Sustainability Science (2021) 16:347–353
https://doi.org/10.1007/s11625-021-00931-0

SPECIAL FEATURE: EDITORIAL

Energy Scenarios for Long-Term Climate Change Mitigation in Japan

Introduction to the special feature on energy scenarios for long-term climate change mitigation in Japan

Masahiro Sugiyama[1] · Shinichiro Fujimori[2,3,4] · Kenichi Wada[5] · John Weyant[6]

Received: 31 January 2021 / Accepted: 14 February 2021 / Published online: 24 February 2021

Introduction

On October 26, 2020, Prime Minister Suga pledged that Japan would be carbon-neutral by 2050 (Suga 2020). The pledge upgraded Japan's previous long-term strategy of reducing emissions by 80% by 2050 to full decarbonization. Against this background, the government issued the Green Growth Strategy in December 2020 (Government of Japan 2020), and is in the process of amending the Law Concerning the Promotion of the Measures to Cope with Global Warming (as of this writing). It is also revising the Strategic Energy Plan, which will be finalized by summer 2021. This month (March 2021) also marks the 10th anniversary of the 2011 Great East Japan Earthquake, which triggered devastating tsunamis and the meltdown of the Fukushima Dai'ichi nuclear power plants. Japan's energy policy is at a crossroads.

The prime minister emphasized in his speech that the transition would entail "transformation of the industrial structure and economy and society" (authors' translation). This is not an understatement; the challenge of decarbonization is widely acknowledged, and decarbonization transition requires a wide range of policies to accelerate technological innovations and societal changes. It is, therefore, vital to improve the science of energy transition to inform such policies.

Energy scenarios constitute one such scientific input. Scenarios describe internally consistent futures and are intended to inform current policy and decision-making. In sustainability science and related fields, scenarios have been used to inform policy debates on various topics, including global climate change mitigation (IPCC 2018; UNEP and UNEP DTU Partnership 2020), global environmental policy (UN Environment 2019), and biodiversity (IPBES 2016; Saito et al. 2019).

The use of scenarios to inform climate and energy policy has expanded recently because of the shift from the top-down regime of the Kyoto Protocol to the hybrid top-down and bottom-up architecture of the Paris Agreement. There have been several coordinated studies of scenarios at the national level as well (see below).

This special feature presents a collection of papers on energy scenarios in Japan. The main pillar is the Stanford Energy Modeling Forum (EMF) 35 Japan Model Intercomparison Project (JMIP), which has provided eight contributions in this issue. In addition, the special feature also includes two external contributions on energy scenarios for Japan. This special feature showcases a collection of the most up-to-date research on energy scenarios in Japan.

EMF 35 JMIP was intended as a multi-model scenario analysis on Japan's nationally determined contribution (NDC) (Government of Japan 2015) and long-term strategy (Government of Japan 2019) in light of a range of uncertainties. Japan's current NDC is a 26% reduction in emissions

Handled by Osamu Saito, Institute for Global Environmental Strategies, Japan.

✉ Masahiro Sugiyama
masahiro_sugiyama@alum.mit.edu;
masahiro@ifi.u-tokyo.ac.jp

[1] Institute for Future Initiatives, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

[2] Graduate School of Engineering, Kyoto University, Kyoto daigaku-katsura, Nishikyo-ku, Kyoto 615-8530, Japan

[3] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan

[4] International Institute for Applied System Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria

[5] Research Institute of Innovative Technology for the Earth, 9-2 Kizugawadai, Kizugawa, Kyoto 619-0292, Japan

[6] Department of Management Science and Engineering, Room 260, Huang Engineering Center, Stanford University, Stanford, CA 94305-4026, USA

relative to the 2013 level by 2030, and its long-term strategy is an 80% reduction by 2050. Although our scenario design includes full decarbonization, our central scenarios focus on an 80% reduction in emissions by 2050 because our project ran from April 2017 until March 2020, which was before the net-zero pledge by the Japanese government in October 2020.

This editorial describes the motivation for this special feature by reviewing policy and the literature, with the latter including several previous EMF studies. We distill the key results of our project from the scenario design paper, cross-cutting analyses, and contributions from individual modeling teams and external researchers.

Literature review

Recently, the literature saw a rapid growth in country-level mitigation scenarios (or pathways), and a number of projects have been conducted, including Low-Carbon Asia Research Project (Matsuoka et al. 2013), MILES (Modelling and Informing Low-Emission Strategies) (Spencer and Coauthors 2015), the Deep Decarbonization Pathways Project (DDPP) (Waisman et al. 2019), CD-LINKS (Linking Climate and Development Policies—Leveraging International Networks and Knowledge Sharing) (Rogelj et al. 2017). In addition, the examples of the ongoing projects include COMMIT (Climate Policy assessment and Mitigation Modelling to Integrate national and global Transition pathways) (COMMIT 2019) and APEC Energy Demand and Supply Outlook (APERC 2019).

Multi-model assessments have also been conducted in some jurisdictions, including the United States (EMF 24) (Fawcett et al. 2014b), the European Union (EMF 28) (Knopf et al. 2013), Brazil (Lucena et al. 2016), China (Lugovoy et al. 2018), and Japan (Sugiyama et al. 2019). The previous EMF studies are particularly relevant to the current special feature.

The EMF 24 study involved extensive policy and technology sensitivity analyses that employed nine models, all of which were a part of the technology sensitivity analysis in (Clarke et al. 2014) and seven of which were in the policy scenario analysis in (Fawcett et al. 2014a). The scenario design included policies with several different stringency levels, technological assumptions [e.g., the availability of nuclear power/carbon capture and storage (CCS), improvements in energy efficiency]. Although the availability of technology greatly affects the cost metric, no single technology was dominant at the level of an 80% reduction in emissions. The policy scenario analysis demonstrated that transportation sector policy (e.g., strengthened fuel economy standards) is not economically effective compared to economy-wide caps and trading.

The sister project of EMF 24 in Europe was EMF 28 (Knopf et al. 2013). The design of study was similar to that of EMF 24, and 13 models participated. The carbon price range found in EMF 28 was slightly higher than that in EMF 24. In the analysis of technological sensitivity, CCS was not found to be essential, a finding identical to that of EMF 24.

More recently, EMF 32 (Fawcett et al. 2018) examined a set of carbon tax scenarios and a set of technology scenarios on key technology dimensions. The carbon tax track of EMF 32 (McFarland et al. 2018) was a follow-up to EMF24. In EMF24, the revenue raised from carbon tax was returned to households as a lump sum; however, EMF 32 explored other policy designs. The results from 11 models of stylized carbon tax scenarios indicated that the revenue recycling design has many implications. The economic costs of carbon taxes can be decreased by reducing capital and labor taxes. Revenue recycling also was found to have distributional impacts.

Another track of EMF 32 explored mitigation in the power sector with idealized carbon taxes modeled after the Clean Power Plan of the Obama administration; 16 models were presented (Bistline et al. 2018). The study found that given various sources of uncertainties (policies, technologies, and the market), the decline of coal and the expansion of natural gas, wind and solar power are robust trends.

In Japan, there were significant model intercomparison projects but many of them were intricately connected with the political process. They were organized by the government and the results of model intercomparisons were not published in the academic literature (Sugiyama et al. 2021 for review). In the academic literature, Japanese modeling teams have been actively contributing to large-scale modeling exercises including the Special Report on Emissions Scenario (SRES) (Morita et al. 2000), Representative Concentration Pathways (RCPs) (Masui et al. 2011), Shared Socioeconomic Pathways (SSPs) (Fujimori et al. 2017), Asian Modeling Exercise (Calvin et al. 2012), DDPP (Kainuma et al. 2015), and EMF studies such as EMF 27 (Kriegler et al. 2014) and European projects (e.g., Kriegler et al. 2015); however, there was no fully fledged, academic MIP dedicated to Japan.

Recently, we began to see more in-depth model intercomparison projects on Japan. As part of CD-Links, Oshiro et al. (2019) utilized two national models and seven global models to compare the consistency between the carbon budget and the long-term strategy. They found that the goal of an 80% reduction in domestic emissions is consistent with economically efficient global pathways for the 2-degree temperature target. As a pilot project on long-term climate policy of Japan, Sugiyama et al. (2019) employed six models to investigate Japan's long-term strategy for 2050, and found that the marginal costs of abatement are comparable to, or higher than, those in the United States or the European Union. They also identified the emissions from the industry sector as the hardest to abate in partial equilibrium models.

Motivations and approaches

The previous analyses, however, did not touch on how Japan could achieve large emissions reductions under many kinds of uncertainty. EMF 35 JMIP is, therefore, intended to analyze long-term energy and climate policy and address multiple sources of uncertainty, including policy stringency, technological constraints, service demand levels, and energy import costs (Sugiyama et al. 2021).

EMF 35 began with the EMF 24, 27, and 28 scenario architecture that explored technological uncertainty and levels of climate change mitigation (note that these three EMF studies have similar scenario architectures). This approach gives us some insights into whether conclusions of global and Western MIPs can be applicable to national, Japanese, context and if not, raise a fundamental question about unique challenges in Japan. In the context of Japanese energy system which currently heavily relies on imports of energy, we explicitly deal with the trade condition as an uncertainty element. Finally, as is quite frequently debated, EMF 35 also examined low-energy-demand options in Japan, as the share of industry in final energy is, and is expected to be, higher in Japan than other OECD countries (e.g., the US and EU) (Sugiyama et al. 2019). In summary, EMF 35 provides meaningful Japanese policy insights as well as an exemplar for demonstrating how to extend the global MIP architecture and contextualize it into a national scenario assessment.

Though the scenario design was informed by previous EMF exercises, EMF 35 did not incorporate a scenario matrix (e.g., one that put policy dimension on one axis and a technological dimension on the other) as that would have led to an impractically high number of scenarios. We studied the technological dimension, service demand levels, and energy import prices independently. For the policy dimension, we analyzed the baseline and the standard policy scenario, which combines the NDC (26% reduction by 2030 relative to the 2013 levels) and the long-term strategy (80% reduction by 2050). This policy dimension was then combined with other dimensions and also examined different emissions reduction levels (70%, 90%, and 100% in 2050, for instance).

EMF 35 JMIP included five energy-economic and integrated assessment models: AIM/Enduse-Japan, AIM/Hub-Japan, DNE21 (distinct from DNE21+, which is a different model), IEEJ_Japan 2017, and TIMES-Japan. The models are energy system models with the exception of AIM/Hub-Japan, which is a computational general equilibrium model. EMF 35 JMP does not represent an exhaustive list of models active in Japan; however, it does represent the modeling activity in the country fairly well.

Key findings

The special feature contains one main paper that laid out the scenario design (Sugiyama et al. 2021) and three cross-cutting papers that addressed essential issues for long-term mitigation in Japan: the expansion of renewables (Shiraki et al. 2021), electrification (Sakamoto et al. 2021), and industrial decarbonization (Ju et al. 2021a).

Sugiyama et al. (2021) identified common patterns for mitigation across different models and scenario settings: economy-wide improvements in energy efficiency, the decarbonization of electricity, and end-use electrification. The models also suggest that heavy industries will be one of the hardest to decarbonize in the absence of structural changes in the economy. Furthermore, the models reveal that future policy must be substantially enhanced, compared to the strength and breadth of current policy, to achieve the goal of an 80% reduction in emissions.

Shiraki et al. (2021) elucidated the role of renewables for the in-depth mitigation emissions from the power sector. Unless nuclear or biomass energy is made widely available, variable renewables will expand greatly, with a median share of 52% under mitigation scenarios. They found that halving the capital costs of renewables could lower policy costs by 8.7% (inter-model median). As the current capital cost of solar PVs in Japan is twice the international standard, there is an opportunity for cost-effective emissions mitigation in the power sector by converging the capital cost of VREs to the international level.

Sakamoto et al. (2021) considered the demand side and analyzed the role of end-use electrification, which both analysts and policymakers recognized as an important strategy. Under the target of an 80% reduction, electrification rates in the models increased to 37–66% in 2050, up from 26% in 2010. The upward trend in electrification is robust against changes in different scenarios, and tightening the stringency of the emissions constraint further increases electrification. There has been a historical trend of electrification (0.30% point/year), but the pace needs to reach the range of 0.46–1.58%/year from 2030 to 2050 to achieve deep decarbonization.

One of the most important sectors for decarbonization in Japan is industry. Industry has a higher share of final energy or emissions in Japan than in the United States or Europe. Many material production processes in the industrial sector are not suitable for electrification and there are no easy solutions to this issue. Ju et al. (2021a) showed that carbon capture and storage (CCS) and hydrogen are key to deep decarbonization, particularly the deep mitigation of steelmaking.

By taking stock of the current modeling of the industrial sector, Ju et al. (2021a) also revealed that more technologies in the early stages of development should be incorporated in current models, particularly in terms of assessing the net-zero target.

Although EMF 35 included a 100% emissions reduction scenario, the focus was on the long-term strategy (an 80% reduction). Furthermore, although current policy has shifted from an 80% emissions reduction to a net-zero goal, our findings constitute a building block for the latter as that requires additional strategies such as carbon dioxide removal and the extended use of new energy carriers such as hydrogen.

Insights from papers in the special feature

The special feature includes contributions from individual modeling teams.

Komiyama and Fujii (2021) studied the power sector using a model that included high spatiotemporal resolutions to investigate strategies to integrate offshore wind power. Although the great resource potential of this power source provides a great opportunity for emissions mitigation, detailed power system planning is necessary because the resources are spatially concentrated and subject to grid constraints. This study identified an optimal system integration for a moderate capacity of offshore wind. Furthermore, as the Japanese government's Green Growth Strategy identified offshore wind as a key technology area, this paper provided a key insight into how best to incorporate this energy source in the power generation mix.

Matsuo and Komiyama (2021) estimated the average and relative marginal system levelized cost of electricity (LCOE) in Japan. Variable renewable energy (VRE) will play a key role in the decarbonization of the Japanese power sector; however, additional "integration" costs related to grid expansion, power curtailment, and power storage would be required as the share of VRE increases. Matsuo and Komiyama (2021) shows that the relative marginal system LCOE of VRE will rise much more sharply than the average marginal system LCOE when the share of VRE rises, even if the cost of VRE declines rapidly in the future. This study contributed to the quantitative assessment of the magnitude of challenges associated with a large-scale introduction of VRE in making Japan's power system low-carbon.

Kato and Kurosawa (2021) explored the role of negative emission technologies (NETs) in energy systems, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS). These technologies should be critical to realizing net-zero emission because emissions must become negative at some point in the future, if Japan maintains its current long-term policy goal. The implication of this study is that earlier deployment of BECCS with domestic biomass can contribute effectively to achieving the target, supported by DACCS at a later period, if both technologies are available. This study simulated the implementation of these NETs, which are inevitable under stringent climate policy goals.

Oshiro and Fujimori (2021) estimated stranded investments in both the supply and demand sides. It is well known that stranded investments in the energy supply sectors occur mainly in coal power plants without CCS capabilities, particularly in scenarios without enhanced near-term mitigation targets. However, and more importantly, increases in stranded investments in energy demand sectors were observed primarily under stringent mitigation scenarios. Oshiro and Fujimori (2021) suggest a complementary subsidy policy in addition to a simple carbon tax for non-fossil-fuel-based devices. They advanced scientific knowledge in a way that would be valuable beyond the Japanese context by estimating stranded assets and conducting a complementary policy assessment under EMF 35.

Silva Herran and Fujimori (2021) assessed the energy and macroeconomic impacts of enhancing the ambitions for 2040 and 2050 emission reduction targets in Japan via a computable general equilibrium (CGE) model. They highlighted the conditions in the 2040s, including emissions levels, energy systems, and macroeconomic responses. These are likely to be discussed intensively in the near future given the post-NDC debate. Silva Herran and Fujimori (2021) showed that, compared to the linear interpolation of the current long-term goal (a 53% reduction in emissions compared to 2005 levels by 2040), enhancing the goals of the 2040 and 2050 targets (a 63% reduction compared to 2005 levels by 2040 and zero emissions by 2050) increased the share of energy from low-carbon sources more markedly than the decreases in energy intensity, and that this increased macroeconomic costs by 19–72%. This paper contributed significantly to enhancing forthcoming climate policy debates and the next cycle of the Global Stocktake under the Paris Agreement.

Takeda and Arimura (2021) examined the implications of recycling the revenue from carbon taxes using a CGE framework. The study examined four revenue recycling scenarios: a lump-sum transfer to households and reduction in taxes on income, corporations, and consumption. The model analysis revealed that reducing corporate tax had the most positive impact on GDP. After Prime Minister Suga made the carbon neutrality pledge in October 2020, the government initiated discussions on carbon pricing. This study provides useful policy inputs on designing a carbon pricing scheme in Japan.

To date, discussions on emissions reduction have been limited to model-based analyses; however, energy scenarios are multi-faceted tools and can also be used for education and outreach. Suzuki et al. (2021) designed a game-based lesson to enhance how key energy policy issues are learned. The game describes strategic interactions among key stakeholders over a decision regarding an energy mix. An analysis of the reports submitted by 128 students who completed the game demonstrated that more than 80% of them reported an improvement in how they learned.

The way forward

This special feature broke new ground and provides numerous new insights into issues related to long-term energy and climate policies. Nevertheless, there are many problems that remain unresolved and should be addressed in future studies.

There is ample opportunity to improve MIP analyses. First, the policy goals should be upgraded from 80 to 100% or even higher and the time horizon should go beyond 2050. Some papers (Oshiro et al. 2018; Schreyer et al. 2020) have already analyzed the net-zero target, but no MIP examined the Japanese target. MIPs are particularly useful for demonstrating a wide range of possible energy and power mixes.

Second, scenario design should be improved to reflect both ongoing policy discussions and the accompanying targets as well as incorporate insights from detailed, sector-based analysis. In terms of innovation, the current scenario setting was idealized and included doubling and halving the costs of renewables. Future scenario design should explicitly reflect the technology development targets of government goals such as the Green Growth Strategy, as one paper from the EMF 34 did (Hodson et al. 2018). Similarly, the demand sensitivity of services was also idealized and can be improved; for example by following the low-energy-demand scenario study (Grubler et al. 2018).

Finally, there are a number of potentially important research topics related to energy scenarios that go beyond model intercomparisons.

Co-production, for example, is a key methodological approach in sustainability science, and scenarios can be co-produced in a participatory manner. This was reported in a special feature (Saito et al. 2019); however, it is not a panacea and suffers from several problems, including the involvement of the fixed, limited set of stakeholders (Lemos et al. 2018). Besides, direct participatory scenario research could be difficult, given the politicization of energy policy in Japan (including that related to nuclear power).

Nevertheless, it is important to facilitate conversations about societal and policy energy scenarios in Japan, and there are many methodologies other than participatory scenario research. As Suzuki et al. (2021) demonstrated, developing effective education tools is an important research area. Therefore, the development of communication tools, including software, allows for the manipulation and visualization of scenarios is also important. One example is "miptool," which is based on the R computational language and has flexibility to deal with the Japanese and other languages (Ju et al. 2021b). Further development on this front is vitally needed.

Finally, there remains a critical issue of how to place energy scenario analysis in policymaking. Both the three-year cycle in which Japan's Strategic Energy Plan is reviewed and the five-year cycle in which international climate policy is reviewed require inputs from energy scenarios. The latter should be updated periodically to reflect both technological developments and changes in society. Exploring a useful method to formally incorporate energy scenario analysis in policy review is, therefore, a key challenge—in part because policy analysis in general in Japan suffers from numerous problems (Adachi et al. 2015). Meta-analysis of energy policy analysis constitutes an important research topic, and the insights from such research would enable energy scenarios to contribute to discussions of energy futures in Japan more fully.

Acknowledgements Most of the papers published in this special feature was supported by the Environment Research and Technology Development Fund (JPMEERF20172004) of the Environmental Restoration and Conservation Agency of Japan. MS was also supported by JSPS KAKENHI (Grant Number JP20H04395). SF was supported by the Sumitomo Foundation.

References

Adachi Y, Hosono S, Iio J (eds) (2015) Policy analysis in Japan. Policy Press, Bristol and Chicago

APERC (2019) APEC energy demand and supply outlook. 7th edition, vol I. Asia Pacific Energy Research Centre, Tokyo

Bistline JE, Hodson E, Rossmann CG et al (2018) Electric sector policy, technological change, and US emissions reductions goals: results from the EMF 32 model intercomparison project. Energy Econ 73:307–325. https://doi.org/10.1016/j.eneco.2018.04.012

Calvin K, Clarke L, Krey V et al (2012) The role of Asia in mitigating climate change: results from the Asia modeling exercise. Energy Econ 34:S251–S260. https://doi.org/10.1016/j.eneco.2012.09.003

Environment UN (ed) (2019) Global environment outlook—GEO-6: healthy planet, healthy people, 1st edn. Cambridge University Press, Cambridge

Clarke L, Fawcett AA, Weyant JP et al (2014) Technology and US emissions reductions goals: results of the EMF 24 modeling exercise. Energy J. https://doi.org/10.5547/01956574.35.SI1.2

COMMIT (2019) Deliverable 2.2: Long-term, low-emission pathways in Australia, Brazil, Canada, China, EU, India, Indonesia, Japan, Republic of Korea, Russia, and United States. PBL Netherlands Environmental Assessment Agency, The Hague

Fawcett AA, Clarke LC, Rausch S, Weyant JP (2014a) Overview of EMF 24 policy scenarios. Energy J. https://doi.org/10.5547/01956574.35.SI1.3

Fawcett AA, Clarke LE, Weyant JP (2014b) Introduction to EMF 24. Energy J. https://doi.org/10.5547/01956574.35.SI1.1

Fawcett AA, Mcfarland JR, Morris AC, Weyant JP (2018) Introduction to the EMF 32 study on US carbon tax scenarios. Clim Chang Econ 09:1840001. https://doi.org/10.1142/S2010007818400018

Fujimori S, Hasegawa T, Masui T et al (2017) SSP3: AIM implementation of shared socioeconomic pathways. Glob Environ Change 42:268–283. https://doi.org/10.1016/j.gloenvcha.2016.06.009

Government of Japan (2015) Submission of Japan's intended nationally determined contribution (INDC)

Government of Japan (2019) The long-term strategy under the paris agreement

Government of Japan (2020) Green growth strategy accompanying the 2050 carbon neutrality (2050 nen kahbon nyuhtoraritih ni tomonau grihn seicho senryaku)

Grubler A, Wilson C, Bento N et al (2018) A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 3:515–527. https://doi.org/10.1038/s41560-018-0172-6

Hodson EL, Brown M, Cohen S et al (2018) U.S. energy sector impacts of technology innovation, fuel price, and electric sector CO_2 policy: Results from the EMF 32 model intercomparison study. Energy Econ 73:352–370. https://doi.org/10.1016/j.eneco.2018.03.027

IPBES (2016) The methodological assessment report on scenarios and models of biodiversity and ecosystem services. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn

IPCC (2018) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pörtner H-O et al. (eds) Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, p 32

Ju Y, Sugiyama M, Silva Herran D et al (2021a) Industrial decarbonization under Japan's national mitigation scenarios: a multi-model analysis. Sustain Sci. https://doi.org/10.1007/s11625-021-00905-2

Ju Y, Sugiyama M, Silva Herran D et al (2021b) An open-source tool for visualization of climate mitigation scenarios: mipplot. Environ Model Softw Rev. https://doi.org/10.1016/j.envsoft.2021.105001

Kainuma M, Masui T, Oshiro K, Hibino G (2015) Pathways to deep decarbonization in Japan. Institute for Sustainable Development and International Relations (IDDRI) and Sustainable Development Solutions Network (SDSN)

Kato E, Kurosawa A (2021) Role of negative emissions technologies (NETs) and innovative technologies in transition of Japan's energy systems toward net-zero CO_2 emissions. Sustain Sci. https://doi.org/10.1007/s11625-021-00908-z

Knopf B, Chen Y-HH, De Cian E et al (2013) Beyond 2020—strategies and costs for transforming the european energy system. Clim Chang Econ 04:1340001. https://doi.org/10.1142/S2010007813400010

Komiyama R, Fujii Y (2021) Large-scale integration of offshore wind into the Japanese power grid. Sustain Sci. https://doi.org/10.1007/s11625-021-00907-0

Kriegler E, Weyant JP, Blanford GJ et al (2014) The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Clim Chang 123:353–367. https://doi.org/10.1007/s10584-013-0953-7

Kriegler E, Riahi K, Bauer N et al (2015) Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. Technol Forecast Soc Change 90:24–44. https://doi.org/10.1016/j.techfore.2013.09.021

Lemos MC, Arnott JC, Ardoin NM et al (2018) To co-produce or not to co-produce. Nat Sustain 1:722–724. https://doi.org/10.1038/s41893-018-0191-0

Lucena AFP, Clarke L, Schaeffer R et al (2016) Climate policy scenarios in Brazil: a multi-model comparison for energy. Energy Econ 56:564–574. https://doi.org/10.1016/j.eneco.2015.02.005

Lugovoy O, Feng X-Z, Gao J et al (2018) Multi-model comparison of CO_2 emissions peaking in China: lessons from CEMF01 study. Adv Clim Chang Res 9:1–15. https://doi.org/10.1016/j.accre.2018.02.001

Masui T, Matsumoto K, Hijioka Y et al (2011) An emission pathway for stabilization at 6 Wm^{-2} radiative forcing. Clim Chang 109:59–76. https://doi.org/10.1007/s10584-011-0150-5

Matsuo Y, Komiyama R (2021) System LCOE of variable renewable energies: a case study of Japan's decarbonized power sector in 2050. Sustain Sci. https://doi.org/10.1007/s11625-021-00914-1

Matsuoka K, Kainuma M, Fujino J, Ehara T (2013) How to approach Asian low-carbon societies? Glob Environ Res 17:3–10

McFarland JR, Fawcett AA, Morris AC et al (2018) Overview of the EMF 32 study on US carbon tax scenarios. Clim Chang Econ 09:1840002. https://doi.org/10.1142/S201000781840002X

Morita T, Nakićenović N, Robinson J (2000) Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES). Environ Econ Policy Stud 3:65–88. https://doi.org/10.1007/BF03354031

Oshiro K, Fujimori S (2021) Stranded investment associated with rapid energy system changes under the mid-century strategy in Japan. Sustain Sci. https://doi.org/10.1007/s11625-020-00862-2

Oshiro K, Masui T, Kainuma M (2018) Transformation of Japan's energy system to attain net-zero emission by 2050. Carbon Manag 9:493–501. https://doi.org/10.1080/17583004.2017.1396842

Oshiro K, Gi K, Fujimori S et al (2019) Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets. Clim Chang. https://doi.org/10.1007/s10584-019-02490-x

Rogelj J, Fricko O, Meinshausen M et al (2017) Understanding the origin of Paris agreement emission uncertainties. Nat Commun 8:15748. https://doi.org/10.1038/ncomms15748

Saito O, Hashimoto S, Managi S et al (2019) Future scenarios for socio-ecological production landscape and seascape. Sustain Sci 14:1–4. https://doi.org/10.1007/s11625-018-0651-5

Sakamoto S, Nagai Y, Sugiyama M et al (2021) Demand-side decarbonization and electrification: EMF 35 JMIP study. Sustain Sci **(in revision)**

Schreyer F, Luderer G, Rodrigues R et al (2020) Common but differentiated leadership: strategies and challenges for carbon neutrality by 2050 across industrialized economies. Environ Res Lett 15:114016. https://doi.org/10.1088/1748-9326/abb852

Shiraki H, Sugiyama M, Matsuo Y et al (2021) The role of renewables in the Japanese power sector: implications from the EMF35. Sustain Sci. https://doi.org/10.1007/s11625-021-00917-y

Silva Herran D, Fujimori S (2021) Beyond Japanese NDC: energy and macroeconomic transitions towards 2050 in emission pathways with multiple ambition levels. Sustain Sci. https://doi.org/10.1007/s11625-021-00930-1

Spencer T et al (2015) Beyond the numbers: understanding the transformation induced by INDCs. IDDRI - MILES Project Consortium, Paris

Suga Y (2020) Inaugural speech of the prime minister at the 203rd session of the Diet (Dai nihyaku san kai niokeru suga naikaku sohri daijin shoshin hyomei enzetsu) (**in Japanese**). https://www.kantei.go.jp/jp/99_suga/statement/2020/1026shoshinhyomei.html

Sugiyama M, Fujimori S, Wada K et al (2019) Japan's long-term climate mitigation policy: multi-model assessment and sectoral challenges. Energy 167:1120–1131. https://doi.org/10.1016/j.energy.2018.10.091

Sugiyama M, Fujimori S, Wada K et al (2021) EMF 35 JMIP study for Japan's long-term climate and energy policy: scenario designs and key findings. Sustain Sci. https://doi.org/10.1007/s11625-021-00913-2

Suzuki K, Shibuya T, Kanagawa T (2021) Effectiveness of a game-based class for interdisciplinary energy systems education in engineering courses. Sustain Sci. https://doi.org/10.1007/s11625-021-00912-3

Takeda S, Arimura TH (2021) A computable general equilibrium analysis of environmental tax reform in Japan. Sustain Sci. https://doi.org/10.1007/s11625-021-00903-4

UNEP, UNEP DTU Partnership (2020) The emissions gap report 2020. United Nations Environment Programme

Waisman H, Bataille C, Winkler H et al (2019) A pathway design framework for national low greenhouse gas emission development strategies. Nat Clim Chang 9:261–268. https://doi.org/10.1038/s41558-019-0442-8