. Smoothing effect estimated by the transfer hypothesis.

Now that we are able to estimate the fluctuation of PV output, we integrate the result into our power planning model. First, we show the necessary adjustments by load frequency control (LFC) based on fluctuations of power demand as shown in Figure 7. As the figure shows, some power plants in electric grids must adjust to fluctuations in power demand during several to 30 minutes, which are defined as LFC power plants. Thus, the greater the fluctuation in power demand, the more LFC power plants that are necessary. Shorter-period fluctuations could be adjusted by governor-free control.

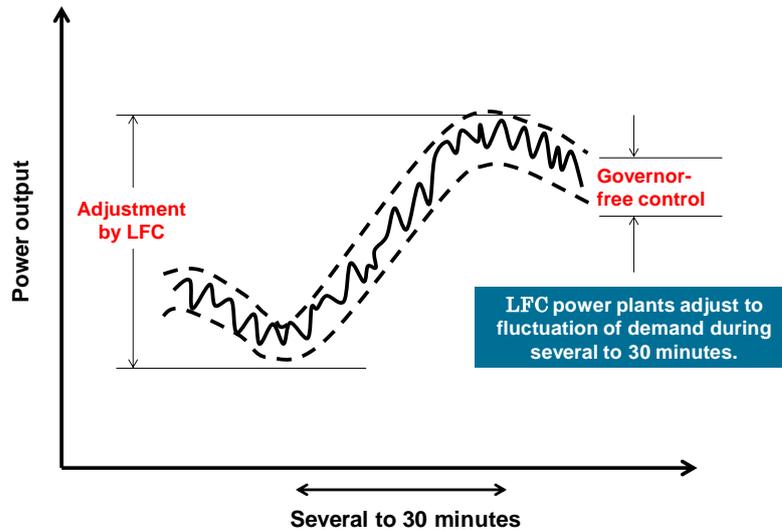


Figure 7. Estimation of necessary adjustments by LFC.

Therefore, we added the following constraints in our electric power planning model for LFC

adjustments. Equation (7) implies that the output of generators under LFC operation must be less than those under ordinary operation by the LFC adjustment width.

$$O(t, r, g, h, d) \leq \{C(t, r, g) \cdot MaxUtil\_D(g, d) - LFC\_C(t, r, g, h, d)\} + LFC\_C(t, r, g, h, d) \cdot (1 - lfc\_range(g) / 2) \quad (7)$$

Equation (8) implies that LFC capacity added by residual adjustment in power grids must be larger than the fluctuation of PV output added by fluctuation in demand.

$$\sum_g \{LFC\_C(t, r, g, h, d) \cdot lfc\_range(g)\} + ePV\_DMD(t, r, h, d) \cdot remain \geq \{ePV\_DMD(t, r, h, d) \cdot lfc\_dmd + PV\_GEN(t, r, h, d) \cdot lfc\_sun(r)\} \quad (8)$$

## 2.4 Final energy demand model

We assume the following conditions to evaluate the final energy demand for households:

- (1) We set demands for electricity, gas, fuel oil, gasoline and so on in 18 income brackets, on the basis of statistical data of household consumption.
- (2) We estimate the proliferation of PV, fuel cells, and electric heat pumps for houses in 2030.
- (3) The percentage of next-generation energy efficient homes (1999 standard) as a stock base is assumed to be 48% in 2030, in accordance with the National Institute of Construction.
- (4) The percentage of next-generation passenger cars as a stock base is assumed to be 50% in 2030. Next-generation passenger cars include hybrid, plug-in-hybrid, electric, fuel cell vehicles and the like.
- (5) The “Top Runner” system is assumed to be continued for domestic electrical appliances and automobiles.
- (6) Based on all of the above assumptions, we revise the demands for electricity, gas, fuel oil, gasoline and so on for households in the 18 income brackets in 2030.
- (7) We also note that the final energy demands adopted here are initial values to be input into the CGE model. Namely, these demands come to different values after convergence of the CGE model.

Among the above assumptions, we evaluate the final energy demands with and without the energy-saving measures described in (3), (4) and (5). In the next section, we name the scenarios “with energy saving” and “without energy saving”, respectively.

## 2.5 Scenarios of energy supply, CO<sub>2</sub> emissions and living standards in 2030

In this section, we describe the assumptions for scenarios of energy supply, CO<sub>2</sub> emissions and living standards in 2030. First, we describe the assumptions for scenarios of economic growth and distribution of power generation in 2030. The scenarios assume the adoption of several energy-saving and renewable technologies with either increased or decreased use of nuclear power plants. In particular, assumptions for nuclear power are significant, taking the impact of the Great East Japan

Earthquake into consideration.

*Case 1: The nominal case*

The nominal case does not adopt any measures to reduce greenhouse gas emissions. GDP is assumed to grow at an annual rate of 1.3% from 2005 to 2020, and more slowly at 0.5% from 2020 to 2030 in view of the falling population and deepening maturity of the economy.

*Case 2: The case of increasing nuclear power*

With the same GDP growth rate as in Case 1, in Case 2 we assume that 14 new nuclear power plants will have been constructed by 2030; note that the 6 reactors at the Fukushima Dai-ichi Nuclear Power Plants are assumed to be decommissioned by 2020. We also assume that the operating ratio of all nuclear plants will have improved to 90% by 2030, in accordance with the to 53 GW in 2030.

*Case 3: The case of maintaining nuclear power*

The assumptions are the same as in Case 2 except we assume that no more nuclear plants will be constructed in future. However the total capacity of nuclear plants will be kept the same as present except for the 6 reactors at the Fukushima Dai-ichi Nuclear Power Plants to be decommissioned. Namely, they will renew the same capacity of the nuclear plants to be decommissioned in future. Solar power generation is assumed to increase to 53 GW in 2030.

*Case 4: The case of decreasing nuclear power*

We assume that no more nuclear plants will be constructed in future, and that all other existing nuclear power plants will be decommissioned after 40 years of operation. Power shortages resulting from closing the nuclear plants will be compensated for mainly by coal, oil and natural gas power plants. Solar power generation is assumed to increase to 53 GW in 2030. All other assumptions are identical to Case 2.

For solar power generation systems, we assume that their cost will decrease as estimated by Yamada *et al.*<sup>[4]</sup> as shown in Table 1. A methodology to evaluate the cost of future power generation systems was reported and published in the proceedings of the 2011 World Engineers' Convention. Basic Energy Plan. Moreover, generation from solar power systems is assumed to increase

**Table 1. Estimates of future cost of solar power generation systems<sup>[4]</sup>**

(Yen/W)

YEAR	2012	2020	2030
PV panel (Yen/W)	100	75	50
BOS* (Yen/W)	150	100	70
PV system (Yen/W)	250	175	120
Efficiency (%)	15	20	30

\* BOS is an acronym of “balance of the system”, implying peripheral equipments of PV systems to supply electricity.

Meanwhile initial costs and conversion efficiencies of conventional technologies for power generation other than PV are assumed as shown in Table 2 according to National Strategy Council<sup>[5]</sup>. No values are shown in table 2 regarding conversion efficiencies for nuclear power and hydropower generation, since they cannot be defined in the same way as fossil-fired power generation.

**Table 2. Assumptions on initial costs and conversion efficiencies of conventional technologies.**

		Yen/W	%
Coal-fired power generation	230	42	
Integrated coal gasification combined cycle		288	48
Gas-fired power generation		120	44
Natural gas combined cycle		120	51
Oil-fired power generation		190	39
Nuclear power generation		350	-
Hydropower generation		850	-
Hydraulic pump-up station		850	70
Biomass-fired power generation		400	20

Costs of fuels for power generation are assumed as shown in table 3 according to National Strategy Council<sup>[5]</sup>. These costs are expressed in terms of primary fuel except for nuclear, so that costs of power generation must be evaluated, taking account of the conversion efficiencies in table 2. In the case of nuclear, however, the value directly expresses the fuel cost for power generation.

**Table 3. Assumption on costs of fuels for power generation.**

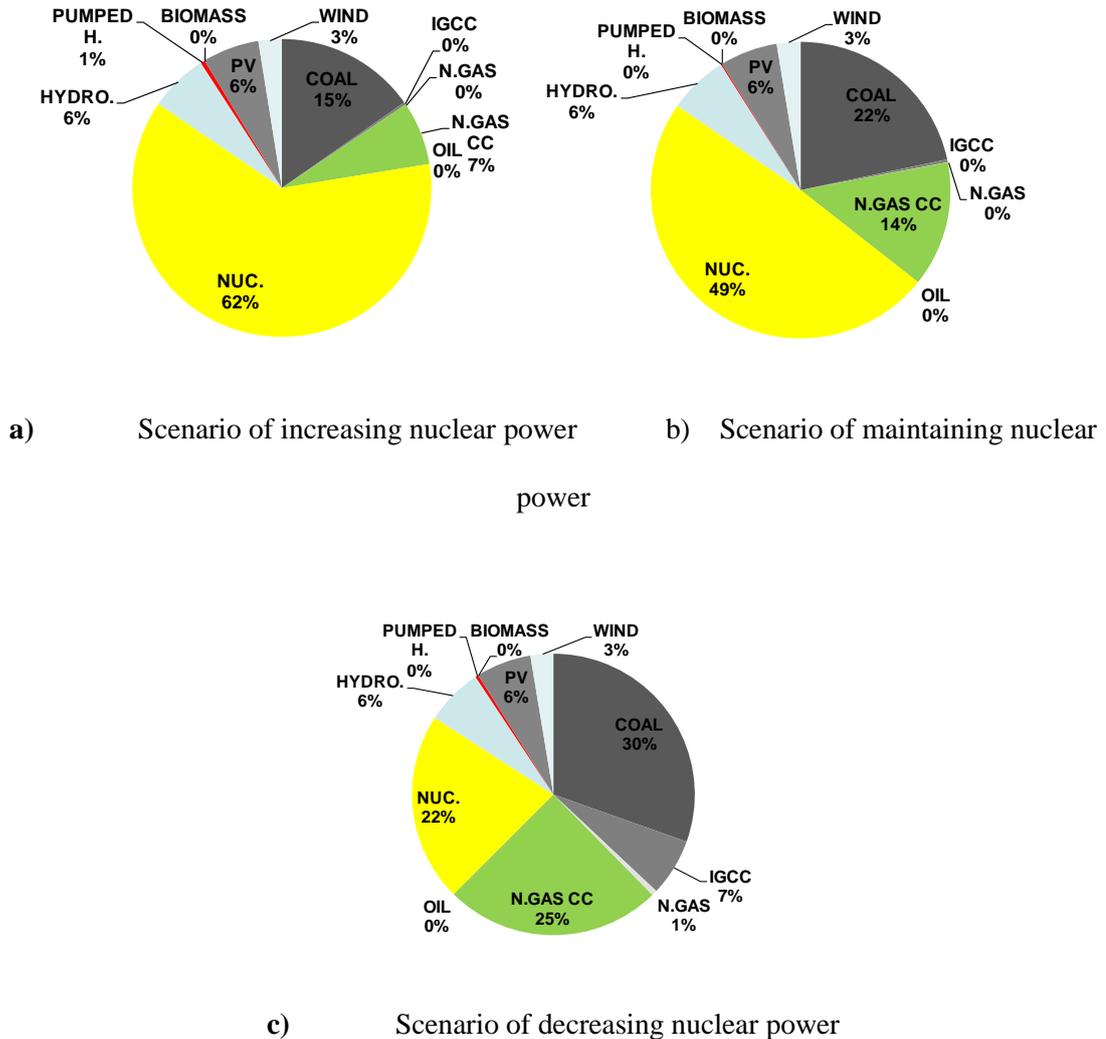
	Yen/kWh					
	2010	2015	2020	2025	2030	
Coal	1.81	1.83	1.85	1.86	1.87	
Gas	4.18	4.32	4.46	4.55	4.65	
Oil		6.47	6.73	6.99	7.14	7.29
Nuclear		1.40	1.40	1.40	1.40	1.40
Biomass		3.52	3.52	3.52	3.52	3.52

On the other hand, the following assumptions for energy efficiency improvement and CO<sub>2</sub> reduction in the industrial and transportation sectors are used in this analysis:

- (1) Natural gas is assumed to replace 80% (relative to 2005 levels) of petroleum products and fuel, including heavy oil, used by all manufacturing sectors (except the petrochemical industry).
- (2) Promoting modal shift: Based on an input-output analysis of distribution, CO<sub>2</sub> emissions in the transportation sector are assumed to be cut by up to 44%.
- (3) Promoting energy savings in industrial sectors: In accordance with the law promoting energy conservation, the annual improvement of energy intensity in each industry is assumed to be 1%.

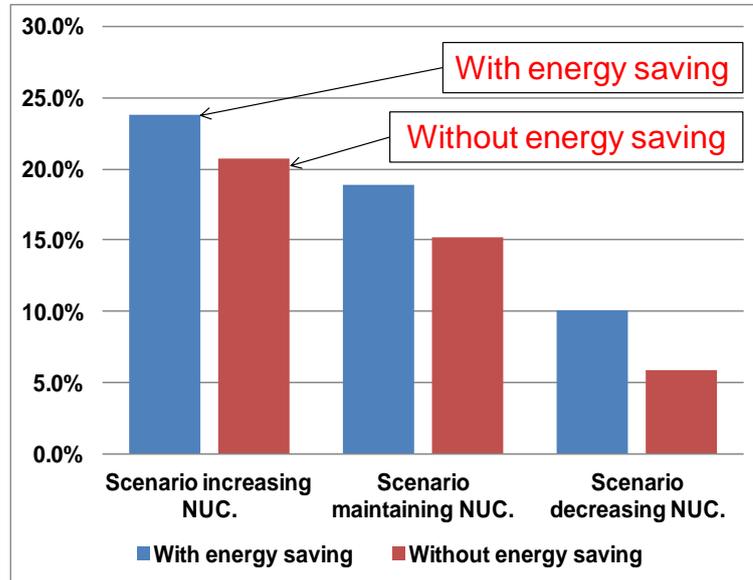
### 3. EVALUATED RESULTS AND DISCUSSION

First we show the results of optimizing the power planning model. Figure 8 shows the share of electricity generated in optimized power planning scenarios. Comparing Figures 10 b) and c) with a), we find that coal fired power plants and the natural gas combined cycle mainly compensate for the decrease of nuclear power plants.



**Figure 8. Share of electricity generated (energy-saving case)**

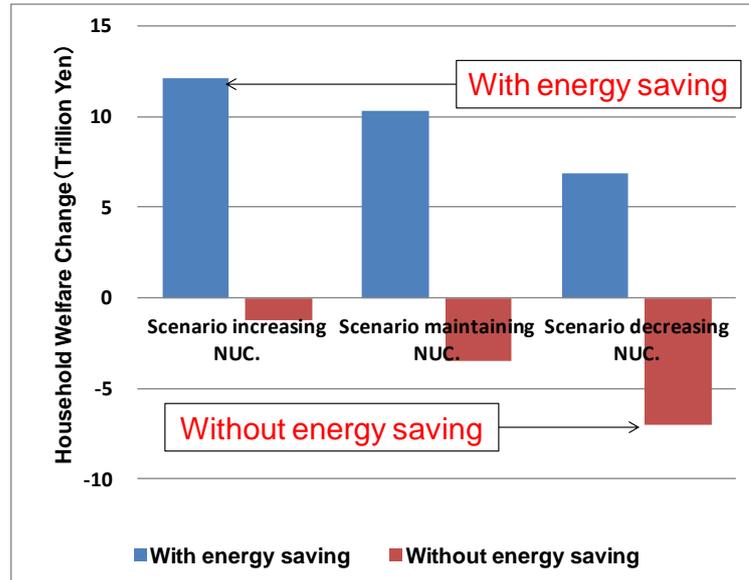
Next, we used the CGE model to estimate the reduction in CO<sub>2</sub> emissions from energy consumption in comparison with the 1990 emissions level. Figure 9 shows the estimated results in 2030.



**Figure 9. Reduction of CO<sub>2</sub> emissions in 2030 compared with 1990.**

The impact of the recent disaster on CO<sub>2</sub> emissions will be extremely high due to the reduced operating ratio of existing nuclear plants and postponement of new construction. This is why there are differences of 13.7–14.8% between the scenarios of increasing and decreasing nuclear power plants.

On the other hand, Figure 10 shows the increases and decreases in household welfare value, namely the estimated difference in welfare value per household for each case compared with Case 1 for 2030. Changes in welfare are translated from changes in utility by using the concept of equivalent variation. Specifically, the welfare changes show changes in utility, based on the concept of equivalent variation, in which the utility changes are expressed in terms of the price of goods and services before the change. We cannot express changes in household welfare in terms of only disposable income, since the prices of goods and services differ depending on each case. Hence, we use household welfare values with equivalent variation.



**Figure 10. Changes in household welfare values in 2030.**

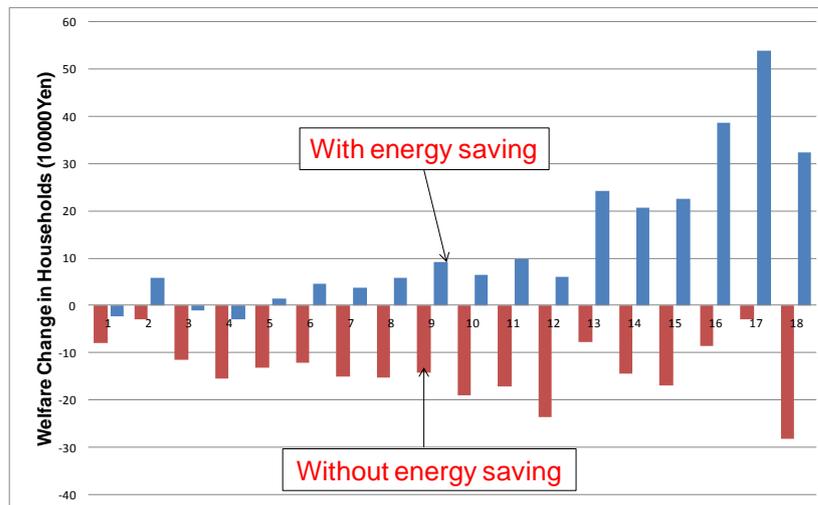
Figure 10 expresses the differences from Case 1, the no reduction case.)

The blue bars in Figure 10 show positive changes from Case 1. This implies that the utilities of households could be considerably improved by the spread of energy-saving products, such as high-efficiency electrical appliances and automobiles. Thus, measures to promote the spread of these products are crucial, regardless of the increase or decrease of nuclear power plants.

On the other hand, the red bars in the figure show negative changes from Case 1, implying that household welfare decreases from Case 1.

Unless we are able to deploy the energy-saving technologies listed in (3), (4) and (5) in Chapter 3, the prices of all consumer goods centered on electricity will escalate in 2030, mainly due to carbon taxes. Carbon taxes are assumed to be imposed at 40 US\$/t-CO<sub>2</sub> in 2030 according to the National Strategy Council<sup>[5]</sup>. The feed-in-tariff for deploying 53 GW of PV also leads to a rise in electricity prices. Since the costs of solar power generation systems are assumed to be reduced as shown in Table 1, the rise in energy price is only about 0.5 yen/kWh due to the feed-in-tariff; thus, the rise in electricity price due to the carbon tax is several times higher than that due to the feed-in-tariff. Furthermore, introduction of a carbon tax will not only raise the electricity price but also raise the prices of gas, fuel oil and gasoline. Therefore, the total impact of a carbon tax is far higher than that of the feed-in-tariff.

Finally, we compare household welfare values in 2030 for all income brackets under Case 2 and Case 3 as shown in Figure 11. This figure shows that household welfare values will increase regardless of the existence of nuclear power plants, as long as the energy efficiency of final consumption is improved using measures (3), (4) and (5) in Chapter 3. Therefore, the most significant factor in establishing a low-carbon society is to promote energy conservation.



**Figure 11. Changes of household welfare values in individual income brackets for Case 5.**

(Figure 11 shows the change in household welfare values relative to Case 1, and we assume promotion of energy-saving measures (3), (4) and (5) in Chapter 3.)

The following implications are deduced from the above analyses.

- Cases 2 and 3, in which we increase or maintain the number of nuclear power plants, are superior in improving household welfare and decreasing CO<sub>2</sub> emissions. Now that acceptability to the public has been lowered due to the accident at the Fukushima Dai-ichi Nuclear Power Plant, these cases are questionable in terms of environmental safety and security.
- Although Case 4, in which we decrease nuclear power plants, is inferior to Cases 2 and 3 in terms of household welfare values, the difference is small. CO<sub>2</sub> emissions are, however, drastically increased in Case 4, which is contradictory to the goal of establishing a low-carbon society in Japan.

#### 4. CONCLUSIONS

This paper investigated energy policies and measures to establish a secure and affluent low-carbon society under the serious situation following the Great East Japan Earthquake. We developed a framework integrating power planning models, a final energy demand model and a computable general equilibrium (CGE) model for Japan. Then we conducted a comparative analysis of the effects of increasing and decreasing the number of nuclear power plants on household welfare and CO<sub>2</sub> emissions. We also used the model to evaluate the effects of deploying renewable energy and energy-saving technologies. As a result, we quantified how the decrease of nuclear power plants had an impact on CO<sub>2</sub> emissions, then we evaluated the impact of the energy scenarios on household welfare. The computed results implied that household welfare could be considerably improved by the spread of energy-saving products, such as high-efficiency electrical appliances and automobiles. Thus, measures to promote the spread of these products are significant, regardless of the increase or decrease of nuclear power plants.

Now that trust in nuclear energy has been severely damaged as a result of the accident at the Fukushima Dai-ichi Nuclear Power Plants, energy policies will inevitably need to be revised. With present technologies and institutions, there is no ideal solution that ensures environmental safety and

security, low-carbon and affluent society. Thus, we need technological and institutional innovations in order to create such a society in the long term. These innovations include reducing the cost of renewable energy technologies, improving energy efficiency, and integrating information technology with the energy system.

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