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Original paper

An assessment of a nuclear power shutdown in Japan using the computable general equilibrium model

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Abstract Following the Great East Japan earthquake and the resulting tsunami, the accident at the Fukushima Daiichi nuclear power station has caused public anxiety about existing nuclear power reactors in Japan. This has made it difficult for the local government to allow the idle nuclear power reactors to resume operation after their scheduled inspection. In 2013, Japan will have to balance electricity supply and demand with zero or very few operating nuclear power reactors. This gap between electricity supply and demand will have to be closed using expensive fossil fuel power generation. Therefore, this study aims to assess the economy-wide and regional impacts of total nuclear power shutdown in Japan using a multi-regional, multi-sectoral, static computable general equilibrium model. The study results indicate that immediate total nuclear power shutdown in Japan would have a significantly negative impact on the country's economy and carbon dioxide emissions. The negative economic impact would differ among regions according to their nuclear dependency and could further accelerate the rise in regional economic disparity.

Key words Nuclear power shutdown, Japan, CGE model

1. INTRODUCTION

The accident at the Fukushima Daiichi nuclear power station caused public anxiety in Japan and damaged confidence in nuclear power generation. On March 11, 2011, the Great East Japan earthquake and the tsunami that followed damaged the nuclear reactors located along the Pacific coastal area of East Japan. The damaged nuclear reactors went into automatic shutdown. Control rods were immediately inserted into the reactors' cores to stop the nuclear chain reaction. The cooling system was expected to absorb the residual heat of the fuel rods. However, the earthquake caused the external power supply at the Fukushima Daiichi nuclear power station to fail. In addition, emergency power generators installed at the power station were flooded by the tsunami, leading to a station blackout and a subsequent failure of the cooling system. According to Tokyo Electric Power Company's review (TEPCO 2012), the leaked hydrogen in the Unit 1 and Unit 3 reactors accumulated at the upper part of the reactor building causing

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an explosion. In the Unit 4 reactor building, hydrogen gas accumulated inside the building by flowing through an area where the Units 3 and 4 pipes leading to the exhaust stack connects, resulting in a hydrogen explosion. In addition to the hydrogen explosion accidents in the Fukushima Daiichi nuclear power station, East Japan suffered a severe electricity shortage in the aftermath of this natural disaster. Following the disaster, Tohoku Electric Power Company's supply capacity decreased from about 14 million kW to about 9 million kW. The fossil fuel power stations of the Tokyo Electric Power Corporation (TEPCO) located in East Japan were forced to suspend the supply of 12 million kW of electricity in the aftermath of the earthquake and the tsunami. Records show that the expected peak demand for electricity in March 2011 was about 41 million kW, which was to be supplied by TEPCO. However, following the disaster, TEPCO's supply capacity dropped to about 31 million kW (METI 2011a). To close this gap between the electricity supply and demand, TEPCO implemented rolling blackouts to many cities in suburban Tokyo, for three to six hours daily, between March 14 and March 28, 2011. Tohoku EPCO cancelled their intended rolling blackout because of a low demand for electric power. In summer 2011, because of expected electricity shortage in Tohoku and Kanto, the government ordered large-volume users of these two companies to decrease their electricity usage by 15% from that of the previous year during peak weekday hours. In this case, large-volume users were defined as offices and factories consuming at least 500 kW of electricity during peak weekday hours. The order was effective from July 1, 2011 to September 9, 2011. In October 2011, the Ministry of Economy, Trade and Industry (METI) released a survey questionnaire to investigate how this order was implemented (METI 2011b). The survey was conducted for 30 firms. Its findings revealed that the surveyed firms adjusted production at plants to reduce peak electricity loads and expanded their usage of on-site power generators to maintain their production levels. Because of these measures, these firms had incurred substantial additional costs, including increased labour costs owing to shift work on holidays and at night and the costs of on-site power generation. According to METI (2011b), these costs ranged from several hundred million yen to several billion yen. In the winter of 2011, the restoration of the damaged fossil fuel power stations helped to close this gap between electricity supply and demand in Tohoku and Kanto, but only just.

2.1 The subsequent shutdown of nuclear power reactors

Before the earthquake and the resulting tsunami, Japan had 54 nuclear power reactors at 18 plants. The four reactors at the Fukushima Daiichi power station have been decommissioned. Only two of 50 reactors are operating as of April 30, 2013. Four reactors at the Fukushima Daini nuclear plant stopped operation after an inspection of the damage they suffered due to the earthquake and/or tsunami. The other nuclear reactors are idle.

In Japan, a nuclear reactor is required to undergo a scheduled inspection in line with the Electricity Utilities Industry Law (1964), according to which all reactors must conduct a scheduled inspection after 13 months of operation. The scheduled inspection at each reactor usually takes about two months, followed by a month of adjustment operations. In addition, in July 2011, the Japanese government required electricity power companies to conduct a stress test on their nuclear reactors under the scheduled inspection as a step toward resuming operations. In September 2012, a new organization, the Nuclear Regulation Authority (NRA), was launched to regulate nuclear power. In April 2013, the NRA proposed new safety standards requiring that electric power companies improve their nuclear plants. For instance, the standards require companies to construct sturdy buildings for emergencies, replace wiring, and install improved ventilation systems. The standards will come into effect in July 2013. The electric power companies have to take measures to meet these standards and pass the NRA's inspection before idle nuclear reactors can resume operation.

Even if electric power companies pass the NRA inspection, the local government where the nuclear power reactor is located is required to give permission to allow the idle reactors to resume activity. Nationwide and local public anxiety about existing nuclear power reactors could make it difficult for the local government to give such approval. Hence, in 2013, Japan would have to balance its electricity supply and demand with very few operating nuclear power reactors. In that case, it follows that the electricity shortage would have to be met by a corresponding increase in fossil fuel power generation.

The International Energy Agency (IEA) (2011) reported that coal- and gas-fired power plants were operated at a relatively high utilization rate in 2009 in Japan. However, only 30% of the oil-fired power generation capacity was used nationwide. Although fossil fuel power plants in Japan are operating at full capacity in peak-demand seasons after the accidents, the Japanese government and electric power companies have asked customers to reduce their consumption of electric power. In addition, since all domestic nuclear power plants are to be stopped, the cost of importing fossil fuels (such as liquefied natural gas (LNG) and crude oil) will increase. This additional fuel cost will push up the price of electricity.

In April 2012, TEPCO increased the price of electricity for commercial users by 14.9% on average and for home users by 8.5% because of the rising input cost of fossil fuel. The other electric power companies plan to increase the price of electricity for commercial and home users for the same reason. From May 2013, the Kansai Electric Power Company and Kyushu Electric Power Company plan to increase the price by about 17.3% and 11.9% for commercial users, respectively, and by 9.8% and 6.2% for home users, respectively. Industry groups have expressed concern over the increase in production costs owing to the steep rise in the cost of electricity.

The economy-wide impact of a total nuclear power shutdown was not estimated for Japan before the nuclear accidents in Fukushima. In Germany, Welsch and Ochsen (2001) assessed the effects of a gradual nuclear phase-out on the country’s economy using a recursive dynamic general equilibrium model, LEAN-TCM. They considered two regions: West Germany and the rest of the European Community (EC9). Each region had 13 sectors, including detailed electricity sectors; that is, nuclear power, renewables, and four distinct types of fossil fuels capable of generating power (hard coal, brown coal, oil, and gas). They assessed the economic and environmental impacts of shortening the lifetime of existing nuclear plants from 40 years to 30 years. They concluded that such shortening would not have a severe negative impact on the German economy. In Japan, Nakata (2002) assessed the effects of a gradual nuclear phase-out using the partial equilibrium model with a detailed energy supply and demand description. However, the above study focused only on the energy supply and demand system, and not on economy-wide impacts. After the nuclear accidents, the economic impact of a phase-out of nuclear power was discussed by the METI committee in 2012 (METI 2012). The committee used four macro-economic simulation models, the AIM/CGE model, Ban model, KEO model, and the DEARS model, to assess five scenarios about reducing the country's dependence on nuclear energy. These scenarios included a total nuclear-phase out in Japan by 2030. According to the simulation results, in 2030, the total nuclear phase-out will decrease Japan’s GDP by 1.0% (compared to the business as usual case) in the most optimistic case and by 5.0% in the most pessimistic case. In addition, it will increase the price of domestic electricity by 104% in the most pessimistic case and by 41.9% in the most optimistic case. The committee provides information on a long-term nuclear phase-out in Japan. However, almost none of the nuclear power plants in Japan are able to resume operation. In addition, the model used by the METI committee is a country-level CGE model. The economic impact of a complete nuclear power shutdown should ideally have been assessed by region, because these impacts will differ among regions, given the varying extent to which they depend on nuclear power.

Therefore, this study aims to provide an understanding of nationwide and regional economic impacts of the total nuclear power shutdown faced by Japan, using a multi-regional, multi-sectoral, static computable general equilibrium (CGE) model. The rest of this paper is structured as follows. Section 2 provides the main structure of the CGE model, including detailed electricity generation. Section 3 describes the data used in this study to build the model. Section 4 presents the simulation results of a complete nuclear power shutdown in Japan. Section 5 concludes.

2. THE COMPUTABLE GENERAL EQUILIBRIUM (CGE) MODEL

4.1 Overview of the model

The model in this study divides Japan into eight regions (i.e., Hokkaido, Tohoku, Kanto, Chubu, Kinki, Chugoku, Shikoku, and Kyushu, which includes Okinawa). Kanto, Chubu, and Kinki include Tokyo, Nagoya, and Osaka, respectively. There are 18 production sectors in each region, including the electricity sector (Table 1). As explained below, electricity is generated by four distinct generation technologies (i.e., nuclear, fossil fuels, hydro, and renewables). From the demand side, production sectors and households can save electricity inputs by substituting these with other inputs. Production sectors trade products with each other within their region, as well as across regions. The model considers the limited capacity of electric power transmission between East Japan and West Japan. Production sectors can also import and export their products from or to a foreign country. Foreign saving is fixed exogenously at the initial level. Accordingly, the rate of foreign exchange is adjusted flexibly and endogenously within the model. A representative household and a local government exist in each region and serve as the final consumers. The central government exists only to transfer tax revenue levied from all production sectors and households to a representative household in each region. All goods' markets are assumed to be perfectly competitive, such that demand equals supply, with zero profit. The detailed structure of the production and labour market in this model is explained below. The model assumes that production sectors and households emit carbon dioxide (CO2) with the combustion of fossil fuels, petroleum and coal products, and gas-based products

Table 1. Production Sectors in the Model

Sector code	Description
AGR	Agriculture and fisheries
MNG	Mining excluding fossil fuels
FFL	Fossil fuels (including crude oil, coal, and natural gas)
FOD	Food products
OMF	Other products
CRP	Chemical products
P_C	Petroleum and coal products
I_S	Iron and steel
NFM	Non-ferrous metal
MCE	Machinery and equipment
EEQ	Electrical devices and equipment
TEQ	Transport equipment
CNT	Construction
ELE	Electricity
GAS	Gas-based products
CMC	Commerce
TRP	Transportation
SRV	Other services

4.2 Production technology

The production technology for each sector is modelled using a nested constant elasticity of substitution (CES) production function in the model. The nesting structures of CES functions and the value of the elasticity of substitution in each CES function refer to those of the Massachusetts Institute of Technology's Emissions Predictions and Policy Analysis (MIT-EPPA) model (Paltsev et al. 2005). A sensitivity analysis was conducted with respect to key substitution parameters in the model, the results of

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which can be seen in Section 4.

The model assumes that there are four types of production structures: manufacturing and services, agriculture and fishery, fossil fuel extraction, and electricity generation. The production structure of manufacturing and services is described in Fig. 1. Parameters to the right of the arcs in Fig. 1 represent the value of the elasticity of substitution among inputs. The output of these sectors is modelled as the Leontief composite among non-energy intermediate inputs and an energy value-added composite input. Note that a vertical line in the nesting diagram represents the Leontief aggregate. The value-added input is modelled as the Cobb–Douglas composite of labour and capital inputs. The energy composite input and the value-added input are assumed to be substitutable and are aggregated using a CES function. The energy composite input is composed of energy good inputs (i.e., electricity, fossil fuels, petroleum and coal products, and gas-based products). At the bottom nest, all energy goods inputs, other than the electricity input, are assumed to be substitutable and are aggregated to be a fuel composite input using a CES function. The fuel composite input and the electricity input are assumed to be substitutable and are aggregated to the energy composite input using a CES function. In the CGE model, a production sector minimizes its unit production cost by choosing an optimum input mix, subject to the constraint of its production technology. Hence, if the electricity price rises while other input prices remain constant, the cost of minimizing electricity use decreases and the cost of minimizing the quantity of other inputs increases. This substitution represents the behaviour of saving electricity by production sectors. Finally, domestically produced goods are transformed to products for domestic sales or export based on the constant elasticity of transformation (CET) function.

Agricultural and fishery output is modelled as the CES composite of a land–material–energy composite input and value-added (see Fig. 2). The land–material–energy composite input is the CES aggregate of land use and the energy–material composite input. The energy–material composite input is the CES aggregate of a material composite input and an energy composite input. The material composite input comprises non-energy intermediate inputs. The energy substitution structure of the agriculture sector is the same as that of the manufacturing and service sector. The structure of fossil fuel extraction is described in Fig. 3. The output of fossil fuels is the CES aggregate of a natural resource input and a non-natural resource composite input. The natural resource is a sector-specific primary factor which each regional household provides. The non-natural resource composite input is the Leontief aggregate of non-energy intermediate inputs, energy goods inputs, and value-added.

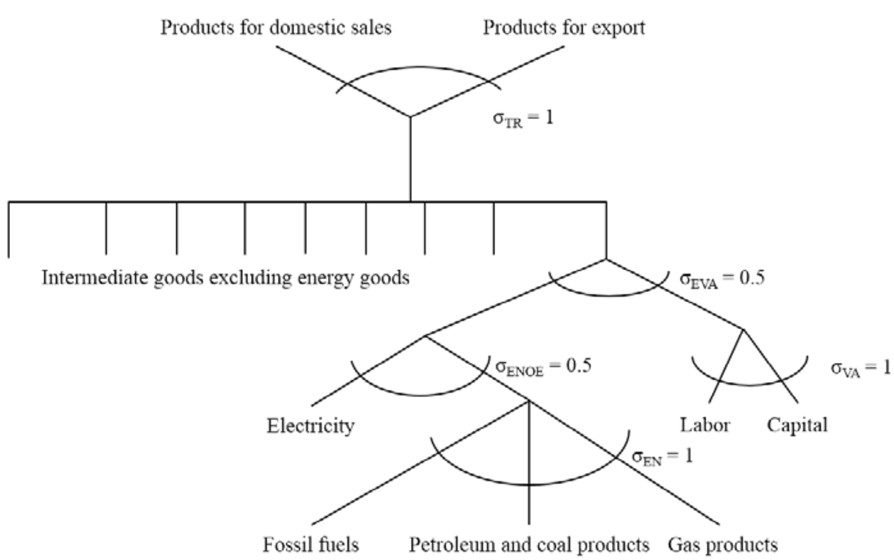

Figure 1. Production structure of manufacture and service

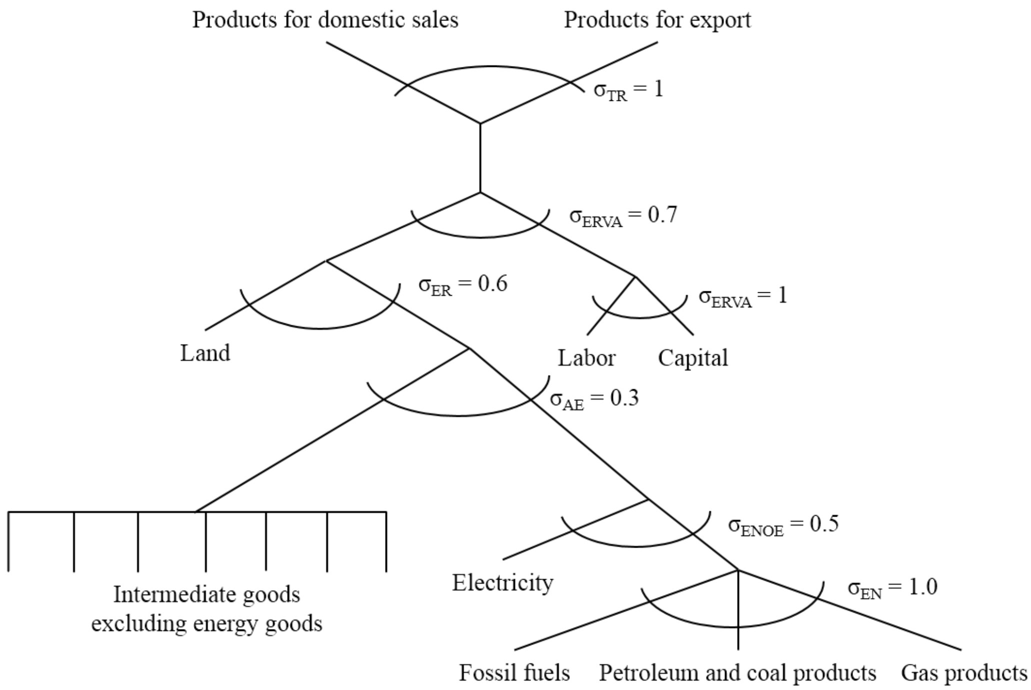

Figure 2. Production structure of agricultural sector

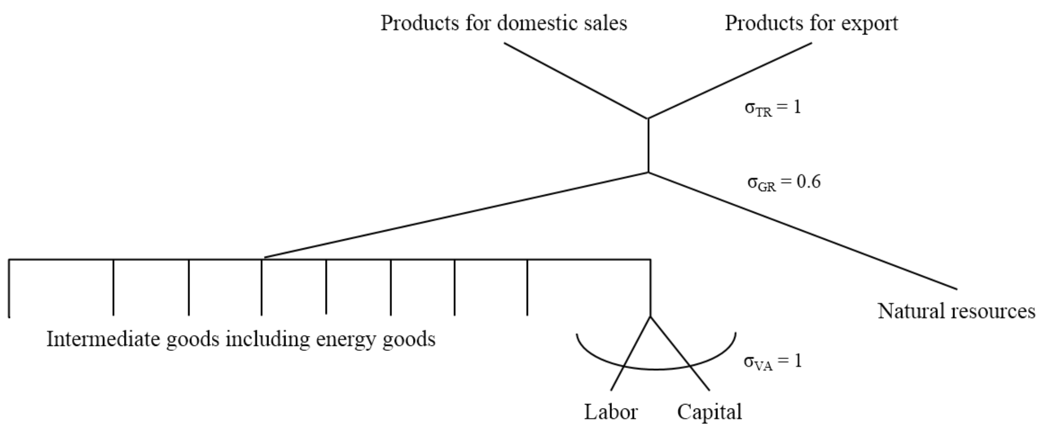

Figure 3. Structure of fossil fuel extraction

4.3 The structure of electricity production

Electricity is generated by four distinct generation technologies in the model (i.e., nuclear, fossil fuels, hydro, and renewables). The CES-nested structure of the electricity sector is described in Fig. 4. It is assumed that there is no difference in the quality of electricity among the generation technologies. The model further assumes that each electricity generation technology needs a technology-specific capital input to generate electricity. A fixed amount of the technology-specific capital is then rented out to electricity sectors within their region. Electricity generation by nuclear energy, hydropower, and renewable resources is modelled as the Leontief aggregate of intermediate inputs, energy goods inputs, and primary factor inputs, including the corresponding technology-specific capital input. With the exception of fossil fuel power generation, the level of electricity generation crucially depends on the

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amount of the technology-specific capital input. This level can be controlled by changing the amount of technology-specific capital exogenously, as seen in the simulation conducted below. Fossil fuel power generation is modelled as the CES composite of the technology-specific capital input and other composite inputs, with the elasticity of substitution being σ_r^T. This production structure reflects the fact that a fossil fuel power station usually has the capacity to increase the amount of power it generates in response to changes in electricity demand. The substitution parameter σ_r^T can be calibrated such that the cost share of the technology-specific capital input for the fossil fuel power generation, represented by θ_r, and the price elasticity of the fossil fuel electricity supply, represented by ε_r^S, are combined, as shown in Equation 1. The subscript r represents each region in the model in Equation 1. The value of σ_r^T ranges from 0.41 in Chugoku to 1.01 in Kinki. The procedure used to derive Equation 1 is explained in the Appendix.

$$\sigma_r^T = \frac{\theta_r \varepsilon_r^S}{1-\theta_r} \tag{1}$$

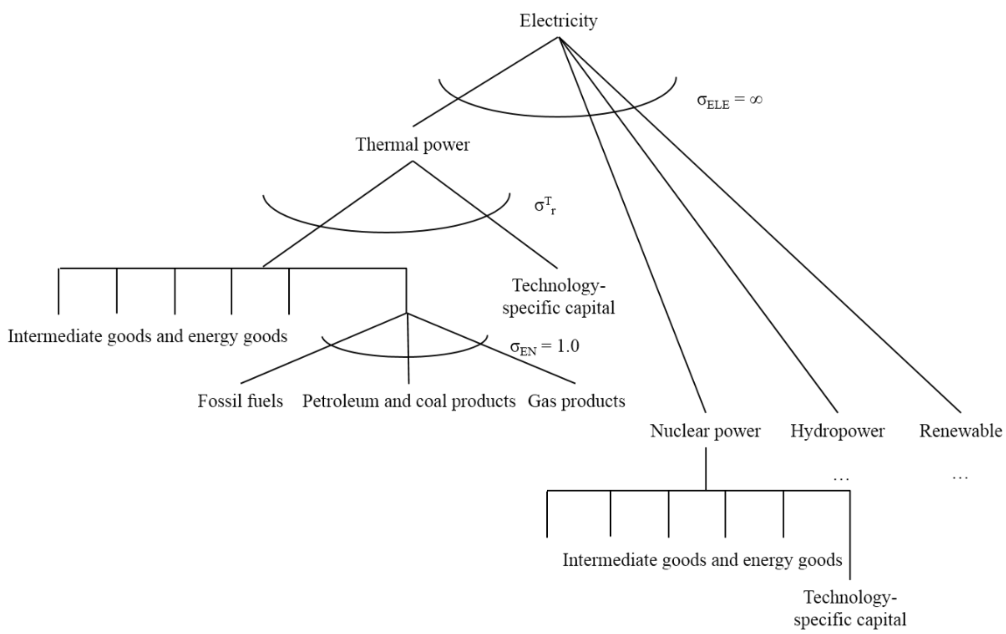

Figure 4. Structure of electricity generation

4.4 Inter-regional trade

Trade exists across regions. This study modelled regional trade as the CES composite among products produced in each region, as described in Fig. 5. The CES function of each region integrates products produced in that region for its own supply and products produced in other regions for export to that region. Upper-tier CES functions integrate the domestic composite and imports in each region. This study set the elasticity of substitution among domestic regions to 0.5. The values of the elasticity of substitution between the domestic composite and imports were provided by the GTAP Database, version 7 (Narayanan and Walmsley 2008).

Electricity trading is an exception. The frequency of electric power in East Japan and West Japan is 50

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Hz and 60 Hz, respectively. Therefore, East Japan and West Japan are unable to exchange electricity with one another, although frequency converters are available to a limited extent. Electricity interchange is also modelled using a CES function with high elasticity of substitution among regions operating at the same frequency. However, the electricity interchange among regions operating at different frequencies is fixed at the initial level through the simulations conducted below. In concrete terms, the model assumes that regions in East Japan (i.e., Hokkaido, Tohoku, and Kanto) can interchange electricity smoothly among themselves. Regions in West Japan (i.e., Chubu, Kinki, Chugoku, Shikoku, and Kyushu) can also interchange electricity smoothly among themselves. However, the share parameters of the CES functions that reflect the actual transmission of electricity exclude unrealistic transmission of electricity in the same frequency zone.

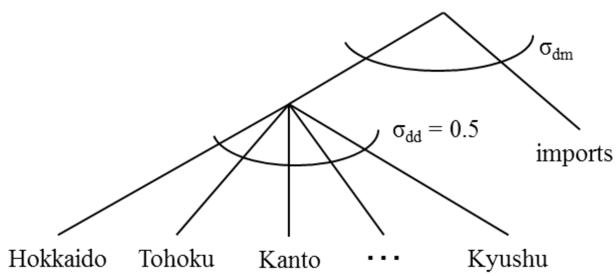

Figure 5. Interregional trade of products except electricity

4.5 Labour market imperfection

An increase in the electricity price for production sectors could have a negative impact on employment, which is an important factor affecting economic growth. If so, a CGE model with a full-employment assumption could underestimate the negative economic impact of a total nuclear power shutdown in Japan. Therefore, this study's model considers both unemployment and full-employment assumptions. To model unemployment, two theories explaining this assumption are considered in this study. In the first theory, wage is downward rigid because of, for example, a minimum wage rate that is required by the minimum wage law. Classical labour market theory assumes that production sectors input labour force until the marginal value productivity of labour input equals the real wage rate. If the real wage rate cannot be less than the minimum wage rate, involuntary unemployment can occur because of a negative economic shock. This study employs the downward rigidity of the wage rate by including the minimum wage rate. The minimum wage rate is set to be the same as the initial wage rate in the model (as expressed in Equation 2), where P_r^W, P_r^C, and P_r^{W0} represent the regional wage index, consumer price index, and initial regional wage index, respectively. Equation 2 is a constraint equation. The equation is maintained by adjusting the amount of labour provided by a regional household. A decrease in the amount of labour provided can be interpreted as involuntary unemployment. Another theory presenting the negative correlation between the unemployment rate and the real wage rate, called the wage curve, is expressed in Equation 3, where ur_r and β represent the regional unemployment rate and the elasticity of unemployment to the real wage index, respectively. Equation 3 is also a constraint equation. Here, ur_r is an endogenous variable. Two theoretical explanations behind the negative correlation are possible. First, from the perspective of the efficiency wage hypothesis (Solow 1979), a high unemployment rate provides a strong incentive for workers to work hard and efficiently, even if firms offer a lower wage rate. The second theory is based on the wage bargaining theory of McDonald and Solow (1981). Here, if a severe unemployment rate exists, unions could alter their objective from claiming a higher real wage rate for their members to claiming an expansion of employment opportunities for non-members. This essentially entails sacrificing a high real wage rate for all workers. Empirical evidence for the wage curve has been provided by several studies, which are introduced in Section 3. The wage curve would be valid when a multi-regional CGE model assumes the immobility of labour among regions. The present study refers to Küster et al. (2007) who model unemployment using the Mathematical Programming System for General Equilibrium analysis within the Generalized Algebraic Modelling System (GAMS/MPSGE). The present CGE assessments of a total nuclear power shutdown were conducted under the two different imperfect labour market assumptions explained above, as well as a full-employment assumption. Simulation results based on these assumptions were compared and used to determine the lower and upper bounds of the economic impact of a total nuclear power shutdown in Japan.

Labour and capital were assumed to be mobile across production sectors within their respective regions. However, the movement of labour and capital were assumed to be sluggish, and were modelled using the CET function with the elasticity of transformation as 0.3. This assumption of sluggish inter-sectoral factor movements was based on the fact that wage rate and profit differentials exist among sectors in Japan. The results of a sensitivity analysis conducted regarding primary factor mobility are presented in Section 4.

$$\frac{P_r^W}{P_r^C} \geq P_r^{W0} \tag{2}$$

$$\frac{P_r^W}{P_r^C} = ur_r^{\beta} \tag{3}$$

4.6 Household and government behaviour

The utility structure of regional representative households was also modelled using the nested CES function and is described in Fig. 6. Household utility is composed of saving and composite consumption. The constant rate of household income is saved for investment. However, the saving is not used for capital accumulation in this static model. The composite consumption comprises energy composite consumption and non-energy composite consumption. A representative household maximizes its utility by choosing an optimum consumption mix, subject to its budget constraint. Hence, if the electricity price rises while other input prices remain constant, the utility of maximizing electricity use decreases and the utility of maximizing the quantity consumed of other goods consumption increases. This substitution represents the behaviour of households saving electricity. The local government consumption in each region was modelled using a single Cobb–Douglas function. The total consumption level of the local government is fixed at the initial level. As mentioned previously, the central government exists only to transfer tax revenue levied from all production sectors and households to a representative household in each region. The level of transfer changes depends on the total tax revenue.

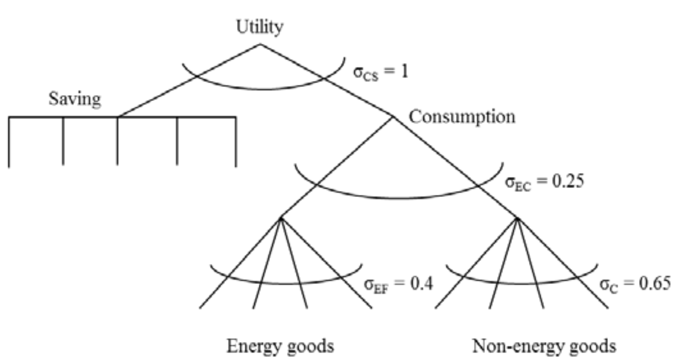

Figure 6. Utility structure of representative households

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3. DATA

3.1. Inter-regional input-output table

The parameters of the model were calibrated against Japan's inter-regional input-output (I-O) table for the year 2005 (METI 2010). Note that the regional classification of the METI's I-O table used in this study is different from that used by the electric power companies when providing their electricity. The correspondence of the two regional classifications is indicated in Table 2. Shizuoka and Nagano, where the Chubu Electric Power Company supplies electricity, are classified into Kanto in the METI's I-O table. Ishikawa and Toyama, where the Hokuriku Electric Power Company supplies electricity, are classified into Chubu in the METI's I-O table. The classification of urban areas is the same in both regions. Hence, the regional characteristics hold, although there are some differences.

This study calibrates the share parameters related to the input of land in the agriculture and fisheries sector and natural resources in the fossil fuels sector using the GTAP Database, version 7 (Narayanan and Walmsley 2008). In this model, the amount of land or natural resources input is divided from the amount of original capital input. In addition, the original inter-regional I-O table has a single electricity sector in each region. This study disaggregated the electricity sector into four distinct electricity generation technologies (i.e., fossil fuels, nuclear, hydro, and renewables) in each region to reproduce the actual five-year average power source share from 2005 to 2010 for each region (see Fig. 7) in the model. The model assumed that fossil fuel power generation inputs all fossil fuels inputted by the original single electricity sector. Each input of the original single electricity sector, other than fossil fuels, is apportioned proportionally among the electricity generation technologies so as to reproduce the average five-year power source share in each region in the model. The model assumes that the apportioned capital for each generation technology is the technology-specific capital and is not mobile across sectors. As depicted in Fig. 7, Kinki, Shikoku, and Kyushu (including Okinawa) depend on nuclear power to a greater extent than the other regions. Therefore, the total nuclear power shutdown could have a relatively larger negative impact on these regions. On the other hand, Chubu tends to depend more on fossil fuel power, and therefore, a complete nuclear power shutdown would have a relatively smaller impact on this region.

To assess the environmental impact of a nuclear power shutdown, the model considered CO2 emission factors for the combustion of each type of fuel (i.e., fossil fuels, petroleum and coal products, and gas-based products). The model employed the national average CO2 emission factors for the input value of each fossil fuel. The national average CO2 emissions factors were calculated using the national I-O table for Japan for the year 2005, which disaggregates energy goods in detail and provides corresponding material flow data. The input volume of each fossil fuel consumed by each sector was divided by the corresponding input value. This result was then multiplied by the CO2 emission factors for the corresponding fuel combustion.

3.2 Elasticity parameters

In simulations of an imperfect labor market, the initial unemployment rate in each region was set as per the Japanese Official Labor Force Survey for 2005 provided by the Ministry of Internal Affairs and Communications (MIAC) (2012). Based on previous studies, when the wage curve assumption was valid, the model used -0.15 as the elasticity of unemployment to the real wage index β in Equation 3. Blanchflower and Oswald (1995) estimated β to be approximately -0.1 for several countries, while Montgomery (1993) estimated it as -0.15 for Japan.

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Table 2. Correspondence of Regional Classifications

Regions in the model	METI's I-O classification	Actual regional classification of electricity supply
Hokkaido	Hokkaido	Hokkaido
Tohoku	Aomori, Iwate, Miyagi, Akita, Yamagata, Fukushima, Nigata	Aomori, Iwate, Miyagi, Akita, Yamagata, Fukushima, Nigata
Kanto	Gunnma, Tochigi, Ibaraki, Saitama, Tokyo, Chiba, Kanagawa, Shizuoka, Nagano	Gunnma, Tochigi, Ibaraki, Saitama, Tokyo, Chiba, Kanagawa
Hokuriku	Included in Chubu	Ishikawa, Toyama, Fukui
Chubu	Ishikawa, Toyama, Gifu, Aichi, Mie	Nagano, Gifu, Aichi, Mie, Shizuoka
Kinki	Kyoto, Osaka, Shiga, Hyogo, Nara, Wakayama, Fukui	Kyoto, Osaka, Shiga, Hyogo, Nara, Wakayama,
Chugoku	Hiroshima, Yamaguchi, Shimane, Tottori, Shimane	Hiroshima, Yamaguchi, Shimane, Tottori, Shimane
Shikoku	Kagawa, Tokushima, Kochi, Ehime	Kagawa, Tokushima, Kochi, Ehime
Kyushu and Okinawa	Fukuoka, Nagasaki, Oita, Saga, Miyazaki, Kumamoto, Kagoshima, Okinawa	Fukuoka, Nagasaki, Oita, Saga, Miyazaki, Kumamoto, Kagoshima, Okinawa

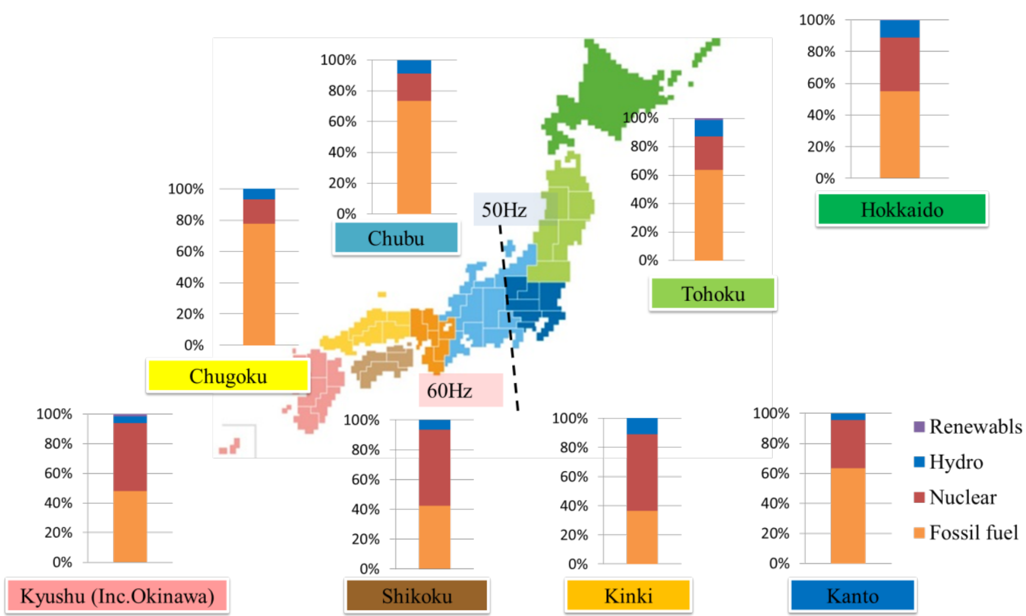

Figure 7. Power source share in each region (five-year average, 2005–2010)

The present study estimated the price elasticity of fossil fuel power supply, which has different values among regional electricity power companies. The price elasticity can be used to calibrate the elasticity of substitution between the technology-specific capital input and a composite-other input in fossil fuel power generation (see Equation 1). The estimation procedure is as follows. First, the unit cost of electricity generation using different fossil fuels was calculated (i.e., coal, LNG, heavy oil, and crude oil) for each company. These unit costs were calculated by dividing the annual cost of each fossil fuel input in 2009 by the corresponding actual power generation in the same year for each company. Second, the potential capacity for annual power generation by each fossil fuel was compiled for each company. Finally, the parameters of a linear regression model, described as Equation 4, were estimated. Here, E_r represents the fossil fuel power generation by an electricity generation company in region r, C_r is a constant term, P_r represents the unit cost of fossil fuel power generation, u_r is an independent identically distributed error term, and ε_r^S can be interpreted as the price elasticity of fossil fuel power supply. Table 3 shows the price elasticity for each region. In Table 3, two asterisks (**) represent a significance level less than 0.01.

$$\ln E_r = C_r + \varepsilon_r^S \ln P_r + u_r \tag{4}$$

Table 3. Estimated Price Elasticity of Fossil Fuel Power Supply

Region (Company)	**Price elasticity of supply**	**R^2**
Hokkaido (Tohoku Electric Power Co.)	1.402**	0.526
Tohoku (Tohoku Electric Power Co.)	1.714**	0.572
Kanto (Tokyo Electric Power Co.)	2.190**	0.416
Chubu (Chubu Electric Power Co.)	1.507**	0.543
Kinki (Kansai Electric Power Co.)	1.777**	0.744
Chugoku (Chugoku Electric Power Co.)	1.837**	0.465
Shikoku (Shikoku Electric Power Co.)	1.528**	0.657
Kyushu (including Okinawa) (Kyushu Electric Power Co.)	1.475**	0.660

4. SIMULATIONS AND THEIR RESULTS

4.1 Simulation setting

To stop nuclear power supply completely in the model, the nuclear-specific capital provided to each regional representative household was reduced exogenously to zero. The output level of hydro and renewable power was assumed to remain unchanged. As the nuclear power supply decreased, fossil fuel power generation started to increase to close the gap between electricity supply and demand. Because of the assumption of sluggish substitution between fossil fuel-specific capital and other inputs, as more fossil fuel power is supplied to the electricity market, the price of electricity increases in the model.

Several indicators might depend on labour market assumptions. Therefore, this assessment allows latitude in the simulation results by showing upper and lower bounds. In the following tables, the abbreviations ASM_WR, AMS_WC, and ASM_FE represent the downward-wage rigidity assumption, the wage curve assumption, and the full-employment assumption, respectively. The simulation results of a complete nuclear power shutdown are explained in the following subsections.

4.2 Impact on regional electricity generation

Table 4a shows the impact of a total nuclear power shutdown on regional electricity prices under different labour market assumptions. In the Kanto region, around Tokyo, the electricity price is shown to increase by 21.82–22.50%. In Shikoku, the most nuclear-dependent region in the analysis, the price of electricity would increase by 53.34–57.49%. Kinki, Shikoku, and Kyushu, which are relatively dependent on nuclear power, would have to bear a steep rise in the electricity price after shutting down their nuclear reactors. Table 4b shows the impact of a total nuclear power shutdown on regional electricity generation. Electricity generation in Kanto would decrease by 10.14–11.43%. Although Kinki, around Osaka, would witness a decrease in electricity generation by 30.17–31.46%, the Chubu region would almost double the transfer of its electricity to Kinki, causing electricity generation in Chubu to increase. Consequently, the price of electricity in Chubu would rise in spite of its low dependency on nuclear energy. The electricity price rise in the simulation result is too high when compared to the actual situation. An interpretation is that the actual price rise is lower than it should be. In fact, when the electric power companies proposed the degree of increase in electricity prices to the committee to review electricity charges, they took into account that some of the reactors were to be allowed to resume operation within 2013 (METI, 2013). Hokkaido EPCO, Kansai EPCO, Shikoku EPCO and Kyushu EPCO are going to apply to the NRA in July 2013 for screening to resume eight idle reactors. However, it is highly uncertain to resume operation of the idle reactors within 2013. Even if a reactor passes NRA screening, consent for the resuming operation is required from local governments that are hosting the nuclear power plant.

Table 4a. Change in Electricity Price

Region	ASM_WR (%)	AMS_WC (%)	ASM_FE (%)
Hokkaido	34.12	36.00	36.64
Tohoku	20.72	21.31	21.42
Kanto	21.82	22.44	22.50
Chubu	29.07	29.33	29.16
Kinki	40.72	42.54	43.13
Chugoku	15.40	16.05	16.06
Shikoku	53.34	56.54	57.49
Kyushu	50.50	53.18	54.03

4.3 Macroeconomic impact

The impact of a complete nuclear power shutdown in Japan on the real gross regional product (GRP) and the real gross domestic product (GDP) are shown in Table 5. Not surprisingly, the results indicate that real GRP impact would be severely negative in Kinki, Shikoku, and Kyushu, where nuclear power generation accounted for about half of the total electricity generation before the earthquake. On the other hand, the real GRP decrease in Chugoku, where nuclear power generation accounted for about 16% of the total electricity supply before the earthquake, would be relatively moderate. Japan’s real GDP would decrease by 0.60–2.14%, which corresponds to the sum of the real GRP impact for each region. The real GRP or real GDP impacts are largely dependent on the assumptions of the labor market structure. The most pessimistic scenario would occur if downward-wage rigidity were valid. On the other hand, the full-employment assumption provides an optimistic scenario.

Table 4b. Change in Electricity Generation

Region	ASM_WR (%)	AMS_WC (%)	ASM_FE (%)
Hokkaido	−16.87	−16.06	−15.91
Tohoku	−9.59	−8.78	−8.65
Kanto	−11.43	−10.30	−10.14
Chubu	2.50	3.10	3.11
Kinki	−31.46	−30.41	−30.17
Chugoku	−2.04	−1.00	−0.90
Shikoku	−26.26	−25.67	−25.57
Kyushu	−21.98	−21.06	−20.85
Japan	−13.54	−12.60	−12.45

From the viewpoint of regional economies, this result indicates that the economic impacts of a total nuclear shutdown differ among regions, depending on their nuclear dependency. In the long term, companies would move their factories from a region where electricity is expensive to one where it relatively cheaper. Such an eventuality indicates that a total nuclear power shutdown would accelerate the increase in regional economic disparity in the long term, which in itself was a serious problem even before the earthquake.

Table 5. Real GRP and Real GDP Impacts

Region	ASM_WR (%)	AMS_WC (%)	ASM_FE (%)
Hokkaido	−2.60	−1.07	−0.62
Tohoku	−2.17	−1.04	−0.88
Kanto	−1.75	−0.52	−0.36
Chubu	−1.16	−0.36	−0.37
Kinki	−3.09	−1.48	−1.09
Chugoku	−1.33	−0.27	−0.21
Shikoku	−3.60	−1.69	−1.22
Kyushu	−3.36	−1.55	−1.05
Japan	−2.14	−0.83	−0.60

4.4 Welfare impact

The welfare impact of a total nuclear power shutdown was measured in terms of household income change by using an equivalent valuation measure. Table 6 shows the equivalent valuation when the reactors are not allowed to resume operation for a year. Similar to the real GRP impacts, the welfare impacts are largely dependent on labour market assumptions. The downward-wage rigidity assumption might provide a pessimistic scenario. On the other hand, the full-employment assumption might take an

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optimistic view of a total nuclear power shutdown. Although the real GDP impact in the Kanto region is relatively small in terms of percentage, the loss of household welfare in this region is the largest because it has the largest population. In contrast, Chubu's household welfare improves when the wage curve assumption is valid. The lower electricity price in Chubu stimulates demand for products made in that region. This, in turn, improves employment, wage rate, and capital rent in Chubu. When the full-employment assumption is valid, household welfare in Chugoku is also shown to improve.

Table 6. Welfare Impacts (yen, billion)

Region	ASM_WR (%)	AMS_WC (%)	ASM_FE (%)
Hokkaido	−590	−272	−204
Tohoku	−546	−127	−66
Kanto	−4,447	−1,893	−1,507
Chubu	−357	348	459
Kinki	−2,335	−1,273	−1,082
Chugoku	−423	−16	54
Shikoku	−413	−189	−146
Kyushu	−1,500	−678	−492
Japan	−10,612	−4,101	−2,985

4.5 Sectoral impact

The nationwide sectoral impacts of a total nuclear power shutdown are shown in Figure 8. Sectoral impacts comprise several factors, including electricity intensity in production costs, change in final demand, and the role in the supply chain network. The increase in electricity prices accompanied by the switch to fossil fuel power generation would also stimulate mining for fossil fuels and the production of petroleum and coal products. High electricity prices do not have considerable negative impacts on equipment-related sectors (i.e., MCE, EEQ, and TEQ). These unintuitive results are caused by two reasons. First, electricity costs do not account for a large share of their total production costs. Second, a large increase in fossil fuel imports depreciates the yen against foreign currency. The depreciated yen, in turn, stimulates exports of machinery and equipment in a sector that, in Japan, is export-dependent to begin with.

4.6 Employment impact

Table 7 shows the initial regional unemployment rates and regional unemployment rates when all nuclear power reactors are shut down. An increase in the regional unemployment rate would decrease regional household income, and therefore, final demand. The decrease in final demand would shrink industrial production levels, especially for electricity-intensive products. When the downward-wage rigidity assumption is valid, the results indicate that high electricity prices would critically affect the unemployment rate. When the wage curve assumption is valid, the negative impact of the nuclear power shutdown on employment would be more moderate. However, the unemployment rate in nuclear power-dependent regions, such as Kinki, Shikoku, and Kyushu, would rise considerably. On the other hand, the unemployment rate in Chubu would improve because of the increase in demand for products made in that region.

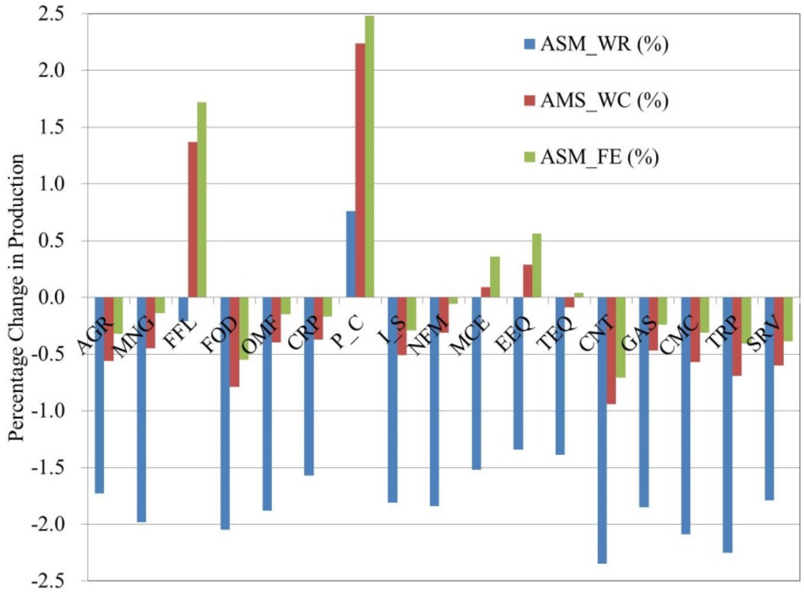

Figure 8. Nationwide sectoral impacts

Table 7. Impact on Regional Unemployment Rate

Region	Initial rate	ASM_WR (%)	AMS_WC (%)	ASM_FE (%)
Hokkaido	5.30	8.43	6.03	0.00
Tohoku	5.10	7.09	5.36	0.00
Kanto	3.80	6.06	4.06	0.00
Chubu	3.30	4.51	3.28	0.00
Kinki	5.20	8.41	5.84	0.00
Chugoku	3.90	5.58	3.97	0.00
Shikoku	3.90	7.73	4.67	0.00
Kyushu	5.30	8.94	6.09	0.00

4.7 Environmental impact

The model assumes that production sectors and households emit CO2 with the combustion of fossil fuels, petroleum and coal products, and gas-based products. Table 8 shows the change in regional and nationwide CO2 emissions if all nuclear reactors were to be shut down. The nuclear power shutdown would have three effects on CO2 emissions from production sectors and households. First, high electricity prices would shrink economic activity and lead to a decrease in the combustion of fossil fuels, petroleum and coal products, and gas-based products. Second, high electricity prices would stimulate the substitution of burning fossil fuels for electricity, including petroleum, coal, and gas products, in production and consumption. Third, the increase in fossil fuel power generation would bring about an increase in fossil fuel combustion. The last two effects would lead to an increase in CO2 emissions, across all regions. At a nationwide level, Japan would see an increase in CO2 emissions by about 19.5–

21.7%, in spite of the decrease in real GDP.

Table 8. Change in Regional and Nationwide CO_2 Emission**s**

Region	ASM_WR (%)	AMS_WC (%)	ASM_PE (%)
Hokkaido	13.75%	15.35%	15.49%
Tohoku	19.00%	20.82%	21.12%
Kanto	15.07%	16.93%	17.22%
Chubu	20.68%	22.32%	22.56%
Kinki	29.22%	31.79%	32.26%
Chugoku	6.42%	8.16%	8.45%
Shikoku	43.38%	45.34%	45.64%
Kyushu	28.14%	30.28%	30.67%
Japan	19.51%	21.44%	21.75%

5. SENSITIVITY ANALYSIS

The results of the CGE assessment could crucially depend on its model structure and the values of several of its parameters. Therefore, this study conducted a sensitivity analysis with regard to the possibility of energy substitution and primary factor mobility. Table 9 shows the results of the sensitivity analysis on real GDP impacts. The following assumptions were considered in the sensitivity analysis. First, the primary factors could move across production sectors in a frictionless manner within each region. Second, substitutability between energy composite input and value-added, as well as among different energy inputs was assumed to have changed. The second change means that σ_{EVA} and σ_{ENOE} are halved, and σ_{EN} of the manufacturing and service sectors double (see Fig. 1).

The frictionless movement of primary factors relieves the negative GDP impacts. However, it did not drastically change the GDP impacts of a complete nuclear power shutdown in Japan. The high possibility of energy substitution also has a positive effect on the real GDP through the improvement of employment. The effect on real GDP is positive when unemployment is likely to occur. Overall, the possibility of energy substitution and primary factor mobility do not have a significant effect on the results.

Table 9. Change in GDP with Different Assumptions

	Frictionless movement of primary factors		
Energy substitution possibility	**ASM_WR (%)**	**AMS_WC (%)**	**ASM_PE (%)**
Low (halved)	−1.93	−0.61	−0.41
Normal	−1.76	−0.59	−0.41
High (doubled)	−1.53	−0.56	−0.42

6. CONCLUSION

After the nuclear accident at the Fukushima Daiichi nuclear power station, public anxiety about nuclear power has made it difficult for nuclear reactors, currently lying idle after their scheduled inspection, to resume operation. With the total shutdown of nuclear reactors in Japan, the resulting gap between electricity supply and demand would need to be closed by fossil fuel power supply, which would entail a significantly higher cost. However, the central government and the public do not agree on the best measures to put in place, because of lack of concrete evidence for the safety of, and the economic role played by, nuclear power generation in Japan. Following the earthquake, the government and public have been arguing about safety-related issues of existing nuclear reactors. By contrast, economic issues related to a complete nuclear power shutdown facing Japan have not received as much attention as they should have.

Hence, this study investigated the economic impact of a total nuclear power shutdown in Japan. The results of the CGE assessment indicate that the immediate shutdown of nuclear power would have a considerable negative impact on the Japanese economy and the environment. Several indicators crucially depend on labour market assumptions. Therefore, this assessment allowed some latitude for the simulation result by considering an upper and a lower bound. Based on the simulation, there is evidence to suggest that a total nuclear power shutdown could decrease Japan's real GDP by 0.60–2.14%. On average, Japan has maintained a real GDP growth of about 1% between 1990 and 2010. Considering the average growth, the simulation result concerning the change in the real GDP is undoubtedly significant. From the viewpoint of the regional economy, the result indicated that the economic impact would differ among regions, depending on their nuclear dependency. Differences in electricity prices among regions might accelerate the increase in regional economic disparity in the long term. From an environmental point of view, a total nuclear power shutdown could increase Japan's CO_2 emissions by 19.5–21.7%. This is because production sectors would be forced to switch to other sources of energy, which, in turn, would increase the use of fossil fuels. To reduce CO_2 emissions, the power source share of renewables, such as photovoltaic solar power, wind energy, and geothermal power generation, would have to be increased. However, thus far, renewables have proved to be an expensive source of power in Japan and are likely to require considerable policy and research interventions before they become economically feasible.

To sum up, following the Great East Japan earthquake and the accompanying tsunami, public anxiety over the safety of existing nuclear reactors has been strong. This is understandable, given that changes in seismic activity have been observed all over Japan. Notwithstanding popular public sentiment, the government would need to consider the economic risks involved in ordering a total shutdown of all nuclear reactors. A gradual phase-out of nuclear reactors appears to be a more rational policy for Japan.

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APPENDIX

Consider a competitive firm generating electricity E. Here, E is assumed to be the CES composite of fuel input F and capital input, K (Equation 5).

$$E = f(F,K) = \left(\beta_F F^{\frac{\sigma-1}{\sigma}} + \beta_K K^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{5}$$

The price elasticity of the electricity supply ε_S is defined, and can be expressed as Equation (6), where P_E, P_F, and P_K represent the unit price of electricity input, fuel input, and specific capital input, respectively.

$$\varepsilon_S = \frac{\partial \ln E}{\partial \ln P_E} = \frac{\partial \ln E}{\partial E}\frac{\partial E}{\partial F}\frac{\partial F}{\partial P_E}\frac{\partial P_E}{\partial \ln P_E} = \frac{1}{E} f_F(F,K)\frac{\partial F}{\partial P_E} P_E \tag{6}$$

From the first order condition of fuel input, we obtain Equation (7). We obtain Equation (8) by combining Equation (6) and (7).

$$\frac{\partial F}{\partial P_E} = -\frac{P_F}{{P_E}^2 f_{FF}(F,K)} \tag{7}$$

$$\sigma = \frac{\theta_K \varepsilon_S}{1-\theta_K} \tag{8}$$