Analysis of the change in the structure of the Japanese power supply using the GTAP-E-power model

Akiko Higashi1 · Ken Itakura2 · Yushi Inoue1 · Hiroaki Otake1

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Abstract
This study analyzes the effect of the change in the structure of the Japanese power supply, which disaggregates the power sector based on the GTAP-E model framework. We analyze the impact of the change in the power structure on Japan’s macroeconomy, power sector, and industry by comparing the results of four scenarios. In our simulations, which are divided into two periods, shocks are introduced to the growth rate in real GDP, labor force, population, and Japanese zero-emission power supply; nuclear power, hydropower, wind power, solar power, and other types of power. First, simulations from 2011 to 2018 were performed to update the GTAP-E-Power database. Next, simulations from 2019 to 2030 were performed for policy scenarios with different growth rates of zero-emission power supply in Japan. The simulation results show that if Japan maintains the same growth rate of zero-emission power supply as that of the Sustainable Development Scenario of the World Energy Outlook 2019, the share of zero-emission power supply in 2030 will achieve the government’s target. The simulation results also show that an increase in zero-emission power supply has a positive effect on the Japanese trade balance.

Keywords GTAP-E-power model · Zero-emission power supply · Japanese power structure

Introduction

After the Great East Japan Earthquake in 2011, the structure of the power sector in Japan changed drastically and will continue to transform toward new targets, such as safety against disasters, zero-emission power source ratio, energy saving, energy self-sufficiency, and energy-derived CO2 emissions. As pointed out by the United...
Nations Office for Disaster Risk Reduction (2015), Japan is one of the countries with the highest absolute annual average loss caused by disasters, making it necessary to consider various aspects of securing power supply in Japan. Although nuclear power plays a major role in reducing emissions in Japan, where there are many natural disasters, such as earthquakes, its supply must be carefully controlled.

Increasing the share of zero-emission power sources is a goal of Japan’s power policy, although there are many aspects to consider to achieve it. This study analyzes the effect of the change in the structure of the power sector in Japan, especially the change in the zero-emission power source ratio, on the Japanese economy beyond 2020, using the GTAP-E-Power model. The latest base year of the GTAP 10.0 database is 2014, when Japan’s nuclear power generation was zero. Since it would be desirable to classify nuclear power independently to analyze the change in the structure of the Japanese power supply, we try to use the GTAP 10.0 database based on the year 2011, in which nuclear power generation is not zero.

Section 2 analyzes Japanese time-series data on the total power generated in Japan. The results of the data survey indicate a significant change in the structure of power supply in Japan after 2011. Section 3 describes the methods for analyzing the economic effects of the change in the structure of Japan’s power sector using the GTAP-E-Power model. Section 4 discusses the simulation results. The change in the supply of zero-emission power affects the supply of other types of base load power and peak-load power. The change in the structure of the power supply introduces changes in both the macroeconomy and microeconomy, such as the industrial output, exports and imports, and consumption. Section 5 concludes the paper.

The simulation results show that if Japan were to make great efforts and maintain the growth rate of zero-emission power as that of the Sustainable Development Scenario of the World Energy Outlook 2019 from 2019 to 2030, the share of zero-emission power in 2030 would achieve the government’s goal. The results also show that an increase in zero-emission power has a positive effect on the Japanese trade balance.

**Background of the Japanese power sector and previous research**

**Time-series data on the total power generated in Japan**

As described in the Fourth Strategic Energy Plan, one of Japan’s energy plan targets before 2011 was to increase the ratio of zero-emission power sources in its power mix, including nuclear power and renewable energy, to attain around 70% by 2030. However, these trends in the Japanese energy plan completely changed after the Great East Japan Earthquake in 2011. Figure 1 presents the main power trends in Japan. In this figure, the decline in the share of nuclear power since 2011 is remarkable; it became 0% in 2014. Natural gas and coal power have maintained the majority share of Japan’s power mix since 2011. Nuclear power

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1 Four databases can be obtained from GTAP 10.0 database; the base years are, respectively, 2014, 2011, 2007, and 2004.
plants restarted in 2015 and thereafter its share of power generation continued to increase, although the level in 2018 was still much lower than that in 2010.

Hydropower generation has maintained a stable share since 2011. In 2018, the amount of power generation from renewable sources including solar, wind, geothermal, and biomass power, remained low when compared with other Japanese sources. However, Fig. 1 shows that when these four power sources were combined, the amount of power generated was higher than that of hydro-, oil, and nuclear power generation in 2018.
The share of zero-emission power in Japan from 2010 to 2018 is shown in Fig. 2. It attained 34.5% in 2010; however, after the Great East Japan Earthquake it fell to 19.4% in 2011 and 11.4% in 2012. Although the share of zero-emission power regained an increasing trend after 2012, and recovered to 23% in 2018, it still remained below the 2010 level.

Plan for the Japanese power sector

Japan’s Fourth Strategic Energy Plan was established in 2014, after the Great East Japan Earthquake. Its main policies differed from those before 2011. Reducing nuclear power and fossil resource dependence and expanding renewable energy became the main targets of the Fourth Strategic Energy Plan.

The Fifth Strategic Energy Plan, established in 2018, renewed the long-term energy supply and demand outlook for 2030 and fixed design scenarios focused on 2050. The Fifth Strategic Energy Plan lists four Japanese structural issues: vulnerability due to high dependency on energy imports, mid- and long-term transition in the energy demand structure (for example, demographic changes), instability of resource prices (for example, increase of energy demand in emerging countries, etc.), and increase of global GHG emissions.

When considering these issues, the Fifth Strategic Energy Plan highlighted five main points in its 2030 energy mix and long-term outlook for 2050: energy saving, ratio of zero-emission power sources in the supply configuration, amount of energy-derived CO₂ emissions, electricity costs, and ratio of energy self-sufficiency. Concerning energy saving, the ratio of zero-emission power sources is expected to reach approximately 44% in fiscal year 2030 by introducing renewable energy and restarting nuclear power plants; the Nuclear Regulation Authority must recognize these as conforming to regulatory requirements which are the strictest worldwide.

Energy-derived CO₂ emissions are targeted to be approximately 930 million tons in fiscal year 2030; electricity costs are targeted at 9.2–9.5 trillion yen the same year. Energy self-sufficiency is expected to be 24% in fiscal year 2030 through the introduction of renewable energy and by restarting nuclear power plants.

Methods

Overview of the GTAP-E and GTAP-E-power models

This study uses the GTAP-E-Power model for its simulations. The content of the GTAP-E-Power model is explained in detail by Peters (2016b). The GTAP-E-Power model is based on the framework of the GTAP-E model, which is an energy-environment version of the standard GTAP model, and breaks down the power sector.

When compared with the standard GTAP model, the main characteristic of the GTAP-E model are energy substitution in the production structure, including inter-fuel substitution and fuel-factor substitution. In the standard GTAP model, energy commodities include coal, oil, gas, petroleum and coal products, and electricity.
These energy commodities are treated as intermediate goods in the production structure, with substitution parameters for energy commodities set to zero. Another difference between the standard GTAP model and the GTAP-E model is that the former does not incorporate the substitution structure between intermediate goods and primary factors; in the latter, however, energy commodities are removed from the intermediate input nest and incorporated into the value-added nest.

The energy commodities in the GTAP-E model are classified into electricity and nonelectricity groups. The nonelectricity group is further separated into coal and noncoal groups. Noncoal groups include gas, oil, and petroleum products. The production structures of the GTAP-E model are shown in Figs. 3. Figures 4 shows a more detailed description of the Capital-Energy Composite of the GTAP-E model found in Fig. 3.

The GTAP-E-Power model is a computable general equilibrium (CGE) model that breaks down the power sector with the framework of the GTAP-E model. The GTAP-E-Power model classifies electricity into 12 categories: transmission and distribution (TnD) and 11 generating technologies. Generating technologies include nuclear, coal, gas base load, gas peak load, oil base load, oil peak load, hydro base load, hydro peak load, wind, solar, and “other” power generation technologies. “Other” types of power include biofuels, waste, geothermal, and tidal technologies.²

Figure 5 shows the power substitution in the GTAP-E-Power model. One of the features of the electricity sector in the GTAP-E-Power model is that it is classified

² This classification is described in Peters (2016a).
Fig. 4 GTAP-E capital-energy composite structure. Source: Burniaux and Truong (2002, Fig. 17, p. 31)

Fig. 5 Nested electric power substitution in GTAP-E-Power model. Source: Peters (2016b, Fig. 2, p. 167)
into base load and peak load, depending on the sector’s capacity for instantaneous adjustment to meet the demand.

**Procedures for creating the GTAP 10.0 database of the GTAP-E-Power model**

Based on the GTAP 9.0 database, whose base year is 2011, the original GTAP-E-Power model database can be created from the GTAP-Power model and the GTAP-E model databases. After analyzing in detail about the data and parameters of the GTAP-E-Power model database, we created the GTAP-E-Power model database specific to this research from the GTAP-Power model and the GTAP-E model databases. As nuclear power generation in Japan became zero in 2014, we avoided using the latest GTAP 10.0 database based on 2014. Therefore, we used a database whose benchmark year is 2011, the next new base year, and employed the GTAP 10.0 database to create the GTAP-E-Power model database for this research.

The total number of data in the GTAP-E-Power model is 67; 46 are obtained from the GTAP-Power database, and other data concerning carbon taxes and CO₂ emissions quotas can be obtained from the GTAP-E model.

Parameters for the GTAP-E-Power model can also be created from the GTAP-Power model and the GTAP-E model databases, consulting those of the original version of the GTAP-E-Power model. The total number of parameters in the GTAP-E-Power model is 31, seven of which are taken from the GTAP-Power model. The most of the other parameters can be obtained from the GTAP-E model.

**Overview of previous studies**

(1) **Overview of the bottom-up and top-down approaches**

To analyze the effect of the change in the structure of the Japanese power supply, it is first necessary to consider two different approaches: the bottom-up approach and the top-down approach.

The bottom-up approach, often called the engineering approach, analyzes energy production technologies and processes in detail. Bottom-up models generally set some policy constraints and attempt to determine the most efficient or least-cost energy system under the set conditions. Often, bottom-up models combine engineering and economic approaches.

One of the most widely used bottom-up models is the TIMES, the successor to MARKAL. As explained by the International Energy Agency (2021), the TIMES model encompasses all the steps from primary resources through the chain of processes that transform, transport, distribute, and convert energy into the supply of energy services demanded by energy consumers. The great advantage of such a bottom-up approach is that it enables a detailed description of the processes and technologies that produce or consume energy, and the incorporation of new technologies. The incorporation of new technologies is advantageous for emis-

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3 The GTAP-Power model uses the framework of the standard GTAP model and breaks down the power sector.
sion analysis. The TIMES model combines a technical engineering approach and an economic approach. Similar to MARKAL, economic indicators, including imports and exports, are given as exogenous variables in the TIMES model, and the main endogenous variables are energy investments and energy consumption. The price of primary energy is given exogenously, and the model simulates the most efficient energy system by minimizing energy-related costs.

The top-down approach, which is an economic approach such as CGE models or econometric models, describes the macro and international economy in detail. It emphasizes the behavioral response in the production and cost functions and, as a result of the interaction of these functions, top-down models simulate the demand for energy inputs and outputs of sectors.

(2) Overview of previous studies on Japanese cases

The effects of Japan’s electricity policy are often analyzed in long-term climate-mitigation policy studies. In these studies, both bottom-up and top-down models were used depending on the purpose. Sugiyama et al. (2019) uses six energy–economic models developed by different institutions to assess Japan’s long-term climate-mitigation policy. The six models used in this research are the most widely used among the models developed to assess Japanese energy and environmental policies: the AIM/CGE, AIM/Enduse, DNE21, DNE21+, IEEJ, and TIMES-Japan models.

The AIM/CGE model is a global, top-down, and dynamic recursive CGE model used mainly to analyze macroeconomic impacts. Fujimori et al. (2012) explains four blocks in the AIM/CGE model: production, income distribution, final consumption, and market. The AIM/Enduse model is a partial, bottom-up, and dynamic recursive model. The TIMES-Japan models are described above, and the other models are partial equilibrium models.4

Several studies using CGE models have analyzed the economic impact of changes in the power sector in Japan. These studies have often been conducted on the theme of disasters, with a special focus on earthquakes. The methods used in these studies can be useful for analyzing the effects of electricity on the economy using CGE models. Hagiwara (2001) assessed the impact of the 1995 Great Hanshin-Awaji Earthquake using the Kobe CGE model to analyze the impact of changes in capital stock and final demand on production in Kobe City from 1995 to 1997.

Ishikura and Ishikawa (2011) evaluated the impact of the reduced use of electric power for the whole of Japan and the Tokyo metropolitan area with a spatial CGE model. This study analyzed the effect of the shock on electricity sector productivity in the Tokyo metropolitan area because of the reduced supply capacity caused by the Great East Japan Earthquake in 2011. Yamazaki and Ochiai (2011) analyzed the impact of restricted electricity supply in the Kanto area on all of Japan and on eight regions caused by the Great East Japan Earthquake. This research used the Japanese multi-regional CGE model developed by the Japan Center for Economic Research. This research reduced the quantity of endowment commodities, that is, capital and labor, and household electricity demand in the Kanto area.

4 Sugiyama et al. (2019) classified these six models mentioned above.
In the above studies electricity was treated as an aggregate sector and electricity-generating technologies were not classified. Tachi and Ochiai (2011) used the Japanese multi-regional CGE model developed by the Japan Center for Economic Research and set exogenous conditions for nuclear, hydroelectric, and thermal power in analyzing the case of complete supply shortage of nuclear electric power in Japan, by modifying the electricity sector’s production function.

The GTAP-E-Power model is an applied economic model that classifies electricity-generating categories and incorporates the energy substitution effect. In addition, it is a CGE model suitable for analyzing the economic effect on trade trends in Japan with its global economic database. As the Japanese economy depends on overseas energy resources, the impact of changes in the power supply configuration on trade would be significant for Japan. Another advantage of the GTAP-E-Power model is that the data are updated every few years, making it easier to obtain new data. When considering these merits of the GTAP-E-Power model, this study analyzes the effects of the change in the structure of the power supply on the Japanese economy.

Although several dynamic recursive CGE models have been developed as mentioned above, along with the dynamic GTAP model, the GTAP-E-Power model is essentially a static model. By incorporating the effects of capital accumulation, we attempted to consider the dynamic transition processes in our time-series analysis.

**Methodology for analyzing the change in the structure of the Japanese power sector using the GTAP-E-Power model**

The simulations made in this study cover two periods: from 2011 to 2018 and from 2019 to 2030. This study focuses only on the analysis of the Japanese power supply and does not consider power supply for countries other than Japan. Therefore, the analysis of the simulation results is limited to the Japanese economy.

Regarding the simulations from 2011 to 2018, the purpose of the simulations is to update the database until 2018. Shocks are given for real GDP, labor force, and population for each country; in the case of Japan, shocks are given for real GDP, labor force, population, and supply of zero-emission base- and peak-load power. GDP growth is taken from The World Bank (2019), and United Nations data are used for each country’s labor force and population. Japan’s electricity data are taken from the Agency for Natural Resources and Energy of the Ministry of Economy, Trade, and Industry of Japan. The categories of the power generation sector are classified as follows: nuclear power (base load), hydropower and wind power (base load), coal power (base load), gas power (base load), oil power (base load), other base load, gas and oil power (peak load), and solar power and hydrowater (peak load).*5*

In the simulations, real GDP, labor force, and population are set as exogenous variables for all regions. As for Japan, in addition to real GDP, labor force, and population, the industrial output of zero-emission power is set as an exogenous

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*5 In the GTAP 10.0 database based on the year 2011, hydropower and gas power for peak load are zero.
variable. With this method, real GDP is common to all scenarios and does not change, as WEO 2019 does. However, economic indicators, such as trade balance, supply in the power sector other than zero-emission power, and industrial output change in each scenario, and it is possible to analyze the impact of the increase in zero-emission power supply on the Japanese economy.

Table 1 shows the share of Japan’s power in 2018 derived from the data of the Agency for Natural Resources and Energy and the simulation results using the GTAP-E-Power model before and after adjustment. When only real GDP, population, and labor force are given in the model as shock values, the result of the power data in 2018 is as shown in the column before adjustment and often does not reflect the actual Japanese data. Looking at the types of zero-emission power (nuclear, hydro, wind, solar, and other types of power) that will be given shock values, the shares of nuclear power, hydropower, and wind power in 2018 obtained from the simulation results exceed the shares calculated from the data of the Agency for Natural Resources and Energy. On the other hand, for solar power and other types of power generation, which have been increasing rapidly since 2011, the shares

| Source: Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry of Japan (2020); World Energy Outlook 2019; results of the GTAP-E-POWER model were simulated by the authors |
|---|---|---|---|
| NuclearBL | 6.2 | 9.0 | 8.9 |
| HydroBL and WindBL | 8.4 | 10.4 | 10.3 |
| CoalBL | 31.6 | 18.4 | 18.3 |
| GasBL | 38.3 | 28.5 | 28.3 |
| OilBL | – | 4.0 | 4.0 |
| OtherBL | 2.4 | 1.5 | 2.0 |
| GasP and OilP | 7.0 | 27.4 | 25.9 |
| SolarP and HydroP | 6.0 | 0.8 | 2.2 |
| Zero-emission power | 23.0 | 21.7 | 23.5 |
| Other power | 76.9 | 78.3 | 76.5 |
| Total | 100 | 100 | 100.0 |

Regarding the transition of electrification, each scenario of WEO2019 has its own settings. In the Stated Policies Scenario in 2040, the share of electricity is 36% for total final consumption, 37% for industry, 10% for transport and 56% for buildings. In the Sustainable Development Scenario in 2040, the share of electricity is 43% for total final consumption, 42% for industry, 26% for transport and 65% for buildings.

6 In the basic closure of the GTAP model, real GDP and industrial output are endogenous variables. However, by swapping the variable real GDP or industrial output with other exogenous variables, they can be set as exogenous variables. The methodology for this swapping of variables is explained in Burfisher (2021).

7 Regarding the transition of electrification, each scenario of WEO2019 has its own settings. In the Stated Policies Scenario in 2040, the share of electricity is 36% for total final consumption, 37% for industry, 10% for transport and 56% for buildings. In the Sustainable Development Scenario in 2040, the share of electricity is 43% for total final consumption, 42% for industry, 26% for transport and 65% for buildings.
obtained from the simulation results in 2018 are much lower than those obtained from the Agency for Natural Resources and Energy. We adjusted them to achieve the share of 2014. As a result, the share of other types of power generation changed slightly after this adjustment. For the period from 2019 to 2030, the growth rate of each zero-emission power will be fixed to finally achieve the cumulative growth rate of each scenario from 2011 to 2030.

There are four scenarios for the simulations from 2019 to 2030 (Table 2). First we performed a simulation for Scenario 1. Scenario 1 is a reference scenario in which no policy is implemented in the power supply configuration. In Scenario 1, shock values are set only for real GDP, labor force, and the population growth rate of each country using the same method as in the simulations for 2011–2018. We use the projections by the WEO 2019 for real GDP and World Population Prospects 2019 for labor force and population.

The zero-emission power generation in our GTAP-E-Power model simulation has the same growth rate from 2019 to 2030 as the WEO 2019 in the following scenarios: Scenario 2 (Stated Policies Scenario of WEO 2019), Scenario 3 (Current Policies Scenario of WEO 2019), and Scenario 4 (Sustainable Development Scenario of WEO 2019). The WEO 2019 uses the World Energy Model and provides various settings to perform its simulations. Although we would not expect the simulation results of both models based on the same scenarios to match, because of the

| Scenario | Description |
|----------|-------------|
| Scenario 1 | Shocks are given only for real GDP, population, and labor force (without setting for power sectors) to all regions |
| Scenario 2 | Shocks are given for real GDP, population, labor force (without setting for power sectors) to regions other than Japan. To Japan, shocks are given for real GDP, population, labor force, and zero-emission power whose growth rate is the same as the WEO 2019 Stated Policies Scenario. The average annual growth rate from 2019 to 2025 is 7.4% for NuclearBL, 1.7% for HydroBL + WindBL, 3.2% for OtherBL, and 14.3% for SolarHP; the average annual growth rate from 2026 to 2030 is 7.4% for NuclearBL, 1.7% for HydroBL + WindBL, 3.2% for OtherBL, and 20.6% for SolarHP |
| Scenario 3 | Shocks are given for real GDP, population, labor force (without setting for power sectors) to regions other than Japan. To Japan, shocks are given for real GDP, population, labor force, and zero-emission power whose growth rate is the same as the WEO 2019 Current Policies Scenario. The average annual growth rate from 2019 to 2025 is 6.5% for NuclearBL, 1.4% for HydroBL + WindBL, 2.6% for OtherBL, and 16.2% for SolarHP; the average annual growth rate from 2026 to 2030 is 6.5% for NuclearBL, 1.4% for HydroBL + WindBL, 2.6% for OtherBL, and 16.2% for SolarHP |
| Scenario 4 | Shocks are given for real GDP, population, labor force (without setting for power sectors) to regions other than Japan. To Japan, shocks are given for real GDP, population, labor force, and zero-emission power whose growth rate is the same as the WEO 2019 Sustainable Development Scenario. The average annual growth rate from 2019 to 2025 is 8.1% for NuclearBL, 4.0% for HydroBL + WindBL, 4.4% for OtherBL, and 14.6% for SolarHP; the average annual growth rate from 2026 to 2030 is 8.1% for NuclearBL, 4.0% for HydroBL + WindBL, 4.4% for OtherBL, and 21.0% for SolarHP |

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8 The scenario description and model structure are detailed in International Energy Agency (2019b).
differences in model types, databases, and settings, the WEO 2019 scenarios would be, nevertheless, useful references for future scenarios assumed for Japan.

In this study, we focus on the analysis of changes in the Japanese economy imposing constraints on zero-emission power generation without imposing constraints on nonzero-emission power generation. The settings regarding zero-emission power generation is given only for Japan. To analyze the simulation results of emissions, it is necessary to impose constraints on both zero-emission and nonzero-emission power generation. Furthermore, as we have seen, there are limits for top-down models, such as the GTAP-E-Power model to reflect the trends of technological progress in detail, which is indispensable for analyzing the simulation results of emissions. Therefore, this study focuses on the impact of the trend of zero-emission power generation on the Japanese economy and does not analyze the simulation results of emissions.

The Stated Policies Scenario is central in the WEO 2019 analysis and considers policies already announced. It reflects the impact of energy-related policies already implemented and an assessment of the expected effects of announced policies, as expressed in official targets and plans. In the Current Policies Scenario; however, such announcements are not considered. The Sustainable Development Scenario sets out the major changes that would be required to attain the United Nations Sustainable Development Goals.

Scenarios 2, 3, and 4 use as shock values real GDP, population, and the labor force growth rate used in Scenario 1 and different settings of the growth rate of zero-emission power. Shock values are given to the industry output of zero-emission power in Japan, that is, nuclear power (base load), hydropower and wind power (base load), other types of power (base load), and solar power and hydropower (peak load).

Aggregation of regions and sectors

The GTAP-E-Power model was developed using 16 regions and 20 sectors of aggregation. This study aims to analyze the impacts of the change in the power configuration only in Japan, and the shocks given to other regions are limited to real GDP, population, and labor force, without setting for power sectors. Therefore, regional aggregation in this study remains at the small size of five regions.

In the original version of the GTAP-E-Power model, the power generation sectors are classified into 11 categories. Because the shock values of the power sectors are relatively large, in this study, they are classified into eight categories. HydroBL and WindBL are both classified as one category, HydWdBL, zero-emission base load power. GasP and OilP are classified in the same category GasOilP, gas,

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9 Takeda et al. (2016) studied the GTAP-Power database in GTAP 9.0 and pointed out that although the power data in the GTAP-Power database are almost consistent with other data, such as those of the IEA, emission data are rather different from IEA statistics. Considering this point in addition to the reasons described in the text, this study does not aim to analyze the simulation results of emissions.
and oil peak-load power, and SolarP and HydroP are classified in the same category SolarHP, zero-emission peak-load power. Other sectors, especially industrial sectors, are classified in more detail than in the original version. Regional disaggregation and sectoral disaggregation are presented in Appendix 1.

Results and discussion

Macroeconomic changes

In the simulations of this study, the growth rate of real GDP is constant for each scenario. However, we can analyze the simulation results of macro-level exports and imports that vary by scenario.
Table 5  Trade balance configuration in 2025 and 2030 (millions, USD)

| Country          | 2025                          | 2030                          |
|------------------|-------------------------------|-------------------------------|
|                  | Scenario1 | Scenario2 | Scenario3 | Scenario4 | Scenario1 | Scenario2 | Scenario3 | Scenario4 |
| North America    | −10,34,143 | −10,34,419 | −10,34,901 | −10,34,293 | −11,96,774 | −11,98,431 | −11,98,619 | −11,98,324 |
| European countries | −70,332    | −71,003    | −71,261    | −70,832    | −84,325    | −87,517    | −87,170    | −87,435    |
| Japan            | 88,465     | 90,852     | 92,394     | 89,334     | 100,093    | 117,468    | 115,625    | 116,097    |
| China            | 307,922    | 306,285    | 305,555    | 306,830    | 423,547    | 413,521    | 414,574    | 413,883    |
| Rest of World    | 731,402    | 731,612    | 730,930    | 732,337    | 811,456    | 808,610    | 808,773    | 809,508    |

Source: The authors
Table 3 shows the simulation results of the changes in the average annual growth rate of real exports. In Japan, when zero-emission power sources increase, exports show a growth trend. In the scenarios based on WEO 2019 scenarios, in which zero-emission power supply increases, exports will increase more than in Scenario 1, especially from 2026 to 2030.

Table 4 shows the simulation results of the changes in the average annual growth rate of real imports. In Japan, as the share of zero-emission power sources increases, imports decline. Here, in the Sustainable Development Scenario, the decrease in imports in Japan is the largest among the four scenarios.

Table 5 shows the simulation results of the trade balance (the value of exports minus the value of imports at the macro level) as of the years 2025 and 2030. In Japan, the increase in the trade balance is the largest in Scenario 2, followed by Scenario 4. As the share of zero-emission power sources increases, imports decline. In Scenario 4, based on the Sustainable Development Scenario, a decrease in imports in Japan is clearly the largest among the four scenarios.

Increasing exports and decreasing imports caused by the increase in the share of zero-emission power lead to an increase in the trade balance and have a positive potential effect on raising Japan’s real GDP growth rate.

**Changes in the power sectors**

Table 6 shows the simulation results of the changes in the average annual growth rate of the power sectors in Japan. In Scenario 1, whose shock values concern only GDP, labor force, and the population growth rate, the share of each power source composition is not much different from that in 2011. The growth rate of nonzero-emission power sectors is higher than that of zero-emission power sectors, and the annual growth rate of NuclearBL tends to decrease. Among zero-emission power sectors, SolarHP has the highest growth rate, with an average annual growth rate of 0.52% from 2026 to 2030. In Scenarios 2, 3, and 4, the growth rates of NuclearBL, Hydro and WindBL, OtherBL, and SolarHP are fixed, while those of other power sectors change depending on the scenario. As the growth rate of zero-emission power sources increases, that of other power sources decreases. The growth rate of all nonzero-emission power sectors decreases in both the base load and peak load from 2026 to 2030.

The simulations in this study provide no shocks to nonzero-emission power sources. When the effects of various policies related to nonzero-emission power are incorporated into the model, the supply of nonzero-emission power may be further reduced.

Figure 6 shows the simulation results of the power supply configuration by 2030 in Japan. Although GasBL remains the largest power sector in all scenarios, its share decreases as the supply of zero-emission power increases, and the difference...
with the share of nuclear power, which is the second largest share, becomes small in Scenario 4.\textsuperscript{11}

Figure 7 show the simulation results of the share of zero-emission power and other types of power in 2030 in Japan. In Scenario 2, the share of zero-emission power, both base load and peak load, is 43.4%, close to the government’s goal. In Scenario 4, the zero-emission power will account for 47.1% of the total power supply in Japan, and it will be possible to achieve the government’s goal.

**Changes in the industrial output**

Figure 8 shows the simulation results of the changes in the industrial outputs of sectors other than power in the average annual growth rate from 2026 to 2030.

The differences by scenario are relatively large in energy sectors, that is, coal, oil, and gas, of which extremely little is produced in Japan, and petroleum and coal products, of which large volumes are produced. As the share of zero-emission power increases, the production of energy sectors shows a declining trend, and production factors will be allocated to other sectors. As a result, the industrial output tends to remain at almost the same level or increases in sectors other than energy sectors.

**Changes in exports by commodity**

Figure 9 shows the simulation results of the changes in exports by commodity in the average annual growth rate from 2026 to 2030.\textsuperscript{12}

In the simulations of this study, the shock value differs by scenario only in Japan, and the impact on the economy of other countries is small. Therefore, the impact on Japan’s exports is not very large. However, changes in production also affect exports in Japan. Although the growth rate is small, commodities such as computers, electronics, optics, and machinery and equipment tend to increase in Scenarios 2, 3, and 4 compared to Scenario 1. These commodities have a large share of exports and contribute to an increase in the total export value.

\textsuperscript{11} For reference, the average annual CO2 emissions in Japan will decrease by 0.56% in Scenario 3, by 0.71% in Scenario 2 and by 0.73% in Scenario 4. Both the simulations results in each scenario and the difference between them are relatively small, and there is almost no change in regions other than Japan. When the effects of various policies in Japan related to non-zero-emission power are incorporated into the model, as mentioned above, and the setting regarding power generation is given both for Japan and for other countries, simulation results concerning CO2 emission would change considerably.

\textsuperscript{12} The agricultural sector, which has a higher growth rate than other sectors, although the absolute amount is very small, is not included in Fig. 10.
|                       | 2019–2025                  | 2025–2030                  |
|-----------------------|----------------------------|----------------------------|
|                       | Scenario1 | Scenario2 | Scenario3 | Scenario4 | Scenario1 | Scenario2 | Scenario3 | Scenario4 |
| NuclearBL             | −0.04     | 7.36      | 6.50      | 8.15      | −0.05     | 7.36      | 6.50      | 8.15      |
| HydroBL and WindBL    | 0.12      | 1.74      | 1.41      | 4.00      | 0.14      | 1.74      | 1.41      | 4.00      |
| CoalBL                | 0.75      | 0.00      | 0.12      | −0.26     | 0.84      | −0.40     | −0.14     | −0.89     |
| GasBL                 | 0.79      | 0.03      | 0.15      | −0.22     | 0.75      | −0.52     | −0.25     | −1.01     |
| OilBL                 | 0.74      | −0.06     | 0.06      | −0.33     | 0.52      | −0.78     | −0.51     | −1.29     |
| OtherBL               | 0.28      | 3.18      | 2.60      | 4.41      | 0.27      | 3.18      | 2.60      | 4.41      |
| GasP and OilP         | 0.64      | −0.79     | −1.29     | −0.62     | 0.64      | −7.23     | −5.60     | −7.14     |
| SolarP and HydroP     | 0.44      | 14.32     | 16.18     | 14.55     | 0.52      | 20.60     | 16.18     | 20.95     |

Source: The authors
Changes in imports

Figure 10 shows the simulation results of the changes in imports in Japan by commodity in the average annual growth rate from 2026 to 2030. We observe a clear difference between the energy sectors and other sectors regarding import trends. Imports in sectors other than energy do not change significantly between the scenarios. On the other hand, imports in the energy sectors decline as the share of zero-emission power increases, leading to a decrease in the total import value.
Conclusion

This study analyzed the effect of changes in the Japanese power supply using the GTAP-E-Power model. The simulation results show that an increase in zero-emission power leads to a reduction in fossil fuel power.

The simulation results show that if Japan were to make great efforts and maintain zero-emission power in Japan at the same growth rate as that of the Sustainable Development Scenario of WEO 2019 from 2019 to 2030, the share of zero-emission power in 2030 would be 47.1%, and the government’s goal will be achieved while maintaining economic growth. This research analyzed the effect of the increase in zero-emission power and did not consider the effects of policies on electricity and energy in detail. If the effects of these policies were included in the analysis, the share of zero-emission power would increase further. The simulation results also show that an increase in zero-emission power has a positive

Fig. 8 Impacts on Japan’s industrial output: the annual growth rate of the nonpower sectors from 2026 to 2030 (percentage). Source: the authors

Fig. 9 Impacts on Japan’s exports by commodity: the annual growth rate from 2026 to 2030 (percentage). Source: The authors
effect on the Japanese trade balance, which would contribute to an increase in the GDP growth rate.

The latest base year of the GTAP 10.0 database is 2014, when Japan’s nuclear power generation was zero. Since it would be desirable to classify nuclear power independently to analyze the change in the structure of the Japanese power supply, in this study, we use the GTAP 10.0 database based on the year 2011. The GTAP database, including nuclear power generation, will be updated in a few years. It is expected that the analysis methodology developed in this study will be applied to a new updated database, including nuclear power generation.

In addition to updating the database, future studies should investigate in detail the parameters for Japan that would reflect the actual situation more precisely. It is also important to incorporate the effects of a wider variety of policies concerning energy and electricity. Furthermore, by providing the same settings as in Japan for other areas and, if possible, by increasing the regional classification, it would be possible to analyze the economic effects of power policies in Japan taking into consideration the wider economic interaction.

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Availability of data and materials
The data used in this study were obtained from the materials listed in References, and the datasets used in the model analysis are the GTAP 10, GTAP-Power 10, and GTAP-E 10 databases.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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