Energy and Climate Change 5 (2024) 100128

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Mid-century net-zero emissions pathways for Japan: Potential roles of global mitigation scenarios in informing national decarbonization strategies

Ken Oshiro [a,*], Shinichiro Fujimori [a,b,c]

[a] Department of Environmental Engineering, Kyoto University, C1-3, Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto, Japan
[b] National Institute for Environmental Studies, Tsukuba, Japan
[c] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

ARTICLE INFO

Keywords:
Climate change mitigation
Long-term strategy
Hydrogen
Integrated assessment model

ABSTRACT

Japan has formulated a net-zero emissions target by 2050. Existing scenarios consistent with this target generally depend on carbon dioxide removal (CDR). In addition to domestic mitigation actions, the import of low-carbon energy carriers such as hydrogen and synfuels and negative emissions credits are alternative options for achieving net-zero emissions in Japan. Although the potential and costs of these actions depend on global energy system transition characteristics which can potentially be informed by the global integrated assessment models, they are not considered in current national scenario assessments. This study explores diverse options for achieving Japan's net-zero emissions target by 2050 using a national energy system model informed by international energy trade and emission credits costs estimated with a global energy system model. We found that demand-side electrification and approximately 100 Mt-CO_2 per year of CDR implementation, equivalent to approximately 10% of the current national CO_2 emissions, are essential across all net-zero emissions scenarios. Upscaling of domestically generated hydrogen-based alternative fuels and energy demand reduction can avoid further reliance on CDR. While imports of hydrogen-based energy carriers and emission credits are effective options, annual import costs exceed the current cost of fossil fuel imports. In addition, import dependency reaches approximately 50% in the scenario relying on hydrogen imports. This study highlights the importance of considering global trade when developing national net-zero emissions scenarios and describes potential new roles for global models.

1. Introduction

In response to the Paris Agreement, countries have formulated long-term low-emission development strategies, including mid-century greenhouse gas (GHG) emission reduction targets. Numerous countries have set goals generally aiming to achieve net-zero emissions by the middle of this century [1]. Although previous integrated assessment models (IAMs) have focused mainly on global changes in energy and land systems associated with climate change mitigation, they have contributed to quantitative assessment of the national net-zero emissions goals in recent years [2–4]. In response to the increased focus on national mitigation scenario assessments, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) called upon research communities to submit national scenarios [5]. The collected national development pathways were summarized in IPCC AR6, but few of these pathways would achieve net-zero emissions by 2050 [6].

More recently, scenario assessments related to national net-zero emissions targets have emerged. These studies have generally indicated that carbon dioxide removal (CDR) and demand-side electrification with upscaling of renewable electricity are critical to reaching net-zero emissions [7–10]. Although few national decarbonization pathways have been described to date, numerous global studies have outlined scenarios for achieving net-zero emissions. The global decarbonization scenarios of IPCC AR6 include various options in addition to CDR implementation and electrification, such as low demand scenarios [11]. In addition, hydrogen and synthetic fuels can facilitate global net-zero energy systems without large-scale implementation of

* Corresponding author.
E-mail address: ohshiro.ken.6e@kyoto-u.ac.jp (K. Oshiro).

https://doi.org/10.1016/j.egycc.2024.100128

Available online 14 February 2024

electrification [12,13]. Furthermore, in the context of national mitigation targets, international emission trading may provide an option to offset residual emissions [14,15], although not all national net-zero emissions goals allow for emission credits. While assessing diverse mitigation options when developing national net-zero emission strategies can be useful, consideration of global energy system context and defining the boundary condition between the national and global models are essential, especially if the international trade of low-carbon energy carriers and emission allowances are included in the analysis.

Few studies have considered the global context when developing national scenarios. Linking Climate and Development Policies - Leveraging International Networks and Knowledge Sharing (CD-LINKS) was the initial model intercomparison project (MIP) related to national low-emission scenarios assessments to couple global and national IAMs, where the national carbon budget output from the global IAM assessment is imposed as a national emission constraint [2,16,17]. The Climate pOlicy assessment and Mitigation Modeling to Integrate national and global Transition Pathways (COMMIT) project was based on a similar framework in terms of national emission scenario development, and its climate policy assumptions were also harmonized between the global and national models [18,19]. Prior to the IPCC AR6 scenario assessments, Fujimori et al. [20] proposed a scenario framework for national mitigation pathway assessment that is linked with global emission scenarios. Although these studies linked global and national mitigation pathways based on carbon budgets, more details, such as global energy prices, have not been sufficiently harmonized between global and national models. More recently, Köberle et al. [21] compared the results of 10 global models and explored their implications for Brazil's bioenergy pathways. Nevertheless, the impacts of new technologies, such as hydrogen trading, on national decarbonization strategies remain unclear.

Japan is a major emitter of CO_2 in which national MIP exercises have been conducted for a decade [4,17,18,22-25]. Although most MIPs, such as CD-LINKS and COMMIT, have focused on Japan's previous long-term target of reducing GHG emissions by 80% by 2050, a few recent studies have assessed Japan's updated long-term emission reduction goal of achieving carbon neutrality by 2050. Nevertheless, these net-zero emissions scenarios have generally relied on CDR, mainly via bioenergy with carbon capture and storage (BECCS) implementation [23,26,27], as Japan will have residual CO_2 emissions in difficult-to-decarbonize sectors such as the steel and cement industries [28], which need to be offset to achieve net-zero emissions. In this context, it is useful to explore the various pathways for reaching the net-zero emissions goal in Japan. Due to the scarcity of domestic energy resources, concern over energy security is a main issue facing Japan's energy systems [29]. As both renewable and fossil fuels are scarce in Japan [30], imports of low-carbon energy carriers may be an attractive option. Given these backgrounds, some scenario studies have considered the role of hydrogen [31–33]. In addition, the governmental expert committee presented several net-zero scenarios, some of which included low-carbon energy imports [34]. However, the scenario presented are mostly on bottom-up estimations. Specifically, the global energy system transition suggested by global IAM analysis is not addressed in the government report. Therefore, it is essential to consider multiple mitigation options including international imports of energy carriers and emission credits.

This study aimed to explore diverse national net-zero emissions pathways and the potential roles of global IAMs in informing national scenario assessments, using Japan's net-zero emissions target of 2050 as an example. To this end, we used a national energy system model for Japan in conjunction with information from the global model on global energy transition.

2. Material and methods

2.1. Model

Quantitative scenario assessment was conducted using AIM/Technology-Japan [35,36], which is a recursive dynamic, bottom-up energy system model for Japan. This model quantifies several indicators related to energy supply and demand, associated GHG emissions, and mitigation cost indicators such as carbon price and additional energy system costs reported in the national scenarios of IPCC AR6 [37]. It also covers non-energy sectors, such as industrial processes and agriculture, whereas land-use emissions and sinks are not included. This model includes diverse energy technology options in both the energy supply and demand sectors, whereas energy service demand information, such as steel production and transport demand, is provided exogenously. In this model, new installation, replacement, and operating conditions of energy technologies were determined via linear programming to minimize the total energy system cost, which includes the annualized initial cost of technologies, operation and management costs, and emission costs. The emission constraints are imposed in assessing the mitigation scenarios, and implicit carbon prices are estimated based on marginal abatement costs. For the power sector, the balance of electricity supply and demand was considered at 1-h intervals. This model is characterized by a detailed regional classification that divides Japan into 10 regions. The full definition, mathematical equations, and parameter assumptions of the model were reported by Oshiro et al. [35].

Several key updates have been made since the model version used in previous studies [35], which allow the analysis of net-zero emissions energy systems for Japan. First, synthetic fuel production from captured CO_2 and hydrogen was modeled in a manner similar to that used by the AIM/Technology-Global [12], as summarized in Table A 1 and Table A 2. Imports of synthetic fuels and hydrogen derivatives, including ammonia and hydrogen in the form of methylcyclohexane (MCH), may be available under some scenarios, as detailed in the next subsection. Although synthetic fuels contain carbon that will eventually be released to atmosphere, associated CO_2 emissions were considered carbon-neutral in this study, as imported synfuels were produced entirely from carbon-neutral sources, i.e., direct air capture (DAC) or biomass, according to the AIM/Technology-Global model results [38]. Second, DAC was modeled for AIM/Technology-Japan. In this model, captured CO_2 can be sequestered underground (DAC with carbon capture and storage [CCS], DACCS) or used for synthetic fuel production (DAC with carbon capture and utilization, DACCU). The parameter assumptions for DAC were set based on the literature [39] and are summarized in Table A 3; these assumptions are similar to those of AIM/Technology-Global [38]. Geological CO_2 storage potential of CCS is summarized in Fig. A 1. Third, because upscaling of variable renewable energies (VREs) will be more important under net-zero emissions scenarios than under scenarios with modest mitigation targets [40], the intra-annual temporal resolution was improved in this model version. The current model considers 12 representative days, corresponding to each month of the year, and 24 h per day, whereas the previous version considered representative days corresponding to the four seasons. Furthermore, renewable power generation costs, specifically those for solar and wind power, were updated according to recent cost declines, as summarized in Table A 4 and Table A 5.

2.2. Scenarios

In this study, five net-zero emissions (NZE) scenarios and one 80% reduction scenario corresponding to Japan's long-term mitigation targets were analyzed, as summarized in Table 1. The NZE scenarios (designated NZE-CR, NZE-AF, NZE-LD, NZE-IM, and NZE-ET) were classified in terms of their energy system transformation characteristics. The former three scenarios, NZE-CR, NZE-AF, and NZE-LD, are

Table 1
Summary of scenario specifications.

Scenario	Description	Model specifications Emission constraint	CCS	Service	H_2 imports	Emission allowance trade
NZE-CR (Carbon dioxide Removal)	NZE with utilization of CDR (BECCS and DACCS)	Net-zero by 2050	Model default	SSP2	No	No
NZE-AF (Alternative Fuel)	NZE with utilization of alternative fuels, including hydrogen and synfuels	Net-zero by 2050	<100 Mt-CO_2 yr^{-1}	SSP2	No	No
NZE-LD (Low Demand)	NZE with reduced energy service demand	Net-zero by 2050	<100 Mt-CO_2 yr^{-1}	Low demand	No	No
NZE-IM (IMport)	NZE with import of low-carbon energy carriers, including hydrogen derivatives and synfuels	Net-zero by 2050	<100 Mt-CO_2 yr^{-1}	SSP2	Yes	No
NZE-ET (Emission Trading)	NZE with import of emission allowances from the international market	Net-zero by 2050	<100 Mt-CO_2 yr^{-1}	SSP2	No	Yes
NDC80	Former emission reduction target of reducing GHG emissions by 80% by 2050	80% reduction by 2050	Model default	SSP2	No	No

characterized by national domestic solutions. First, the NZE-CR (carbon dioxide removal) scenario is based on the default model assumptions of AIM/Technology-Japan, following the model default assumptions presented by Oshiro et al. [35] with no additional constraints, in which the technical potential of CCS was approximately 300 Gt-CO_2 per year (Fig. A 1). This scenario was associated with CDR implementation, as no additional constraints were placed on CCS implementation, in contrast to other scenarios. The NZE-AF (alternative fuel) scenario is characterized by the upscaling of alternative fuels, such as hydrogen derivatives and synfuels. In this scenario, CCS implementation is constrained to 100 Mt-CO_2 per year, because the CCS limitation could result in upscaling of the hydrogen derivative penetration to decarbonize energy demand sectors, based on the results of previous studies [16]. The NZE-LD (lowering energy demand) scenario considers a large reduction in energy service demand relative to other scenarios. The energy service demand assumptions are based on the assumptions of previous research [35], as presented in Fig. A 2. CCS constraints assumed in the NZE-AF scenario were also applied in this scenario.

The latter two NZE scenarios depend upon non-domestic mitigation options, i.e., the import of low-carbon energy carriers and emission allowances. Because the costs of these options are highly dependent on global energy system conditions, the parameter assumptions were taken from the results of a global model [38]. In the NZE-IM (import) scenario, energy import prices were obtained from the global model, as presented in Fig. A 3a. While the costs of hydrogen and ammonia continue to decrease due to global cost reductions in solar and wind power, synthetic fuel costs have increased slightly over time due to increasing CO_2 cost [12]. The NZE-ET (emission trading) scenario considered the import of emissions allowances from the international market. Emission pricing information was derived from global model carbon price results [38], as presented in Fig. A 3b. In these two scenarios, CCS constraints were the same as in the NZE-AF scenario. Finally, the NDC80 (nationally determined contribution and 80% reduction) scenario was analyzed as a reference scenario, as it corresponds to the previous target of 80% reduction by 2050 relative to the 2010 level [41]. In addition to these main scenarios, the NZE-HD (High Demand) and NZE-LB (Limited Bioenergy) scenarios were quantified as sensitivity scenarios. In the NZE-HD scenario, socioeconomic assumptions were based on Shared Socioeconomic Pathway (SSP) 5, as it had the highest estimates for Japan among the SSPs. In the NZE-LB scenario, dedicated energy crops were not available, similar to the scenario design in the global model assessment [38], while the potentials for other biomass sources were based on Wu et al. [42]. Other technological and socioeconomic assumptions in the sensitivity cases were the same as those used with NZE-CR. The results of the sensitivity scenarios are summarized in the SI.

Across all mitigation scenarios, emission trajectories were defined based on the national scenario assessment framework [20], with near- and mid-term emissions constraints in 2030 and 2050 following the national targets and linear interpolation between those dates. Emissions under 2030 in the NZE scenarios will show a 46% reduction compared with the 2013 level according to the current national targets, whereas the NDC80 scenario shows a 26% reduction based on the NDC announced in 2015. As the national net-zero emissions target in Japan does not explicitly define the coverage of GHGs, the scenarios covered all Kyoto gasses in accordance with the proposed scenario framework [20], while emissions from international bunker were not included. The assumptions about nuclear power availability are consistent with those of previous studies [41,43]. The energy service demand assumptions in the default cases (excluding the NZE-LD scenario) were based on the SSP2 [44]. Details on energy service demand estimation were presented by Oshiro et al. [35].

3. Results

3.1. Emissions

The five NZE scenarios commonly achieve net-zero emissions by 2050 with reduced emissions from energy sectors and CDR, although the compositions of those emissions vary among scenarios (Fig. 1a, Fig. A 4). In the NZE-CR and NZE-ET scenarios, collective CO_2 emissions from energy demand sectors, industrial processes, and non-CO_2 emissions account for approximately 150 Mt-CO_2 per year in 2050, and these emissions are offset by CDR and emission allowances. Among energy sectors, CO_2 emissions in the industry and transport sectors remain under these scenarios; however, those from the buildings sector are dramatically reduced, reaching nearly zero in 2050 across all NZE scenarios (Fig. 1b). In contrast, dramatic emission reductions in the industry and transport sectors are observed in the NZE-AF, NZE-LD, and NZE-IM scenarios. Approximately 70 Mt-CO_2 per year of non-energy CO_2 emissions and non-CO_2 gasses remain, which are offset by the implementation of BECCS and DACCS.

As shown in Fig. 1c, the implementation of carbon capture, utilization, and storage (CCUS) in 2050 varies among the NZE scenarios. In the NZE-CR scenario, nearly 300 Mt-CO_2 is stored underground in 2050. Because this study's NZE scenarios require the offsetting of non-CO_2 emissions as well as energy-related CO_2 emissions, CCS implementation is greater than in a previous study [26] that considered only energy-related CO_2 emissions. Although fossil fuel use in the industry sector and biomass are the main sources of captured carbon in the NZE scenarios, CO_2 capture via DAC reaches approximately 60 Mt-CO_2 per year by 2050 in the NZE-CR scenario. CCU is also implemented in the NZE-AF, NZE-LD and NZE-IM scenarios, resulting in reduced CO_2 emissions from the energy demand sectors.

The NZE scenarios require CDR implementation to offset emissions from hard-to-decarbonize sectors (Fig. 1d). In the NZE-CR scenario, CDR implementation in 2050 reaches approximately 160 Mt-CO_2 per year, driven by BECCS and DACCS. In the NZE-AF, NZE-LD, and NZE-IM

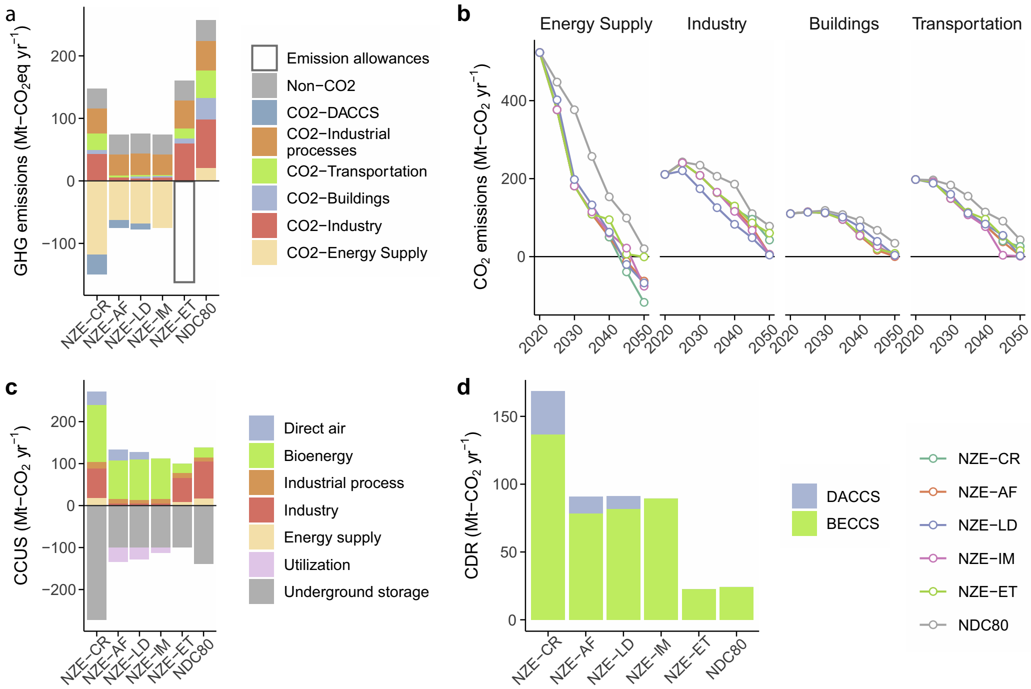

Fig. 1. GHG emissions and CCUS implementation. a) GHG emissions in 2050 across all mitigation scenarios. Import of emission allowances is displayed as negative values, as it offsets emissions in other sectors. Non-CO_2 includes CH_4, N_2O, and fluorinated gasses (F-gasses). b) Sectoral direct CO_2 emissions from the energy supply and demand sectors. c) Carbon capture (positive numbers) and utilization and storage (negative numbers) in 2050. c) CDR implementation in 2050, including BECCS and DACCS.

scenarios, CDR implementation account for approximately 90 Mt-CO_2 per year by 2050, and DACCS implementation is relatively limited. The NZE-ET and NDC80 scenarios also depend on CDR, but are limited to approximately 20 Mt-CO_2 per year in 2050. In the sensitivity scenarios, which include the NZE-HD and NZE-LB, upscaling of DACCS is observed by 2050 due to the negative emission requirements and limited potential

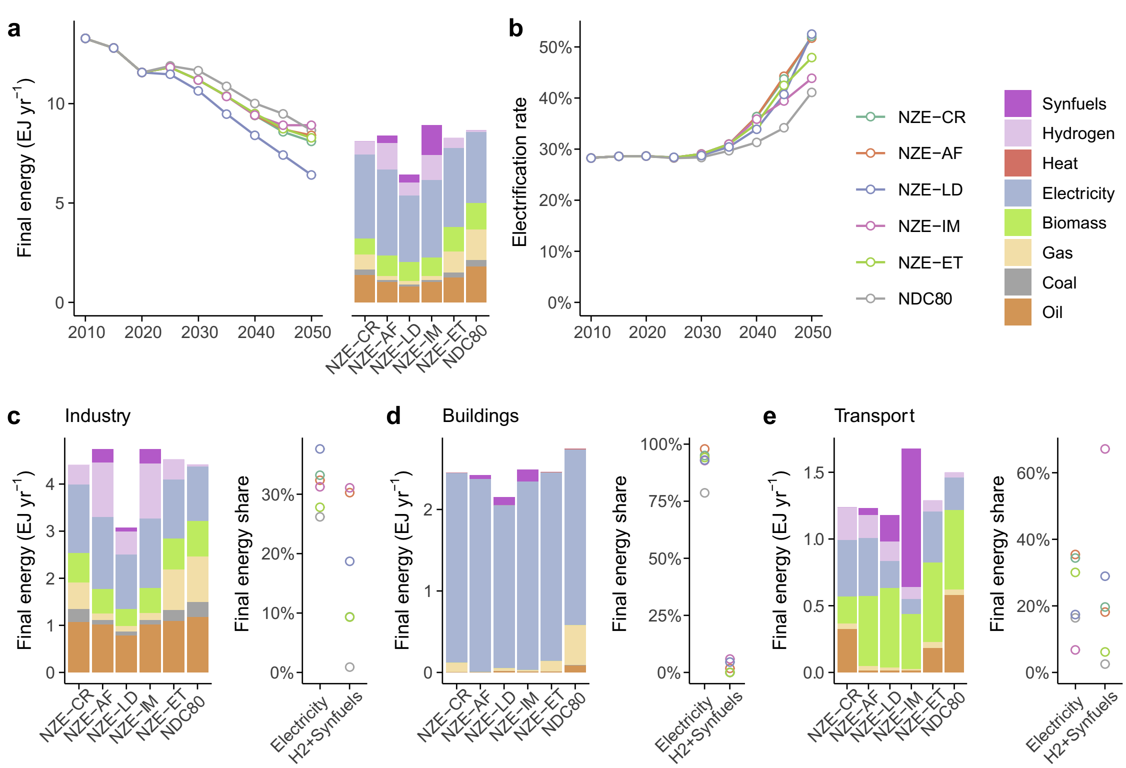

Fig. 2. Energy system changes in terms of final energy demand. a) Total final energy demand. Right panel refers to values in 2050 by energy carrier. b) Electrification rate. C–e) Sectoral final energy demand in 2050. Right panels illustrate shares of electricity and hydrogen derivatives in each sector. Energy for feedstock use is included in the industry sector.

of BECCS in these scenarios.

3.2. Energy system transformation

Fig. 2a compares final energy demand among energy carriers. Across all mitigation scenarios, electrification is the major driver of CO_2 emissions reduction in the energy demand sectors, and reduced energy demand also contributes to decreasing emissions in the NZE-LD scenario. The electrification rate exceeds 40% in all NZE scenarios, and is more than 50% in the NDC-AF and NDC-LD scenarios (Fig. 2b). In contrast, the composition of other low-carbon energy carriers, hydrogen and synfuels, differs among scenarios. In particular, under the NZE-AF and NZE-ET scenarios, domestic or imported hydrogen-based energies could be used, whereas the contributions of these energy carriers are limited under other NZE scenarios.

Sectoral final energy demand is presented in Fig. 2c-e and Fig. A 5. In the buildings sector, electrification presents majority of emission reduction in the NDC80 scenario as well as the NZE scenarios, which contributes to the near-zero sectoral emissions presented in Fig. 1a. In the industry sector, several energy options are used in addition to the electrification presented in the NDC80 scenario. Although fossil fuel use accounts for approximately half of energy demand in the industry sector in the NZE-CR and NZE-ET scenarios because it is relatively difficult to electrify, hydrogen utilization contributes to decreasing emissions in the NZE-AF and NZE-IM scenarios, mainly for processes associated with steel and heat generation. In the NZE-LD scenario, energy demand reduction is the major driver of industrial emission reduction, in accordance with a previous study [35]. In the transport sector, electrification and the use of hydrogen and bioenergy are the main drivers of emissions reduction, but relative contributions vary among scenarios. In the NZE-AF, NZE-LD, and NZE-IM scenarios, the transport sector is nearly decarbonized using these alternatives. In the NZE-IM scenario, synfuels are widely used as carbon-neutral fuels for road and air transport (Fig. A 6). Because the internal combustion engine is less energy efficient than an electric vehicle, final energy demand for transport sector is the greatest in the NZE-IM among all mitigation scenarios.

Decarbonization of the energy supply, specifically in the electricity and hydrogen generation sectors, is a major driver of sectoral net-zero emissions. As shown in Fig. 3a-b, power and hydrogen productions are nearly decarbonized through the upscaling of solar and wind power generation. Due to increased electrification and hydrogen use in the energy demand sectors, electricity generation is greater in 2050 than today across all NZE scenarios, whereas power generation in NDC80 is similar to the 2010 level (Fig. 3a, Fig. A 7). Specifically, the NZE-AF scenario requires doubling power generation in 2050 relative to the 2010 level due to increased demand for hydrogen and synfuel production, which is associated with energy losses. In NZE scenarios excluding the NZE-ET, BECCS is used in the power sector, resulting in negative CO_2 emissions from the power sector in 2050, and contributing to offsetting of emissions from other sectors (Fig. 1b). Deployment of hydrogen-fueled gas turbine generators is observed only in the NZE-IM scenario to stabilize VRE intermittency due to an abundant hydrogen supply, whereas hydrogen use in the power sectors is very low in the other scenarios. Increases in electricity storage and curtailment occur in these scenarios (Fig. A 8). These electricity losses are greatest in the NZE-AF scenario, which is characterized by the large-scale introduction of VREs.

Although hydrogen supply is relatively small in the NDC80 scenario, the NZE scenarios are associated with increases in hydrogen supply to decarbonize hard-to-decarbonize sectors such as long-distance transport and heavy industries (Fig. 3b, Fig. A 9). Although hydrogen production in 2050 accounts for less than 1 EJ per year in the NZE-CR and NZE-ET scenarios, it reaches approximately 1.2 EJ per year in the NZE-LD scenario despite energy demand reduction. Domestic hydrogen production is greatest under the NZE-AF scenario, reaching more than 2 EJ per year in 2050. Although the amount of domestic hydrogen production is similar between the NZE-IM and NDC80 scenarios, approximately 4 EJ per year ammonia and synfuels are imported in 2050 in NZE-IM. Hydrogen import in the form of MCH does not occur due to its high cost compared with other hydrogen derivatives.

3.3. Energy trade and import dependency

Heterogeneity of the energy system transition among NZE scenarios have diverse impacts on import costs and dependency among scenarios, although all scenarios are associated with improvement in import dependencies due to the phase-out of fossil fuels (Fig. 4a, Fig. A 10). Although import dependency in the NDC80 scenario reaches approximately 50% in 2050, they fall to less than 20% by 2050 in the NZE-AF and NZE-LD scenarios due to upscaling of domestic energy resources, mainly solar and wind power. In contrast, import dependency in the NZE-IM scenarios reaches approximately 50% in 2050, which is similar to the level in the NDC80 scenario, due to the import of hydrogen derivatives. Improvement of import dependency by around 30–40% is also observed in the NZE-CR and NZE-ET scenarios, although they rely more on fossil fuel imports than other NZE scenarios.

Fig. 4b shows the import costs of energy carriers and emissions allowances. Import costs associated with fossil fuels decreased dramatically across all NZE scenarios as well as the NDC80 scenario (Fig. A 11). In the NZE-AF, NZE-LD and NZE-IM scenarios, import costs decrease to approximately 20 billion US$ per year by 2050 due to the phase-out of fossil fuel usage. Despite reduced fossil fuel import costs, the NZE-IM and NZE-ET scenarios are associated with increased total import costs relative to the 2010 level due to imports of low-carbon energies and emission allowances. Costs associated with low-carbon energy imports

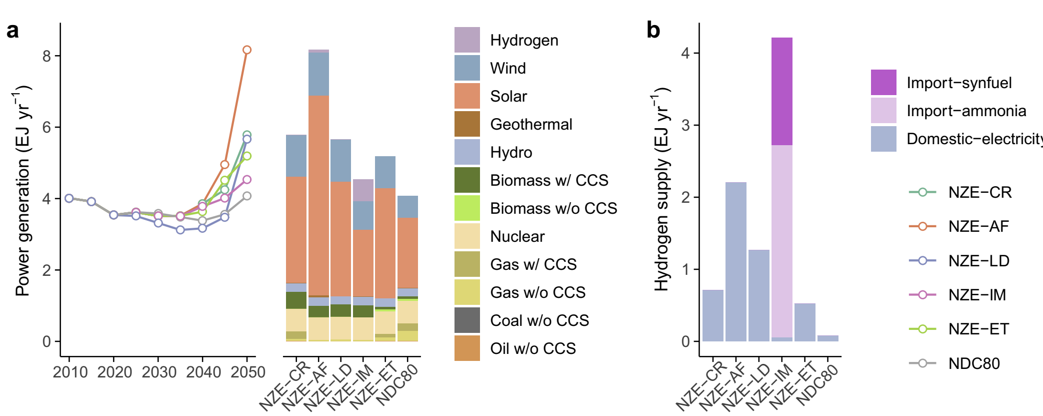

Fig. 3. Energy system changes in the energy supply sectors. a) Power generation, including electricity used for hydrogen production. Right panel shows values in 2050 by power source. b) Domestic production and import of hydrogen derivatives and synfuels in 2050.

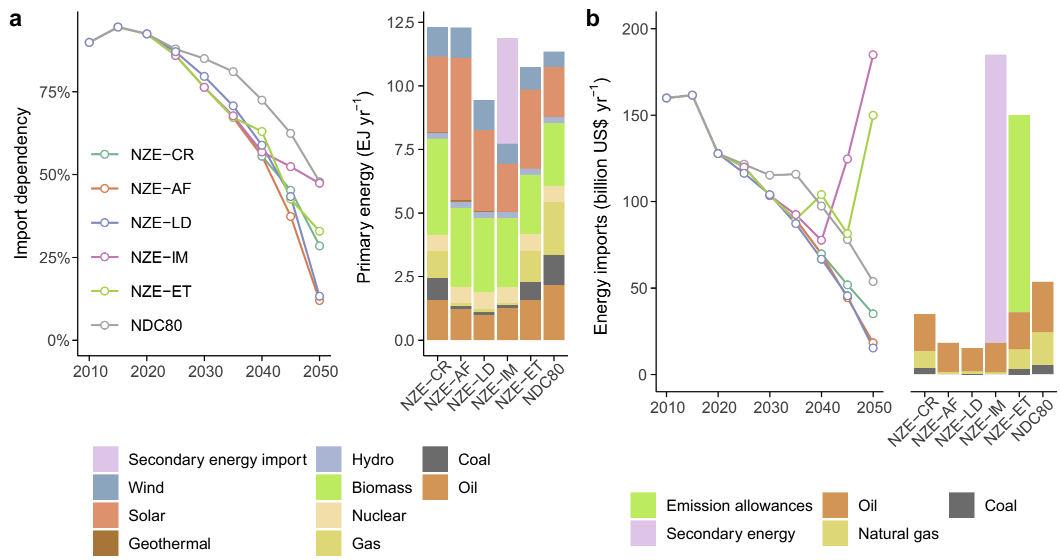

Fig. 4. Primary energy supply and energy import costs. a) Import dependency of energy supply and primary energy supply in 2050. Secondary energy imports include ammonia and synthetic fuels. b) Import costs of energy carriers and emission allowances.

and emission allowances increase rapidly after 2040 because these options are required only in the stringent emission constraints, whereas more cost-effective options, such as renewable upscaling and electrification in the energy demand sectors, are widely implemented before 2040.

3.4. Economic implications

Fig. 5a and b show carbon prices, and cumulative additional energy system costs discounted at a 3% discount rate. All NZE scenarios are associated with increased mitigation costs compared with the NDC80 scenario. Carbon prices in the NZE-CR and NZE-ET scenarios are 600–700 US$ per t-CO_2 in 2050, whereas other NZE scenarios involve increased carbon prices exceeding 1000 US$ per t-CO_2 by 2050. In particular, under in the NZE-CR and NZE-LD scenarios, the carbon price reaches nearly 2000 US$ per t-CO_2 by 2050 mainly due to CCS constraints that are generally associated with increased mitigation costs [45,46]. Cumulative energy system costs in the NZE scenarios reach 2–3 times those in the NDC80 scenario. The estimated carbon prices in Japan are relatively high compared with the global level because of the higher share of emissions from difficult to decarbonize sectors and the low renewable potential [23,30], although the carbon prices in this study are lower than those reported previously due to the decline in renewable costs [26]. Although energy system costs are lowest in the NZE-LD scenario among NZE scenarios, additional costs associated with energy demand reduction are notably excluded from this model. Mitigation costs in the NZE-IM and NZE-ET scenarios are similar to those in the NZE-CR scenarios, as these scenarios involve increased import costs while domestic energy investments are lower than in other scenarios.

Fig. 5c illustrates investment requirements for mitigation options. In the NZE-CR, NZE-AF, and NZE-LD scenarios, where net-zero emissions are accomplished through domestic mitigation options, the required investments are double to triple those in the NDC80 scenario. Decarbonization of electricity requires the largest investment among sectors, accounting for more than half of the total investment. In contrast, domestic investments are moderate in the NZE-IM and NZE-ET scenarios, at nearly the same level as the NDC80 scenario. Despite lower domestic investments, the NZE-IM and NZE-ET scenarios involve increased import costs for low-carbon energy or emission allowances (Fig. 4b).

4. Discussion and conclusions

4.1. Challenges and opportunities related to the net-zero emissions target in Japan

Our results identified the mitigation options that are commonly

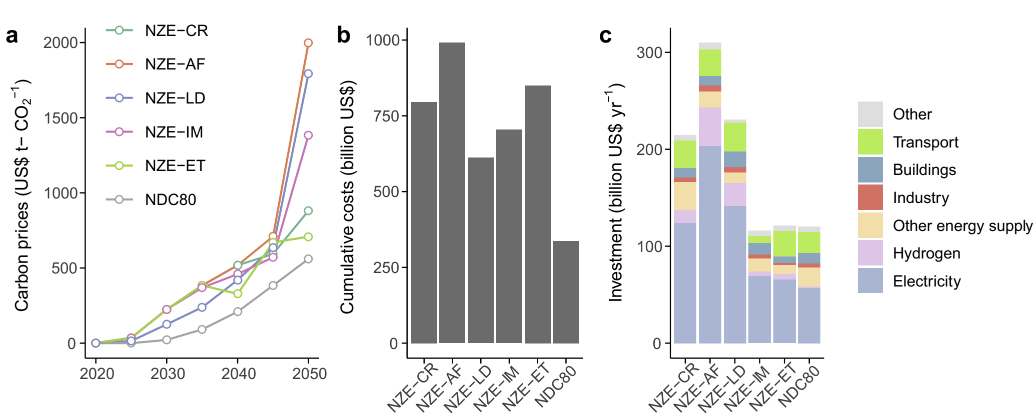

Fig. 5. Mitigation costs and investments. a) Carbon prices. b) Cumulative additional energy system costs in 2021–2050, discounted at 3%. c) Additional domestic investment in 2050.

essential to achieving the net-zero emissions target among various scenarios. In all NZE scenarios assessed in this study, electrification of energy demand and decarbonization of the power system are common strategies. Although the importance of these options is noted in a previous analyses of the 80% reduction target [41], our findings emphasize the need for enhancing these options to reach the net-zero emissions target. Under all NZE scenarios, CDR implementation is indispensable to offsetting the emissions from hard-to-decarbonize sectors. Even in the NZE-AF, NZE-LD, and NZE-IM scenarios, where emissions from energy demand sectors are dramatically reduced, CDR plays an important role in offsetting CO_2 emissions from industrial processes as well as non-CO_2 emissions.

In addition to these measures, the NZE scenarios assessed in this study involve diverse options. First, as presented in the NZE-CR scenario, upscaling of CDR is a cost-effective option if increasing the amount of geological storage is feasible, as other NZE scenarios associated with CCS limitation involve increased mitigation costs. Lowering energy demand can also be a cost-effective option if major lifestyle and behavioral changes are feasible, while additional costs required for energy service demand changes are not considered in this study. The utilization of hydrogen generated from domestic resources is an option for decarbonizing some transport and industry sectors for which electrification is difficult or costly, although it leads to increased mitigation cost. Importing of low-carbon energy carriers and emission allowances can be effective, but concerns over import cost and energy security must be considered, as these options may be associated with high import dependency and increased import costs. Although this study explored diverse options for achieving net-zero emissions targets of Japan, each scenario involves several technological, economic and societal challenges. Therefore, it is essential to develop national decarbonization strategies that take these risks into account.

Several caveats related to the interpretation of this study's model results should be noted. First, although we considered constant prices for the import of low-carbon energies and emission allowances based on the global model results, these assumptions have several uncertainties. Although a previous study indicated that the cost of low-carbon hydrogen is much greater than electricity costs [38], the key parameter assumptions need to be updated accordingly, based on the most current technology perspectives. Technological advances in the production of hydrogen derivatives could promote import-dependent scenarios, wherease the literature provides a more conservative assumption of the Fischer-Tropsch processes [47]. Furthermore, the cost of emission allowance is assumed based on idealized conditions with a uniform global carbon prices in the global energy system model. Nevertheless, the prices and availability of emissions allowances depends on international climate policies and the framework of international trading schemes. In particular, for net-zero emissions to be achieved globally, trading negative emissions is necessary to acquiring emission allowances, and such trading requires legal and political considerations [48]. Second, there are several limitations associated with the structure of AIM/Technology-Japan model. Although this study included only BECCS and DACCS as CDR options, various options such as afforestation, enhanced weathering and biochar, are not considered in this model. Although these options may have smaller negative emission potentials than BECCS and DACCS [49], exploring their potential and costs would be useful. Because the energy service demand is the exogenous parameter in this model, it is not affected by emission constraints or the associated price changes. When the energy service demand estimation is endogenized, CDR and hydrogen derivative requirements would be reduced compared with the results of this study to some extent. Nevertheless, it would not hinder the importance of CDR, given that the energy demand reduction alone does not remove the residual emissions. Third, the NZE-IM scenario associates import cost increases with concerns about import dependency. Energy security risks depend on the diversity of the exporting countries [50], which this study did not analyze explicitly. Because regional distributions of hydrogen derivative exporters may differ from those of today's fossil fuels, a more detailed analysis of international trade of hydrogen derivatives would be useful for informing energy security concerns for national policymaking.

4.2. *Potential role of global scenarios in national scenario development*

The results of this study highlight the importance of global climate change mitigation scenarios to the development of national decarbonization strategies. In particular, for countries that may participate in low-carbon energy trading, quantitative estimation of tradable low-carbon energy carriers with a global model is useful. National models must consistently incorporate such global scenario information. Furthermore, although the results of this study are based on a single global model, the consideration of outputs from multiple models would be beneficial, as uncertainties in energy price or potential estimates could be considered. In addition, international trading of hydrogen derivatives and synthetic hydrocarbon fuels requires the tracking of emissions associated with their supply chains [51]. Although imported hydrogen and synfuels are assumed to be derived from carbon neutral sources in this study, there may be risks of emission leakage or unintended emission increases under specific conditions, such as fragmented international climate policies. Thus, information about the emission intensity of these energy carriers is essential when considering hydrogen trading in national scenario assessment. Although global IAMs have already demonstrated their economic outputs for various scenario users [52], the provision of specialized scenario information on energy trade is expected in the future.

In addition, because the cost of hydrogen derivatives can be affected significantly by technology development, it is useful to update the global scenarios frequently, based on the latest technology perspectives for renewable energies and electrolyzer cost. Moreover, because the technology development and cost decrease of DAC would contribute to reducing international carbon prices [53,54], updated information from the global models is useful for national mitigation strategies when considering emission trading as an option.

Although national models have clear advantages in their detailed representation of nation-specific contexts, their assessments may carry the potential risk of high dependency on the import of low-carbon energy carriers and emission allowances, which could potentially lead to a mismatch between national and global information, as reported for the accounting of land-use fluxes [55]. A similar issue may emerge in energy sectors associated with international trade; thus, the research community faces the challenge of developing a framework that ensures consistency between global energy supply potential and collective national energy demand information.

Transparency about the model assumptions of national scenarios is needed. In particular, for any scenario that assumes low-carbon energy imports, clarification of cost assumptions is essential. Furthermore, an approach similar to this study can be applied to sub-national and institutional decarbonization strategies, using information from national or global IAMs. In this regard, improving the transparency of national models and provision of national scenario for various uses will be useful.

CRediT authorship contribution statement

Ken Oshiro: Conceptualization, Methodology, Software, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Shinichiro Fujimori:** Methodology, Software, Writing – review & editing.

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.

Data availability

The Scenario data generated in this study are available at the Zenodo repository (https://doi.org/10.5281/zenodo.10068134). The source code used for scenario data analysis and figure production is provided in the GitHub repository (https://github.com/kenoshiro/JapanNZE). The source code of the AIM/Technology-Japan is available at https://github.com/KUAtmos/AIMTechnology_core. Data not included in these repositories are available from the corresponding author upon reasonable request.

Acknowledgements

This study was supported by the JST Social scenario research program towards a carbon neutral society (JPMJCN2301), JSPS KAKENHI Grant Number JP23K04087, the Environment Research and Technology Development Fund (JPMEERF20211001) of the Environmental Restoration and Conservation Agency provided by the Ministry of Environment of Japan, and the Sumitomo Electric Industries Group CSR Foundation.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100128.

References

[1] N. Höhne, M.J. Gidden, M. den Elzen, F. Hans, C. Fyson, A. Geiges, et al., Wave of net zero emission targets opens window to meeting the Paris Agreement, Nat. Clim. Chang. 11 (2021) 820–822, https://doi.org/10.1038/s41558-021-01142-2.
[2] M. Roelfsema, H.L. van Soest, M. Harmsen, D.P. van Vuuren, C. Bertram, M. den Elzen, et al., Taking stock of national climate policies to evaluate implementation of the Paris Agreement, Nat. Commun. 11 (2020) 2096, https://doi.org/10.1038/s41467-020-15414-6.
[3] D-J van de Ven, S. Mittal, A. Gambhir, R.D. Lamboll, H. Doukas, S. Giarola, et al., A multimodel analysis of post-Glasgow climate targets and feasibility challenges, Nat. Clim. Chang. 13 (2023) 570–578, https://doi.org/10.1038/s41558-023-01661-0.
[4] H. Waisman, C. Bataille, H. Winkler, F. Jotzo, P. Shukla, M. Colombier, et al., A pathway design framework for national low greenhouse gas emission development strategies, Nat. Clim. Chang. 9 (2019) 261–268, https://doi.org/10.1038/s41558-019-0442-8.
[5] C. Guivarch, E. Kriegler, J. Portugal-Pereira, V. Bosetti, J. Edmonds, M. Fischedick, et al., Annex III: scenarios and modelling methods, editors, in: PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, D McCollum, et al. (Eds.), Climate Change 2022: Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, 2022.
[6] F. Lecocq, H. Winkler, J.P. Daka, S. Fu, J.S. Gerber, S. Kartha, et al., Mitigation and development pathways in the near- to mid-term, editors, in: PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, D McCollum, et al. (Eds.), Climate Change 2022: Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, 2022.
[7] R. Rodrigues, R. Pietzcker, P. Fragkos, J. Price, W. McDowall, P. Siskos, et al., Narrative-driven alternative roads to achieve mid-century CO2 net neutrality in Europe, Energy 239 (2022) 121908, https://doi.org/10.1016/j.energy.2021.121908.
[8] M. Browning, J. McFarland, J. Bistline, G. Boyd, M. Muratori, M. Binsted, et al., Net-zero CO2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy Clim. Chang. 4 (2023) 100104, https://doi.org/10.1016/j.egycc.2023.100104.
[9] F. Schreyer, G. Luderer, R. Rodrigues, R.C. Pietzcker, L. Baumstark, M. Sugiyama, et al., Common but differentiated leadership: strategies and challenges for carbon neutrality by 2050 across industrialized economies, Environ. Res. Lett. 15 (2020) 114016, https://doi.org/10.1088/1748-9326/abb852.
[10] H. Duan, S. Zhou, K. Jiang, C. Bertram, M. Harmsen, E. Kriegler, et al., Assessing China's efforts to pursue the 1.5°C warming limit, Science 372 (2021) 378–385. https://www.science.org/doi/abs/10.1126/science.aba8767.
[11] K. Riahi, R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, et al., Mitigation pathways compatible with long-term goals, editors, in: PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, D McCollum, et al. (Eds.), Climate Change 2022: Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press, Cambridge, UK and New York, 2022.
[12] K. Oshiro, S. Fujimori, T. Hasegawa, S. Asayama, H. Shiraki, K. Takahashi, Alternative, but expensive, energy transition scenario featuring carbon capture and utilization can preserve existing energy demand technologies, One Earth. 6 (2023) 872–883, https://doi.org/10.1016/j.oneear.2023.06.005.
[13] I. Azevedo, C. Bataille, J. Bistline, L. Clarke, S. Davis, Net-zero emissions energy systems: what we know and do not know, Energy Clim. Chang. 2 (2021) 100049, https://doi.org/10.1016/j.egycc.2021.100049.
[14] S. Fujimori, I. Kubota, H. Dai, K. Takahashi, T. Hasegawa, J.-Y. Liu, et al., Will international emissions trading help achieve the objectives of the Paris Agreement? Environ. Res. Lett. 11 (2016) 104001 https://doi.org/10.1088/1748-9326/11/10/104001.
[15] J. Edmonds, S. Yu, H. McJeon, D. Forrister, J. Aldy, N. Hultman, et al., How much could Article 6 enhance nationally determined contribution ambition toward Paris Agreement goals through economic efficiency? Clim. Chang. Econ. (Singap) 12 (2021) 2150007. https://www.worldscientific.com/doi/abs/10.1142/S201000782150007X.
[16] K. Oshiro, K. Gi, S. Fujimori, H.L. van Soest, C. Bertram, J. Després, et al., Mid-century emission pathways in Japan associated with the global 2°C goal: national and global models' assessments based on carbon budgets, Clim. Change 162 (2019) 1913–1927, https://doi.org/10.1007/s10584-019-02490-x.
[17] R. Schaeffer, A.C. Köberle, H.L. van Soest, C. Bertram, G. Luderer, K. Riahi, et al., Comparing transformation pathways across major economies, Clim. Change 162 (2020) 1787–1803, https://doi.org/10.1007/s10584-020-02837-9.
[18] L.B. Baptista, R. Schaeffer, H.L. van Soest, P. Fragkos, P.R.R. Rochedo, D. van Vuuren, et al., Good practice policies to bridge the emissions gap in key countries, Global Environ. Change 73 (2022) 102472, https://doi.org/10.1016/j.gloenvcha.2022.102472.
[19] H.L. van Soest, L. Aleluia Reis, L.B. Baptista, C. Bertram, J. Després, L. Drouet, et al., Global roll-out of comprehensive policy measures may aid in bridging emissions gap, Nat. Commun. 12 (2021) 6419, https://doi.org/10.1038/s41467-021-26595-z.
[20] S. Fujimori, V. Krey, D. van Vuuren, K. Oshiro, M. Sugiyama, P. Chunark, et al., A framework for national scenarios with varying emission reductions, Nat. Clim. Chang. 11 (2021) 472–480, https://doi.org/10.1038/s41558-021-01048-z.
[21] A.C. Köberle, V. Daioglou, P. Rochedo, A.F.P. Lucena, A. Szklo, S. Fujimori, et al., Can global models provide insights into regional mitigation strategies? A diagnostic model comparison study of bioenergy in Brazil, Clim. Change 170 (2022) 2, https://doi.org/10.1007/s10584-021-03236-4.
[22] P. Fragkos, H.L. van Soest, R. Schaeffer, L. Reedman, A.C. Köberle, N. Macaluso, et al., Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States, Energy 216 (2021) 119385, https://doi.org/10.1016/j.energy.2020.119385.
[23] M. Sugiyama, S. Fujimori, K. Wada, K. Oshiro, E. Kato, R. Komiyama, et al., EMF 35 JMIP study for Japan's long-term climate and energy policy: scenario designs and key findings, Sustain. Sci. 16 (2021) 355–374, https://doi.org/10.1007/s11625-021-00913-2.
[24] P. Fragkos, K. Fragkiadakis, L. Paroussos, R. Pierfederici, S.S. Vishwanathan, A. C. Köberle, et al., Coupling national and global models to explore policy impacts of NDCs, Energy Policy 118 (2018) 462–473, https://doi.org/10.1016/j.enpol.2018.04.002.
[25] K. Calvin, L. Clarke, V. Krey, G. Blanford, K. Jiang, M. Kainuma, et al., The role of Asia in mitigating climate change: results from the Asia modeling exercise, Energy Econ. 34 (2012) S251–SS60, https://doi.org/10.1016/j.eneco.2012.09.003.
[26] K. Oshiro, T. Masui, M. Kainuma, Transformation of Japan's energy system to attain net-zero emission by 2050, Carbon. Manage 9 (2018) 493–501, https://doi.org/10.1080/17583004.2017.1396842.
[27] E. Kato, A. Kurosawa, Role of negative emissions technologies (NETs) and innovative technologies in transition of Japan's energy systems toward net-zero CO2 emissions, Sustain. Sci. (2021), https://doi.org/10.1007/s11625-021-00908-z.
[28] M. Sugiyama, S. Fujimori, K. Wada, S. Endo, Y. Fujii, R. Komiyama, et al., Japan's long-term climate mitigation policy: multi-model assessment and sectoral challenges, Energy 167 (2019) 1120–1131, https://doi.org/10.1016/j.energy.2018.10.091.
[29] K. Oshiro, M. Kainuma, T. Masui, Assessing decarbonization pathways and their implications for energy security policies in Japan, Clim. Policy. 16 (2016) S63–S77, https://doi.org/10.1080/14693062.2016.1155042.
[30] G. Luderer, R.C. Pietzcker, S. Carrara, H.S. de Boer, S. Fujimori, N. Johnson, et al., Assessment of wind and solar power in global low-carbon energy scenarios: an introduction, Energy Econ. 64 (2017) 542–551, https://doi.org/10.1016/j.eneco.2017.03.027.
[31] Y. Matsuo, S. Endo, Y. Nagatomi, Y. Shibata, R. Komiyama, Y. Fujii, A quantitative analysis of Japan's optimal power generation mix in 2050 and the role of CO2-free hydrogen, Energy 165 (2018) 1200–1219, https://doi.org/10.1016/j.energy.2018.09.187.
[32] A. Ozawa, Y. Kudoh, A. Murata, T. Honda, I. Saita, H. Takagi, Hydrogen in low-carbon energy systems in Japan by 2050: the uncertainties of technology development and implementation, Int. J. Hydrogen. Energy 43 (2018) 18083–18094, https://doi.org/10.1016/j.ijhydene.2018.08.098.
[33] T. Otsuki, H. Obane, Y. Kawakami, K. Shimogori, Y. Mizuno, S. Morimoto, Y. Matsuo, Energy mix for net zero CO2 emissions by 2050 in Japan, Electr. Eng. Jpn. 215 (2022) e23396, https://doi.org/10.1002/eej.23396.
[34] METI. Comparison of the results of 2050 scenario analysis (in Japanese). 2021. https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/2021/045/045_004.pdf.

[35] K. Oshiro, S. Fujimori, Y. Ochi, T. Ehara, Enabling energy system transition toward decarbonization in Japan through energy service demand reduction, Energy 227 (2021) 120464, https://doi.org/10.1016/j.energy.2021.120464.
[36] S. Fujimori, K. Oshiro, H. Shiraki, T. Hasegawa, Energy transformation cost for the Japanese mid-century strategy, Nat. Commun. 10 (2019) 4737, https://doi.org/10.1038/s41467-019-12730-4.
[37] E. Byers, V. Krey, E. Kriegler, K. Riahi, R. Schaeffer, J. Kikstra, et al., AR6 Scenarios Database hosted by IIASA. International Institute for Applied Systems Analysis, International Institute for Applied Systems Analysis, 2022 editor, https://data.ene.iiasa.ac.at/ar6/.
[38] K. Oshiro, S. Fujimori, Role of hydrogen-based energy carriers as an alternative option to reduce residual emissions associated with mid-century decarbonization goals, Appl. Energy 313 (2022) 118803, https://doi.org/10.1016/j.apenergy.2022.118803.
[39] G. Realmonte, L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A.C. Köberle, M. Tavoni, An inter-model assessment of the role of direct air capture in deep mitigation pathways, Nat. Commun. 10 (2019) 3277, https://doi.org/10.1038/s41467-019-10842-5.
[40] E. Baik, K.P. Chawla, J.D. Jenkins, C. Kolster, N.S. Patankar, A. Olson, et al., What is different about different net-zero carbon electricity systems? Energy Clim. Chang. 2 (2021) 100046 https://doi.org/10.1016/j.egycc.2021.100046.
[41] K. Oshiro, M. Kainuma, T. Masui, Implications of Japan's 2030 target for long-term low emission pathways, Energy Policy 110 (2017) 581–587, https://doi.org/10.1016/j.enpol.2017.09.003.
[42] W. Wu, T. Hasegawa, S. Fujimori, K. Takahashi, K. Oshiro, Assessment of bioenergy potential and associated costs in Japan for the 21st century, Renew. Energy 162 (2020) 308–321, https://doi.org/10.1016/j.renene.2020.08.015.
[43] K. Oshiro, S. Fujimori, Stranded investment associated with rapid energy system changes under the mid-century strategy in Japan, Sustain. Sci. 16 (2020) 477–487, https://doi.org/10.1007/s11625-020-00862-2.
[44] K. Riahi, D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, et al., The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview, Global Environ. Change 42 (2017) 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.
[45] V. Krey, G. Luderer, L. Clarke, E. Kriegler, Getting from here to there – energy technology transformation pathways in the EMF27 scenarios, Clim. Change 123 (2014) 369–382, https://doi.org/10.1007/s10584-013-0947-5.
[46] K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, et al., Locked into Copenhagen pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals, Technol. Forecast. Soc. Change 90 (2015) 8–23, https://doi.org/10.1016/j.techfore.2013.09.016.
[47] G. Zang, P. Sun, A.A. Elgowainy, A. Bafana, M. Wang, Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process, J. CO2 Utiliz. 46 (2021) 101459, https://doi.org/10.1016/j.jcou.2021.101459.
[48] W. Rickels, A. Proelß, O. Geden, J. Burhenne, M. Fridahl, Integrating carbon dioxide removal into European emissions trading, Front. Clim. 3 (2021). https://www.frontiersin.org/article/10.3389/fclim.2021.690023.
[49] J. Fuhrman, C. Bergero, M. Weber, S. Monteith, F.M. Wang, A.F. Clarens, et al., Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system, Nat. Clim. Chang. 13 (2023) 341–350, https://doi.org/10.1038/s41558-023-01604-9.
[50] D.L. McCollum, V. Krey, K. Riahi, P. Kolp, A. Grubler, M. Makowski, N. Nakicenovic, Climate policies can help resolve energy security and air pollution challenges, Clim. Change 119 (2013) 479–494, https://doi.org/10.1007/s10584-013-0710-y.
[51] K. Bruninx, J.A. Moncada, M. Ovaere, Electrolytic hydrogen has to show its true colors, Joule 6 (2022) 2437–2440, https://doi.org/10.1016/j.joule.2022.09.007.
[52] S. Battiston, I. Monasterolo, K. Riahi, B.J. van Ruijven, Accounting for finance is key for climate mitigation pathways, Science 372 (2021) 918–920. https://www.science.org/doi/abs/10.1126/science.abf3877.
[53] C. Chen, M. Tavoni, Direct air capture of CO2 and climate stabilization: a model based assessment, Clim. Change 118 (2013) 59–72, https://doi.org/10.1007/s10584-013-0714-7.
[54] J. Fuhrman, A. Clarens, K. Calvin, S.C. Doney, J.A. Edmonds, P. O'Rourke, et al., The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5°C and +2°C futures, Environ. Res. Lett. 16 (2021) 114012, https://doi.org/10.1088/1748-9326/ac2db0.
[55] G. Grassi, E. Stehfest, J. Rogelj, D. van Vuuren, A. Cescatti, J. House, et al., Critical adjustment of land mitigation pathways for assessing countries' climate progress, Nat. Clim. Chang. 11 (2021) 425–434, https://doi.org/10.1038/s41558-021-01033-6.