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# JMIP 2 Part 1: Technology uncertainty and robustness in Japan's net-zero pathways

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A R T I C L E I N F O

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A B S T R A C T

Japan's commitment to reach net-zero 2050 hinges on innovation in emerging, uncertain technologies. Yet, no study has systematically examined uncertainties in technology development for Japan's net-zero goal in a multi-model framework. Here, we close this research gap by presenting the results of the Japan Model Intercomparison Project (JMIP) 2. Across models and technology scenarios with wide spreads in costs of emerging technologies, we consistently identify the following robust strategies for net zero: (1) reducing unabated fossil fuels, (2) improving economy-wide energy efficiency, (3) decarbonizing the power sector, and (4) deploying carbon dioxide removal. We also find that although the expansion of variable renewable energy and end-use electrification is robust, the precise level in 2050 remains uncertain. Using technology sensitivity scenarios, we show that the marginal cost of abatement (or carbon price) is significantly affected by the availability of carbon removal. Affordability of hydrogen and ammonia imports significantly affects primary energy supply in some models, underscoring a policy architecture that can flexibly adapt as the techno-economic landscape evolves.

## 1. Background: net-zero goal under technological uncertainties

In December 2023, at the 28th Conference of the Parties (COP) in Dubai, United Arab Emirates, the Parties to the 2015 Paris Agreement concluded their first round of the global stocktake, an exercise to assess the collective progress of efforts towards the goal of the Paris Agreement every five years. Each member state is expected to update its own nationally determined contribution (NDC). The NDC framework is a key feature of the Paris Agreement, which leaves member states to define the goal and structure of mitigation policies. As countries have different resource endowments, capabilities, and economic structures, each country's policy should be carefully assessed in the context of its unique situation and conditions. Another new trend in the COP 28 decision was the focus on sectoral mitigation approaches. The adopted document notes the aspirational goals of tripling the global renewable energy capacity and doubling energy efficiency improvements by 2030, as well as other technologies such as nuclear power, carbon capture, utilization and storage, and hydrogen [89].

Japan was the fifth largest emitter of carbon dioxide ($CO_2$) in 2021 [22]. It is heavily dependent on imported energy and resources, but has a strong manufacturing sector. Various policies related to climate change mitigation have been strengthened, after committing to the 2050 target of net-zero greenhouse gas (GHG) emissions in 2020 [78]. Before the 2021 Leaders Summit on Climate hosted by President Biden of the

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United States, Japan ratcheted up its 2030 target from 26 % emissions reduction to 46 % reduction, while pursuing efforts towards "the lofty goal of cutting its emission by 50 %" [30].

Japan's climate policy emphasizes innovation, particularly with emerging, uncertain technologies. In 2021, as part of the 3rd supplementary budget, the government launched a Green Innovation Fund of approximately 2 trillion yen within the New Energy and Industrial Technology Development Organization (NEDO). The Green Innovation Fund is intended to support technology development for up to 10 years in 14 priority fields, including offshore wind, hydrogen and ammonia, nuclear power, carbon recycling, and batteries. Recently, Japan adopted the Green Transformation (GX) policy package, which aims to mobilize 150 trillion yen through public-private partnerships for investment over the next decade. Within this 150 trillion yen, the 20 trillion yen will come from the government, financed by transition government bonds, and an additional 130 trillion yen will be mobilized from the private sector. These public-private partnership investments cover a wide range of technology areas, including advanced renewable energy, clean vehicles, hydrogen, carbon dioxide removal (CDR).

Technology is a key pillar of climate change mitigation both in Japan and worldwide. Recent advances in solar photovoltaics (PV), wind power, and electric vehicles attest to this [36]. For example, the unit cost of solar PV decreased by 85 % between 2010 and 2019. However, technological development remains highly uncertain, and it has been difficult to adequately reflect these uncertainties in policy analysis. Many scenarios have underestimated solar PV innovation [20,40,76] and its role in mitigating climate change. Therefore, it is important to explore mitigation opportunities and barriers while considering a wide range of technological uncertainties.

However, few studies have comprehensively analyzed mitigation challenges [13] and examined such technological uncertainties in a country-specific context such as Japan, using a multi-model framework. This study aims to fill research gaps on granular mitigation pathways by conducting a multi-model analysis that addresses technology uncertainties for Japan. In particular, we explore uncertainties in key technological areas in Japan's GX policy: renewable energy, CDR, and clean energy imports (e.g.,. hydrogen and ammonia), and electrification. By doing so, we identify robust strategies for Japan's net-zero goal.[1]

This paper provides an overview of the Japan Model Intercomparison Project (JMIP) 2 Net Zero. It builds on the previous projects: JMIP 0 [80] and Stanford Energy Modeling Forum (EMF) 35 JMIP 1 [82,83]. Inspired by the long tradition of the Stanford EMF, JMIP was established to provide a platform where modelers, policymakers, and stakeholders can discuss modeling issues related to energy, economics, and the environment. The goal is to share lessons learned from model intercomparisons and to identify further research priorities. This is Part 1 of the JMIP 2 study, and further results on the supply and demand details are provided in companion papers (Frazer et al., submitted; Cao et al., submitted) .[2]

This study provides policy evidence for the ongoing debate on climate change mitigation policies in Japan. The results are also applicable to other regions, such as South Korea and Taiwan, which share similar characteristics, including high population density, a large manufacturing presence, and a (relative) lack of energy connectivity through power grid networks and pipelines.

The remainder of this paper is organized as follows. Section 2 reviews Japan's climate policy and its modeling analysis. Section 3 outlines the participating models and scenario design. Section 4 presents the results and describes the robust strategies and uncertainties. Section 5 concludes the paper with a discussion and policy implications.

## 2. Review of Japan's climate policy and quantitative scenario analysis

### 2.1. Policy review: innovation as a climate policy

To provide a background, we first briefly review the official policies of Japan as well as the literature on Japan's climate policy.

Since the adoption of the Kyoto Protocol in 1997, Japan has gradually strengthened its climate policy, and now aims to reduce its GHG emissions to net zero by mid-century, in line with many developed economies. Its target for 2030 is to achieve a 46 % reduction in emissions. Prior to the Paris Agreement, Japan's climate policy emphasized energy efficiency through Top Runner Programs, building codes, and labeling, as well as voluntary actions by industry [82] (and references therein). Following the commitment to net-zero emissions, the government placed innovation at the forefront of climate change mitigation [56]. By promoting green innovation, Japan is attempting to pursue environmental protection and economic growth simultaneously. This is in line with the policies of the United States (e.g., the Inflation Reduction Act) and the European Union (e.g., the Green Deal Industrial Plan).

In recent years, Japan has implemented numerous policies to achieve these goals, with some tangible results in recent years. Japan's GHG emissions peaked in 2013 at 1.4 $GtCO_2$-eq/yr (Fig. 1). Subsequently, GHG emissions have declined at approximately the pace required to meet the NDC by 2030. The government has noted that the progress is "on-track" [61], although the sufficiency of the progress is disputed [45].

Japan's emissions are dominated by $CO_2$, particularly those related to energy, which accounts for about 85 % of the emissions. Although the 2011 Great East Japan Earthquake and the associated tsunami temporarily shut down all of Japan's nuclear power fleets owing to safety concerns, and only a small fraction of the nuclear fleets have returned online, Japan has managed to sustainably reduce emissions to date (Fig. 1).

The main policy framework for climate change is the Act on Promotion of Global Warming Countermeasures and, given the centrality of energy, the Basic Act on Energy Policy. The Basic Act stipulates that the government formulate a Strategic Energy Plan every three years, which serves as a basis for energy and climate policies. In February 2025, Japan promulgated its 7th Strategic Energy Plan along with a new NDC. The emissions reduction targets are 46 %, 60 %, 73 %, and 100 % (net zero) by FY2030, FY2035, FY2040, and 2050, respectively, relative to the FY 2013 levels [39]. Here, FY stands for fiscal year.

Numerous sectoral policies have been introduced, including the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities, which introduced feed-in tariff (and later feed-in premium) schemes and auctions for renewable energy. The GX policy package is a new addition that includes the GX Promotion Act, GX Decarbonization Electricity Act, and GX Promotion Strategy [55].

Japan's GX policy is a green industrial policy emphasizing innovation. The 20 trillion yen of government spending will be supported by the issuance of government bonds called the Japan Climate Transition Bonds and not by concurrent carbon pricing [15]. This creates a gap between the timing of investment support policy and carbon pricing. The government has started to direct its 20 trillion yen investment; however, carbon pricing will occur later.

Explicit carbon pricing will be gradually phased in. The plan includes an emissions trading system starting in 2026, introducing tariffs on fossil

[1] While this study provides a comprehensive analysis of the differences among the participating models, we do not attempt to identify the causes of these differences, in line with the approach taken by many previous studies, including recent ones [23,74]. Although understanding the causes of these differences is very important, such endeavors have remained challenging due to the high degree of model heterogeneity and the vast number of parameters in each model. Note that some scholars have made efforts to examine the differences systematically [32,48], and this remains an important and active area of research.

[2] An earlier result with a focus on CDR has been published elsewhere [81].

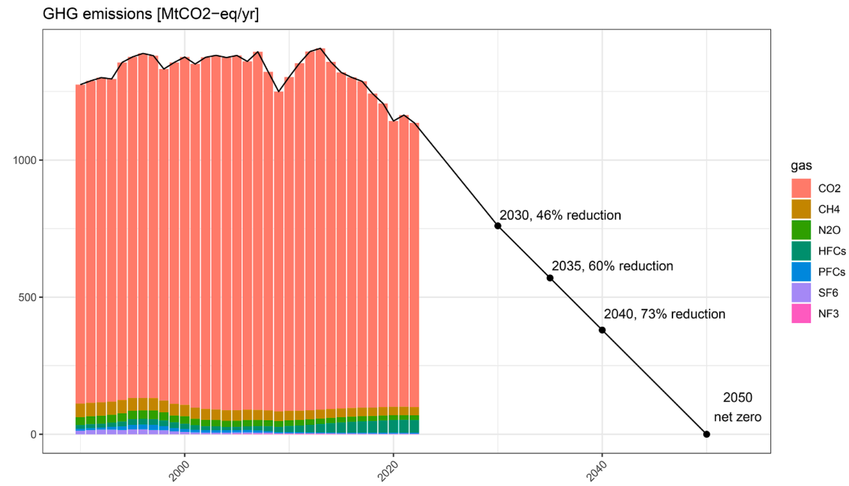


**Fig. 1.** Japan's GHG emissions based on the National Greenhouse Gas Inventory [62] and emission reduction targets for 2030, 2035, 2040, and 2050.

fuel imports in 2028, and implementing an emissions trading auction system for power generators by 2033 [1,55]. The details of this process are currently under discussion. Although Japan has numerous fossil fuel-related taxes (e.g., taxes on gasoline), the current carbon pricing is weak. For example, the explicit carbon tax, the global warming countermeasure tax, is at 289 yen/t$CO_2$ [59]. The compliance emissions trading market has been limited to Tokyo [9].

Hydrogen is particularly noteworthy among the various technological options considered in Japan's GX policy. In 2017, Japan developed the world's first national strategy for hydrogen [57]. It was revised in 2023 [58], and Japan is now considering both domestic production and foreign imports of hydrogen and related carriers such as ammonia. In addition, the expected uses include not only industry and heavy-duty transportation, but also power generation, which is not emphasized in other countries [63]. This can be achieved by co-firing ammonia in existing coal-fired power plants. The emphasis on hydrogen and related carriers has spawned considerable policy debates too [46,75,87].

Carbon capture and storage (CCS) are other areas of interest. Japan has recently passed the Act on Carbon Dioxide Storage Businesses. However it is unclear whether Japan can secure sufficient and socially acceptable storage capacity. Japan is now promoting the Asia Carbon Capture, Utilization, and Storage Network in conjunction with the Asia Zero Emission Community (AZEC), and is considering trading $CO_2$ captured from power generation and industry to Asian countries.

It is instructive to review the actual and planned power generation mix, as it can reveal the progress and setbacks of climate and energy

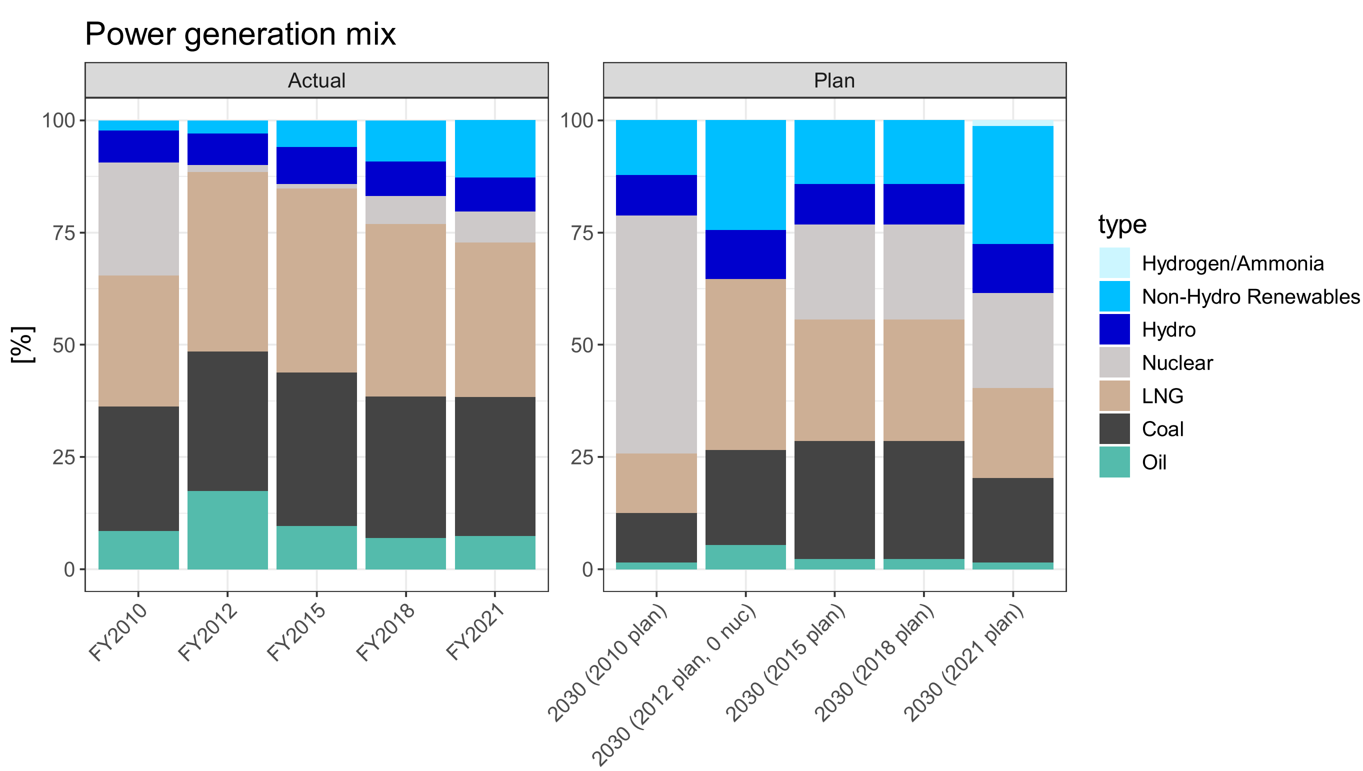


**Fig. 2.** Historical and target power generation mix for 2030. The actual data are taken from [7]. The long-term scenarios are shown based mainly on the Long-term Energy Supply and Demand Outlooks [4–6,26,54]. The 2010 plan did not show the breakdown between hydropower and non-hydro renewables, and we assumed a 9 % share for hydropower, based on the historical trend and other plans. For the 2012 plan, the government presented three scenarios, but we only present the zero nuclear case here, which received the highest share for the "strongly support" response in a 2012 deliberative polling® [14].

policies (Fig. 2). Before the Fukushima nuclear accident in 2011, the expected share of nuclear power in the power mix by 2030 was >50 %, which dropped to zero immediately after the accident. In the 2015 plan and beyond, the share of nuclear power rebounded. Meanwhile, renewables continued to expand, supported by feed-in tariff schemes, auctions, and other policies. The latest plan for 2030 shows a 36–38 % share of renewables in 2030. Another notable point is the expected 1 % of electricity generation from hydrogen/ammonia. Although small, this inclusion indicates the government's intent.

Fig. 2 also shows the past power mix. The continued expansion of non-hydro renewables is evident, with solar PV accounting for the largest share of renewables. Although the pace of expansion is slower than that in other countries of similar size, such as Germany and the United Kingdom [35], it still represents progress in clean energy in Japan.

### 2.2. Review of model-based scenario analysis

Starting with few regions [17,66,70], research on net-zero scenarios has made significant advances in identifying the essential elements of net-zero energy and sociotechnical systems. However, much remains to be explored, particularly regarding the specific contexts of individual countries and regions. This is because they have different situations in terms of resource endowments, costs, public acceptance, and historical developments [11], necessitating region-specific analyses. For example, a recent large-scale study of net-zero scenarios for the United States and Europe, based on the US Energy Modeling Forum 37 and European Climate and Energy Modeling Forum, found different net-zero paths between these two regions. Industry in the United States and transportation in Europe are the most challenging sectors for electrification [74].

In Japan, studies have examined net-zero scenarios based on various models, some with global and national coverage in the regions, as reviewed by [64] and [81]. Earlier studies include [44,66,82].

Recently, [64] combined a national energy systems model, AIM-Technology-Japan, with scenarios from a global version of the AIM-Technology model, to analyze the implications of international trade in hydrogen, synthetic fuels, and carbon removal credits for the net-zero goal. They found that a CDR deployment of ~ 100 $MtCO_2$/yr, roughly corresponding to 10 % of the current emissions, is essential and robust across scenarios, and that imports of hydrogen-based fuels and CDR credits are effective mitigation options.

This finding was corroborated by a multi-model analysis of residual emissions and CDR deployment [81], which used four energy-economic and integrated assessment models to analyze the path to net-zero $CO_2$ emissions in Japan. They found that, while about 90 % of the current emissions are reduced through abatement, the inter-model median of CDR deployment reaches ~ 130 $MtCO_2$/yr by 2050. This study also confirmed the high sensitivity of marginal costs to CDR constraints.

[69] employed an energy systems model with a high time resolution and conducted a comprehensive sensitivity analysis on the availability of CCS to achieve net-zero emissions. They found that CCS is critical for containing mitigation costs, consistent with the findings of the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). They also confirmed that CCS provides substantial value even at a high cost.

Outside the peer-reviewed academic literature, many scenarios have been published, particularly regarding the role of variable renewable energy (VRE) [71] published a 100 % renewable scenario for decarbonization in 2021. The model used is identical to that used in many academic papers by Christin Breyer and his colleagues on 100 % renewable energy systems [12]. Since 2011, WWF Japan has published a series of high renewable penetration scenarios, with the most recent iteration published in 2024 [88]. This line of research emphasizes the role of renewables and energy efficiency, and argues against nuclear power.

These studies have established common strategies for achieving the net-zero goal, which is broadly consistent with the findings of the IPCC energy chapter [19], as 85 % of Japan's emissions originate from energy-related $CO_2$.

(1) Economy-wide improvements in energy efficiency (e.g., measured by the energy intensity of economic output, such as gross domestic product (GDP)).
(2) Decarbonization of the power sector combined with renewable energy expansion.
(3) End-use electrification.
(4) Substantial reduction in fossil fuels and increased use of clean fuels such as hydrogen, bioenergy, and ammonia in non-electrified sectors.
(5) Carbon dioxide CDR to offset residual emissions from harder-to-abate sectors.

These findings are noteworthy given Japan's unique characteristics such as its relatively low renewable potential [51] (due to its high population density) and the large presence of heavy industries [42,82].

Although broad outlines have been identified, several issues remain unaddressed. In particular, technology uncertainty is of paramount importance given Japan's focus on innovation efforts. For example, what is the potential impact of the progress or lack thereof in hydrogen technology on the net-zero goal? How does this technology compete with other types of technologies?

Another key consideration is the interaction between these uncertainties and model uncertainties. As is well established in the literature, the choice of model leads to different results [23,47,82] and it is critical to adopt a multi-model perspective.

## 3. Method

### 3.1. Participating models

This study employs a multi-model framework to analyze robust mitigation pathways and technology uncertainties for Japan's net-zero goal. In this study, we use five participating models (Table 1) (we also include a limited set of results from another leading model, [3] DNE21+, as shown in the Supplementary Information). Four of these are partial equilibrium models. Not all models submitted all the scenarios, and we present their results as appropriate.

The steering committee (MS, HS, SF, and KW) reached out to numerous modeling teams active in Japan.[3] However, due to resource constraints, only five models could participate. These five models represent a diverse and experienced group, with their modeling frameworks extensively published in the peer-reviewed literature (see Appendix 10.1 for model descriptions).

### 3.2. Scenario design

Our general scenario notation takes the form, XX_yy, where XX implies a policy goal and yy describes a technology assumption. There are four policy goals for XX, and six technology assumptions for yy, resulting in twenty combinations.

#### 3.2.1. Harmonized assumptions

Future service demand is a strong determinant of the challenges and costs of the energy transition [31,65,82]. Population and GDP are two important factors that determine service demand. As in our previous work, we harmonize the population and economic growth rates (not absolute GDP). The population is based on [37] and the GDP is based on

[3] Appendix 2 of a project report [84] provides a meta-analysis of existing model-based scenarios.

**Table 1**
Models used in this study.

| Model (short name for visualization purposes) | Solution concept | Region | Temporal treatment | Non-AFOLU CDR options | Storage location | Secondary energy trade (with outside Japan) | Version | Institute | Reference |
|---|---|---|---|---|---|---|---|---|---|
| AIM-Hub-Japan (AIM-Hub) | General equilibrium | Japan as one region | Recursive dynamic | BECCS, DACCS | Domestic | Biofuel | 2.4 | Kyoto U / Ritsumeikan U / NIES | [27] |
| AIM-Technology-Japan (AIM-Tech) | Partial equilibrium | 10 regions | Recursive dynamic | BECCS, DACCS | Domestic | Hydrogen, ammonia, synthetic liquid fuels, e-methane | 2.1 | Hokkaido U | [65] |
| d-TIMES | Partial equilibrium | 351 nodes and 47 preferectures | Intertemporal | DACCS | Domestic | Hydrogen | 3.1 | Deloitte | [60] |
| IEEJ-NE_Japan (IEEJ-NE) | Partial equilibrium | 5 regions | Intertemporal | BECCS, DACCS | Domestic and overseas (export) | Hydrogen and ammonia | 2023 | Yokohama National U / Ritsumeikan Asia Pacific U / IEEJ | [67,68] |
| TIMES-Japan (TIMES-J) | Partial equilibrium | Japan as one region | Intertemporal | BECCS, DACCS | Domestic | Hydrogen, ammonia, carbon-neutral synthetic natural gas | 3.4 | IAE | Kato & Kurosawa [44] |

the Shared Socioeconomic Pathway (SSP) 2 [24].

### 3.2.2. Policy dimension

Owing to the gas coverage of the participating models, our emission ceilings are expressed in terms of $CO_2$ emissions. Land Use, Land-Use Change and Forestry (LULUCF), international aviation and shipping are excluded from the study. Because Japan's non-$CO_2$ emissions are approximately 10 % of the current levels, we vary the stringency of the policy from 100 % emissions reduction to 110 % emissions reduction (relative to the 2013 levels, in line with government policy). Table 2 describes the policy dimensions of the scenario design. Emissions constraints are implemented as caps on emissions in models, and because of duality of prices and quantities, they can be interpreted as a carbon tax or an emissions trading.

Since some models cover only $CO_2$, it is essential to convert the government's net-zero GHG emission target to $CO_2$ emissions. Figure A 1 shows the net emissions of Kyoto GHG for the selected scenarios. Net-zero GHG emissions are found between 100 % and 105 % $CO_2$ emission reduction for AIM-Technology and between 105 % and 110 % $CO_2$ reduction for AIM-Hub. Obviously, the actual net-zero GHG emissions would depend on the modeling assumptions and cannot be unambiguously determined. For simplicity, we use the 105BY50_yy scenarios, which are roughly equivalent to net-zero GHG emissions. This choice of the 105BY50_yy scenarios as the focus of the analysis differs from that of our recent paper [81].

**Table 2**
Policy dimensions of the scenario design. yy represents the technology scenario assumption, which will be described below. We also use two alternative scenario labels: Baseline and Net Zero (eq) for BASELINE_deftech and 105BY50_deftech, respectively.

| Scenario | Description |
|---|---|
| BASELINE_yy | Baseline, without strong climate policy (i.e., carbon pricing). |
| 100BY50_yy | 46 % emissions reduction by 2030 and 100 % $CO_2$ emissions reduction by 2050, with equal carbon prices across different GHGs in models with multiple gases. The base year for the reduction is 2013. The emission cap between 2030 and 2050 follows a piecewise linear function. |
| 105BY50_yy or Net Zero (eq) | Similar to 100BY50_yy but with a 105 % reduction in emissions by 2050. |
| 110BY50_yy | Similar to 100BY50_yy but with a 110 % reduction in emissions by 2050. |

### 3.2.3. Technology dimension

Our scenario design analyzes several dimensions relevant to ongoing research and innovation efforts. Specifically, they focus on renewable energy, CDR, and clean energy imports (e.g., hydrogen and ammonia). This choice of technological area is relevant to ongoing policy discussions [8] (Table 3).

VRE is expected to become a "main power source" (*shuryoku dengen*) and constitutes a key pillar of emissions reduction. Since the introduction of a full-fledged feed-in tariff scheme in 2012, various policies have been implemented, including policies to support deployment (e.g., feed-in premiums and auctions), grid expansion and flexibility markets, and zoning for renewables. However, Japan is facing unique challenges.

**Table 3**
Technology dimension of the scenario design. XX represents the policy scenario assumption (Table 2).

| Scenario | Description |
|---|---|
| XX_deftech | Default technology assumption, except that the maximum deployment of CDR[1] is limited to 100 $MtCO_2$/yr throughout. The CDR constraints here are limited to those directly related to $CO_2$ from energy and industrial processes and DACCS (e.g., BECCS, DACCS, utilization) that are targeted for emission reductions. Afforestation/reforestation is excluded from the CDR constraint. |
| XX_re | The costs (both capital and O&M) of solar and wind power are halved by 2050 compared to the default technology assumptions in each model, introduced on a linear schedule between 2030 and 2050. Otherwise, the technology assumptions are identical to XX_deftech, compared to the default. |
| XX_import | The costs of carbon-free energy imports (hydrogen ($H_2$), (clean) ammonia, e-fuel, carbon-neutral LNG, etc.), excluding bioenergy, halved by 2050, introduced by a linear schedule. Fossil fuel prices should remain unchanged. |
| XX_cdr | Same as XX_deftech, except that the maximum CDR deployment is set to the modeler's choice and is allowed to exceed 100 $MtCO_2$/yr constraint as used in the deftech scenario. |
| XX_eletech | The costs of end-use electrification technologies[2] (heat pumps for heating/cooling/water heating and electric vehicles (battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)) are halved by 2050, phased in on a linear schedule, compared to the deftech scenario. |
| XX_innov | Best innovation technology case, i.e., all the innovations described above are introduced together. |

[1] We followed the definition of CDR from IPCC (https://apps.ipcc.ch/glossary/): "[a]nthropogenic activities removing carbon dioxide ($CO_2$) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products."

[2] This cost reduction is applied to the industrial electrification technologies, including heat pumps.

Compared to other countries, renewable energy in Japan is expensive, despite continued efforts [85]. For instance, the International Renewable Energy Agency (IRENA) reports that Japan has the highest installation cost of utility-scale solar PV among the countries surveyed [38] (before considering unique geographic conditions such as capacity factor). As expensive renewables hinder the decarbonization of electricity and the use of green (or renewable-based) hydrogen, they could even lead to the relocation of (some parts of) the industrial value chain [73]. These models do not assume a sudden decrease in the cost of renewable technologies in the default setting (Figure A 3), and it is crucial to explore the possibility of accelerating cost reductions in Japan.

Hydrogen can be imported along with other fuels such as ammonia. Compared with other countries, Japan places a high priority on hydrogen [63]. However, there is considerable uncertainty in the cost of hydrogen owing to uncertainties in the costs of renewable energy, electrolyzers, and transportation. Many countries, including Japan, have ambitious hybrodgen cost targets. The United States' Hydrogen Shot aims to achieve $1 per 1 kg in 1 decade ("1 1 1″) [25]. Japan has set a goal of achieving 20 JPY/ ($Nm^3$) or approximately 2.22 USD/kg by 2050; however, there is no technological guarantee that this will be achieved. Studies diverge regarding the role of hydrogen, and its sources. For instance, for the analysis of power-sector decarbonization, [52,53] showed the importance of hydrogen imports, but [75] revealed that their modeling framework prioritized domestic hydrogen production. It is therefore important to investigate these uncertainties (Figure A 4). There is a substantial import of bioenergy from countries such as Vietnam and the United States into Japan, and a large drop in the cost of bioenergy is not currently mentioned in the energy policy debate. Therefore, we do not assume a rapid cost reduction in bioenergy in the import scenario.

The available amount of CDR is highly uncertain owing to technological, economic, social, and political considerations [81]. Focusing on CCS-related CDR, the government has identified a geophysical storage capacity of 16 $GtCO_2$ at 11 sites [18] with an estimated annual storage of 0.12–0.24 $GtCO_2$/yr. The storage size can also be compared to the current emissions (~ 1$GtCO_2$/yr) or the expected CDR (~0.1$GtCO_2$/yr). However, there is still no serious debate on where to store $CO_2$ due to potential societal acceptance issues, mostly because the majority of the public is unaware of CCS or CDR [10,72]. In addition, the long lead time associated with this type of large-scale infrastructure introduces another source of uncertainty.

On the demand side, end-use electrification (combined with clean electricity) can accelerate mitigation [50,79,93]. However, Japan is lagging in terms of vehicle electrification [34]. Besides, Japan's introduction of heat pumps is moderate but not as fast as that in Europe [33]. Part of the reason is the costs of end-use electrification technologies, and it would be instructive to examine the implications of lower costs of such technologies.

Based on these considerations, our technology scenarios are as follows. Note that the deftech scenario imposes a constraint on CDR, which ensures that all technology sensitivity scenarios relax (rather than further constrain) the technology assumptions.

## 4. Results

### 4.1. Robust strategies for the net-zero target

We first describe the economic and demographic backgrounds of the scenarios. The models suggest that, even in the Baseline scenario, final energy consumption falls toward 2050 due to a declining and aging population, despite sustained growth in GDP. In the absence of climate policy, $CO_2$ emissions do not significantly decline with considerable variation across the models. Climate policy significantly reduces final energy consumption and total $CO_2$ emissions (Fig. 3). Some models suggest a final energy consumption of ~ 8 EJ/yr, which is a significant decrease from the levels found in the 2010′s (~13 EJ/yr).

Next, we document robust results across different models, followed by differential results.

In all participating models, $CO_2$ emission reductions occur across all sectors, complemented by CDR. Fig. 4 describes the sectoral emissions and removals by model for the 105BY50_deftech scenario. As noted in the scenario description, our main scenario is the 105BY50_yy (Net Zero (eq)) scenarios, and the $CO_2$ emissions become net-negative by 2050 owing to CDR. The residual emissions come mainly from the industry and transport sectors, although the largest remaining emissions differ between the models. All sectors contribute to significant emissions reductions compared to the Baseline scenario (Figure A 2).

Fig. 5 shows five key mitigation indicators: the share of unabated fossil fuels (i.e., without CCS in the present context) in the primary energy supply, the energy intensity of GDP as a measure of economy-wide energy efficiency, the $CO_2$ intensity of electricity generation, the share of electricity in final energy consumption as a measure of end-use electrification, and the share of VRE (solar plus wind) in total power generation. As expected from the emissions time series, the share of

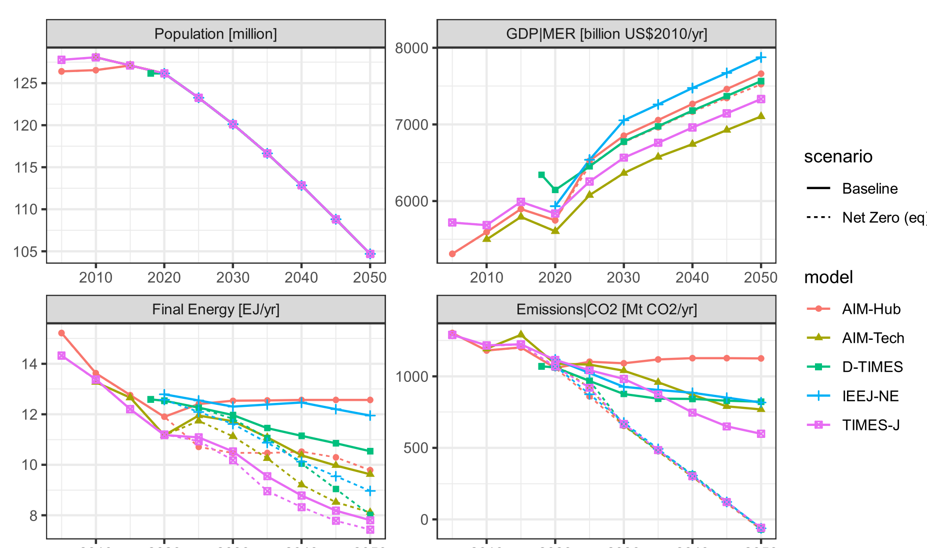


**Fig. 3.** (Upper left) Population, (upper right) GDP, (lower left) final energy, and (lower right) $CO_2$ emissions for the Baseline and Net Zero (eq) (105 % $CO_2$ emissions reduction) scenarios with default technology assumptions.

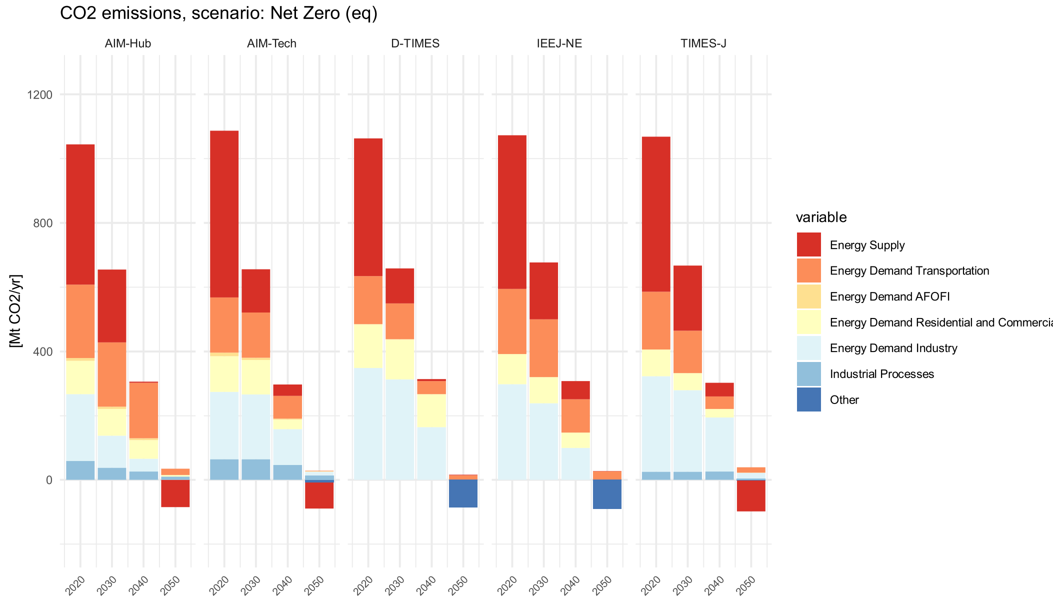


**Fig. 4.** $CO_2$ emissions (excluding AFOLU) by sector and model for the Net Zero (eq) (105BY50_deftech) scenario. The other in the AIM-Technology, D-TIMES, and IEEJ-NE represents DACCS. AFOFI signifies $CO_2$ emissions from fuel combustion in agriculture, forestry, and fishing. Because different models have different reporting years, the 2010 bar has been made translucent.

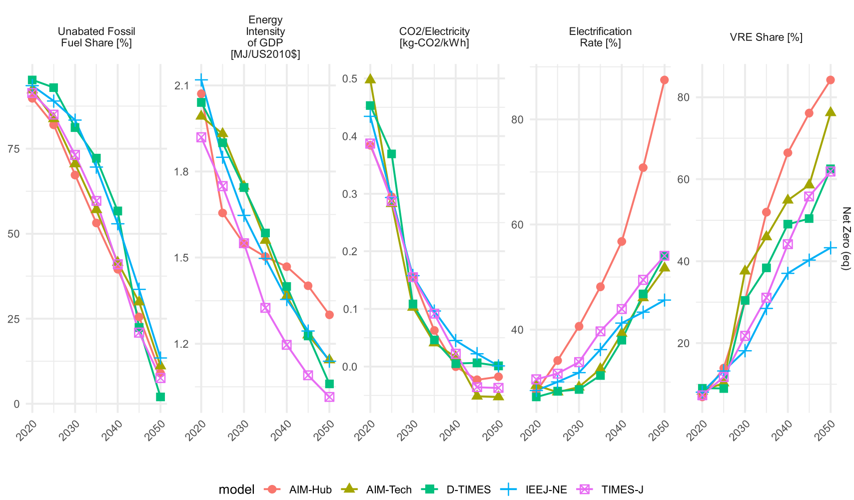


**Fig. 5.** Indicators of strategies for climate change mitigation. (From the left) Share of fossil fuels without CCS in primary energy, energy intensity of GDP, $CO_2$ intensity of electricity, the share of electricity in final energy consumption, and the share of VRE (solar plus wind) in power generation. Values are from the Net Zero (eq) (105BY50_deftech) scenario.

unabated fossil fuels dwindles towards 2050, although it doesn't disappear completely by 2050, reaching 2.0 % (D-TIMES) to 13.4 % (IEEJ-NE_Japan). The energy intensity of the economy and the $CO_2$ intensity of electric power decrease significantly across the models, supporting increasing energy productivity and decarbonization of the power sector as robust strategies.

Some strategies are supported in terms of direction, but their actual value remains uncertain. With the help of decarbonized electricity, end-use sectors are increasingly relying on clean electricity for mitigation. However, the actual electrification rate varies from 45.6 % (IEEJ-NE_Japan) to 87.5 % (AIM-Hub). Similarly, the VRE share in 2050 ranges from 43.3 % (IEEJ-NE_Japan) to 84.2 % (AIM-Hub).

In terms of temporal development, the $CO_2$ intensity of energy and its time derivative decrease almost steadily, implying an accelerating trend. Energy intensity also decreases steadily; however, there is no clear trend in the time derivative across the models (Figure A 5).

How does this robust strategy translate into implementation? Fig. 6 shows the time series of renewable capacity and electricity generation for the Baseline and Net Zero (eq) scenarios. In the Baseline scenario, renewables do not appreciably increase. The Net Zero (eq) policy significantly expands renewables, but the tripling goal is not always met. Two models achieve the capacity target whereas the others do not.

As our companion paper clarifies, the expansion of renewables in the power sector is a robust feature (Frazer et al., to be submitted), which is accompanied by the continued decline of fossil fuels. On the end-use side, widespread electrification is also a robust finding. However, the degree varies by sector, with buildings almost completely electrified in many scenarios and across models (Cao et al., submitted).

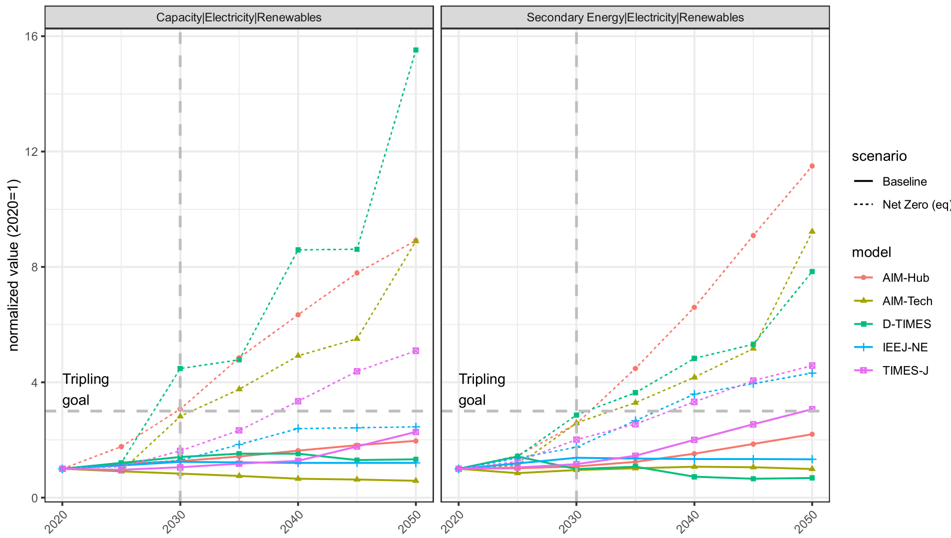


**Fig. 6.** Normalized renewable energy capacity (left) and electricity generation (right). Note that the goal is set for 2030, not 2050.

Our analysis identifies where the models agree and disagree. Fig. 7 shows decomposition of the primary energy, electricity generation, and final energy consumption by source or carrier. For the purposes of this study, the technology assumptions regarding the availability, cost, and potential of these energy sources are not harmonized across the models. For instance, the AIM-Hub model does not represent hydrogen import. Uncertain results should be interpreted as representing a wide range of uncertain technological parameters in the future.

At the primary energy level, two models (AIM-Technology and AIM-Hub) rely significantly on renewable energy, whereas the other three rely on secondary energy trade, which represents the imports of clean energy carriers such as hydrogen and ammonia. In these three models, the share of clean energy imports reaches 30 % or higher. A significant portion of the imported energy is used for power generation.

Solar PV and wind power are the main contributors to power generation by 2050, but their magnitudes vary across the models, which is consistent with Fig. 5. Solar PV is projected to be the largest contributor in all the models. Solar power is followed by wind power in all three models except for the IEEJ-NE_Japan model, in which natural gas with CCS is the second largest generation technology. In addition, the total electricity generation varies significantly, being 1.3 PWh/yr in the TIMES-Japan model and reaching 2.7 PWh/yr in the AIM-Hub model. Likewise, the magnitude of VRE varies widely. The solar generation in the AIM-Hub model is more than three times that of the IEEJ-NE_Japan model.

Electricity is projected to be the dominant component of final energy consumption in all five models. However, its proportion varies considerably. Moreover, the fractions of other energy carriers (e.g., gases and liquids) differ across the participating models.

Different model responses to hydrogen and ammonia can also be observed in import dependence. (Fig. 8). Japan is heavily dependent on energy imports, with a modeled import ratio of ~ 90 % in 2020. This is projected to decrease significantly in the decarbonization scenario, but the magnitude of the decrease varies between the models. In IEEJ-NE_Japan, D-TIMES, and TIMES-Japan, the import ratio is still above 50 % in 2050. Although this is still a decrease from the current level, our results suggest that depending on the decarbonization strategy, Japan may still face energy security issues in the mid-century. Note that primary energy, as defined here, includes the import of secondary energy carriers such as hydrogen and ammonia, following the IPCC reporting convention.

### 4.2. Technology and policy sensitivity analysis

We now shift our focus from the main scenario (Net Zero (eq) or 105BY50_deftech) to a broader set of scenarios. Table 4 summarizes the model feasibility under various scenarios. In other words, it indicates whether each model can produce a solution for each scenario. Model feasibility is sometimes confused with more broader notions of feasibility (e.g., political feasibility) [41,43,77,91]. To avoid confusion, we add the qualifier "model" before feasibility.

All participating models have solutions for the 100BY50_yy and 105BY50_yy scenarios (though some models did not run a specific set of scenarios). In the case of the most stringent emissions constraints (110BY50_yy), all models except IEEJ-NE_Japan suggest that CDR of >100Mt$CO_2$/yr is required for these models; only the 110BY50_cdr and 110BY50_innov scenarios are feasible in terms of modeling. Note that even default assumptions allow for a CDR deployment of up to 100Mt$CO_2$/yr.

Next, we examine robust strategies across sensitivity scenarios in Fig. 9, which encompasses both policy and technology sensitivity analyses. The chart shows that reduced fossil fuel usage and power-sector decarbonization exhibit high robustness. The directions of economy-wide energy efficiency, electrification, and renewable energy expansion are also common; however, their magnitudes are affected by scenario assumptions. Similarly, the size of CDR deployment varies across models, policy targets, and technology assumptions.

A more detailed analysis can clarify how models respond to changes in technology assumptions and whether such changes are consistent with expectations (Fig. 10). Technology scenarios have varying impacts on the indicators of the strategies for 2050. The models exhibit some of the expected patterns. The eletech scenario has the lowest energy intensity and highest electrification rate. The cdr scenario represents the largest amount of unabated fossil fuels and CCS-based CDR. The VRE reaches its highest value in the re scenario. However, in some instances, the impact deviates from simple expectations. For instance, the innov or cdr scenario does not always have the largest impact on the variable.

As an example of the uncertainty in the energy mix, we display the composition of electricity generation (Fig. 11) (see Figure A 6, Figure A 7, and Figure A 8, for primary energy, electricity generation, and final energy, respectively, for all scenarios). The AIM-Hub and AIM-Technology models do not show any power supply from hydrogen and ammonia, but they occupy an important portion of the other three models in the deftech and most of the technology sensitivity scenarios. Nevertheless, in the 105BY50_re scenario, where renewable energy costs are assumed to continue to decline, the hydrogen/ammonia power

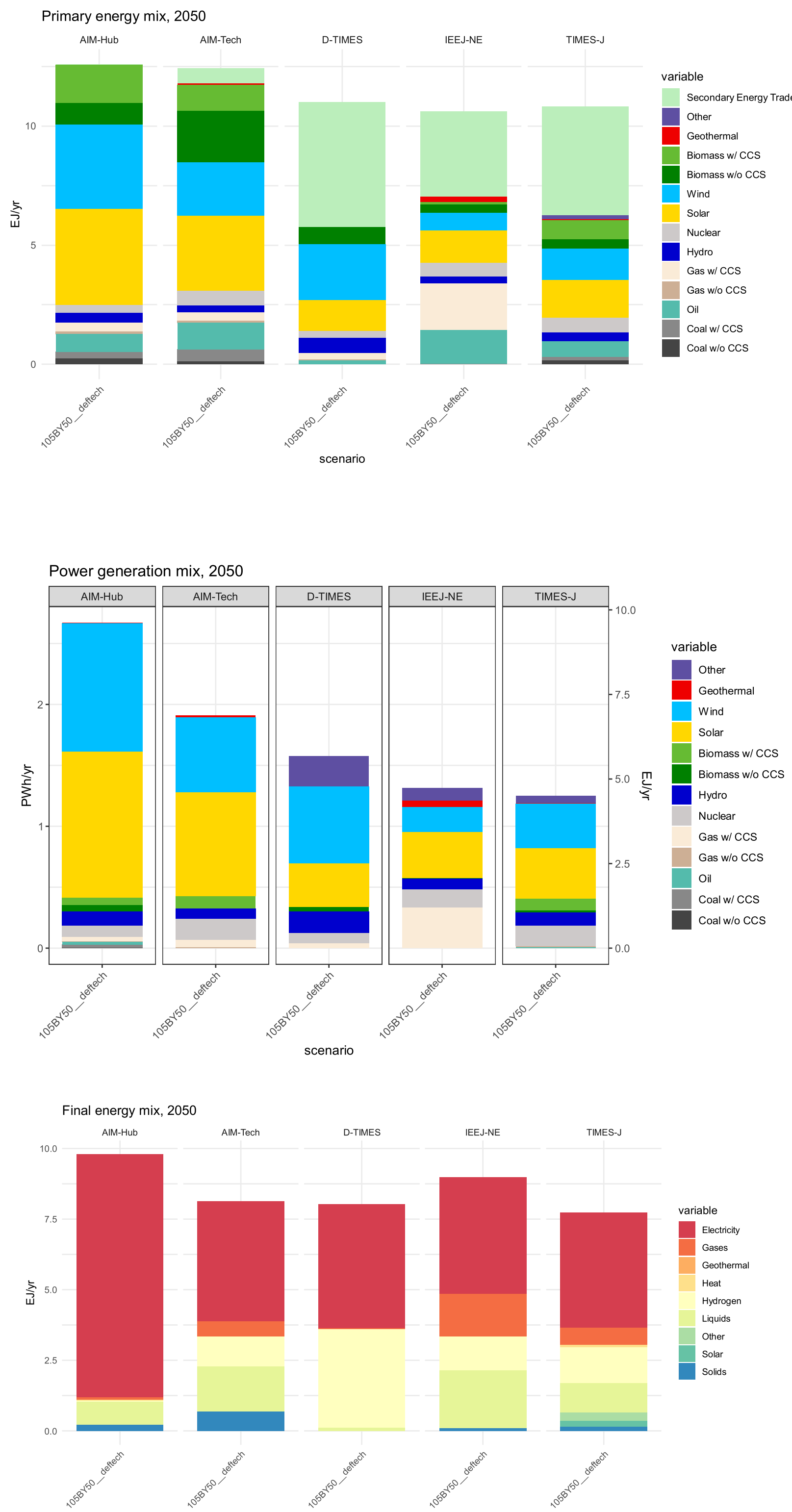


**Fig. 7.** Composition of (top) primary energy, (middle) power generation, and (bottom) final energy for the Net Zero (eq) (105BY50_deftech) scenario in 2050.

generation virtually disappears in the IEEJ-NE_Japan model (shown as "Other" in purple). In contrast, the share of this generation increases to ~ 50 % in the import scenario, where the cost of imported clean fuels is reduced. In summary, the generation mix is uncertain in that it varies significantly by model and technology assumptions.

Finally, we present cost measures, which were one of the most uncertain aspects of mitigation scenarios in our previous study, mainly for the 80 % emissions reduction [82]. Fig. 12 depicts the time evolution of the marginal cost of abatement for the technology sensitivity scenarios for the 105 % reduction case, as well as the boxplot by technology scenario. For the 2050 carbon price values, the results are sorted according to the maximum carbon price. As expected, carbon prices remain one of the most uncertain indicators in these scenarios. The median for the deftech scenario reaches 2085 USD2010/t$CO_2$ by 2050.

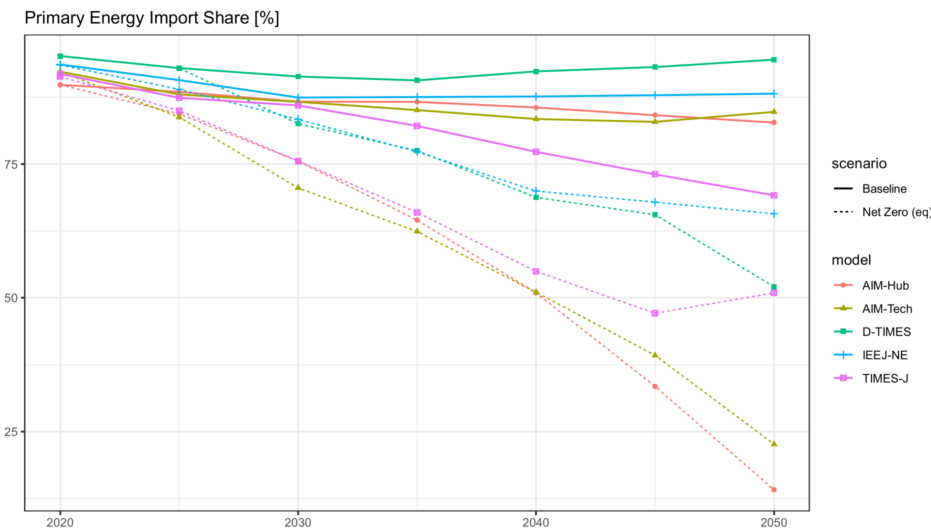


**Fig. 8.** Import share of primary energy in the Baseline and Net Zero (eq) (105BY50_deftech) scenarios.

**Table 4**
Model feasibility of scenarios for sensitivity analysis. Scenarios that were not run are not shown (filled with white space), and those that were "model infeasible" are shown in gray. Model names are abbreviated as follows: AH for AIM-Hub, AT for AIM-Technology, DT for D-TIMES, IE for IEEJ-NE_Japan, TI for TIMES-Japan.

| | 100BY50 | 105BY50 (Net Zero (eq)) | 110BY50 |
|---|---|---|---|
| deftech | AH,AT, IE,TI | AH,AT,DT, IE,TI | AH,AT, IE,TI |
| re | AH,AT, IE,TI | AH,AT, IE,TI | AH,AT, IE,TI |
| eletech | AT, IE,TI | AT, IE,TI | AT, IE,TI |
| import | AT, IE,TI | AT, IE,TI | AT, IE,TI |
| cdr | AH,AT, IE,TI | AH,AT,DT,IE,TI | AH,AT, IE,TI |
| innov | AH,AT, IE,TI | AH,AT, IE,TI | AH,AT, IE,TI |

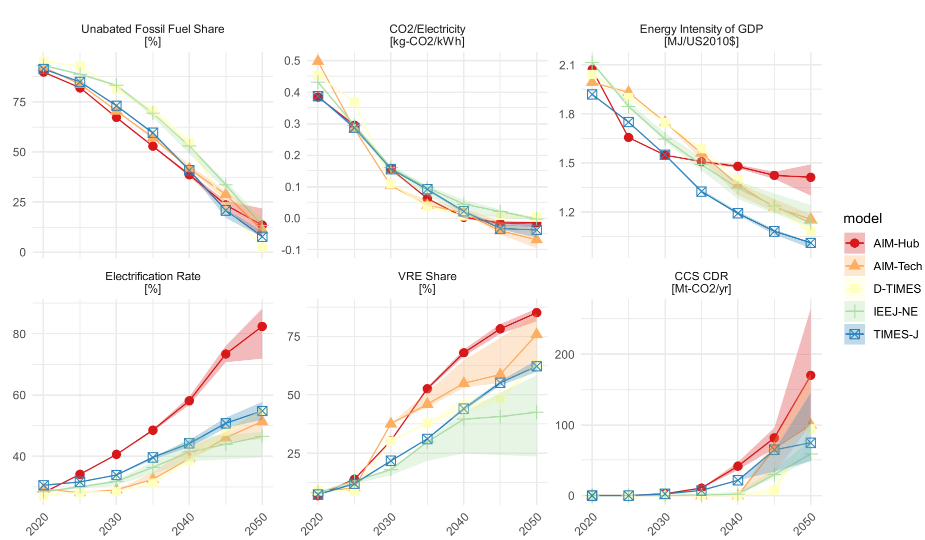


**Fig. 9.** Robust strategies under policy and technology uncertainties. As in Fig. 5 but in a different layout and with CDR.

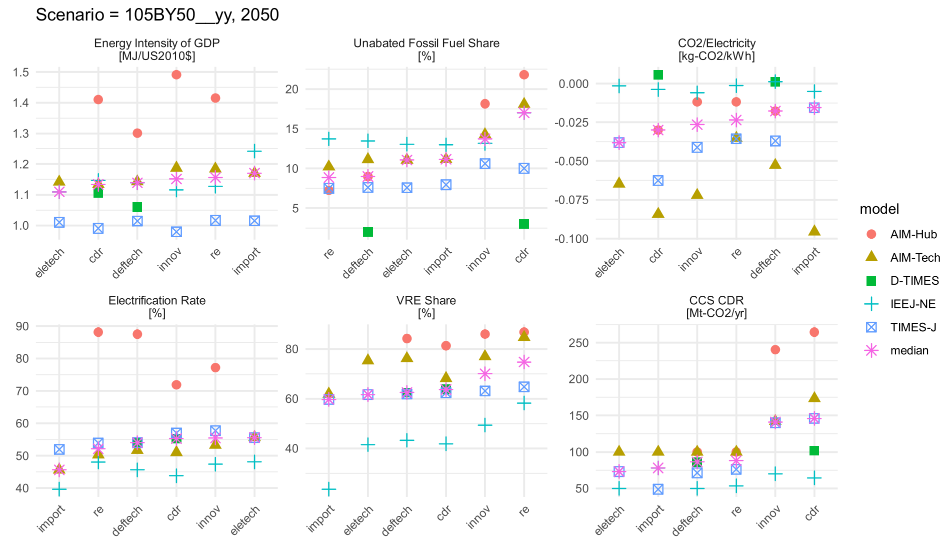


**Fig. 10.** Indicators of robust strategies by technology scenario. The horizontal axis is sorted by the median of the indicators so that each panel has a different horizontal axis.

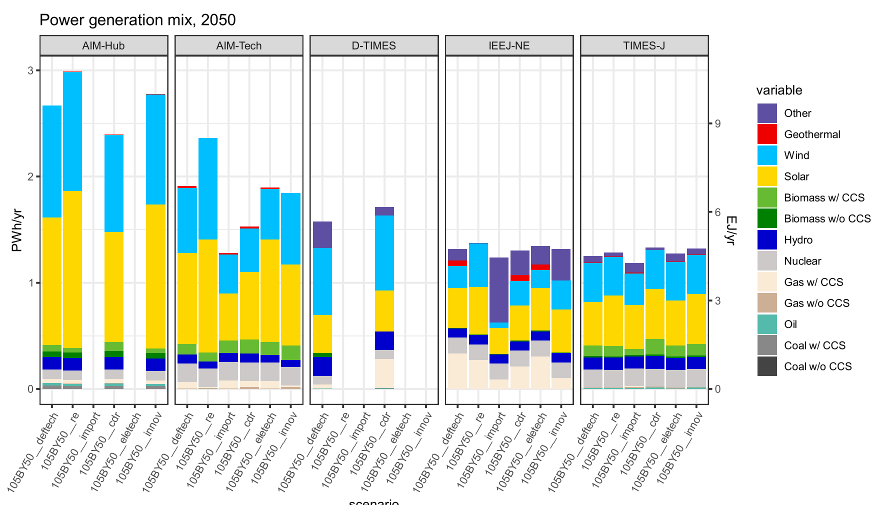


**Fig. 11.** Electricity generation mix for the technology sensitivity scenarios for the 105BY50_yy scenarios, where yy refers to one of the following: deftech, re, import, cdr, and innov. The other mostly represents hydrogen and ammonia, but the details vary by model: hydrogen fuel cells (which dominates) and ammonia for D-TIMES, ammonia for IEEJ-NE_Japan, and hydrogen combined-cycle turbines (which dominates) and top pressure recovery turbines for TIME-Japan.

Conversely, the median of the best case (innov) is <433 USD2010/t$CO_2$; the high prices are constrained in 2050. The impact of technology availability on carbon prices is broadly similar across policy objectives, although some scenarios were infeasible in the models (Figure A 9).

We also compare the present results with those from an analysis by the Energy Modeling Forum 37 for North America and the European Climate and Energy Modeling Forum for Europe [74]. We use the maximum, median, and minimum carbon price values. While the American and European studies do not report technology sensitivity scenarios, their results reveal a much wider range, perhaps reflecting the larger number of participating models in their study (more than ten). In terms of the results, the median of the innov scenario is approximately the same as the medians of the US and EU study, and the cdr scenario is also slightly higher. For comparison, the Net Zero scenario in our previous study [81] had a median price of ~ 650 USD2010/t$CO_2$, whereas the 100BY50_cdr scenario had a median price of 537 USD2010/t$CO_2$.

However, the dominance of CDR is not observed in discounted costs, and the variation in cost is model-dependent. Fig. 13 shows the discounted costs for the three measures of carbon price, consumption loss per GDP, and additional energy systems costs per GDP. Unlike the previous figure, the cdr scenario does not guarantee the lowest cost. For instance, aside from the best innovation case (innov), the discounted carbon price in the IEEJ-NE and TIMES-J models do not show lowest values. There is no clear pattern in the order among the scenarios across the models for policy costs (consumption loss and energy systems cost). See also **Figure A 10** for the 100BY50 and 110BY50 scenarios, which iterate over the same point.

## 5. Discussion and conclusions

### *5.1. Policy implications under technology uncertainties*

In this study, we explored uncertainties in key technological areas by changing the assumptions on CDR availability, clean energy imports, renewable costs, and end-use electrification technologies. Despite the wide spread of technology assumptions, our results consistently identify robust strategies for achieving net-zero emissions in Japan across different model choices, policy stringencies, and technical assumptions:

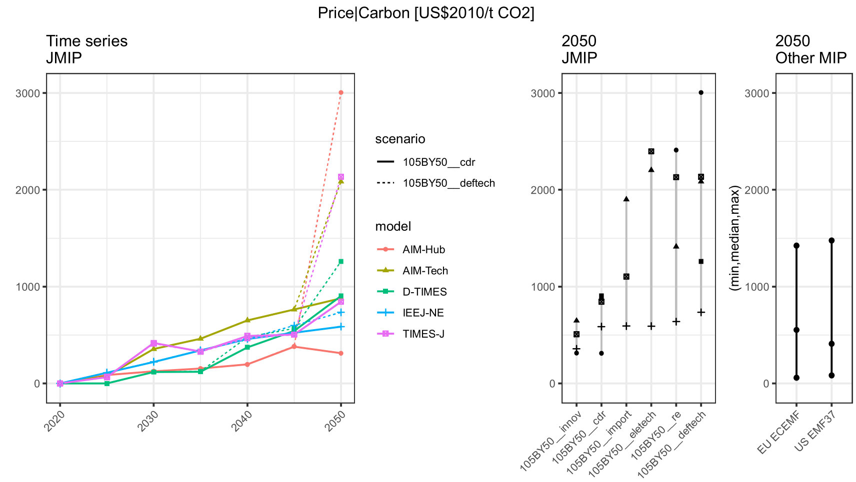


**Fig. 12.** Carbon price for the five participating models . (Left) time series, (middle) the 2050 values by technology scenario, and (right) the comparison with American and European studies. Note that the target of the EU ECEMF emissions reduction was net-zero GHG emissions whereas that for the US EMF 37 was net-zero $CO_2$ emissions. In the middle panel, the technology scenario is sorted by the maximum of carbon price.

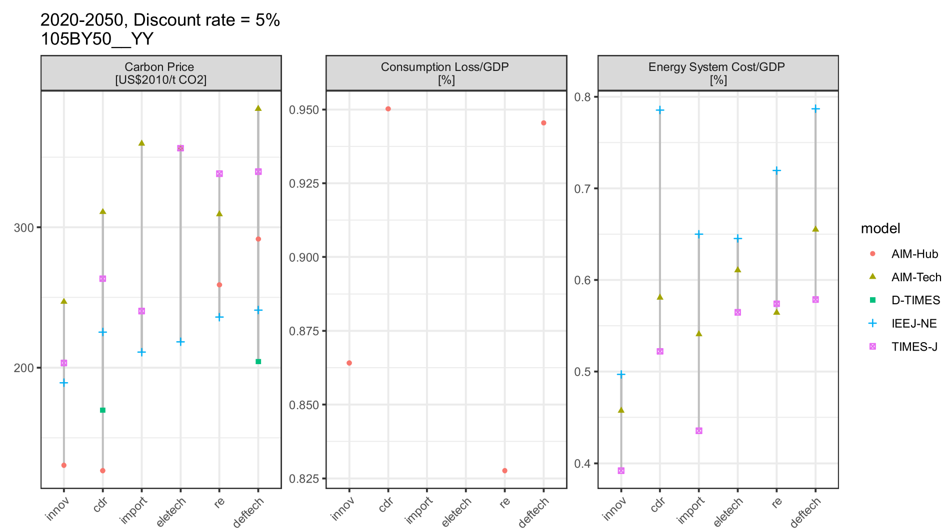


**Fig. 13.** Costs (carbon price, consumption loss as a percentage of GDP, and additional energy systems cost per GDP, from left to right) for the Net Zero (eq) by technology sensitivity scenario and model, discounted at a rate of 5 % for 2020–2050. The technology scenarios are presented in the same order as in Fig. 12.

- Significant reduction of (unabated) fossil fuel use;
- Rapid decarbonization of the power sector;
- Economy-wide energy efficiency improvements;
- Extensive electrification of end-use sectors; and
- Implementation and scale-up of CDR.

These findings are in line with multi-model studies for the United States and Europe [13,74], the IPCC assessment [19], and the emerging literature on net-zero scenarios. Given the robustness of these strategies, policies should emphasize effective measures, including power-sector decarbonization, electrification of end-use sectors, improvement of energy efficiency across all sectors, and investment in CDR options.

Simultaneously, our analysis highlights significant uncertainty related to emerging technologies, particularly the role of imported clean fuels, such as hydrogen and ammonia. Given Japan's unique geographic constraints, such as no external electricity grid connections or gas/oil pipelines, the potential reliance on imported hydrogen and ammonia appears to be substantial. However, our modeling results reveal high sensitivity to assumptions regarding the costs with these clean fuels. Consequently, the viability and cost-effectiveness of large-scale clean fuel imports require additional scrutiny through targeted analyses and real-option evaluations to inform policy and investment decisions.

In addition, the high sensitivity of emerging innovations such as hydrogen/ammonia power generation to technology assumptions has implications for energy innovation policy (e.g., Fig. 11). This deserves special attention also because of the ongoing policy debate surrounding hydrogen and ammonia. Some experts, including civil society organizations, have criticized Japan's emphasis on hydrogen and ammonia imports, especially for the power sector, on cost and environmental grounds [46,75,87].

The scenario literature (based on systems modeling and related fields) is replete with stories of "getting technology cost assumptions wrong," ranging from solar PV (as reviewed in Section 1) to wind power and nuclear [28] to batteries and fuel cells [49]. Because our study design explicitly addressed some of these uncertainties, we reconfirmed the sensitivity of energy futures to these technology assumptions. To deal with pervasive uncertainty, policies must be flexible enough to accommodate it.

First, policies must explicitly acknowledge uncertainties and competition among technologies. Japan has set detailed targets for specific technological areas (e.g., domestic hydrogen consumption of 20Mt-$H_2$/yr at a cost target of 20 yen/$Nm^3$ of hydrogen by 2050), but they should be interpreted as aspirational and should not be used as concrete, stringent targets. Rather, a firm goal should be placed on more robust features such as power-sector decarbonization or end-use electrification.

Second, policies should include a mechanism to deal with continuous technological changes. Although Japan's Basic Act on Energy Policy allows for updating the Strategic Energy Plan every three years, the government should strengthen its mechanisms for reviewing technological developments.

Nevertheless, the current knowledge and situations pose a fundamental conundrum. If Japan requires large-scale import of hydrogen or ammonia, it needs to develop a supply chain and infrastructure for such clean fuels [58]. Flexibility is important given the uncertain future of emerging technologies such as hydrogen and ammonia, but investors and businesses need stable and predictable policies. In other words, there is a trade-off between policy flexibility and stability. Here, the government can adopt a staged approach [92] more explicitly. As the current government is fostering "all of the above" approach, the initial stage of climate innovate policy is sufficient. Policymakers would need to filter non-competitive technologies from larger government support schemes.

### *5.2. Conclusions and future directions*

This study conducted a multi-model analysis of Japan's scenarios toward the goal of net-zero GHG emissions, covering key technological uncertainties. We approximated the net-zero GHG goal as a 105 % reduction in $CO_2$ emissions based on the results from the two models with full GHG coverage. Our scenario design comprehensively address policy and technology uncertainties. Despite model differences and variations in scenario assumptions, achieving decarbonization requires robust responses, including rapid power-sector decarbonization, economy-wide energy efficiency improvements, end-use electrification, introduction of new clean fuels, and the deployment of carbon removals. The models also reveal that the composition of primary energy and electricity generation is subject to significant uncertainty, as is the cost of mitigation. Some models include significant amounts of clean energy imports, such as hydrogen and ammonia, whereas others do not.

One limitation of the present study is the limited space of the designed scenarios. For example, the present study did not systematically explore the uncertainties in energy service demands due to demand-side solutions [21,31,86]. For instance, the diffusion of self-driving cars may facilitate the spread of car- and ride-sharing, reducing transportation emissions and emissions from the industry sector that provides steel for automobile manufacturing [2].

Another aspect worth further research is a more thorough investigation into the international aspect. Relocating part of the manufacturing value chain to regions with abundant and cheap renewable energy would reduce emissions in Japan [16,29] due in part to "renewables pull" (incentives because of affordable renewable energy and green hydrogen) [73,90]. International energy trade (e.g., through international grid connection or hydrogen trade) requires a deeper investigation.

Similarly, our scenario design does not explicitly include stringent sector-specific policies. There is increasing interest in the 100 % renewable scenario [12], but this was not included in our scenario design, and we did not analyze the costs and benefits of such scenarios. Neither do we examine the scenarios with bans on internal combustion engine cars and gas grid connections. A broader set of scenarios is left for future research.

## Data availability

The data supporting the results of this study will be publicly available at at the following URL/DOI: https://doi.org/10.5281/zenodo.16559129.

## Declaration of use of generative AI and AI-assisted technologies in the research and writing processes

During the preparation for this study, the authors used DeepL and OpenAI ChatGPT to improve the clarity of the English writing. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. The authors also used OpenAI ChatGPT to facilitate the coding process, although the final code was fully verified and tested by the authors.

## CRediT authorship contribution statement

**Masahiro Sugiyama:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Formal analysis, Conceptualization. **Hiroto Shiraki:** Writing – review & editing, Methodology, Investigation. **Shinichiro Fujimori:** Writing – review & editing, Supervision, Methodology. **Kenichi Wada:** Writing – review & editing, Methodology. **Tao CAO:** Writing – review & editing, Formal analysis. **Eamon Frazer:** Formal analysis. **Hiroshi Hamasaki:** Software, Formal analysis. **Etsushi Kato:** Software, Formal analysis. **Yuhji Matsuo:** Investigation, Formal analysis. **Osamu Nishiura:** Software, Formal analysis. **Tatsuya Okubo:** Software, Formal analysis. **Ken Oshiro:** Software, Formal analysis. **Takashi Otsuki:** Software, Formal analysis. **Fuminori Sano:** Software, Formal analysis, Conceptualization. **Hiroki Yoshida:** Software, Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100210.

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