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RESEARCH ARTICLE

Impact on the power mix and economy of Japan under a 2050 carbon-neutral scenario: Analysis using the E3ME macro-econometric model

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ABSTRACT
This study uses the E3ME macro-econometric model to simulate what Japan's macroeconomy would look like and how Japan's energy composition would change if the country were to achieve carbon neutrality by 2050. The results indicate that renewable energy will account for about 90% of the power supply configuration in 2050, assuming nuclear power plants are phased out by 2040. It is also predicted that GDP will increase by 4.0%–4.5% compared with the baseline scenario and that employment will improve by 1.5%–2.0%, resulting in simultaneous achievement of carbon neutrality and economic growth. The main reasons for these projected outcomes are that increased investment in renewable generation capacity in the power sector would be accompanied by increased investment in decarbonization technologies across individual economic sectors, increased private consumption resulting from increased employment and energy efficiency savings, and an improvement in the trade balance due to a substantial reduction in fossil fuel imports. In addition, the costs of energy due to policies to reduce or eliminate carbon would rise by 45%–55% point at most above the baseline scenario even in 2050; however, this would be of little burden on the economy, considering the substantial reduction in fossil fuel energy demand. Overall, it is estimated that energy bills would be 45% lower for consumers and 11% lower for industry in 2050 compared with the baseline.

Key policy insights

- The study shows that achieving climate neutrality does not require difficult trade-offs with economic growth. Instead, it can provide economic opportunities that arise from switching to renewables and decarbonization technologies.
- The rapid reduction in global renewable costs for wind and solar technologies means that the net zero transition does not have to rely on relatively more expensive nuclear power. The true costs of nuclear could be a lot higher when the costs of safety regulations are properly accounted for. Instead, investment in electricity storage should be prioritized.
- A well balanced decarbonization policy mix for each sector is required. Policy makers should not rely on carbon pricing instruments alone. Supporting policies such as R&D spending, renewable subsidies, regulations and energy demand reduction should also be considered.

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2050 carbon neutral; E3ME; macro-econometric model; energy mix; decarbonization technology; Japanese economy

1. Introduction

Global warming countermeasures by national governments have shifted course toward achieving carbon neutrality by 2050. In December 2019, the European Union announced the European Green Deal, a roadmap for achieving net zero greenhouse gas emissions by 2050. Furthermore, in March 2020, the EU unveiled a long-

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term strategy with a firm commitment to climate neutrality by 2050. The United Kingdom's Climate Change Act (revised in June 2019) calls for greenhouse gas neutrality by 2050. In the US, President Joe Biden has announced goals of carbon-free power generation by 2035 and net zero emissions by 2050.

Similar moves are also apparent in East Asia. In September 2020, at a speech to the UN General Assembly, Chinese President Xi Jinping stated his aim to achieve carbon neutrality in China by 2060. On October 26, a month later, in a policy speech following his appointment, Japanese Prime Minister Yoshihide Suga declared that Japan would become carbon neutral by 2050 (Ministry of the Environment, Japan, 2020). Two days later, President Moon Jae-in of South Korea announced to the National Assembly that the country would aim to have zero greenhouse gas emissions by 2050 (Ministry of Economy and Finance, South Korea, 2020).

Globally, fossil fuels accounted for roughly 85% of total energy consumption in 2018 (BP, 2020). In Japan, the figure is similar to the global average, where 85.5% of the primary energy supply comes from fossil fuels (Ministry of Economy, Trade and Industry, 2020a, 2020b). Reducing the consumption of fossil fuels, which account for the bulk of energy consumption, to virtually zero over the next 30 years would likely impose considerable economic burdens but also new investment and growth opportunities.

In recent years there has been rapid development in a variety of decarbonization technologies, including renewable energy, electric vehicles (EVs), and hydrogen production, shining a light on the road to carbon neutrality. The EU's early declaration of its carbon neutral aspirations was based partly on expectations that innovations in decarbonization technologies created in the process would strengthen its industrial competitiveness, cementing its position as a global economic leader (European Commission, 2018).

Against the backdrop of the above development in climate neutrality pledges around the world, the focus of this study is on the impacts of Japan's 2050 carbon neutrality target. It aims to quantitatively estimate the impacts on Japan's macroeconomy and changes in its power generation mix. The results are taken from simulations from the E3ME model.[1] The E3ME model is a global econometrics model with linkages between energy, environment and economy. It is also integrated with Future Technology Transformation (FTT) sub-models for detailed technology diffusions in the key energy users.

The remainder of this paper is structured as follows. The next section presents the background of the study and reviews relevant literature. The third section gives an overview of the E3ME model. The fourth section describes the baseline and policy assumptions to achieve carbon neutrality in Japan by 2050 in the E3ME simulations. The fifth section provides results and discussions from the simulations, including the power generation mix and impact on the Japanese economy. Finally, the sixth section summarizes the study and suggests areas for further investigation.

2. Literature review

Following the Japanese government's declaration of its intent to achieve carbon neutrality by 2050 target on 26th October 2020, the government formulated a strategy, "Green Growth Strategy Through Achieving Carbon Neutrality in 2050' (Cabinet Secretariat, Growth Strategy Committee, 2020). The strategy includes an action plan that sets ambitious goals for 14 sectors that are expected to grow economically and for which reducing greenhouse gas emissions is essential. To reach carbon neutrality by 2050, the Japanese government wants to mobilize JPY 240 trillion (USD 2.1 trillion) in private sector cash reserves and deposits in order to create employment and growth, anticipating an economic impact.

The government plan is to increase the share of renewables in power generation to roughly 50%–60% and the share of hydrogen and ammonia power generation to around 10% by 2050. The remaining shares of 30%–40% will come from nuclear and thermal generation involving CO_2 capture. The government expects an increase of about 30%–50% in electricity demand from current levels by 2050 due to further electrification of the industrial, transportation, and household sectors.

[1]Refer to the E3ME manual for details of the E3ME model, including composition, scope of application, simulation procedures, and setting technical parameters such as cost and efficiency. E3ME Technical Manual v6.1 (original English edition, September 2019) https://www.e3me.com/wp-content/uploads/2019/09/E3ME-Technical-Manual-v6.1-onlineSML.pdf. For more details on E3ME, refer to www.e3me.com.

For a comparison between the CGE and E3ME models, refer to the reference materials for the second Study Group on the Greening of the Whole Tax System and Carbon Tax in Japan (https://www.env.go.jp/policy/tax/conf/conf01-11/ref01.pdf).

So far there has been little research on the economic impact of achieving carbon neutrality by 2050 in Japan. This study is the first to provide comprehensive analysis, using a policy-based simulation approach, of Japan's carbon neutrality target. The authors of this study previously used the E3ME model to simulate the impact of long term 60~80% reduction in greenhouse gas emissions in East Asia. The analysis showed positive economic impacts from long term decarbonization in all four countries. However, it did not examine the impact of carbon neutrality (Lee et al., 2019).

Research relevant to the present study in Japan includes Lee et al. (2020). Lee et al. (2020) also used the E3ME model to conduct simulations on the macroeconomy and power mix in 2050 assuming that coal-fired and nuclear power plants are phased out. The results showed that the elimination of these two major power sources before 2050 would have a very little adverse impact on the economy. Lee et al. (2020) is significant in that it forecasts the economic impact of an early phase-out of coal-fired and nuclear power generation; however, it only addresses the power sector.

The present study is pioneering and original in that it uses a large-scale macro-econometric model to simulate policy measures, designed by this study, to achieve carbon neutrality in Japan by 2050. This study also provides the first analysis of the impacts on the Japanese economy and power generation.

3. E3ME model overview

E3ME is a macro-econometrics model that is based on Post-Keynesian theory. The full model manual (Cambridge Econometrics, 2019) is available on the model website (www.e3me.com) and a complete list of E3ME equations is given in Mercure et al. (2018). E3ME covers 61 world regions with 43 sectors in each region. Sectors are linked by input-output tables and regions are linked by bilateral trade matrices. E3ME contains endogenous links between energy, environment and economy. Furthermore, it contains an energy technologies sub-model for key energy users (power, road transport, steel and heating). The labour market is also covered in detail and it is possible to estimate involuntary unemployment.

E3ME has been used extensively to provide analysis of the net zero transition around the world. In the EU, E3ME (econometric model) was used alongside another model GEM-E3 (general equilibrium model) to provide economic impacts of the EU 2050 carbon neutrality target by the European Commission (2018). The results from the E3ME model show a boost to GDP in the EU by 1.48% compared to the baseline scenario,[2] when the EU acts alone, whereas global carbon neutrality action would boost GDP by 2.19%.

In contrast, the GEM-E3 model forecasts a negative impact on the economy compared to the baseline scenario. If the EU alone were to achieve carbon neutrality, GDP would be 0.63% lower, and there would be a fall of 1.3% if carbon neutrality were achieved worldwide. The difference in findings of the two models reflects the fundamental differences in the underlying economic assumptions. As a general equilibrium model, GEM-E3 assumes that the economy is at an equilibrium without spare capacity while E3ME, a simulation based econometrics model, allows for spare unused resources in the economy and it allows debt-finance to fund additional investment without full crowding out (Pollitt & Mercure, 2018). That is, if there is idle capital, crowding out or shrinking in other sectors is unlikely, even if effective demand such as investment and consumption increases, and there will be a positive impact on the economy.

Initially, the model was mainly used for the analysis of EU member states. The East Asian Environmental Policy Research Group, to which the authors of this study belong, and Cambridge Econometrics have jointly expanded the model coverage so that the same analysis can be applied to major Asian countries and regions, including Japan, China, Korea, and Taiwan (for details refer to Lee et al. (2015) and Lee et al. (2019)).

The model has four advanced Future Technology Transformations (FTT) sub-models – power, transportation, heating, and steel sectors – in which the impact of technological innovations for decarbonization (and the resulting cost-reduction effects) of these sectors are determined endogenously from the bottom up.[3] The

[2]'Baseline scenario' here refers to economic projections if the EU did not implement any additional measures to combat global warming.

[3]The four FTT sub-models are FTT:Power (featuring 24 types of power technologies), FTT:Steel (seven types of steelmaking technologies), FTT: Transport (nine modes of transportation), and FTT:Heat (seven types of heating technology in the building sector), all of which are determined endogenously. For details on FTT sub-model mechanisms and simulations, refer to Lee et al. (2019).

four FTT sub-models are hard-linked to the main E3ME model. For example, once electricity demand is determined based on annual economic activity and electricity price from the main E3ME model, this is relayed to FTT: Power. The power mix is determined endogenously for each year by considering a range of parameters, including power generation unit costs and unit cost dispersion for each technology in the FTT:Power, service life, construction period, learning curve leading to technology cost reduction, and policy variables (e.g., carbon pricing, regulations[4] and feed-in-tariff (FIT) schemes).

Under the E3ME model, new investment (effective demand) and the effects that decarbonization policies (and associated cost reductions) have on technological innovation lead to changes in energy costs. The energy system feeds back to an economy via four channels: the input-output relationship, consumer spending on energy, investment, and energy prices. This led to further rounds of impacts including indirect effects through supply chains, jobs, inflation, trade balance, and energy demand.

4. Setting baseline and policy scenarios

4.1. Baseline scenario

In this research, it was necessary to establish a baseline scenario for Japan in E3ME so as to make comparisons with a policy scenario (a group of policies to achieve carbon neutrality by 2050). The baseline scenario normally assumes a continuation of current policies with no additional special measures and shows how the power mix, economy, and environment (for example CO_2 emissions) are expected to unfold.

For the baseline scenario (scenario "BA" in this study), we calibrated the E3ME baseline to the 2021 reference scenario published in 2021 by the Institute of Energy Economics, Japan (IEEJ, 2021) in IEEJ OUTLOOK 2022.[5] The IEEJ reference scenario forecasts economic (e.g., GDP), demographic (e.g. population), environmental (e.g., CO_2 emissions), and energy-related indicators (e.g. power mix) in Japan until 2050, assuming that no additional special measures are implemented.

Under the IEEJ OUTLOOK 2022 reference scenario, from 2018 to 2050, GDP grows by an annual average of 0.7% from USD 6.2 trillion (2010 prices) to reach roughly USD 7.7 trillion (2010 prices), final energy consumption declines by 20.8% to 224 million tons of oil equivalent (Mtoe), power generation rises by 3% to 1,082 TWh, and energy-related CO_2 emissions fall by 31.7% from 1,081 mtCO2to 738 mtCO2. Coal share in power generation is expected to fall from 32% in 2018 to 24% in 2050 and LNG from 36% to 27%. However, nuclear share is expected to rise from 6.2% to 13% and renewables share (including large-scale hydro) from 18.8% to 33.8%.

4.2. Policy scenarios

Unlike most studies, this study does not rely on carbon pricing alone when drafting policy scenarios to achieve carbon neutrality by 2050. Rather, we adopted an approach that used a mix of policy measures in conjunction with carbon pricing for different sectors. This is because reliance on carbon pricing alone (a carbon tax in this study) tends to require tax rates that are very high and politically unpopular. Another reason is that achieving carbon neutrality would require new low carbon technologies that need to mature and become mainstream in the near future. This cannot be achieved via carbon pricing alone. In addition to carbon pricing, a wide range of policy instruments, including regulations, energy efficiency investment, CO_2 standards, and renewable investment subsidies, are needed to promote such behaviour. Based on these ideas, we propose a range of policies in the policy scenarios to achieve carbon neutrality in Japan by 2050 (Table 1).[6]

The ongoing use of nuclear power in Japan is determined mainly by government policy rather than the market and was thus included in this study under the following two cases. The first case makes the share of nuclear conform to that in the IEEJ OUTLOOK 2022 reference scenario, rising from 6.2% in 2018 to 13% in 2050 (generating 141 TWh). The second case assumes that nuclear is phased out by 2040. Under this scenario,

[4]This is modeled by removing choices to the investors (mainly industry sectors) in the simulation program.

[5]IEEJ OUTLOOK is annual report on energy and economic long term forecasting (by 2050) of Asian countries issued by the Institute of Energy Economics, Japan (IEEJ). For IEEJ OUTLOOK 2022, refer to https://eneken.ieej.or.jp/data/10041.pdf

[6]We were able to create policy scenarios by sectors and technologies in this study because of the four abovementioned FTT sub-models.

Table 1. Policy scenarios for achieving carbon neutrality by 2050 in Japan.

Category		Scenario settings	Notes
Carbon tax		Tax rate applied to all sectors, set to increase progressively from USD 50/tCO_2 in 2021 to USD 400/tCO_2 in 2040. Kept at USD 400/tCO_2 from 2040 to 2050.	To keep tax revenue neutrality, carbon tax revenue will be used to pay for the costs incurred by the government, including energy efficiency investment, renewable subsidies, and the stranded costs of thermal power.
Power generation sector	Nuclear	Two sensitivities: ○1. OUTLOOK 2022 reference scenario ➡ Share of 2050 power generation: 13% ○2. Phase out by 2040 ➡ Share of 2040 power generation: zero	
	Coal-fired	○Phase out by 2040 ➡ Share of 2040 power generation: zero	
	Renewables	○Apply FIT scheme to wind and biomass generation from 2021–2035 ○Start-up subsidies for biomass+CCS ➡Subsidize 60% of the initial investment until 2030	FIT does not apply to solar
Transport sector	Passenger vehicle sales	○Restrictions on gasoline/diesel vehicle sales from 2035	Maintain hybrid car sales
	EV subsidies	○Maintain purchase subsidies until 2025 ➡ Subsidies of USD 8,000–13,000 per vehicle	
	Biofuel mandate	○Mandate share of biofuels to be used in cargo vehicles and aircraft ➡ Increase gradually from 5% in 2021 to 100% in 2050	
Steel sector		○Reduce blast furnace emissions to zero by 2050	
Building heating		○Phase out fossil fuel boilers by 2050 ○Energy efficiency investment	
Other industries		○Energy efficiency investment ○Assume manufacturing emissions intensity reduced by 4% per annum in the net zero scenario	

Note: In the power generation sector, solar power of 250 kW or more was changed from fixed tariff pricing to an auction system, starting in 2020. Biofuel is imported but biomass can be produced domestically in the model.
Source: Authors' own assumptions.

no new nuclear power plants are constructed after 2018, and plants are basically all shut down successively after operating for 40 years.[7] Therefore, as shown in Table 1, this study examines two policy package scenarios: one with nuclear power (scenario "NZ") and one without (scenario "NZ_noNC").

Apart from differences in nuclear power assumptions, both policy scenarios for achieving carbon neutrality by 2050 were set in the same way as follows (Table 1). First, a carbon tax rate is applied to all sectors and set to increase progressively from USD 50/tCO_2 in 2021 to USD 400/ton CO_2 in 2040 and then maintained at USD 400/tCO_2 from 2040 to 2050. In line with the principle of tax revenue neutrality, revenue generated under this carbon tax scenario will be used to cover the cost of low-carbon and carbon-neutral investments incurred by the government, subsidies and the stranded costs of thermal power plants that have been phased out.

At the sector level, starting with power generation, we created a scenario in which coal-fired power is phased out by 2040, based on the view that achieving carbon neutrality by 2050 would require an early phase-out. We assumed that from 2021, inefficient plants with a long operating history would be successively shuttered.[8] The carbon neutrality scenario included FIT schemes for wind and biomass from 2021–2035 but excluded solar and hydroelectric power generation. This is because the scheme for solar power was changed from FIT to auctions for projects of at least 250 kWh from 2020.

[7]Refer to Lee et al. (2020) for details of the scenario setting methodology.
[8]It is possible to create a regulation scenario for the power sector in the E3ME model's FTT:Power sub-model. Under the coal-fired power phase-out scenario, of the 151 plants operating in Japan, subcritical (sub-C) plants operating for more than 40 years would be closed in FY2025 and the supercritical (SC) would be closed by FY2027. By FY2030, utilization would be one-third of current levels. Regarding new coal-fired power plants (USC/IGCC) currently under construction, operation would be limited to a maximum of 15 years and phased out by 2040. For details on these scenario settings, see Lee et al. (2020).

For the transportation sector, in line with the Japanese government's December 2020 announcement that it would ban the sale of gasoline-powered cars in the mid-2030s, this study assumes that sales of passenger cars with only internal combustion engines cease from 2035.[9] Furthermore, for EVs, the study incorporates subsidies of USD 8,000–13,000 per vehicle depending on installed battery capacity at the time of purchase until 2025. The study also mandates the percentage of biofuels to be used in cargo vehicles and aircraft until 2050.

In the industrial sector, the policy scenario for the steel industry, which accounts for roughly 40% of industrial sector CO_2 emissions and 12.7% of energy-related CO_2 emissions for the overall economy,[10] include a carbon tax and regulatory measure in which CO_2 emissions from blast furnaces in the steel industry are phased out by 2050.[11] For other industrial sectors, a general carbon tax is applied alongside energy efficiency measures. Finally, in the building sector, the study used the FTT:Heat sub-model and assumes that boilers using fossil fuels will be phased out by 2050.

5. Impact on power mix and the economy of achieving carbon neutrality by 2050

5.1. Impact on CO_2 emissions pathway and power mix

As described above, this study uses the E3ME model to run simulations under two scenarios: Policy Scenario Net Zero (NZ) and Policy Scenario Net Zero with No Nuclear (NZ_NoNC). NZ adopts all of the policy measures listed in Table 1 and follows the baseline scenario for nuclear power from OUTLOOK 2022, whereas NZ_NoNC adopts all of the policy measures listed in Table 1 but assumes that nuclear power is phased out by 2040.

The results from the policy scenarios are then compared against the baseline. In the baseline scenario, CO_2 follows the path in IEEJ OUTLOOK 2022 with a 31.7% drop from 2018 to 2050 (Figure 1). Under Scenarios NZ and NZ_NoNC, CO_2 emissions fall to roughly 80 mtCO2 in 2050 (Figure 1). The 80 mtCO2 in 2050 is assumed to be offset by the amount absorbed in land use, land-use change, and forestry.[12]

Emission reductions by sectors are similar in both NZ and NZ_NoNC scenarios. Compared with the baseline scenario, emissions fall by 100% in the power and road transportation sectors, roughly 50% in the industrial sector, 60% in other transportation sector (excluding roads), and 85% in the household sector. The remaining 80 million tons of emissions is offset by absorption, bringing about overall carbon neutrality. The 80 million tons of emissions in 2050 represents a 92.4% reduction from 2018.

To achieve carbon neutrality, electrification of the transportation and household sectors are required. Thus, power consumption is projected to increase by about 4% by 2030 and 10–12% by 2050 compared with the baseline scenario. There are slight differences in power demand between NZ (nuclear accounts for 13% of power generation in 2050) and NZ_NoNC (no nuclear power generation in 2050), due to the impacts on electricity price under different power generation mix outcomes.

In Policy Scenario NZ, renewables account for 77% of the power supply in 2050, whereas LNG accounts for 3.8%, nuclear 10.5%, oil 4.1% as a backup source,[13] and other 4.7% (Figure 2, Table 2). Wind power (27.7%) and

[9]It is possible to stipulate the ban of sales of internal combustion engine vehicles in 2035, EV subsidies, and biofuel mandates in the E3ME FTT: Transport sub-model, which is being adapted to incorporate hydrogen fuel cell vehicles as a new technology. Future investigations will need to include new developments in hydrogen.

[10]In 2018, Japan's economy as a whole generated 1.244 billion tons of energy-related CO_2 emissions, including 396 million tons from the industrial sector and 158 million tons from the steel industry (Ministry of Environment, 2020). The E3ME model has only detailed technologies treatment for the steel sector: FTT:Steel among the industrial sector because of the difficulty in obtaining various technological data. Technological innovations in the industrial sector excluding steel are determined using a top-down methodology in the main E3ME model. In other industrial sectors such as cement and chemicals, CO_2 emissions tend to depend heavily on the characteristics of the raw materials used, and the benefits of using an FTT model that determines technologies in a bottom-up manner are still limited, so the use of an FTT model is a matter for future investigation.

[11]FTT:Steel incorporates 25 technologies that are determined in a bottom-up manner, including hydrogen reduction, direct reduction, and electric furnaces, and it is possible to specify scenarios including economic measures such as subsidies as well as adjust the speed of technological innovation, but for the sake of simplicity, the study adopted a direct regulation scenario for blast furnaces. The creation of various bottom-up scenarios for steel technology is a matter for future investigation.

[12]According to the Ministry of Environment (2020), land use, land-use change, and forestry accounted for 56 million tons of CO_2 absorption in 2018. This study assumes that improvements in afforestation technology result in 80 million tons of CO_2 absorption in 2050.

[13]In the FTT:Power sub-model, if renewable energy increases substantially, oil plays a role in adjusting for output fluctuations despite a loss of competitiveness.

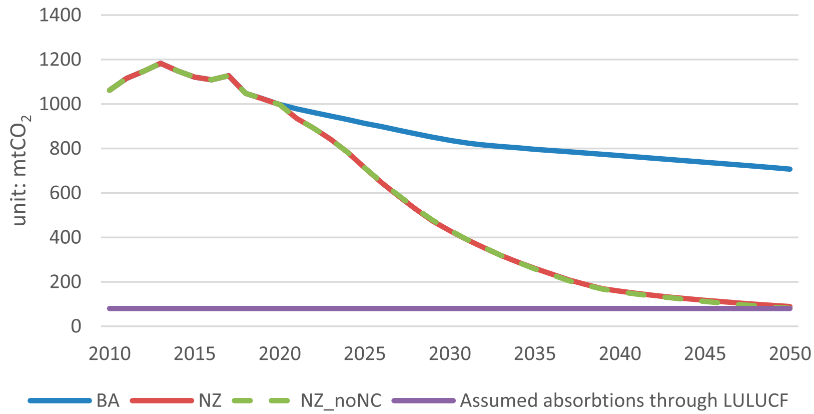

Figure 1. CO_2 emissions under carbon neutrality by 2050. Note: CO_2 emissions fall by a similar amount in Policy Scenarios NZ and NZ_NoNC. "BA" stands for the baseline scenario (carbon tax = 0), "NZ" denotes the Net Zero policy scenario assuming nuclear power in line with the reference scenario in the IEEJ OUTLOOK 2022, and "NZ_noNC" is the Net Zero with No Nuclear policy scenario where nuclear power is phased out by 2040. LULUCF stands for land use, land-use change, and forestry. Source: E3ME model estimates from this study

solar (25.4%) account for the bulk of renewable power sources in 2050. There are limits to the potential of geothermal and hydroelectric power, and it is difficult for them to grow more than in the baseline scenario. The share of Biomass + CCS is projected to grow to a share of 5.5% by 2050 as a result of start-up subsidies under the Policy Scenarios.

When nuclear is phased out in 2040, renewables shares increase to 89.1% of the power supply in Policy Scenario NZ_NoNC, whereas LNG accounts for 2.3%, nuclear 0%, oil 3.5%, and other 5.2% (Figure 2, Table 2). Among renewables, wind power accounts for 39.8% and solar 25.8%, a larger share than in NZ. In NZ_NoNC, wind power replaces virtually all of the portion related to the phase-out of nuclear, primarily by offshore wind power, which has high potential. Similar to NZ, there are limits to the potential of geothermal and hydroelectric power generation, and it is difficult for them to grow more than in the baseline scenario in NZ_NoNC. Biomass

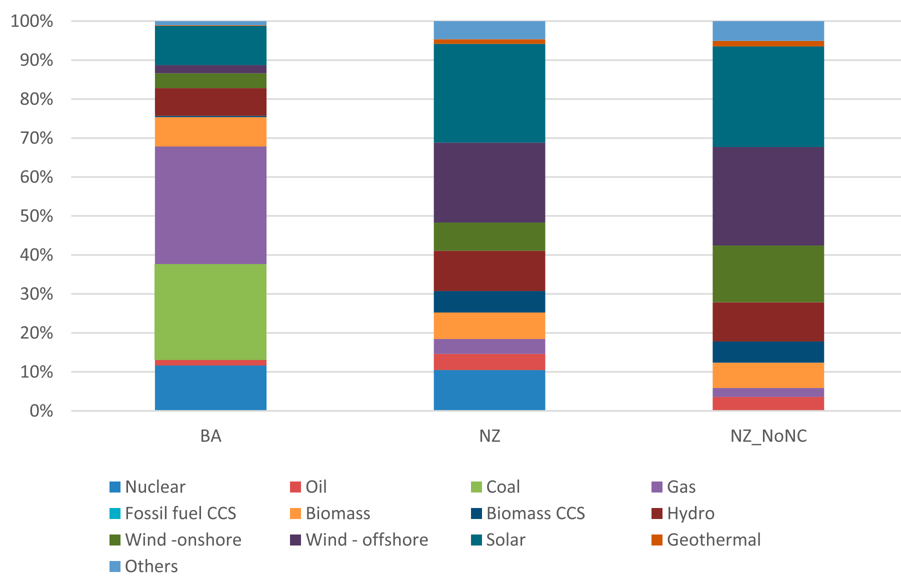

Figure 2. Change in 2050 power mix due to carbon neutrality in 2050. Source: E3ME model estimates from this study.

Table 2. Impact of Net Zero in 2050 on 2050 power mix (units: TWh, % in parenthesis).

Power type	2018	2050		
		BA	Policy Scenario NZ	Policy Scenario NZ_NoNC
Coal	339 (32)	262 (24)	–	–
Oil	52 (4.9)	–	55 (4.1)	47 (3.5)
LNG	378 (36)	288 (27)	51 (3.8)	30 (2.3)
Nuclear	65 (6.2)	141 (13)	140 (10.5)	–
Renewables	198 (18.8)	372 (34.4)	1029 (77.0)	1181 (89.1)
Hydro	81 (7.7)	94 (8.7)	138 (10.3)	133 (10.0)
Geothermal	2.5 (0.2)	13 (1.2)	16 (1.2)	19 (1.4)
Solar	63 (6.0)	123 (11)	339 (25.4)	342 (25.8)
Wind	7.5 (0.7)	64 (5.9)	371 (27.7)	528 (39.8)
Biomass	44 (4.2)	78 (7.2)	91 (6.8)	87 (6.6)
Biomass + CCS	–	–	74 (5.5)	72 (5.4)
Other	19 (1.8)	19 (1.8)	62 (4.7)	67 (5.2)
Total	1050 (100.0)	1082 (100.0)	1337 (100.0)	1325 (100.0)

Note: Figures in parentheses indicate the percentage share of the power mix.
Source: E3ME model estimates from this study.

+ CCS was zero under the baseline scenario but is projected to grow to a share of 5.4% by 2050 as a result of start-up subsidies, which is nearly the same as in NZ.

5.2. Economic impact

Both Policy Scenarios NZ and NZ_NoNC are projected to boost Japan's GDP compared with the baseline scenario. GDP increases by nearly 3% compared with the baseline scenario until around 2030, and about 4%–4.5% by 2050 (Figure 3). The fluctuations in GDP impacts in the period to 2040 reflect additional renewable capacity investment in the power sector which corresponds to phase out assumptions. The impact on GDP from 2030 to 2050 is slightly higher (0.1–0.2 percentage points) for NZ_NoNC than NZ. This suggests that the cost of renewables as an alternative to nuclear power will fall sufficiently and the benefits of investing in areas such as renewables to replace nuclear power will produce better economic outcomes.

The positive impacts on GDP from achieving carbon neutrality by 2050 include increased decarbonization investment in various sectors of the economy (a roughly 8% increase versus baseline), and higher employment and stimulus to consumption by the associated growth in wages (a roughly 4% increase versus baseline), which

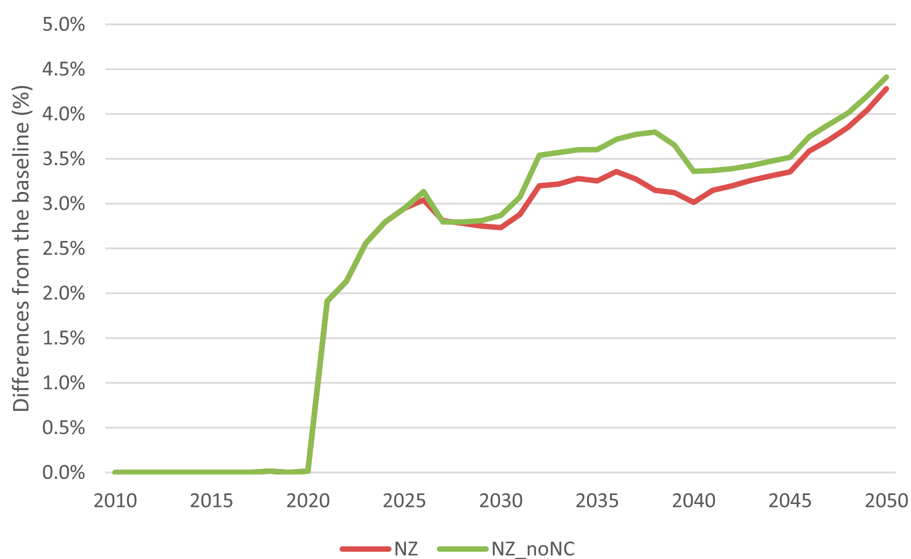

Figure 3. Impact on GDP from carbon neutrality in 2050. Source: E3ME model estimates from this study.

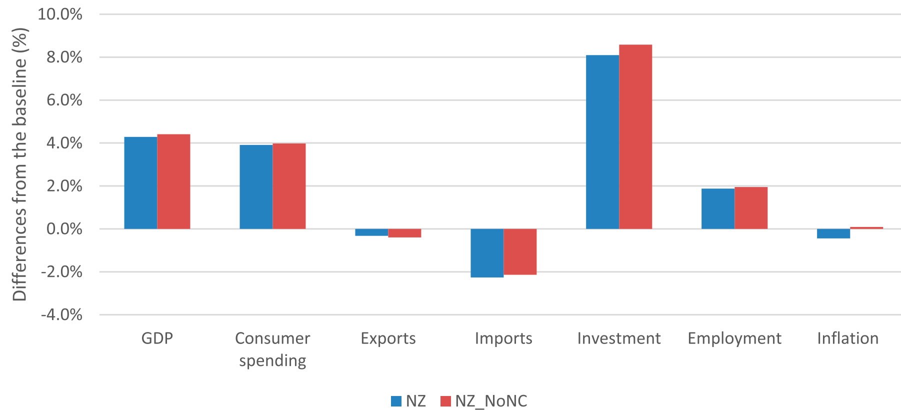

Figure 4. Impact of achieving carbon neutrality in 2050 on the macroeconomy. Source: E3ME model estimates from this study.

would outweigh higher energy costs. Furthermore, energy saving measures lead to reductions in energy bills for many users. The reduction in fossil fuel consumption also reduced demand for imported fossil fuels and improves the trade balance, resulting in higher GDP (Figure 4).[14]

The positive GDP impacts in Japan from E3ME simulations are notably higher than the GDP impacts in the EU from E3ME reported in the EU 2050 carbon neutrality study by the European Commission (2018), despite the fact that both EU and Japan are net energy importers. The differences can partly be explained by different methodologies as E3ME was used to analyze economic impacts for a given energy pathway rather than analysing climate policy simulations as in this study. However, it also reflects that the low carbon transition is already happening in the EU under the business-as-usual scenario. In contrast, Japan's business-as-usual is still reliant on fossil fuels and therefore has more to do; more effective investment is needed to achieve carbon neutrality.

The approximately 8% increase in investment breaks down roughly into 30% for renewable power generation in the electricity sector, about 50% to reduce carbon emissions in the industrial sector, and 20% for decarbonization in the transportation and other sectors. Policies aimed at achieving carbon neutrality increase electricity costs versus the baseline by roughly 11% by 2030 and 45% by 2050 in NZ and roughly 12% by 2030 and 55% by 2050 in NZ_NoNC, but investment in carbon reduction, energy savings, and renewable energies would stimulate the economy to a greater extent on the demand side, and fossil fuel energy demand would decline to nearly zero, so the overall burden of energy expenses on the economy would be lower compared with the baseline scenario.[15] Furthermore, as shown in Figure 4, employment would increase by 1.5% compared with the baseline scenario in 2030 and about 2% by 2050 due to increased investment and higher GDP.

The increase in employment in the Policy Scenarios mainly occurred in the renewables and construction sectors which benefit from low carbon investment. There are also increases in consumer-related employment as households spend additional money saved from lower energy bills. Although Japan is an aging society, higher economic activities and wage levels would lead to increased labour participation among different age and gender groups, resulting in increased availability in the labour supply.

6. Conclusions and future issues

This study uses a simulation based analysis to estimate the macroeconomic impacts of Japan's implementation of its carbon neutrality target (Net Zero) in 2050. Given the special nature of nuclear power and its role in the

[14]For example, Japan imported JPY 19.3 trillion worth of fossil fuels such as oil, LNG, and coal (roughly 20% of imports) in 2018 according to the Agency for Natural Resources and Energy (Ministry of Economy, Trade and Industry 2020c). A sharp decrease in imports would contribute to a substantially improved trade balance. It should be noted that hydrogen is assumed to be produced domestically. Even if Japan plans to import hydrogen, it will not offset the huge reduction in fossil fuel imports.

[15]For example, despite higher electricity costs, there is a decline of 41% in household sector energy expenses compared with the baseline scenario by 2050 due to the lower demand for gas and oil.

power sector, we created two policy scenarios: one in which nuclear power continues to be used (Policy Scenario NZ), and one in which it is phased out by 2040 (Policy Scenario NZ_NoNC). The results suggest that under both scenarios, it would be possible to achieve carbon neutrality and a growing economy by 2050.

The main reasons for positive economic outcomes are increased investment in the power sector in renewable energy generation capacity and increased investment across other economic sectors in decarbonization technologies. Additional investment demand and energy saving measures lead to higher employment and increased private consumption. Furthermore, there is an improvement in Japan's trade balance due to a substantial reduction in fossil fuel imports. Although the costs of energy due to policies to reduce or eliminate carbon would rise by 45%–55% compared to the baseline scenario in 2050, this would not create additional burden to the economy, considering the substantial reduction in fossil fuel energy demand. Overall, it is estimated that energy bills would be 45% lower for consumers and 11% lower for industry in 2050 compared to the baseline.

This study also highlights several issues that require further investigation and refinement. The first is improving FTT sub-models to better reflect emerging decarbonization technologies. Here it is extremely important that the model properly reflect the speed of innovation across a variety of decarbonization technologies. The FTT sub-models used this research set the speed of such technological innovations according to learning curves based on the pace of past technology diffusions. However, the speed of other relevant decarbonization technologies, which are still in their infancy stage today (e.g. hydrogen in steel production, fuel cell vehicles and electro fuel[16]) also need to be properly reflected in FTT sub-models. Adjusting the learning curves of these technologies to accurately reflect the impact of technological innovation is a topic for future investigation.[17]

The second issue is that electricity costs in 2050 are roughly 45∼55% point higher than the baseline under NZ_NoNC (no nuclear power) than under the NZ (with nuclear power) Policy Scenario. This is because under the FTT:Power sub-model, the simulated cost of nuclear power was lower than other energy sources. The main reason is that the existing FTT:Power sub-model does not reflect initial construction costs under strengthened safety regulations in the wake of the Fukushima Daiichi nuclear power plant accident, nor does it reflect the cost of additional safety regulations. Revising the nuclear power generating cost data in the FTT:Power sub-model and reflecting the cost of safety regulations would be a matter for future investigation.

Finally, the setup of the E3ME model in this study assumes that Japan will achieve carbon neutrality by 2050 and that other countries will continue their current policies. If other countries were also to become carbon neutral, then Japan's competitive structure, especially vis-à-vis international markets, and the impact on the economy would change. For example, there will be technology spillovers, where costs of renewables and low carbon technologies fall faster when all countries act simultaneously. However, if other countries also simultaneously take climate action then this could lead to shortages in materials needed for low carbon equipment, increasing the price of raw materials and hence low carbon technologies. This will be a factor that could limit GDP growth. Research into the impact on Japan's economy when other countries (especially the EU and US, followed by China, South Korea, and Taiwan) enact carbon neutral policies is another area for future investigation.

The modelling methodology and results in this study provide an insightful analysis for policy makers facing different policy choices to achieve carbon neutrality. In contrast, existing tools often aimed at cost minimization of the energy system can be subject to huge uncertainties. The simulation based approach of E3ME takes into account technological path dependency and learning-by-doing. It can be used to analyze socioeconomic impacts from different policy combinations. The methodology used in this study can easily be applied to other countries and regions. Importantly, the E3ME model highlights the costs of a low carbon transition but at the same time demonstrates new economic opportunities from the transition through additional investments, reduction in energy bills and reduction in a country's energy import dependencies.

[16]Electro fuels or e-fuels (synthetic fuels) are an emerging class of drop-in replacement fuels that are made by storing energy from renewable sources in the chemical bonds of liquid or gas fuels. In contrast to conventional fuels, they do not release additional CO_2 but are climate-neutral.

[17]For example, rather than learning curves based on history to date, new learning curves based on the latest data obtained through company interviews could be used in the FTT sub-models.

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