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# Impact of Carbon Neutrality on the Economy and Industry Assuming Japan's Achievement of 2030 Power Mix Plan: A 2050 Perspective Based on the E3ME Macro-Econometric Model

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**Abstract:** Japan faces the challenge of reducing its greenhouse gas emissions while maintaining economic growth and energy security. This study aims to analyze the potential impact on Japan's economy and industries if the country achieves its 2030 greenhouse gas reduction target, implements a power mix plan to meet that target, and simultaneously pursues the Growth Strategy Council's proposal for a power mix plan to achieve carbon neutrality by 2050. The study also investigates an alternative carbon neutrality pathway without nuclear power. The research question is whether these low-carbon policies can lead to both economic growth and decarbonization in Japan. To address this question, the study uses the E3ME-FTT macroeconomic model with endogenous technology diffusion to simulate different policy scenarios and assess their economic and environmental impacts. The results indicate that by 2050, Japan could meet its carbon neutrality target, and at the same time, the GDP could increase by approximately 3% compared with the baseline scenario, with or without nuclear power. This growth is expected to occur in several sectors due to increased demand for decarbonization-related investments and strong private consumption. Additionally, the overall economy is expected to benefit from the increased demand for low-carbon and decarbonization-related investments, reduced costs associated with renewable energy generation, and an improved trade balance resulting from a significant decrease in fossil fuel imports.

**Keywords:** 2050 carbon neutrality; E3ME; macro-economic model; energy mix; decarbonization innovation; Japanese economy

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## 1. Introduction

Attaining carbon neutrality by mid-century has emerged as an irreversible global trend. In October 2020, the Japanese government pledged to achieve carbon neutrality by 2050. In April 2021, it declared its decision to augment Japan's greenhouse gas (GHG) reduction target to 46% below the 2013 level by 2030. In June of the same year, it revised its power mix plan, which outlined a comprehensive framework for the extensive integration of renewable energy sources. The Ministry of Economy, Trade, and Industry (METI) [1] presented a comprehensive power mix plan for 2050 that entails the integration of renewable energy sources, including solar power, wind power, hydroelectric power, geothermal power, and biomass, aiming to account for 50–60% of the total power supply. Additionally, the plan proposes a combination of nuclear energy and thermal power with $CO_2$ capture (thermal power + CCUS) constituting 30–40% of the total power supply, while 10% will be generated from hydrogen and ammonia power.

There has been scant research into the potential impact of the Japanese government's 2030 GHG reduction target, the power mix plan, and the 2050 power mix plan study on the cost of electricity production, the Japanese economy, and industry, as it progresses toward achieving carbon neutrality by 2050. We employed the E3ME macro-econometric model to evaluate the effects on the Japanese economy and industry assuming Japan were to concurrently achieve (1) its 2030 GHG reduction objective and adoption of a power mix plan aligned with the said target and (2) the METI's [1] proposal to examine a power mix plan geared toward achieving carbon neutrality by 2050. Further, we assessed Japan's economic and industrial ramifications if these two initiatives were to be implemented in tandem. To facilitate comparisons with the above estimates, we also employed the E3ME model to evaluate the energy mix of power sources and the economic and industrial implications when Japan attains carbon neutrality by 2050, considering the discontinuation of coal-fired and nuclear power generation by 2040.

## 2. Literature Review

The European Commission [2] conducted simulations using the E3ME (Energy-Economy-Environment Macro-Econometric) model to project the economic impacts of achieving carbon neutrality by 2050. Compared with the baseline scenario, the attainment of carbon neutrality solely by the EU is anticipated to yield a GDP growth of 1.48%. Additionally, achieving global carbon neutrality will result in a substantial growth of 2.19%. These outcomes bear favorable implications for the economy. They indicate that if the EU were to achieve carbon neutrality by 2050, economic growth would continue on an upward trajectory compared with the baseline, and "decoupling" could be accomplished.

Pollitt's [3] simulation analysis using the E3ME model suggests that China's attainment of carbon neutrality will lead to a cumulative reduction of approximately 215 Gt of its $CO_2$ emissions. Moreover, China's economy is poised to benefit from an anticipated 5% increase in the GDP over the next decade, driven by heightened investment in the power sector, technological advancements linked to coal abandonment, and the encouragement of fuel substitution. These developments are expected to favorably affect China's economic performance.

Lee et al. [4] present a relevant domestic study. They employed the E3ME model to simulate the impact of an 80% reduction in GHG emissions on the economies and low-carbon technological innovation in East Asian regions and countries, including China, Japan, and South Korea. However, while the study considers the impact of an 80% GHG reduction by 2050, it does not analyze the ramifications of achieving carbon neutrality. Thus, this study requires further exploration to identify the effects of carbon neutrality.

Furthermore, Lee et al. [5] employed the E3ME model to simulate the macroeconomy and energy mix of power sources until 2050 considering the phase-out of coal-fired and nuclear power plants in the power generation sector. The study's findings demonstrate that phasing out both power sources before 2050 will have minimal adverse effects on the economy in areas such as GDP, employment, and other macroeconomic indicators. However, the study also highlights that $CO_2$ emission reductions from the power sector will amount to approximately 20% than the baseline scenario. This is because liquefied natural gas-fired power generation (LNG) will expand more than renewable energy generation, serving as an alternative to coal-fired and nuclear power generation. Although this study is significant for predicting the economic impact of the early phase-out of coal-fired power generation, it is limited in its coverage of the power generation sector and the use of only coal-fired and nuclear power plants as policy instruments in the simulations.

Finally, Lee et al. [6] is the most relevant study for this research. They employed the E3ME model to explore the macroeconomic implications of achieving carbon neutrality in Japan by 2050 and how Japan's energy mix will transform. The results indicated that the energy mix of power sources in 2050 (assuming a nuclear power plant phase-out in 2040) will comprise approximately 90% renewable energy. The GDP will increase by 4.0–4.5%, while employment will rise by 1.5–2.0%, compared with the baseline scenario.

This demonstrates the possibility of achieving carbon neutrality and economic growth simultaneously. However, this study was limited as it only simulated the macroeconomic impacts, specifically the GDP, and did not examine the effects on specific industries owing to constraints in the available data.

In our study, the GHG reduction target for 2030 and the power mix plan are designated exogenously as a roadmap toward attaining carbon neutrality by 2050. This study not only examines the energy mix of power sources and the associated electricity generation costs until 2050 but also explores the macroeconomic implications and industry-specific $CO_2$ emissions, along with their influence on production. This uniqueness and originality of this research distinguish it from previous studies in the field.

## 3. E3ME Model Overview

The E3ME model is a comprehensive system of simultaneous equations comprising macroeconomic sectors (consumption, investment, trade, employment, prices, and government sectors), 42 industries, 12 fuels (coal, oil, electricity, gas, heat, etc.), and 24 power sources (seven conventional sources, such as nuclear, coal, gas, and oil, and 12 renewable energy sources, such as solar and wind power) for 59 countries and regions, including Japan. The model enables a quantitative analysis of the effects of various energy and environmental policy changes on the economy, industry, and $CO_2$ emissions by 2050. The technical manual for the E3ME model is available at https://www.e3me.com/ (accessed on 1 August 2023).

As previously mentioned, the E3ME model possesses exceptional capabilities in analyzing the economic and environmental impacts of energy and environmental policies. Therefore, it has been used extensively by the European Commission and the UK government to design energy and climate change policies and institutions. For example, the EU's report [2], which underpins the EU's 2050 GHG policy of zero emissions, draws extensively on the simulation outcomes from the E3ME model. Additionally, the model has been previously used to produce many low-carbon analyses in Japan (Lee et al. [7]) and East Asia contexts (Lee et al. [8]).

The E3ME model is constructed based on national income accounts and input–output tables, which are categorized according to the economic and industrial classifications of the analyzed country. The energy sub-model, integrated into the econometric model, enables the calculation of energy demand and $CO_2$ emissions. The system of equations in the E3ME model encompasses GDP components (consumption, investment, and net exports), various prices, energy demand, and demand for significant mineral resources, by both country and sector.

The E3ME model additionally incorporates four cutting-edge Future Technology Transformation (FTT) sub-models. They use a bottom-up approach to endogenously determine the impact of various low-carbon technology innovations in sectors such as power supply, industry, and transportation, as well as the effects on the cost reduction in low-carbon technologies. These four FTT sub-models are firmly integrated with the E3ME core. For instance, in the FTT-Power sub-model created for the power generation sector, the E3ME model first determines the required electricity demand resulting from economic activity each year, which is then transmitted to FTT-Power. FTT-Power uses this prediction as an exogenous input and subsequently determines the annual energy mix for each power source endogenously. This determination considers factors such as the unit price, price dispersion, service life, construction period, and learning curve (where the rate of technological innovation or unit price decline is slower for more mature power sources and faster for new ones) for each power source, as well as policy variables, including carbon pricing and feed-in tariffs (FITs). In Japan, the ongoing transition toward adopting a feed-in premium (FIP) is underway; however, owing to inherent data limitations, the incorporation of the FIP is omitted from this model. For further information on the FTT sub-model mechanisms and simulations, please refer to [4].

Additionally, the E3ME model is underpinned by the post-Keynesian theory, which posits that the economy is inherently imbalanced and effective demand is the principal driver of the GDP. Consequently, in situations with idle capital, an increase in the effective demand, such as investments and consumption, yields positive economic effects. Thus, if the technological innovation effects of low-carbon policies (leading to cost reductions) and new investments (boosting effective demand) engender changes in energy costs, the energy input coefficient for each industry will endogenously change annually by 2050. This mechanism spurs the economy by adjusting the capital and energy input rates, thereby facilitating the transition to a low-carbon energy industrial structure.

The E3ME model is often compared with the Computable General Equilibrium (CGE) models that are commonly employed to examine energy and environmental policy outcomes. Consequently, the European Commission (EU) uses econometric models, such as the E3ME and CGE models, as benchmarks when formulating and comparing energy and climate change policies.

CGE models assume perfect knowledge and rational behavior, which means that the demand is simply a factor to set prices. The whole system may be solved using optimization principles since it is assumed that markets clear. In contrast, econometric models like E3ME use historical datasets to try to determine behavioral factors on an empirical basis and do not assume optimal behavior. The treatment of capacity explains most of the differences between the two modeling approaches. If all available capacity is used to begin with, any additional demand, such as that from low-carbon investment, must displace (or "crowd out") other activity. Deviating from the optimal path in a CGE model, for example, because of a carbon tax, leads to economic costs. In contrast, creating additional demand in E3ME allows for an expansion of total activity by drawing on previously unemployed resources.

Jansen and Klaassen [9] and Bosetti et al. [10] describe some of the differences between modeling approaches in the context of environmental tax reform. The European Commission [11] provides a discussion of the importance of capacity constraints in the two approaches. Mercure et al. [12] focuses on how the two approaches treat finance, technology, and economic development.

## 4. Baseline and Policy Scenarios

### *4.1. Setting of Baseline Scenario*

In our study, the "baseline scenario" refers to a situation where no additional measures or policies beyond the existing low-carbon and decarbonization policies (i.e., global warming mitigation measures) are implemented. Therefore, we first calculated the GHG emission trajectories, energy structure, and economic and industrial production up to 2050 assuming that this scenario is implemented.

On the other hand, the "policy scenarios" in this study establish the government's 2030 GHG reduction target (46% reduction from 2013 levels) and the requisite low-carbon and decarbonization policy package (described in the next section) to achieve carbon neutrality by 2050. We conducted simulations to assess the potential outcomes if the policy scenario were to be implemented. Consequently, our study assessed the impact of the new low-carbon policy package on power, the economy, and industry based on the degree of deviation from the baseline scenario.

The baseline scenario is adopted as a "reference case" from the "IEEJ OUTLOOK 2022" report (herein referred to as OUTLOOK 2022) by the Institute of Energy Economics, Japan (IEEJ) [13]. The reference case represents a scenario in which no specific measures were implemented, serving as a benchmark for comparison with a scenario that incorporates the implemented measures. Therefore, this reference case predicts Japan's economy trajectory (e.g., GDP), environment (e.g., $CO_2$ emissions), and energy-related metrics, such as the power supply mix up to 2050, without including any extraordinary policies. Furthermore, OUTLOOK 2022 presents a reference case for GHG emissions up to 2050 but only for energy-related $CO_2$ emissions. The E3ME model endogenously simulates energy-related

$CO_2$ emissions only, whereas other GHGs are emitted at a fixed ratio to $CO_2$ emissions. Consequently, this study focuses on analyzing energy-related $CO_2$ emissions.

In the OUTLOOK 2022 reference case, Japan's GDP is expected to increase at an average annual rate of 0.7%, from USD 6.2 trillion in 2019 (in 2010 prices) to around USD 7.8 trillion in 2050 (in 2010 prices). As a result, the final energy consumption compared with 2019 is projected to decline by 20.4% by 2050, reaching 222 million toes. Furthermore, electricity generation is expected to reach 1099 TWh by 2050, 6.0% higher than that in 2019. Consequently, energy-related $CO_2$ emissions are projected to reach 691 million $CO_2$ tons ($CO_2$t) in 2050, which is 34.7% lower than the 1059 million $CO_2$t in 2019 (as presented in Table 1).

**Table 1.** Key indicators in the OUTLOOK 2022 reference case.

| | 2019 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| GDP (billion USD, 2010 prices) | 6211 | 6664 | 7227 | 7761 |
| Final energy consumption (million toes) | 279 | 259 | 240 | 222 |
| Electricity generation (TWh) | 1037 | 1045 | 1079 | 1099 |
| Nuclear | 64 (6.2) | 157 (15.0) | 141 (13.1) | 141 (12.8) |
| Renewables | 205 (19.8) | 255 (24.4) | 305 (28.3) | 365 (33.2) |
| Coal | 329 (31.7) | 257 (24.6) | 247 (22.9) | 221 (20.1) |
| LNG | 385 (37.1) | 338 (32.3) | 358 (33.2) | 354 (32.2) |
| Energy-related $CO_2$ emissions (million $CO_2$t) | 1059 | 885 | 792 | 691 |

Note: Figures in parentheses represent the share of each power source in total power generation (%). Source: [13].

Regarding the energy mix of power sources, coal-fired power is expected to decrease from 31.7% in 2019 to 20.1% in 2050, and LNG-fired energy is expected to decrease from 37.1% in 2019 to 32.2% in 2050. On the other hand, nuclear power is projected to increase from 6.2% in 2019 to 12.8% in 2050, whereas renewable energy generation (including large hydropower) is anticipated to expand from 19.8% in 2019 to 33.2% in 2050.

### *4.2. Setting of Decarbonization Policy Package and Policy Scenarios*

In addition to attaining carbon neutrality by 2050, this study aims to simulate the achievement of the 2030 reduction goal as an intermediate step. Based on the baseline scenario of the preceding section, an analysis of energy-based $CO_2$ emissions reveals a modest reduction of 16.4% by 2030 and 32.9% by 2013, compared with the emission levels recorded in 2019. Hence, a decarbonization policy that facilitates a 46% reduction relative to 2013 by 2030 and the attainment of the 2050 carbon neutrality objective must be developed.

The decarbonization policy scenarios to achieve carbon neutrality are based on the following two scenarios. The first scenario, referred to as policy scenario 1 (hereinafter referred to as "S1"), assumes that the power mix plan for 2030 will align with the Sixth Strategic Energy Plan (METI [14]) proposed by the government, while the power mix plan for 2050 will follow the study proposal of METI [1]. In this scenario, the share of nuclear power plants increases from 6.2% in 2019 to 20% in 2030 (20–22% in the power mix plan). However, the share of nuclear power will then decrease to 10% in 2050. In contrast, renewable energy will expand from 19.8% in 2019 to 38% (36–38% in the power source plan) by 2030 and 60% by 2050. Table 2 lists the shares of other energy sources.

The second scenario (policy scenario 2 (hereinafter, referred to as "S2")) diverges from the government's plan for the energy mix and instead relies on this study's settings (Tables 2 and 3). Nuclear power plants will be phased out by 2040, with no new plants built after 2018 and a phase-out based on the number of years in operation (40 years). Similarly, coal-fired power plants will be phased out by 2040, beginning in 2021, based on their inefficiencies and operating histories. We established these setups to demonstrate the feasibility of achieving carbon neutrality without relying on nuclear and coal-fired power.

These conditions are similar to settings in a recent research by Lee et al. [5]. Other power sources are determined endogenously. Therefore, the simulation of the decarbonization policy package adopted in this study (Table 4) comprises two cases: a case in which the power generation sector follows the government's 2030 and 2050 power plans (S1) and a case unique to this study (S2) (Tables 2 and 3).

**Table 2.** Energy mix of power sources in 2030 under S1 and S2.

| | | S1 (Power Mix Plan for 2030) | S2 (Setting of This Study) |
|---|---|---|---|
| Greenhouse gases in 2030 | | −46% (compared with 2013) | −52% (compared with 2013) |
| Nuclear | | 20% | 8.9% |
| Coal | | 19.0% | 10.0% |
| LNG | | 20.0% | 12.9% |
| Oil | | 2.0% | 4.0% |
| Renewables | Subtotal | 38.0% | 64.1% |
| | Solar | 15.7% | 38.6% |
| | Offshore | 3.7% | 5.6% |
| | Onshore | 1.8% | 4.1% |
| | Geothermal | 1.2% | 1.7% |
| | Hydro | 10.5% | 7.9% |
| | Biomass | 5.1% | 6.2% |
| Hydrogen and ammonia | | 1.0% | 0.0% |
| Total | | 100.0% (Total generation: 934 billion kWh) | 100.0% (Total generation: 1069 billion kWh) |

Note: (1) The values in S2 are the result of simulations. (2) Nuclear and coal will be phased out by 2040, while other sources are determined endogenously. Source: Based on [14] and this study's setting.

**Table 3.** Energy mix of power sources in 2050 under S1 and S2.

| | S1 (Power Mix Plan in 2050) | S2 (Setting of This Study) |
|---|---|---|
| Greenhouse gases in 2050 | Carbon neutrality | Carbon neutrality |
| Nuclear | 10% | Phase out by 2040 |
| Thermal + CCUS | 30% | Phase out by 2040 for coal-fired |
| Renewables | 60% | Endogenously determined |
| Hydrogen and ammonia | 10% | Endogenously determined |
| Total | 100% | 100% |

Note: The detailed sources of thermal + CCUS and renewable energy are not provided in the government's 2050 power mix plan draft. The share of detailed sources is determined endogenously in the model. Source: Based on [1] and this study's setting.

Considering the above two policy scenarios, the prescribed policy framework for attaining carbon neutrality by 2050 is delineated as follows (refer to Table 4). First, a carbon tax is implemented in addition to the current "global warming tax", with a rate that increases proportionally from USD 50/$CO_2$t in 2021 to USD 410/$CO_2$t in 2040 and remains constant until 2050. The revenue generated from the carbon tax is earmarked to cover expenses linked to low-carbon and decarbonized investments, FIT, and phasing out of thermal power. This use of tax revenue adheres to the tax revenue neutrality principle.

In the transportation sector, according to the policy announced in January 2021 to achieve a 100% electric vehicle sales rate for new cars by 2035, passenger vehicles that solely rely on internal combustion engines must not be sold in 2035 under this study's policy. The government has established a price range of USD 8000 to USD 13,000 per electric vehicle, contingent on the storage battery capacity at purchase, to be implemented by 2025. The use of biofuels is mandatory for cargo vehicles and aircrafts until 2050.

**Table 4.** Decarbonization policy package for achieving carbon neutrality by 2050 in Japan.

| Category | | Scenario Settings |
|---|---|---|
| Carbon tax | | Tax rate applied to all sectors, set to increase progressively from USD 50/$CO_2$t in 2021 to USD 410/$CO_2$t in 2040. Maintained at USD 410/$CO_2$t from 2040 to 2050. |
| Power generation Sector | Nuclear | S1: Power generation share: 20% in 2030 and 10% in 2050<br>S2: Phase out by 2040 |
| | Coal-fired | S1: Share of 2030 power generation: 19%<br>S2: Phase out by 2040 |
| | Renewables | S1: Power mix plan in 2030 [14] and 2050 [1]<br>S2: Endogenously determined by the model |
| Transport sector | Passenger vehicle sales | Restrictions on gasoline/diesel vehicle sales from 2035 |
| | EV subsidies | Maintain purchase subsidies until 2025 |
| | Biofuel mandate | Mandate share of biofuels to be used in cargo vehicles and aircraft |
| Steel sector | | Reduce blast furnace emissions to zero by 2050 |
| Building heating | | Phase out fossil fuel boilers by 2050 |

Note: In cases where S1 and S2 are not explicitly specified, both scenarios are applicable. Source: [6]. For further details, refer [6].

Policy scenarios were formulated solely for the steel industry, which is responsible for 12.7% of the economy's overall energy-related $CO_2$ emissions and approximately 40% of total emissions in the industrial sector. A regulatory scenario was established for the steel industry to eliminate $CO_2$ emissions by 2050, assuming a 100% hydrogen reduction method for the blast furnace sector by 2050. Finally, FTT-Heat (Knobloch et al. [15]) was used to determine the phase-out of fossil fuel-powered boilers by 2050 for the building sector (including households). The modeled heating decarbonization policies include taxes on household use of fuels for heating and capital cost subsidies for heat pumps and solar water heaters, as well as a ban on the sale of new fossil fuel-based boilers.

## 5. Impact on Energy Mix and the Economy of Achieving Carbon Neutrality by 2050

### *5.1. Impact on $CO_2$ Emissions Pathway*

As previously described, this study simulated two scenarios—S1 and S2—using the E3ME model to achieve carbon neutrality by 2050. First, the GHG emissions pathway in the baseline scenario follows OUTLOOK 2022, which is expected to reduce by 34.7% in 2050 compared with 2019. In this study, the GHG emissions pathway under S1, depicted in Figure 1, is projected to decrease to 46% of the 2013 level by 2030 and continue to decline to approximately 65 million $CO_2$t by 2050. By 2050, the remaining 65 million tons of GHG emissions will be mitigated by land use, land use change, and forestry (LULUCF), as well as biomass with carbon capture and storage (CCS) in the power generation sector. According to MOEJ [16], Japan's $CO_2$ absorption through sinks amounted to 44.5 million tons in 2018. However, considering advancements in afforestation technology and other relevant factors, this study posits an estimated absorption capacity of 65 million tons of $CO_2$ by sinks by 2050.

S1 will yield a 55.6% decline in energy-related $CO_2$ emissions by 2030 relative to 2013, accomplishing a 46% decrease in GHG emissions. Conversely, in S2, the reduction in energy-related $CO_2$ emissions by 2030 relative to 2013 will increase to 61.6%.

The sector-specific $CO_2$ reduction rates in 2050 relative to the baseline scenario (with a 34.7% reduction in 2050 compared with 2019) are 114% in the power sector and 100% in the road transport sector, whereas the industrial and residential sectors achieve only approximately 72% and 82% in reductions, respectively (as shown in Figure 2). A percentage reduction exceeding 100% in the power sector results from the combined reduction achieved through biomass and CCS technologies.

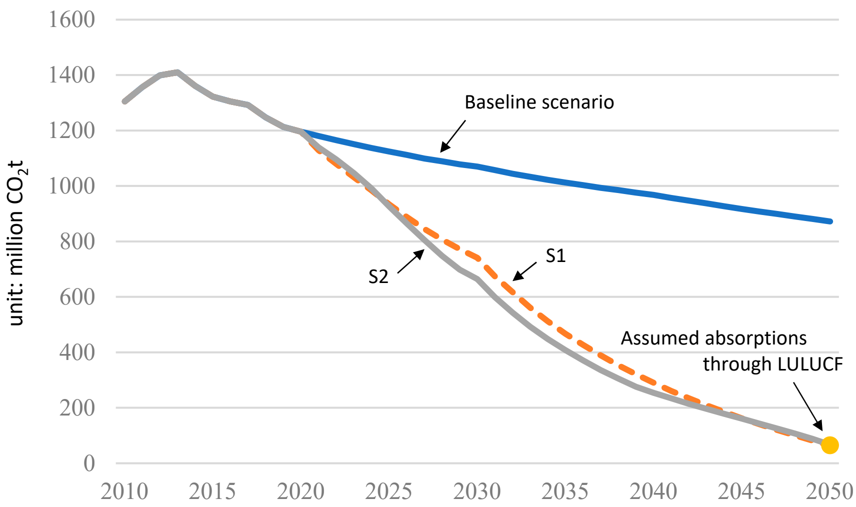


**Figure 1.** GHG emission pathways for the baseline and individual policy scenarios. Note: (1) The baseline scenario uses the OUTLOOK 2022 reference case. (2) S1 is the scenario considering the Japanese government's 2030 GHG emission target. (3) S2 assumes that the 2040 phase-out of nuclear and coal-fired power generation. The same is shown in the following figures. Source: E3ME model estimates from our study.

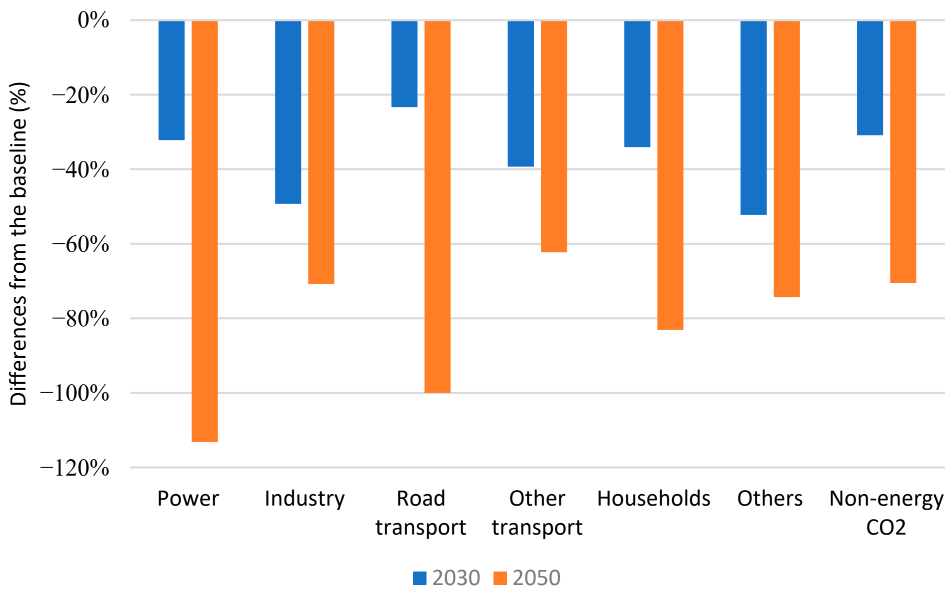


**Figure 2.** Sectoral $CO_2$ reduction rates. Note: The results of S2 closely resemble those of S1, hence their omission from the notation. Source: E3ME model estimates from our study.

### 5.2. Impact on Energy Mix and Electricity Costs

The electricity demand necessary to achieve carbon neutrality by 2050 is expected to decrease by a maximum of 4% of the baseline level by 2035 because of increased generation costs associated with implementing a carbon tax and other decarbonization policy packages. However, electricity demand is projected to increase by around 2035 as the economy becomes more electrified. Consequently, the electricity generation costs in both scenarios are estimated to rise by 9–11% by 2050 relative to the baseline (Figure 3).

In S1, the aggregate portions of nuclear power, fossil fuel (mainly LNG) + CCS, and biomass + CCS are exogenously established at 30% in compliance with the government's power mix plan (Table 5 and Figure 4). However, because of insufficient data, hydrogen + ammonia power generation is excluded from the E3ME-FTT simulation. S2, similar to the 2030 power mix plan, is determined endogenously, except for the 2040 phase-out of nuclear and coal-fired power. Consequently, in S2, nuclear power and fossil fuels, including CCS, will be completely phased out by 2050. Additionally, all renewable energy sources are expected to be employed, except for 3% of LNG-fired power, which remains a regulating source. LNG-fired power persists because of the structural design of the FTT-Power sub-model, which ensures that a specific amount of capacity continues to function as a regulating power source, even if thermal power becomes less competitive as renewable energy expands significantly.

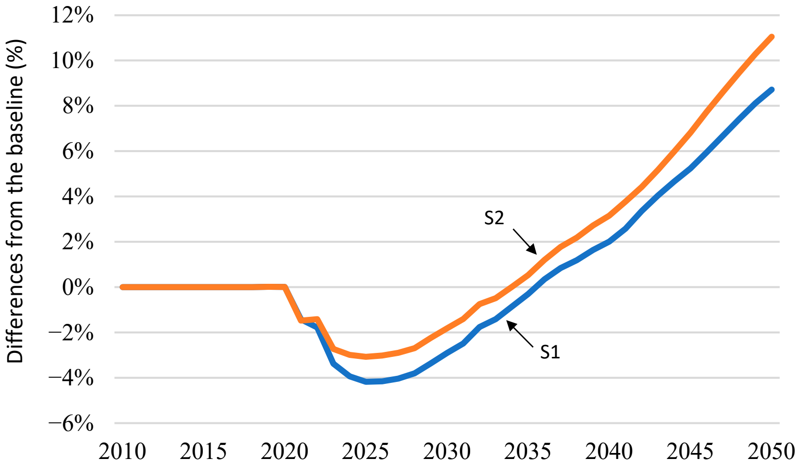


**Figure 3.** Electricity demand pathway for each policy scenario. Source: E3ME model estimates from our study.

**Table 5.** Impact on the energy mix in 2050 for each policy scenario. (Unit: TWh, % in parentheses.)

| | 2019 | 2050 | | |
|---|---|---|---|---|
| | | Baseline | S1 | S2 |
| Nuclear | 64 | 151.0 | 118.9 (10.9) | 0.0 (0.0) |
| Oil | 36 | 0.2 | 0.0 (0.0) | 0.0 (0.0) |
| Coal | 329 | 242.2 | 0.0 (0.0) | 0.0 (0.0) |
| LNG | 385 | 356.5 | 0.0 (0.0) | 38.5 (3.0) |
| Fossil + CCS | 385 | 356.5 | 157.2 (12.6) | 0.0 (0.0) |
| Hydro | 80 | 105.1 | 127.8 (10.2) | 86.3 (6.8) |
| Onshore | 7.5 | 50.6 | 61.1 (4.9) | 151.1 (11.9) |
| Offshore | 0.2 | 15.8 | 117.6 (9.4) | 336.7 (26.4) |
| Solar | 69 | 131.7 | 332.0 (26.5) | 427.3 (33.5) |
| Biomass | 45 | 94.7 | 96.0 (7.7) | 62.8 (4.9) |
| Biomass + CCS | 0.0 | 0.0 | 96.6 (7.7) | 84.4 (6.6) |
| Geothermal | 2.8 | 13.9 | 25.0 (2.0) | 50.8 (4.0) |
| Other | 19 | 0.0 | 119.0 (9.5) | 37.2 (2.9) |
| Total | 1037 | 1367.2 | 1251.2 (100.0) | 1275.1 (100.0) |

Source: E3ME model estimates from our study.

The onshore wind power share among renewable energy sources is anticipated to rise from 4.9% in S1 to 11.9% in S2. In comparison, offshore wind power is projected to increase from 9.4% to 26.4%, and solar power is expected to increase from 26.5% to 33.5%. Notably, the share of offshore wind power, which exhibits significant potential, is expected to increase substantially.

Nevertheless, given the potential limitations, the power source composition of geothermal and hydropower highlights the difficulty of surpassing the baseline scenario. On the other hand, the share of biomass + CCS power, which was non-existent in the baseline scenario, is estimated to rise to approximately 7% in 2050, owing to the impact of start-up subsidies (60% of initial investment) in both S1 and S2.

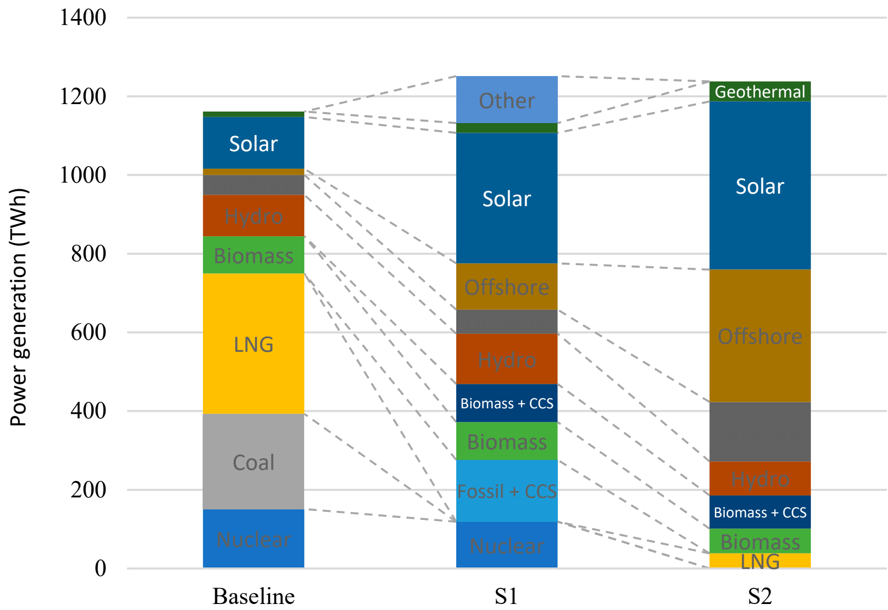


**Figure 4.** Energy mix in 2050 for each policy scenario. Source: E3ME model estimates from our study.

Figure 5 and Table 6 exhibit the effects of the policy scenarios on generation costs. S1 and S2 indicate that the carbon tax is expected to increase electricity generation costs to 15% by 2040 as coal-fired power plants are phased out. Regarding S1, electricity generation costs are expected to increase persistently until 2050 because of the government's power mix plan, which proposes the use of fossil fuels + CCS. Conversely, in S2, a temporary shock in the model ascribed to the compelled discontinuation of nuclear and coal-fired power generation engenders a decline in the short-term expenses of power provision. However, commencing from 2040, power generation expenditure begins a descending trajectory, owing to the reduction in renewable energy generation costs, particularly solar power. This suggests that in the long term, as renewable energy generation costs decline significantly, a more significant proportion of renewable energy in the energy mix results in relatively lower overall generation costs. Furthermore, achieving carbon neutrality by 2050 will affect economic activity and industrial production, which are explored in the next section. Nevertheless, as indicated in Table 6, there is no anticipated decline in offshore wind electricity generation costs beyond 2030. This is attributable to the scarcity of suitable sites and the substantial escalation in grid connection expenses accompanying the proliferation of offshore wind power, impeding the reduction in power generation costs.

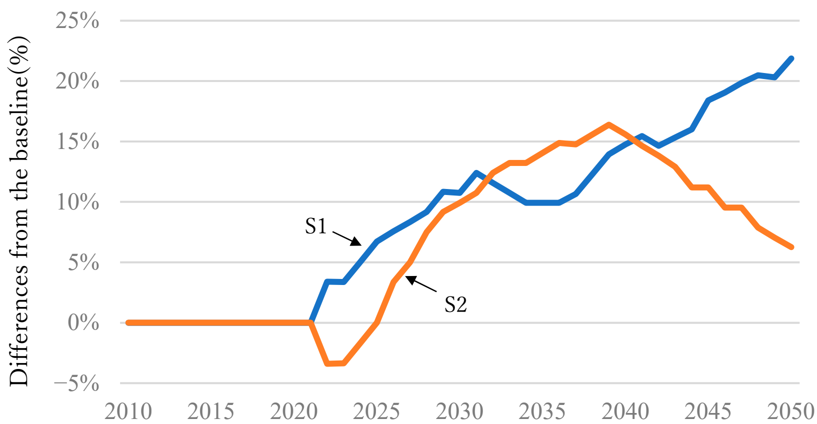


**Figure 5.** Impact on power generation costs for each policy scenario. Source: E3ME model estimates from our study.

**Table 6.** Expected cost of electricity generation (unit: JPY/kWh).

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Nuclear | 10.2 | 10.2 | - | - |
| Oil | 26.5 | 42.0 | 50.3 | 50.8 |
| Coal | 7.4 | 31.2 | - | - |
| LNG | 10.7 | 22.7 | 29.0 | 29.2 |
| Hydro | 10.8 | 10.8 | 10.8 | 10.8 |
| Biomass | 28.1 | 28.1 | 27.6 | 23.3 |
| Onshore | 14.6 | 11.8 | 11.7 | 11.3 |
| Offshore | 21.1 | 18.2 | 18.8 | 19.3 |
| Solar | 12.0 | 10.5 | 9.0 | 7.5 |
| Geothermal | 10.9 | 10.9 | 10.0 | 9.9 |

Note: (1) The generation costs for 2020 and 2030 are derived from the data provided by METI [17]. In contrast, the generation costs for 2040 and 2050 are derived from the simulations conducted in this study. (2) The simulation outcomes of S1 are presented exclusively, given their partial resemblance to the corresponding results of S2. Source: Based on the government's 2030 power mix plan and E3ME model simulations for S2 of our study.

## 6. Impact on the Macroeconomy and Major Industries

### *6.1. Impact on the Macroeconomy*

Based on the E3ME model simulations, implementing S1 and S2 are expected to increase GDP by approximately 2% relative to the baseline scenario by 2030 and further by approximately 3% by 2050, as indicated in Table 7. Additionally, the findings demonstrate negligible variation in the impact of the policies on the GDP increase. Given that the diffusion of renewable energy by 2050 is more advanced in S2 than in S1, the expected boost in GDP may appear diminished because of the simultaneous rise in energy costs. Nevertheless, the increase in investment demand under S2 and the subsequent reduction in generation costs attributable to the diffusion of renewable energy will have an equal impact on GDP as in S1. Both scenarios resulted in a notable enhancement in GDP, primarily driven by the stimulation of various sectors, such as power generation, industry, and transportation. This was because of the low-carbon and decarbonization-related investment demands required to achieve carbon neutrality, leading to an increase of 6–7% relative to the baseline, as shown in Table 7.

**Table 7.** Macroeconomic impacts of achieving carbon neutrality by 2050.

| | (Differences from the Baseline) | | | |
|---|---|---|---|---|
| | 2030 | | 2050 | |
| | S1 | S2 | S1 | S2 |
| GDP | 2.0% | 1.9% | 3.1% | 3.1% |
| Consumption | 0.5% | 0.5% | 2.3% | 2.5% |
| Investment | 7.7% | 7.5% | 7.0% | 6.0% |
| Exports | −0.4% | −0.5% | −0.3% | −0.2% |
| Imports | 0.2% | 0.1% | −2.1% | −2.7% |
| Employment | 1.1% | 1.2% | 1.4% | 1.5% |
| Inflation | 3.3% | 3.3% | −0.3% | −1.4% |

Source: E3ME model estimates from our study.

Implementing a decarbonization policy package will result in higher energy costs by 2030, particularly for power generation, leading to higher prices. However, the cost of generating renewable energy as a substitute for fossil fuels is projected to decrease significantly by 2050, which will have a downward effect on prices.

Furthermore, implementing low-carbon and decarbonization investment demands leads to the creation of new job opportunities, resulting in an estimated 1.4–1.5% increase in employment by 2050 relative to the baseline in both policy scenarios. This employment boost, in turn, leads to solid consumption (2.3–2.5% above the baseline) owing to income effects. An additional significant economic impact of achieving carbon neutrality by 2050 is the enhancement of the trade balance. Anticipated exports are projected to experience a slight decline (−0.2 to −0.3%), primarily attributed to reduced exports of certain capital goods. However, an enhanced trade balance resulting from a significant decrease in fossil energy import demand is anticipated to contribute to the GDP. For example, Japan's fossil energy imports, including crude oil, LNG, and coal, reached a sum of 19.3 trillion yen in 2018 (equivalent to approximately 20% of total imports, as documented in ANRE [18]). Therefore, a reduction in this import value assumes significance in enhancing trade balances.

### *6.2. Impact on $CO_2$ Emissions and Production in Major Industries*

#### 6.2.1. Impact on $CO_2$ Emissions

Figure 6 illustrates the effects of S1 on the reduction in sectoral $CO_2$ emissions by both 2030 and 2050. The power generation sector is the leading contributor toward attaining carbon neutrality by 2050, with a decrease of −39.1 million tons of $CO_2$ emissions owing to the introduction of biomass + CCS, combined with a significant decrease in non-fossil energy sources. This reduction will play a significant role in counterbalancing the remaining GHG emissions of non-power generation sectors.

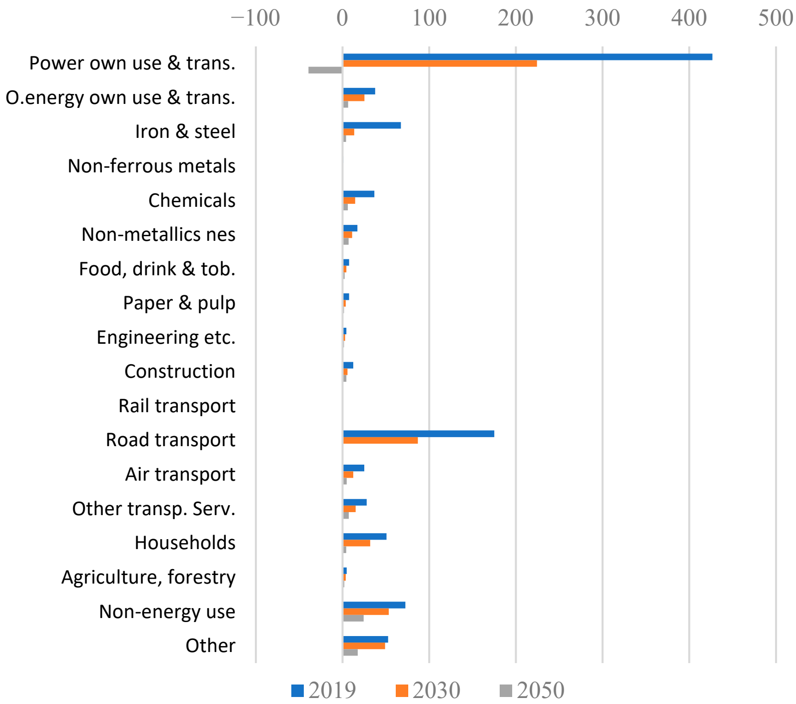


**Figure 6.** Impact on $CO_2$ emissions by each sector (unit: million tons of energy-related $CO_2$ emissions). Note: (1) "Non-energy use" refers to emissions stemming from applying non-energy resources in manufacturing, exemplified by using coke within the steel sector. (2) The results of S2 closely resemble those of S1, hence their omission from the notation. Source: E3ME model simulations from our study.

Emission reductions in the manufacturing industry are projected to be substantial, particularly in energy-intensive sectors such as steel, paper, nonferrous metals, and chemicals, as well as in other sectors, such as road transportation, where the use of zero-emission vehicles, such as EVs, has become more widespread. Notably, the steel industry, which accounts for 40% of $CO_2$ emissions in the manufacturing industry, is expected to achieve a complete reduction in the blast furnace sector, resulting in emissions of approximately 4.1 million tons by 2050. By 2050, it is anticipated that an aggregate of 56.9 million tons of energy-related $CO_2$ will persist in emissions, which will be counterbalanced by the sinks mentioned previously.

6.2.2. Impact on Production by Major Industry Sector

The E3ME model estimation under the carbon-neutral policy scenario reveals an industry-specific production outlook until 2050, as demonstrated in Figure 7. The graph shows the industry-specific production prospects for 2030 and 2050 as a percentage of the baseline. It projects a decline in industrial production in 2050 relative to the baseline, primarily in energy-intensive industries, such as processed fuels (e.g., oil refining), chemicals, non-metallic minerals (e.g., cement), and gas. Nevertheless, most other sectors will likely observe an increase in production relative to the baseline, driven by low-carbon and decarbonization-related investment demand and robust private consumption. Notably, the power generation sector is expected to witness a significant 9.1% upsurge in production relative to the baseline owing to the ongoing electrification of the economy.

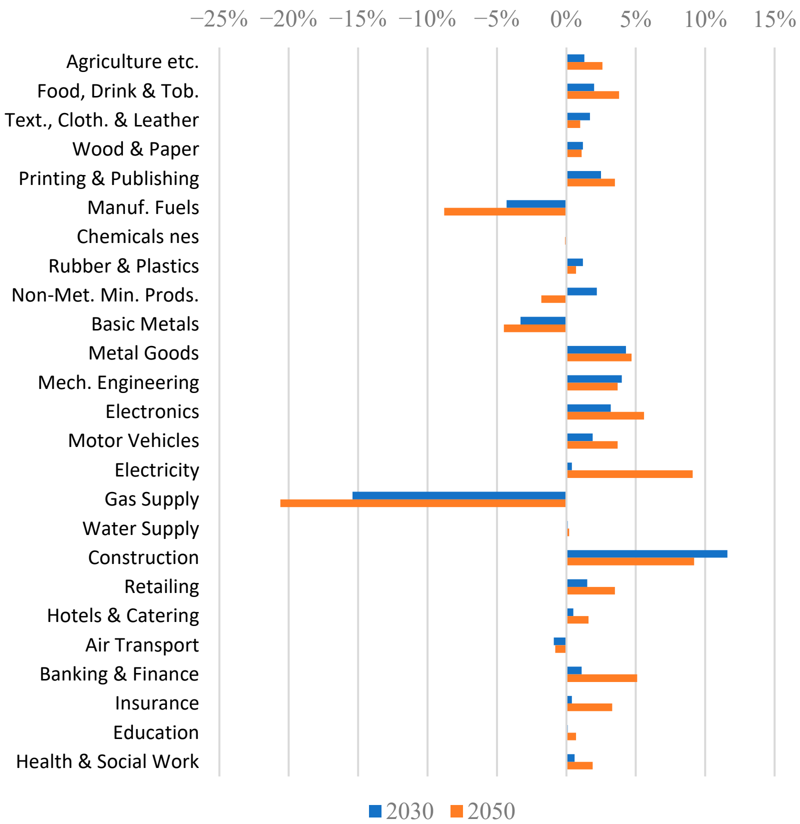


**Figure 7.** Impact on production by each sector. (Differences from the baseline.) Note: The results of S2 closely resemble those of S1, hence their omission from the notation. Source: E3ME model simulations from this study.

However, it is nearly impossible to accurately predict the transformation of industrial structures up to 2050 using simulations. The development of IoT, AI, and big data in economic and social systems—known as the Fourth Industrial Revolution—is expected to drive significant changes in future industrial and employment structures. This transformation will be propelled by the creation of new industries, emerging value chains, and industry clusters, resulting in a significant overhaul of the industrial system, driving the economy and industry forward.

The E3ME model employed in this study, similar to other large-scale econometric models, cannot accurately estimate significant structural changes in industries that are inherently difficult to quantify. In essence, projections for achieving carbon neutrality by 2050 promise transformative decarbonization innovations, the emergence of novel sectors, and an extensive shift in the industrial structure that far surpasses the ambit outlined by large-scale econometric models. Therefore, when interpreting simulations of sectoral impacts of decarbonization policies aimed at achieving carbon neutrality, it is critical to consider these constraints and possibilities.

## 7. Discussion

We used the E3ME-FTTmodel to assess the impact of Japan's 2030 GHG reduction target and carbon neutrality target in 2050 under different power generation mix plans on the Japanese economy and industry. The findings reveal a promising outlook for a low-carbon, decarbonized society. Economic growth and near-zero GHG emissions can be simultaneously achieved by implementing ambitious decarbonization. The beneficial effects of decarbonization policies include increased demand from all sectors for low-carbon investments, decreased renewable energy generation costs, and a significant reduction in fossil fuel imports, result in an improved trade balance that outweighs the drawbacks of higher energy costs. Furthermore, concerns regarding surges in fuel prices such as the one triggered by the crisis in Ukraine could be addressed in the future by moving away from fossil fuels.

The simulations in this study also indicate that the phase-out of nuclear and coal-fired power plants and the implementation of a carbon tax are expected to cause a temporary increase in the cost of power generation and likely to trigger general inflation as a result. However, the inflationary pressure resulting from low-carbon policies is expected to be temporary. This study indicates that in the long term, electricity generation costs will decrease with the expansion of renewable energy sources, particularly solar power.

The rapid reduction in renewable energy costs has been hindered recently due to disruptions in the global supply chain caused by COVID-19 backlogs and the Russian war. To provide a more comprehensive analysis of the potential impacts of low-carbon policies, it is important to consider potential limitations on the availability of renewable energy supply, as well as skilled labor needed for the low-carbon transition. Policymakers should pay special attention to the availability of renewable energy supplies and the reskilling of its taskforce.

Our macroeconomic results differ significantly from those of Herran et al. [19], who used a CGE model to examine the impact of Japan's 2050 emission pathway on GDP. According to their simulation results, an extremely high carbon tax would result in a maximum GDP impact of −72%. This discrepancy contrasts with our modeling approach. The limitations of the model used by Herran et al. stem from the equilibrium assumptions and the lack of endogenous learning regarding new low-carbon technologies.

The results of simulations on decarbonization policies for other countries vary due to differences in the tools and assumptions used. For instance, Rajbhandari et al. [20] used a CGE model to simulate the impact of a carbon-neutral policy on Thailand's economy, which resulted in a −8.5% GDP decline for the country. However, these findings are mainly based on the assumptions of the CGE model and differ from the results obtained through our E3ME model, a non-equilibrium model with endogenous technology diffusion.

On the other hand, Pareliussen et al. [21] analyzed the impact of a carbon-neutral policy on the UK's economy using a CGE model (ThreeME) and found positive results by returning carbon tax revenue directly to households. Similarly, Simon et al. [22] used the Climate Policy Assessment Tool (CPAT) to suggest that utilizing carbon tax revenues for productive investment, instead of other revenue recycling methods, may lead to positive GDP outcomes under a carbon neutrality context. It is worth noting that these positive results align with those derived from our E3ME model.

Furthermore, Swamy and Agarwal [23] used the India Energy Policy Simulator (EPS) to investigate the potential macroeconomic impacts of a long-term decarbonization scenario aligned with India's 2070 net zero emissions target. The study found a positive effect of approximately 2.2% of GDP in 2050, which closely aligns with the findings of this study.

Other studies that employed the E3ME model to examine carbon-neutral policies include the UK Climate Change Committee [24] and the European Climate Foundation [25]. The Climate Change Committee (CCC) conducted simulations for the UK's 6th carbon budget, which demonstrated a positive impact on the GDP [24]. Additionally, the European Climate Foundation [25] showed that achieving net zero emissions in the EU could increase the EU GDP by 2.1% and generate 1.8 million jobs by 2050. These results are consistent with our findings.

Our power generation mix results are consistent with previous studies. Ozawa et al. [26], who used the MARKAL (MARKetALlocation) energy model, concluded that Japan's electricity sector must achieve complete decarbonization by 2040 to achieve net zero $CO_2$ emissions by 2050. Although our study does not require full decarbonization in the power sector by 2040, it does necessitate full decarbonization in the mid-2040s, resulting in a similar conclusion.

Our results (S2) are also in line with the Renewable Energy Institute [27] "Sustainable Energy Mix" projected for 2030. The European Climate Foundation [27] conducted simulations using an inter-regional supply–demand model, which simulates interconnectors between Japan's ten regional service areas. The resulting "sustainable energy mix" projected for 2030 is as follows: nuclear, 0%; coal, 1%; LNG, 52%; oil, 0%; solar, 21%; wind, 9%; geothermal, 1%; hydro, 10%; biomass, 6%; and hydrogen and ammonia, 0%. Notably, this outcome aligns more closely with our simulation results than with the METI power mix plan. Additionally, the International Energy Agency (IEA) [28] presented the global energy mix in 2050 in its carbon-neutral scenario, which includes a significant portion of solar and wind power generation, similar to the results of our study for Japan.

In this study we accepted the METI power sector generation target as official, without providing our own assessment of its feasibility. The achievement of these targets depends on government policies and support. However, it is worth noting that the METI target relies on nuclear power and allows for the use of fossil fuels in combination with CCS technologies. We believe that these technologies may be relatively more expensive compared with solar and wind technologies, which have seen significant cost reductions in recent years.

In our FTT model, we endogenously determined the power mix and introduced a restriction to phase out nuclear power. This was done to demonstrate the feasibility of achieving carbon neutrality without relying on nuclear power. The model is path dependent and includes learning spillovers for renewable technologies globally. As a result, this scenario resulted in a larger share of solar and wind power in the mix compared with the METI target. Our results provide an alternative pathway to achieving carbon neutrality that is both compatible with the target and more cost-effective than the METI pathway.

## 8. Conclusions

This study examined the potential impact of Japan's low-carbon policies on its economy and industries, with a focus on achieving the 2030 emission reduction target and long-term carbon neutrality target in 2050. The study found that Japan can achieve both economic growth and its 2050 carbon neutrality target simultaneously by implementing an ambitious mix of low-carbon policies. The positive impacts of around 3% of GDP can be achieved with or without nuclear power.

The study identified several factors that contributed to these positive impacts. First, low-carbon investment can create new jobs and stimulate economic growth. Second, carbon tax revenue recycling can boost consumer demand and further stimulate economic growth. Third, reducing the country's fossil fuel imports can help to reduce the trade deficit and improve energy security. Finally, several sectors are expected to experience growth due to increased demand for decarbonization-related investments and strong private consumption.

The study uses a non-equilibrium approach combined with an endogenous technology diffusion model (E3ME-FTT) to model the outcomes. Unlike many existing tools used in low-carbon policy analysis, the E3ME-FTT does not assume that the economy is operating in equilibrium as a starting point or that technology costs are fixed. This allows for a more accurate assessment of the potential macroeconomic impacts of low-carbon policies.

The findings of this study have significant implications for policymakers and stakeholders in Japan and other countries that rely heavily on fossil fuel imports. By implementing ambitious low-carbon policies, countries can achieve both economic growth and decarbonization, while also addressing the challenge of reducing greenhouse gas emissions and maintaining energy security. However, it is important to note that this study's key limitation is an assumption of the availability of renewable energy supply and skilled labor.

An extension of this research could focus on combining this modeling approach with supply-side restrictions. This would provide a more comprehensive analysis of the potential impacts of low-carbon policies on the economy and industries, taking into account potential limitations on the availability of the renewable energy supply and skilled labor. Such an analysis could help policymakers to identify potential challenges and opportunities associated with the implementation of low-carbon policies and develop strategies to address them.

This study confronts other limitations. To achieve carbon neutrality by 2050, it is essential to consider the role of negative emissions, such as plantations and regenerated forests, soil carbon sequestration, biochar, accelerated weathering, wetland and coastal restoration (blue carbon), biomass + CCS (BECCS), direct air capture with carbon capture and storage (DACCS), and ocean alkalinization. However, this study only included biomass + CCS in the context of power generation. Hence, incorporating a broader range of negative emission technologies into the model constitutes an area for future research.

Moreover, within the purview of this study, the E3ME model operates under the assumption that countries apart from Japan will continue with their existing policies. However, it is imperative to acknowledge that in reality, international spillover effects concerning decarbonization technologies exist as the global community strives toward achieving carbon neutrality. Notably, substantial mass production activities in China and other nations are anticipated to make noteworthy contributions to cost reductions in solar and wind power generation. Therefore, future studies should consider the influence of these effects. Additionally, a substantial proportion of solar and wind power generation equipment is manufactured internationally, potentially failing to generate new employment prospects or foster domestic investment. This situation has the potential to negatively affect trade balances because of import inflows.

Furthermore, the E3ME model employed in this study posits that countries other than Japan will uphold their existing policies. Assuming that countries beyond Japan also strive to achieve carbon neutrality could alter Japan's competitive landscape, consequently impacting its economy. Investigating the repercussions on the Japanese economy in the event of carbon neutrality achievements by countries and regions such as the EU, the USA, China, and South Korea constitute a subject for future research.

Finally, the low-carbon technologies included in the E3ME model are restricted to those that can be anticipated at present. Technological advancements are inherently uncertain, and breakthroughs may occur unexpectedly. Efforts are underway to incorporate the unpredictability of technological innovation into macro-econometric models using approaches such as game theory. However, these models are yet to be developed on a scientifically sound basis. Analyzing decarbonization using a model that accounts for the unpredictability of technological innovation is a topic for future research.

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