Energy 167 (2019) 1120–1131

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges

Masahiro Sugiyama [a, *], Shinichiro Fujimori [b, c], Kenichi Wada [d], Seiya Endo [e], Yasumasa Fujii [f], Ryoichi Komiyama [f], Etsushi Kato [g], Atsushi Kurosawa [g], Yuhji Matsuo [e], Ken Oshiro [h], Fuminori Sano [d], Hiroto Shiraki [i]

[a] *Policy Alternatives Research Institute, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*
[b] *Department of Environmental Engineering, Kyoto University, Japan*
[c] *National Institute for Environmental Studies, Japan*
[d] *Research Institute of Innovative Technology for the Earth, Japan*
[e] *Institute of Energy Economics, Japan*
[f] *School of Engineering, The University of Tokyo, Japan*
[g] *Institute of Applied Energy, Japan*
[h] *Mizuho Information & Research Institute, Inc., Japan*
[i] *School of Environmental Science, The University of Shiga Prefecture, Japan*

A R T I C L E I N F O

Article history:
Received 14 March 2018
Received in revised form
23 September 2018
Accepted 15 October 2018
Available online 9 November 2018

Keywords:
Climate change mitigation
Model intercomparison project
Sectoral mitigation
Energy scenarios

A B S T R A C T

Japan is the sixth largest greenhouse gas emitter in 2016 and plays an important role to attain the long-term climate goals of the Paris Agreement. One of the key policy issues in Japan's energy and environmental policy arena is the energy system transition to achieve 80% emissions reduction in 2050, a current policy goal set in 2016. To contribute to the ongoing policy debate, this paper focuses on energy-related CO_2 emissions and analyzes such decarbonization scenarios that are consistent with the government goals. We employ six energy-economic and integrated assessment models to reveal decarbonization challenges in the energy system. The modeling results show that Japan's mitigation scenarios are characterized by high marginal costs of abatement. They also suggest that the industrial sector is likely to have a large final energy share and significant residual emissions under the 80% reduction scenario, though it is generally thought that the transport sector would have large decarbonization challenges. The present findings imply that not only energy policy but also industrial policy may be relevant to the long-term environmental target. Given the high marginal costs exceeding those of negative emissions technologies that could place a cost ceiling, further model development would be crucial.

1. Introduction

1.1. Policy backgrounds: repercussions of the 3/11

In the global energy landscape, Japan occupies a unique position as it had to significantly adjust its energy and climate policy after a sudden shock of the 2011 Great East Japan Earthquake, associated tsunamis, and the nuclear disaster at the Fukushima Daiichi nuclear power plant. The support for nuclear power was already low before the tragedy of March 11, 2011, and the belief in nuclear had been completely shaken [3]. This has resulted in significant changes in every corner of energy and climate policy, ranging from nuclear safety to renewables to electricity and gas market reform (See Refs. [4–6] for reviews on Japan's climate and energy policy).

It is this context within which Japan, the sixth largest emitter of greenhouse gases [7], had to significantly adjust its long-term climate and energy policy. After the 3/11 triple tragedy, Japan retracted from the previous goal of 25% emissions reduction from the 1990 levels by 2020, which was to be supported by a plan to generate more than 40% of electricity with nuclear power. The new goal is a 3.8% reduction by 2020 (see Ref. [8]; and [9] for the previous 2020 goal).

In 2015, Japan submitted its intended Nationally Determined Contribution (NDC) in the run-up toward the Paris Climate Change

* Corresponding author.
E-mail addresses: masahiro_sugiyama@alum.mit.edu, masahiro@pari.u-tokyo.ac.jp (M. Sugiyama).

https://doi.org/10.1016/j.energy.2018.10.091

Table 1
Models participating in this study. The abbreviations for organizations are as follows. NIES: National Institute for Environmental Studies; UTokyo: The University of Tokyo; RITE: Research Institute of Innovative Technology for the Earth; IEEJ: Institute of Energy Economics, Japan; and IAE: Institute of Applied Energy. DNE21+ (MILES version) is abbreviated as DNE21 + V. MILES hereinafter.

Model	Institute	Solution concept	Intertemporal treatment	Regional coverage	Characteristics
AIM/CGE [global]	NIES	General equilibrium	Myopic	Global	Multiple economic sectors represented. Strong at analyzing macroeconomic implications.
AIM/Enduse [Japan]	NIES	Partial equilibrium	Myopic	Japan	Regional breakdown for better power sector representation
DNE21	UTokyo	Partial equilibrium	Intertemporal	Global	Detailed representation of global energy transportation and power generation dispatch
DNE21+ (MILES version)	RITE	Partial equilibrium	Intertemporal	Global	Detailed representation of energy technologies
IEEJ	IEEJ	Partial equilibrium	Intertemporal	Japan	Various hydrogen technologies incorporated. Soft-linked to a macroeconomic model.
TIMES-Japan	IAE	Partial equilibrium	Intertemporal	Japan	Various hydrogen technologies incorporated. Soft-linked to detailed sector models (buildings and power)

Conference, and pledged to reduce its greenhouse gas emissions by 26% by FY2030 from the FY2013 level [10]. The role of nuclear was significantly reduced and it is now expected to supply 20–22% of power generation in FY2030. Japan has also formulated its long-term policy and “aims to reduce greenhouse gas emissions by 80% by 2050 as its long-term goal, while pursuing the global warming countermeasures and the economic growth at the same time”, [11]. The two main ministries responsible for climate and energy issues subsequently produced reports on the prospect of long-term mitigation as a starting point for discussing Japan's mid-century strategy under the Paris Agreement [13,14]. The new 2018 Strategic Energy Plan [71] also includes a scenario framework for 2050.

It is crucial to incorporate the unique plight of each country (such as Japan's reorientation after the 3/11) into scientific assessment of climate policy. The recent shift of global climate policy toward the bottom-up architecture, as espoused by the Paris Agreement, highlights the critical role of scientific assessments of policies of member states. Critical appraisal of submissions of NDCs and mid-century strategies would facilitate the ratchet mechanism to strengthen global mitigation efforts [15]. Because the effort level of each country is affected by not only climate policy stringency but also economic structures, energy endowments, and social predicaments, a careful analysis of individual cases as well as application of consistent and comprehensive approaches is desirable.

1.2. Review of the past modeling research

A number of papers assessed long-term mitigation policies and proposals of Japan, using energy-economic models and integrated assessment models (IAMs) (e.g., [16–22]. Some focused on key sectors such as transport [23].

Only few studies, however, systematically explored the inter-model uncertainty and robustness of the costs and effects of climate policy proposals. Hanaoka and Kainuma [24] evaluated the marginal costs of abatement in 2020 and 2030 for major regions in the world, including Japan, using 5 models. Akimoto et al. [25] analyzed Japan's NDC, using the DNE21 + and AIM/Enduse models, and Aldy et al. [15] compared NDCs of major economies. For Japan, they applied MERGE, GCAM, and DNE21+. More recently, Oshiro et al. (2018, under review) analyzed the link between Japan's NDC and 2050 target and the carbon budgets implied by the Paris Agreement temperature goals. However, Japan's 2050 target has not been analyzed with a multi-model approach.

In fact, there have been very few academic model intercomparison exercises led by a Japanese team (except for [24], whether or not it has to do with long-term climate policy. Many domestic exercises such as expert groups for the Mid-Term Target Evaluation Committee (*Chūki Mokuhyō Kentō Iinkai*) [26] and the Energy and Environmental Council (*Enerugī Kankyō Kaigi*) were carried out but these were essentially integral parts of the political process, and did not produce peer-reviewed articles.

This study attempts to fill the knowledge gap by conducting a pilot, six-model intercomparison study on Japan's long-term climate policy[1]. In particular, we ask the following research questions.

(1) What is the cost and feasibility of Japan's current long-term climate policy? What is the range of possible futures of Japan's energy system? How does it compare to other countries?
(2) Do the strategies found effective in other contexts (power-sector decarbonization, electrification, energy efficiency) also work well in Japan?
(3) Is there any specific, unique pattern in Japan's decarbonization strategies? For example, which sector is hardest to mitigate?

Note that our inquiry cannot answer many questions concerning individual model behaviors because of the lack of harmonization of input assumptions.

2. Method

2.1. Participating models

Table 1 shows the six models participating in this study. This is not an exhaustive list of all models active in Japan. Still, our set encompasses a wide range of models in terms of research institutes and modeling methodologies. For a recent review of energy scenario modeling by Japanese researchers, see the special issue in *Energy and Resources* in 2016 [27].

AIM/CGE [Global] is a global, top-down, dynamic recursive integrated assessment model with 17 geopolitical regions and 42 industrial classifications [28]. The energy sectors, including power sectors, as well as agricultural sectors, are disaggregated in detail to assess energy and land-use implications of climate policy.

AIM/Enduse [Japan] is a partial equilibrium, recursive dynamic model, focusing on Japan. The version used here explicitly distinguishes 10 regions broadly coinciding with the business areas of 10 electric utilities, in order to consider regional differences in renewable energy potentials and energy demand characteristics [23].

[1] Older versions of this paper have been published at conferences [1,2].

Dynamic New Earth 21 model (DNE21) is a partial equilibrium model with 54 regions and detailed intra-regional and inter-regional transportation of fuel, electricity, and CO_2, and detail nuclear fuel cycles and advanced nuclear technologies [29,30]. The model has 40 million constraints and 20 million endogenous variables.

DNE21 + is an intertemporal, partial equilibrium model with 54 nations/regions for assessing global energy systems and global warming mitigation options. The energy supply sectors are hard-linked with energy end-use sectors, including energy exporting/importing, with explicit consideration of working lifetimes of facilities for around 300 technologies [31].

IEEJ Japan model is a regional model that combines an energy technology model based on MARKAL-JAPAN [32] and an econometric, supply-demand analysis model [33]. It has been developed at the Institute of Energy Economics, Japan (IEEJ). It allows for disaggregated projections of energy service demands as well as detailed representation of new technologies such as hydrogen-based technologies.

TIMES-Japan is a regional model developed at the Institute of Applied Energy [34] using the TIMES modeling framework [35]. The model has a detailed energy system based on MARKAL-JAPAN model [32], and an additional energy carrier of imported hydrogen has been incorporated.

One of the important assumptions in our analysis is the parameter assumptions and detailed modeling approaches for the industrial sector, which is shown to play an important role. All the partial equilibrium models (that resolve the industry sector) have price-inelastic service demands in the industrial sector (see Fig. S3 for the steel subsector).[2] On the other hand, five models have various mitigation technologies, including a carbon capture and storage (CCS) option for the industry sector.

2.2. Scenarios

For this pilot study, we analyze the following six scenarios (Table 2). We take the current policy (NDC and the 2050 goal) as a starting point of our analysis.

The choice of the baseline scenario is left to the modeling teams, and we did not harmonize assumptions on socioeconomic drivers such as economic growth and population changes (Figs. S1 and S2 in the Supplementary Online Material (SOM)), incorporation of various assumptions related to energy policy (e.g., lifetime of nuclear power (40 years vs. 60 years)), nor the import prices of fossil fuels (Figs. S3–S5). All the models submitted two main scenarios (baseline and NDC&2050-80%) but not all scenarios.

Table 2
Scenarios in this study.

Scenario	Description
Baseline	The baseline scenario, which is left to the individual modeling group's choice.
NDC&2050-80%	A mitigation scenario, which combines the FY2030 NDC goal (26% reduction relative to FY2013 levels) and the 2050 goal (80% reduction).
NDC&2050-70%	As in NDC&2050-80% except for the 2050 goal is replaced with 70% reduction.
NDC&2050-60%	As in NDC&2050-80% except for the 2050 goal is replaced with 60% reduction.
NDC&2050-50%	As in NDC&2050-80% except for the 2050 goal is replaced with 50% reduction.
NDC&2050-80%MCE	As in NDC&2050-80% except that marginal costs of abatement are equalized across regions. Applicable only to global models.

For policy scenarios, we consider the implementation of NDC alongside with the 2050 vision. (The government has set the goal for 2020 but the inclusion of this policy was left for modelers.) As with previous Stanford Energy Modeling Forum (EMF) studies for EU and USA [36,37], we vary the stringency of the 2050 reduction goal and analyzed emissions reductions of 50%, 60%, 70%, and 80% to see the interplay between climate policy and the energy system, and its cost implications. The last scenario, NDC&2050-80%MCE, is the same as NDC&2050-80% except that the emissions reduction target is imposed globally. In other words, in the NDC&2050-80% MCE scenario, marginal costs of abatement are equalized across the borders.

Since the government has not specified the reference year for the 2050 goal, we do not adopt a common reference year either.[3] The following are the respective reference years for each model: AIM/CGE used 2005, AIM/Enduse 1990, DNE21 1990, DNE21 + 2005, IEEJ FY2013, TIMES-Japan 2005.

The 2030 constraint is based on Japan's NDC. Japan's NDC has detailed information on the power generation mix and sectoral mitigation contributions. It sets the total amount of electricity generation in FY2030 (1.065 PWh) as well as an approximate breakdown of electricity generation by source (renewables: 22–24%; nuclear: 20–22%; coal: 26%; natural gas: 27%; oil: 3%).

From a modeling standpoint, applying this breakdown of electricity generation as constraints in a model essentially fixes the solution, removing any flexibility. Two models (DNE21 + and IEEJ) imposed such a restriction for 2030. Another model (AIM/Enduse [Japan]) included the share constraint on nuclear power. Other groups did not include such constraints. Sano et al. [38] explored the implications of relaxing this NDC constraint, and found that the power generation constraint significantly increases the marginal cost. For instance, relaxing the power mix constraint and retaining only the nuclear share as a constraint reduces the marginal cost of abatement from about 380 USD2000/t-CO_2 to approximately 190 USD2000/t-CO_2.

We restrict ourselves to CO_2 emissions from fossil fuels and industrial processes, which comprise about 90% of GHG emissions in Japan. This ratio is highest among the largest GHG emitters in the world [7]. However, different models applied different scopes for mitigation. For instance, AIM/CGE covers all Kyoto gases including land-use change emissions, AIM/Enduse and DNE21 + deal with Kyoto 6 gases. This should have affected our quantitative results, but not qualitative ones.

For this study, we assume no emissions trading across countries for global models, except for the NDC&2050-80%MCE scenario.

To place our analysis in a broader context, we also use the database for the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (https://tntcat.iiasa.ac.at/AR5DB/dsd) as a supplementary data source.

3. Results and discussion

3.1. Analysis of the two main scenarios

Fig. 1 depicts the time series of CO_2 emissions for the two main

[2] DNE21 does not explicitly model service demands. Rather, it takes fuels and electricity demands.

[3] The actual emissions of CO_2 (excluding those from land-use change) in those years are 1157.2 [$MtCO_2$] in 1990, 1307.7[$MtCO_2$] in 2005, 1313.7 [$MtCO_2$] in 2013 [40]. The corresponding emissions caps for the 2050 policy of 80% reduction are 231.44 [$MtCO_2$] (1990 reference year), 261.54 [$MtCO_2$] (2005 reference year), and 262.74 [$MtCO_2$] (2013 reference year).

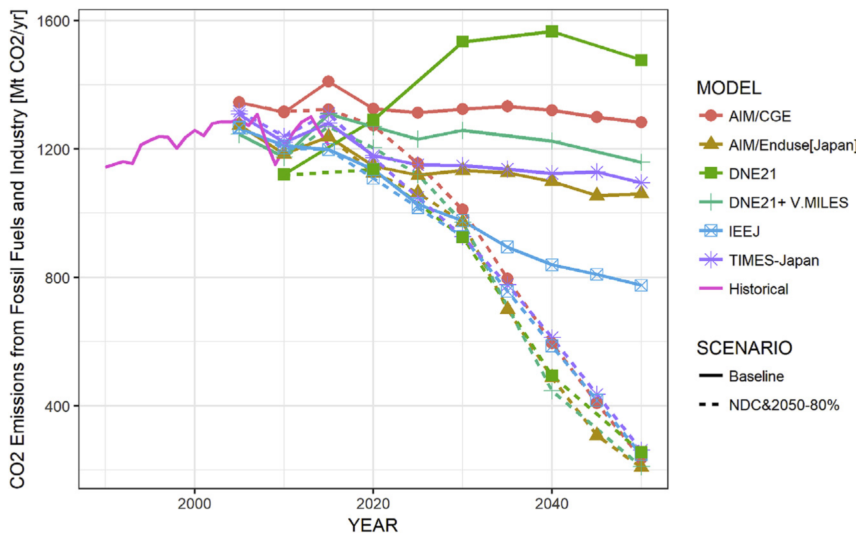

Fig. 1. Carbon dioxide emissions from fossil fuels and industrial processes for the baseline and NDC&2050-80% scenarios. The historical data are taken from UNFCCC [39].

scenarios: baseline and NDC&2050-80%. The CO_2 emissions in the initial periods (2005 or 2010, depending the model) differ somewhat because different models use different datasets. For instance, there are two primary sources of energy balance (Agency for Natural Resources and Energy, Ministry of Economy, Trade, and Industry, and the International Energy Agency). For the GHG emissions data, some models use MOE [40] whereas others use the data from the Emissions Database for Global Atmospheric Research (EDGAR).

In the baseline scenario, the models show a wide range of emissions, partly because we did not harmonize socioeconomic drivers such as population and GDP (Figs. S1 and S2). The difference in emission drivers however does not easily translate into the variations in emissions. For instance, the IEEJ model projects the highest GDP in 2050 but shows the lowest emissions in the baseline scenario in 2050.

The mitigation scenario (NDC&2050-80%) shows that the models are broadly consistent with the scenario specification and the range of the 2050 emissions is 208.1–261.6 Mt-CO_2, though some variations are inevitable because of the differences in emissions in the initial periods (e.g., 2010) and the choice of reference years used to measure reductions.

Note that we constrain our models so that the emissions reduction rate in 2030 is consistent with the NDC of Japan. This might have consequences on the results shown below.

We next examine a few cost metrics. We start with the marginal cost of abatement (carbon price), which is shown in Fig. 2. In 2030, the full price range is 44.29–345.60 USD/tCO_2, with a median of 149.80USD/tCO_2. This range is similar to that of Aldy et al. [15]; who found 43–283 USD2015/tCO_2. The uncertainty range becomes very large in 2050; the minimum, the median, and the maximum values are 273USD/tCO_2, 2818 USD/tCO_2, and 7730 USD/tCO_2, respectively.[4] Normalizing carbon prices with values for the NDC&2050-50% scenario does not reduce the uncertainty range (Fig. S6). One of the key drivers for this high price is inflexible demand of energy-intensive sectors (Fig. S7), to which we will come back below.

We can place the current results for 2050 in a global context by comparing ours to those from the recent EMF projects. The EMF 24 study [36] investigated into long-term climate policies for the US and the EMF 28 study [37] looked at the European mitigation pathways. Both studies investigated into the cost implication of a climate policy with 80% emissions reduction by 2050. The marginal costs of abatement from these two studies are shown in Table 3, demonstrating that the costs in Japan are higher and the range is wider than those in the US and Europe. The EMF 24 and 28 studies, however, did not constrain the 2030 emissions. This partially explains the high cost estimates found here because postponing mitigation action leads to a higher, total cost.

The marginal cost is a useful metric since it can be obtained regardless of model types. Nevertheless, since it reflects the cost of reducing the final one tonne of the emissions, it could go very high if the abatement cost curve rises steeply. It is thus necessary to examine other cost indicators.

As an example, we show the increment in the total energy systems cost and the consumption loss (per unit GDP) for four models in Fig. 3. The differences here are much smaller than those found in Fig. 2. The results are, for example, similar to those from EMF 28, which shows a GDP loss of ~1–~10% relative to the baseline (their Fig. 10).

The high marginal costs found in this study implies that the models have been pushed close to their limits of applicability. Although many models take into consideration a number of innovations and mitigation options, a slight change in technology assumptions would affect the results greatly since the models are at the tail of the marginal cost curve, which is highly uncertain.

The converse of this is that one should pay more attention to other cost metrics such as the energy system cost or consumption loss, which are more stable as shown in Fig. 3. Although the magnitude of such integrative cost measures is comparable to other studies, it may be more significant for Japan because of its low potential economic growth and depopulation trend.

To achieve deep emissions reduction, the models rely on all of the following strategies: energy efficiency (in terms of energy intensity of GDP), decarbonization of energy sources (in terms of carbon intensity of final energy), and end-use electrification

[4] To convert USD to Japanese yen, a conversion rate of 1USD = 100 JPY would suffice for the purpose of obtaining a rough estimate.

[5] We converted at an approximate exchange rate of 1 EUR2010 = 1.2 USD2005. In terms of euros, the median is 521 EUR2010/tCO_2 and the Interquartile range 240–1127 EUR2010/tCO_2.

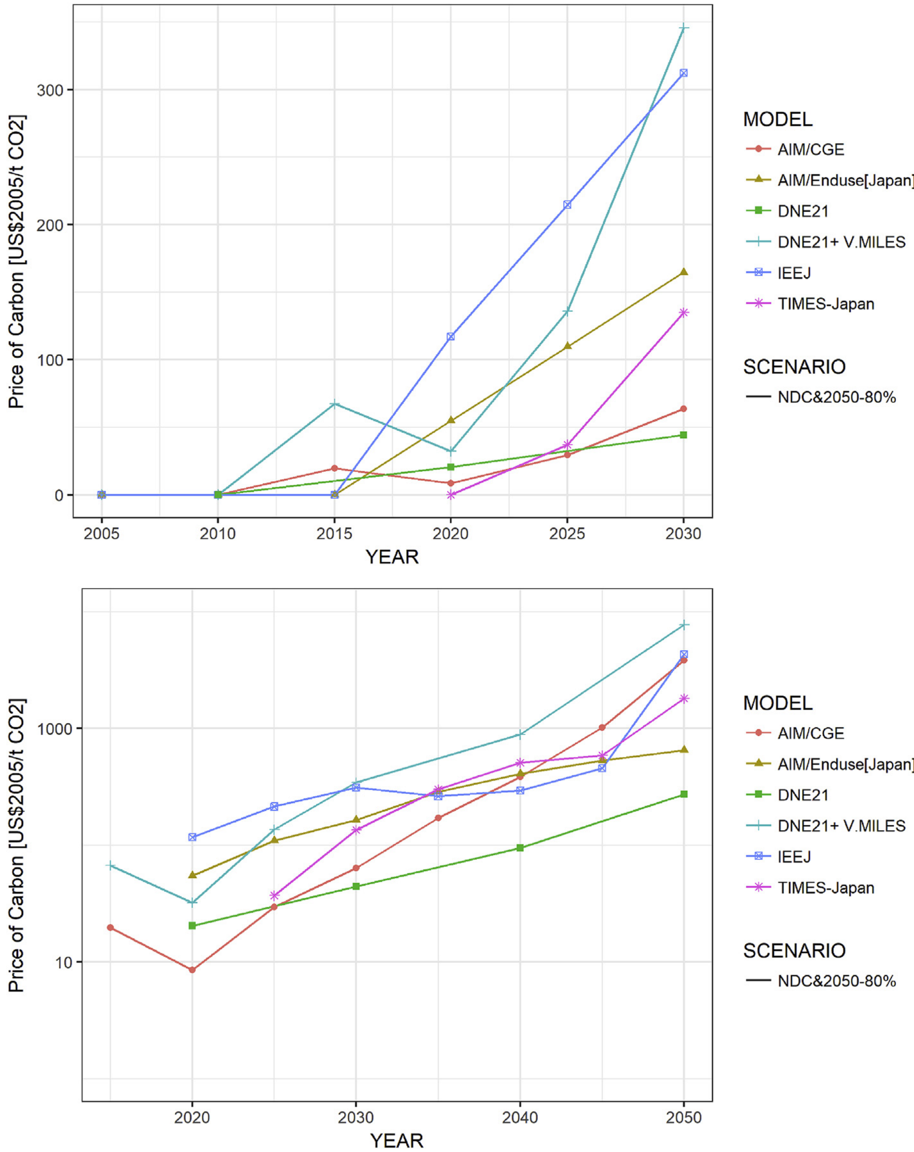

Fig. 2. Marginal costs of abatement in the NDC&2050-80% scenario. Until 2030 on a linear scale (top) and until 2050 on a logarithmic scale (bottom).

Table 3
Marginal costs of abatement from this study and EMF 24 and 28 studies.

Study	Region	Results
This study	Japan	(Min., Median, Max.) = (273, 2818, 7730) USD2005/tCO_2
EMF 24 [36]	The United States	~100–500 USD2005/tCO_2 (80% reduction from 2005 levels)
EMF 28 [37]	The European Union	Median 625 USD2005/tCO_2
		Interquartile range 288-1352USD2005/tCO_2 (80% reduction from 1990 levels)[5]

(Figs. S8–S10). This is consistent with the findings from other long-term mitigation assessments, including those from the IPCC Fifth Assessment Report [42].

The power sector is expected to make significant contributions to emissions reduction, also consistent with many previous analyses [42]. Coal and natural gas become dominant electricity sources by 2050 in the baseline (Fig. 4, top panel). On the other hand, various low carbon technologies (such as nuclear, renewables, and fossil energy with carbon capture and storage) penetrate in the NDC&2050-80% scenario (Fig. 4, bottom panel). No single power source is found to be dominant in the mitigation scenario. The "Other" consists mainly of carbon-free hydrogen and also includes power generation using municipal solid waste.[6] The IEEJ and TIMES-Japan models allow for hydrogen import[7] while DNE21 + restricts itself to domestic usage.

The total electricity generation decreases in NDC&2050-80%

[6] In the case of DNE21+, it represents a combination of power generation from hydrogen and solar photovoltaics for electrolysis.

[7] The price of imported hydrogen is 20 JPY/N m^3 [69] in the IEEJ model and 35 JPY/N m^3 for the TIMES-Japan model. Because of relatively low costs, hydrogen is not the determinant of the high marginal costs for these two models.

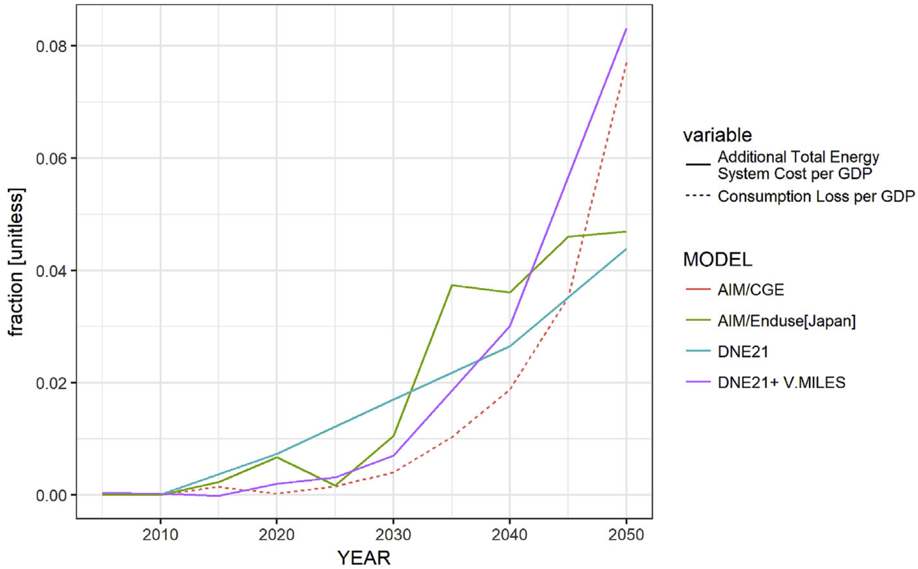

Fig. 3. The additional energy system cost and the consumption loss, both per unit GDP at the market exchange rate, for the NDC&2050-80% scenario.

relative to the level found in the baseline for AIM/CGE and AIM/Enduse, while other models exhibit an increase, with a relatively large increase for DNE21+. There are two competing factors: a decrease of power generation of energy efficiency improvement, and an increase of power demand from electrification (fuel switching from non-electric secondary energy to electricity) and new service demands. In particular, hydrogen production through electrolysis accounts for about one fourth of power generation in DNE21+. Electricity generation also increases in IEEJ, in which energy demand seems to change more flexibly from fossil fuels to electricity than other models.

With electricity increasingly carbon-free, which sector continues to emit CO_2?

We now look at the sectoral decomposition of CO_2 emissions (Fig. 5). The residential and commercial sector shows a great improvement of energy efficiency, and the emissions from this sector are substantially reduced with electrification and decarbonization of electricity. Though the literature often emphasized the difficulty of reducing transport emissions [42], it is not the transport but the industry that has the largest share of residual emissions in the partial equilibrium models in this study. (AIM/CGE, which is a general equilibrium model, has significant residual emissions in the transport.)

The participating partial equilibrium models have fixed service demands for the industry sector (see Fig. S7 for an example of the steel subsector).[8] That is, the service demand levels do not respond to the increases in energy prices (although they could change with different GDP assumptions). The mitigation potentials in the partial equilibrium models are therefore limited by technological representation, and the models have in fact taken great care in representing the industry sector. For instance, all the models except the IEEJ model include a CCS option for steelmaking, as noted above. Inflexible demands, however, render it difficult to reduce industrial emissions further.

[8] In DNE21, the demands are treated as final energy demands of fuels, heat, and electricity, not as service demands. The model however allows for demand reduction in response to price increases [70]. In fact, DNE21 has the lowest marginal cost of abatement among all the models.

3.2. Scenarios with varying stringency

We now turn to scenarios with varying levels of stringency. We have already showed the marginal cost of abatement for the NDC&2050-80% scenario (Fig. 2), which features extremely high values. How does the stringency of climate policy affect the marginal cost?

Fig. 6 shows how the 2050 carbon price varies with the emissions reduction target. The marginal cost increases very steeply from the 70% reduction scenario to the 80% reduction scenario, and this is common across the top-down (AIM/CGE) and bottom-up models (all other models). For the 70% reduction scenario, only one model (AIM/CGE) reports a carbon price higher than 1000 USD2005/tCO_2, which is 1140 USD2005/tCO_2. For the 80% reduction, the four models report a carbon price beyond 1000 USD/tCO_2.

Two global models analyzed scenarios with global equalization of the marginal cost. The marginal cost for the NDC&2050-80%MCE scenarios falls roughly between the NDC&2050-60% and NDC&2050-70% scenarios.

In contrast to the drastic changes in marginal costs, the energy mix shifts only gradually with climate policy stringency. Fig. 7 shows how the primary energy mix changes from the baseline to the 80% reduction scenario (NDC&2050-80%). Except for the sudden introduction of imported hydrogen in the IEEJ model, the changes in the energy mix are gradual. This characteristic allows us to focus on the two main scenarios (baseline and NDC&2050-80%) when examining the energy pathways.

We next examine sectoral mitigation. We already noted that the industrial emissions remain in 2050 under the mitigation policy. Fig. 8 shows relative mitigation efforts by sector. There is no clear difference across the sectors for the 50% reduction scenario (NDC&2050-50%). At the 80% emissions reduction, however, the industry sector exhibits the least fractional emissions reduction for all the partial equilibrium models, though the level of relative mitigation challenges as indicated in the figure varies across models. (Again, the AIM/CGE model, a general equilibrium model, behaves differently.)

How does the difficulty of industrial decarbonization compare with other studies? We next compare our results to the scenarios contained in the IPCC AR5 database. We specifically extracted

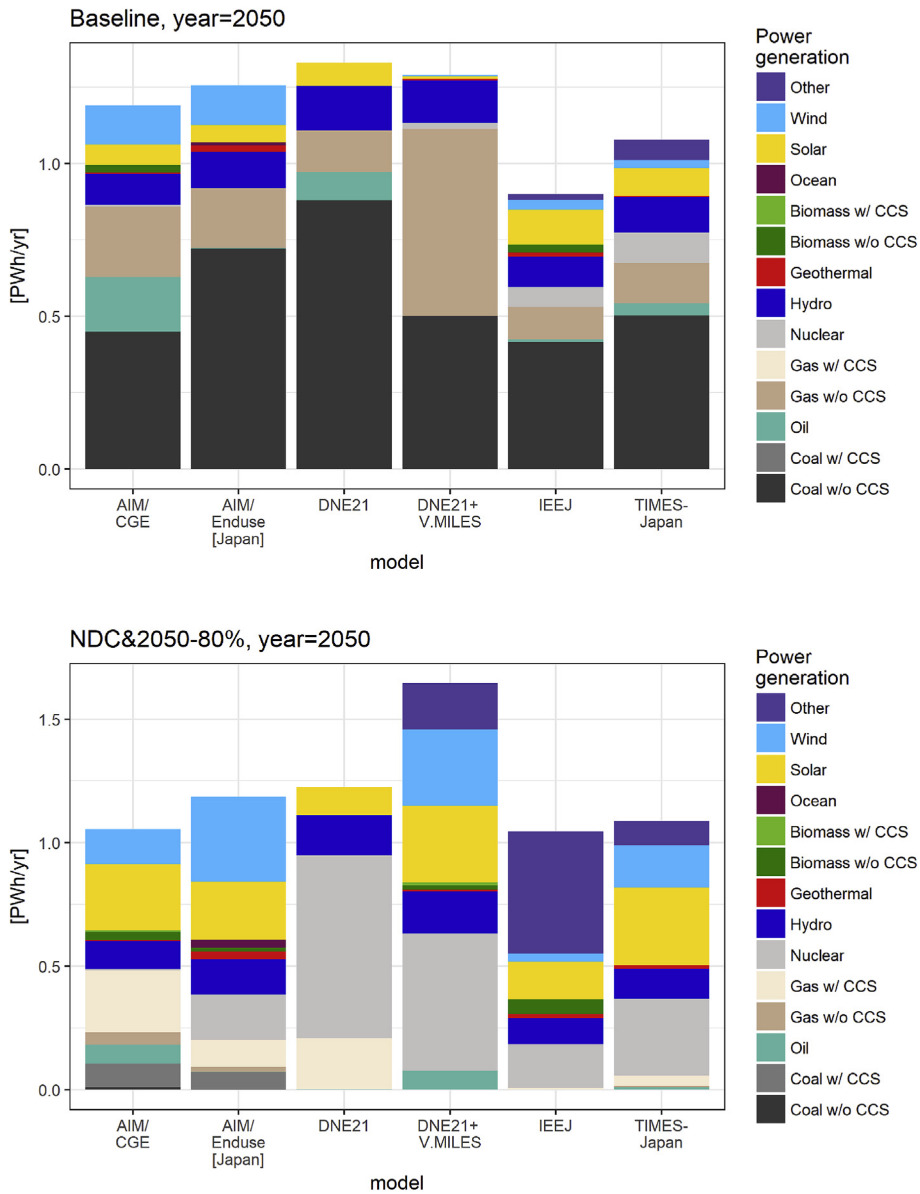

Fig. 4. Electricity generation mix in 2050 for the baseline (top) and NDC+2050-80% (bottom) scenarios.

scenarios classified as Category 1 and Category 1–2 in the CLIMATE category and T0 in the TECHNOLOGY category, which are thought to have similar mitigation levels compared to the NDC+2050-80% scenario. Because few scenarios provide sectoral emissions, we rather focus on final energy demand.

Fig. 9 depicts sectoral final energy demands from the present study and the IPCC AR5 database. Since the IPCC AR5 database does not have the region corresponding to Japan, we use the data for OECD90 and the world. Japan's final energy demand share for the industry indeed tends to be higher, which is consistent with Japan's NDC. Besides, the share increases with time for Japan whereas those for the OECD90 region and the world average remain flat, though there are large uncertainties.

Note that 5 out of 6 models participating in this study are partial equilibrium models, and this bias might have affected our results, as discussed above. A further analysis on this point is left for future research.

4. Conclusions and policy implications

4.1. Summary and study limitations

We have described the results of a pilot model intercomparison project to analyze long-term climate policy of Japan, which can be used to inform the ongoing energy policy debate (e.g., [43,44]. The present study reconfirms many of the findings made in other studies in the context of long-term energy and climate policy such as previous EMF studies (e.g., [37,41]. To achieve deep emissions reduction, energy efficiency should accelerate, clean energy must scale up rapidly, and much of energy usage must be electrified.

Our analysis has also revealed peculiarities of Japan's situation. Models show that the inter-model range of marginal abatement cost is wider and higher for Japan compared to those for the United States and Europe as suggested by the recent EMF exercises. This is in fact a recurring theme in climate policy debate in Japan (e.g.,

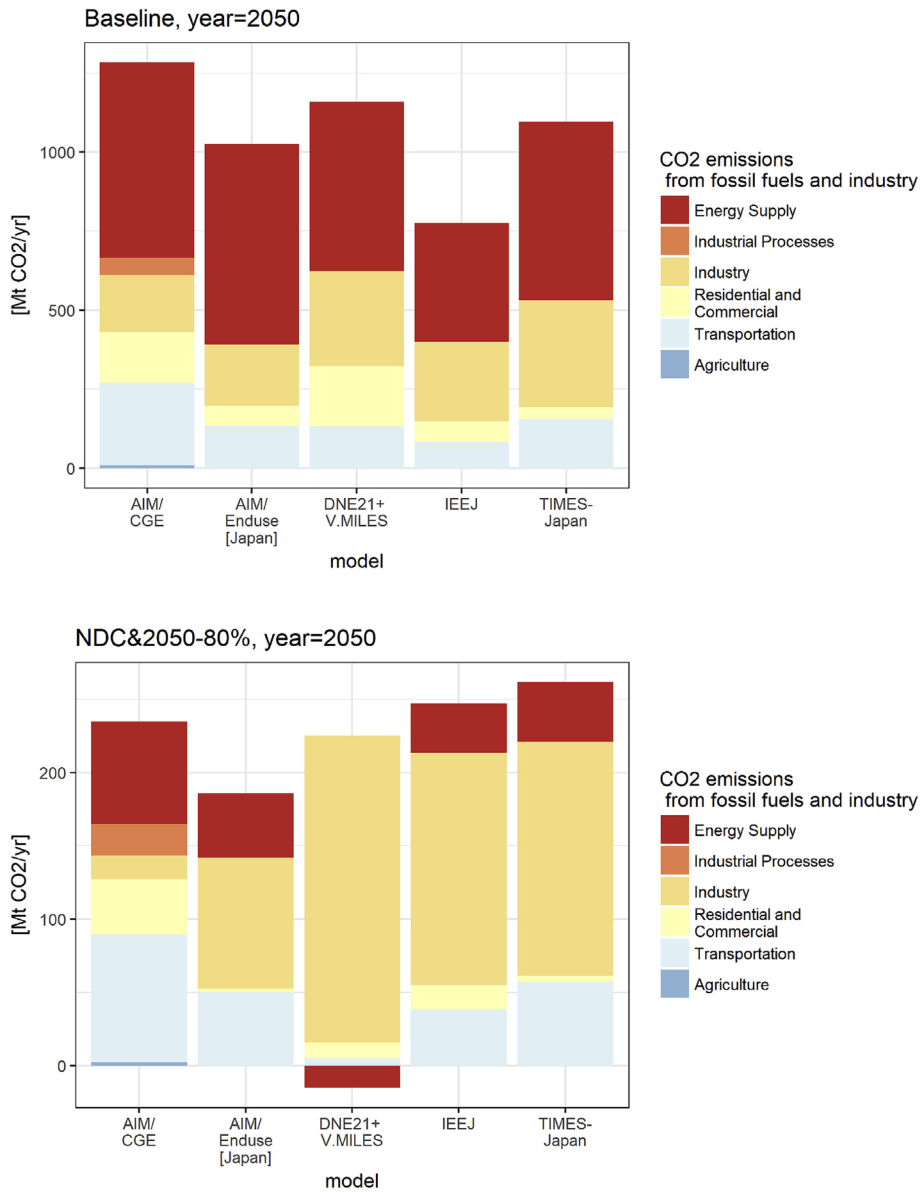

Fig. 5. CO_2 emissions by sector in 2050 for the baseline (top) and NDC&2050-80% (bottom) scenarios. Note that the version of DNE21 used in this study doesn't explicitly model some demand sectors (including the industry) and is not included in this figure.

[26,45]. Our results have also demonstrated that in our partial equilibrium models, it is the industry sector, not the transport, that has the largest residual carbon dioxide emissions in the 80% reduction scenario because of their large share in final energy. Lastly, as a country with few resource endowments, imports of carbon-free energy such as hydrogen could play a critical role.

Note that there is an ongoing research and demonstration project funded by the New Energy and Industrial Technology Development Organization (NEDO) in Japan to explore the feasibility of producing carbon-free hydrogen from lignite coal in Australia and transporting it from there [46].

There are many caveats to this paper, but most of them are not unique to ours. Our results are not predictions but scenarios and hence treated as such. Moreover, the value of model intercomparison lies with the insights it can provide, not the actual values. The high marginal costs reported in this study are highly uncertain as indicated by the maximum-minimum range as well as the limitations of the participating models. Allowing service demands to be elastic, including a few negative emissions technologies [47], or incorporating demand-side digital innovations [48] could greatly alter the marginal costs. Nevertheless, low renewable endowments [49], high costs of renewables, an already energy-efficient economy, and a large share of industry in the final energy consumption all point to a possibility of high marginal cost in Japan.

As in the literature [36], we did not harmonize input socioeconomic assumptions such as GDP, population, and energy service demands, which prevented us from understanding which factor (e.g., choice of model, socioeconomic assumptions, and technology parameters) has led to the different results among the models. For instance, the reason for different power generation mixes (Fig. 4) remains unclear and cannot be easily explained by costs or resources (see Table S1 for the case of renewables). This point deserves more careful scrutiny.

However, a few points are worth explicit mention. As with other studies, our analysis suffers from the problem of an "ensemble of opportunity" [50,51]; our model set does not span the possible

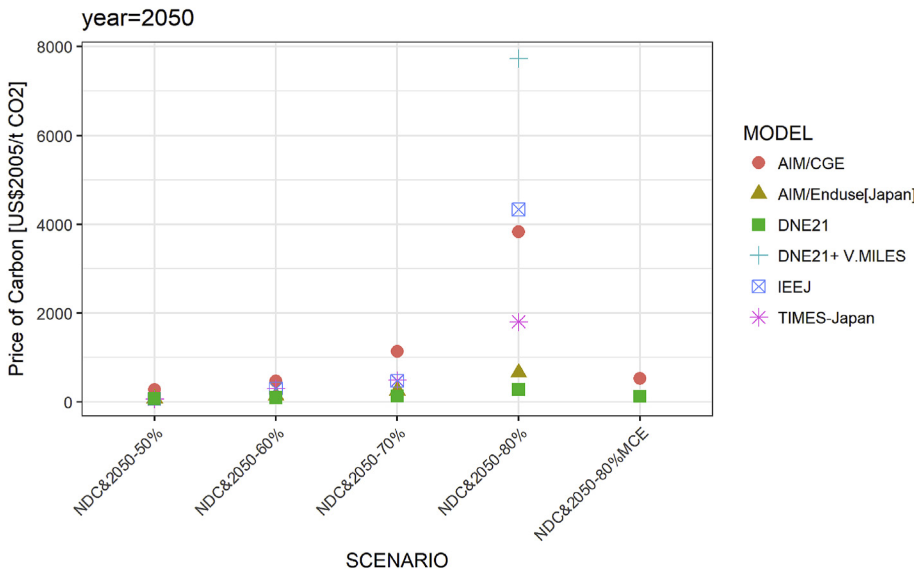

Fig. 6. 2050 carbon price by scenario. The same variable for NDC&2050-80% is also shown in Fig. 2 on a logarithmic scale. The number of models for each scenario is 5 for NDC&2050-50%, NDC&2050-60%, NDC&2050-70%, 6 for NDC&2050-80%, and 2 for NDC&2050-80%MCE.

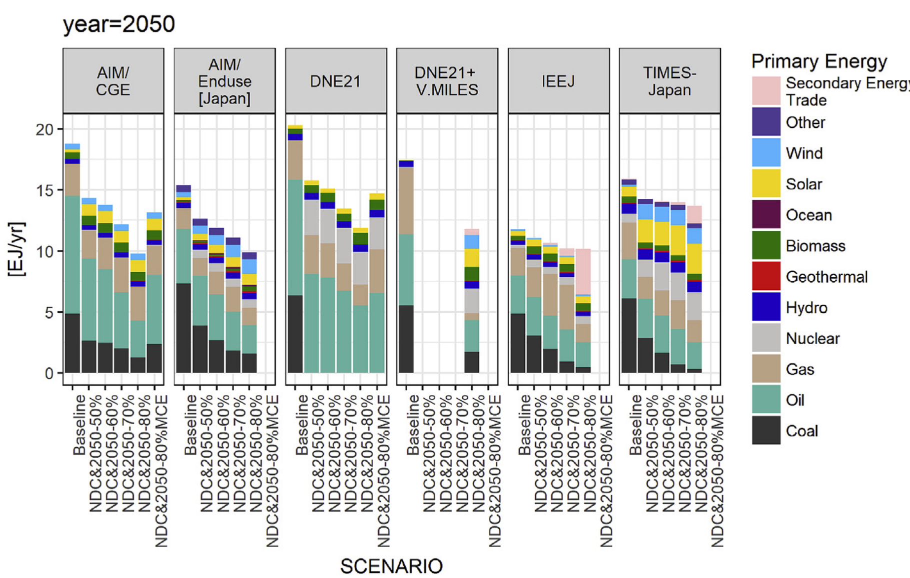

Fig. 7. Primary energy mix for 2050 by model and scenario. The secondary energy trade includes imported hydrogen.

uncertainty range in a systematic or random manner. In particular, in this study, only Japanese teams are participating. Previous studies already hinted at the divergence of modeling results between Japanese and foreign modeling teams [15], which was also confirmed by Oshiro et al. [52]. Since this project only utilizes national models, we will not be able to answer why there is such a divergence.

Another key issue concerns with the 2030 NDC. Many analyses have already clarified the need to go beyond the currently proposed NDCs to attain the 2-degree or 1.5-degree target. However, we have fixed the 2030 emissions level to the one in Japan's NDC.

We have reported carbon prices greatly exceeding 1000 USD/tCO_2. One could argue that inelastic demand may not be justified under such a high level of carbon price owing to decreased competitiveness of the industry,[9] or that expectation for such a price renders climate policy politically untenable because of lobbying from the affected stakeholders. Also, in such a regime with high carbon prices, other factors such as non-CO_2 greenhouse gases and land-use change will be crucial. High prices could spur radical innovations too, which could bring down the marginal costs of abatement. We did not consider these issues in this study.

We did not address a number of potentially important policy issues, including high costs of renewables in Japan and the future of nuclear power in Japan. The power generation costs of solar photovoltaics [53,54] and wind [55] are substantially higher than the global prices. How fast and to what extent the costs of these renewables decline are an important factor determining the mitigation cost. Also, the unclear future of nuclear should affect multiple

[9] The competitiveness of an industry has to do with relative prices across countries and materials. As our focus is on domestic climate policy of Japan, evaluation of international competitiveness is out of scope of the present study.

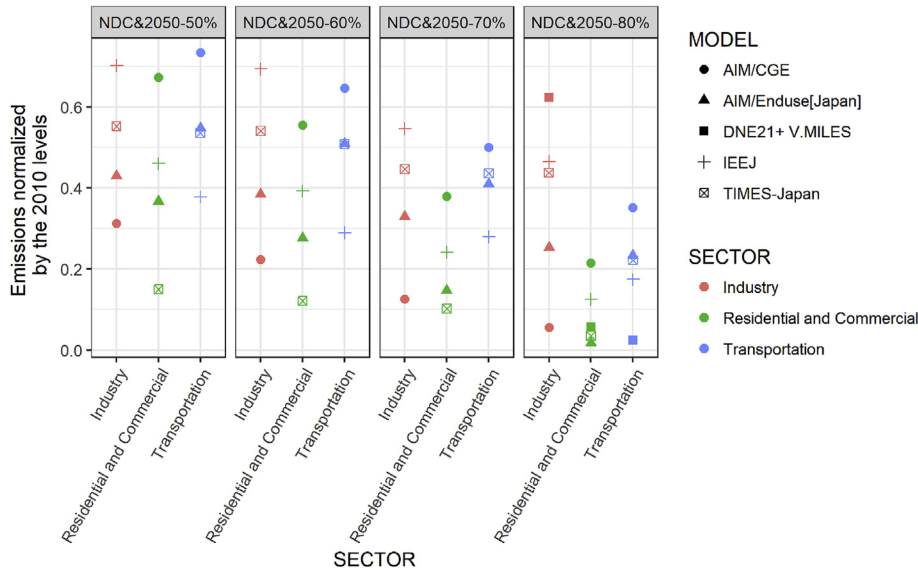

Fig. 8. Emissions by sector for 2050, normalized by the respective 2010 levels.

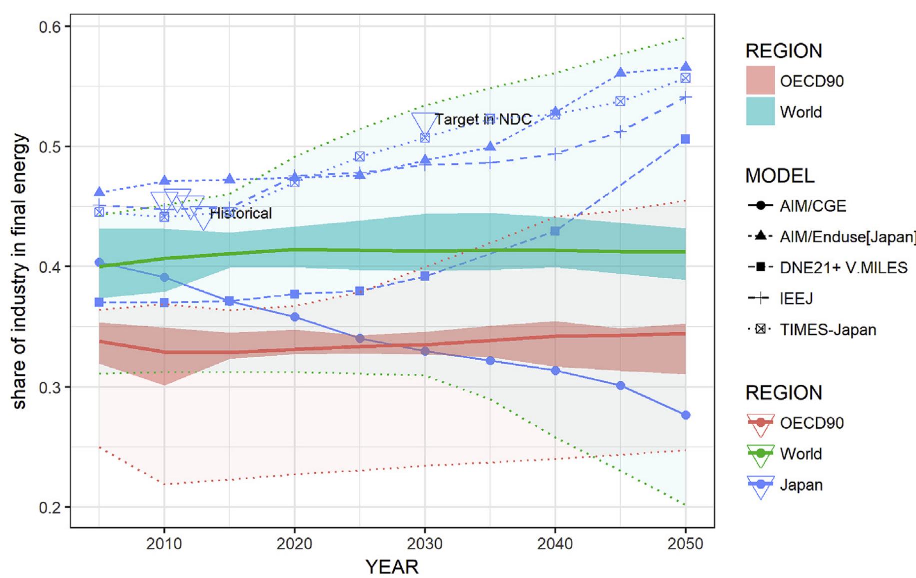

Fig. 9. The ratio of the industrial final energy demand to the total final energy in the NDC&2050-80% scenario in this study (Japan) and in selected scenarios in the AR5 database (OECD90 and World). Bold lines, ribbon graph, and dotted lines show averages, ranges of 25th to 75th percentiles, and maximum and minimum, respectively, for OECD90 and World. Individual model results are shown for Japan. The historical values and the NDC target are shown for Japan with triangles.

aspects of energy policy [5], including energy self-sufficiency, climate mitigation, and the energy cost. To a first approximation, these issues can be analyzed with conventional technology sensitivity analysis (e.g., [36,37,56], which is left for future research.

Nonetheless, these issues would not affect the marginal cost of climate policy that is characterized by the option to reduce the last one tonne of carbon dioxide because the power sector goes through extensive decarbonization in the NDC&2050-80% scenario.

4.2. Policy implications

Our analysis points to the centrality of industrial decarbonization, although the assumption of inelastic service demands in the industrial sector have affected our results. Interestingly, importance of residual, industrial emissions has been noted by the two preparatory reports by the Ministry of Economy and the Ministry of the Environment [13,14].

The IPCC AR5 demonstrated the difficulty of transport decarbonization [42], and the detailed studies confirm it (e.g., [57], though some acknowledge possible further mitigation in the transport [58]. Nevertheless, it is important to realize that the modeling community is slower to include detailed representation for the industry than for the transport. For instance, as part of the Stanford EMF 27 study that constituted one of the backbones of the IPCC AR5 review, Sugiyama et al., [59] showed that 10 out of 16 models have explicit representation of industry end-use technologies whereas 15 out of 16 models do for the transport.

The industry sector is important not just for Japan but also for other Asian economies, which dominate heavy industrial production. For instance, in 2017, China, Japan, and India are the top three producers of crude steel, and South Korea ranks the sixth, after the United States and closely following Russia [60]. From a modeling standpoint, more granular analysis of the industrial sector would be vitally needed both for Japan and beyond. In addition, further push for research and development on industrial decarbonization would be crucial.

Interestingly, the Government of Japan, [12] has begun pushing for digitalization of the whole economy under the framework of "Society 5.0," where digital technology permeates the entire society. According to IEA [61]; for instance, additive manufacturing could fundamentally change the demand for raw materials, reducing the marginal cost substantially. This again points to the importance of industrial policy in consideration of climate policy.

Another interesting observation is that the cost numbers reported here are far higher than the estimated costs of many negative emissions technologies (NETs) or carbon dioxide removal (CDR) options [62], which may act as a backstop option to place a price ceiling. Since the upper end of the NETs cost is often assumed to be 1000USD/t-CO_2 [47], any price exceeding 1000 USD/t-CO2 should not be taken too literally. A recent review on the net zero-emissions energy system [63] also suggests that addressing the emissions from the difficult-to-decarbonize sectors might necessitate NETs/CDR, which they call carbon management, and our finding is consistent with theirs.

Often NETs and CDR are discussed in a global context [64,65], but they can play a vital role for regional or national climate policy. There are exceptions (see Solano Rodriguez et al. [66] for bioenergy with CCS (BECCS) in the European Union and Sanchez et al. [67] for BECCS in western North America; Kraxner et al., [68] for South Korea). Such an analysis would be necessary for Japan as well. Though there remains a question on whether Japan would be able to deploy such technologies domestically, it might be feasible to include them in the international schemes for mitigation (e.g., a future extension of the Joint Crediting Mechanism established by the Government of Japan (https://www.jcm.go.jp/)). The models should also be extended to represent such (domestic) NETs/CDR options.

Acknowledgments

This study was supported by the Environment Research and Technology Development Fund 2-1704 of the Environmental Restoration and Conservation Agency and the Kikawada Foundation. Shinichiro Fujimori was also supported by JSPS KAKENHI Grant Number JP16K18177.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.energy.2018.10.091.

References

[1] Sugiyama M, Fujimori S, Wada K, Endo S, Fujii Y, Komiyama R, Kato E, Kurosawa A, Matsuo Y, Oshiro K, Sano F. Japan's mid- and long-term mitigation pathways and associated challenges:A model intercomparison pilot project. In: Proceedings of the 33rd conference on energy, economy, and environment; 2017 [in Japanese].
[2] Sugiyama M, Fujimori S, Wada K, Endo S, Fujii Y, Komiyama R, Kato E, Kurosawa A, Matsuo Y, Oshiro K, Sano F, Shiraki H. Japan's long-term mitigation pathways and challenges: a pilot model intercomparison project. In: Paper presented at the international energy workshop 2017, Maryland, USA. (The presenter is registered as Shiraki, H., on the IEW; 2017. website at, https://events.pnnl.gov/Default.aspx?topic=IEW_2017:_Papers_and_Slides.
[3] Poortinga W, Aoyagi M, Pidgeon NF. Public perceptions of climate change and energy futures before and after the Fukushima accident: a comparison between Britain and Japan. Energy Pol 2013;62:1204–11. https://doi.org/10.1016/j.enpol.2013.08.015.
[4] International Energy Agency (IEA). Energy Policies of IEA countries. Japan 2016 review. Paris: OECD/IEA; 2016.
[5] Kuramochi T. Review of energy and climate policy developments in Japan before and after Fukushima. Renew Sustain Energy Rev 2015;43:1320–32. http://doi.org/10.1016/j.rser.2014.12.001.
[6] Takase K, Suzuki T. The Japanese energy sector: current situation, and future paths. Energy Pol 2011;39(11):6731–44. http://doi.org/10.1016/j.enpol.2010.01.036.
[7] Olivier JGJ, Schure KM, Peters JAHW. Trends in global CO2 and total greenhouse gas emissions. The Hague: PBL Netherlands Environmental Assessment Agency; 2017. Retrieved from, http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2017-trends-in-global-co2-and-total-greenhouse-gas-emissons-2017-report_2674.pdf.
[8] Government of Japan. Basic energy plan. 2010. http://www.enecho.meti.go.jp/category/others/basic_plan/pdf/100618honbun.pdf [in Japanese].
[9] Duffield JS, Woodall B. Japan's new basic energy plan. Energy Pol 2011;39(6):3741–9. https://doi.org/10.1016/j.enpol.2011.04.002.
[10] Government of Japan. Submission of Japan's intended nationally determined contribution (INDC). 2015. http://www4.unfccc.int/submissions/INDC/Published%20Documents/Japan/1/20150717_Japan's%20INDC.pdf.
[11] Government of Japan. The plan for global warming countermeasure. 2016. http://www.env.go.jp/press/files/jp/102816.pdf [in Japanese].
[12] Government of Japan. The 5th science and technology basic plan. Government of Japan; 2016 [in Japanese].
[13] Ministry of Economy, Trade, and Industry. Long-term global warming countermeasure platform (Choki Chikyu Ondanka Taisaku Prattohommu). 2016. http://www.meti.go.jp/press/2017/04/20170414006/20170414006-1.pdf [in Japanese].
[14] Ministry of the Environment. Long-term, low-carbon vision. 2016. http://www.env.go.jp/press/103822/105478.pdf [in Japanese].
[15] Aldy J, Pizer W, Tavoni M, Reis LA, Akimoto K, Blanford G, Carraro C, Clarke LE, Edmonds J, Iyer GC, McJeon HC, Richels R, Rose S, Sano F. Economic tools to promote transparency and comparability in the Paris Agreement. Nat Clim Change 2016;6(11):1000–4. http://doi.org/10.1038/nclimate3106.
[16] Masui T, Matsuoka Y, Kainuma M. Long-term CO_2 emission reduction scenarios in Japan. Environ Econ Pol Stud 2006;7:347–66. http://doi.org/10.1007/BF03354007.
[17] Fujino J, Hibino G, Ehara T, Matsuoka Y, Masui T, Kainuma M. Back-casting analysis for 70% emission reduction in Japan by 2050. Clim Pol 2008;8(S1):S108–24. http://doi.org/10.3763/cpol.2007.0491.
[18] Ashina S, Fujino J, Masui T, Ehara T, Hibino G. A roadmap towards a low-carbon society in Japan using backcasting methodology: feasible pathways for achieving an 80% reduction in CO_2 emissions by 2050. Energy Pol 2012;41:584–98. https://doi.org/10.1016/j.enpol.2011.11.020.
[19] Kainuma M, Oshiro K, Hibino G, Masui T. Pathways to deep decarbonization. 2014 report. Japan chapter. SDSN & IDDRI; 2014. Retrieved from, http://unsdsn.org/wp-content/uploads/2014/09/DDPP_2014_report_Japan_chapter.pdf.
[20] Masui T, Oshiro K, Kainuma M. Eighty percent reduction scenario in Japan. In: Nishioka S, editor. Enabling Asia to stabilise the climate. Singapore: Springer; 2016.
[21] Akimoto K, Sano F. Analyese on Japan's GHG emission reduction target for 2050 in light of the 2°C target stipulated in the Paris Agreement. J Jpn Soc Energy Resour 2017;38:1–9.
[22] Oshiro K, Kainuma M, Masui T. Assessing decarbonization pathways and their implications for energy security policies in Japan. Clim Pol 2016;16(sup1):S63–77.
[23] Oshiro K, Masui T. Diffusion of low emission vehicles and their impact on CO_2 emission reduction in Japan. Energy Pol 2015;81:215–25. http://doi.org/10.1016/j.enpol.2014.09.010.
[24] Hanaoka T, Kainuma M. Low-carbon transitions in world regions: comparison of technological mitigation potential and costs in 2020 and 2030 through bottom-up analyses. Sustain Sci 2012;7(2):117–37. http://doi.org/10.1007/s11625-012-0172-6.
[25] Akimoto K, Tehrani BS, Sano F, Oda J, Kainuma M, Masui T, Oshiro K. MILES (modelling and informing low emissions strategies) project - Japan policy paper: a joint analysis of Japan's INDC. 2015. http://www.iddri.org/Publications/Collections/Analyses/MILES_Japan%20Policy%20Paper.pdf.
[26] Fukui T, editor. Explanation of the mid-term target for global warming countermeasures (Chikyū Ondanka Taisaku Chūki Mokuhyō no Kaisetsu). Tokyo: Gyosei; 2009 [in Japanese].
[27] Mori S. Outline of energy models as a policy analysis tool. Energy Resour 2016;37(1):28–32. http://ci.nii.ac.jp/naid/40020708577.
[28] Fujimori S, Masui T, Matsuoka Y. AIM/CGE [basic] manual. Discussion Paper Series. Center for Social and Environmental Systems Research, National Institute for Environmental Studies, Japan; 2012. http://www.nies.go.jp/social/dp/pdf/2012-01.pdf.
[29] Endo S, Fujii Y, Komiyama R. Integrated assessment of the prospects for hydrogen technology through 2100 using a regionally disaggregated DNE21. IEW 2016 (international energy workshop 2016). Ireland: University College Cork (UCC); 2016. June 1, 2016.
[30] Fujii Y, Komiyama R. Chapter 5: long-term energy and environmental strategies. In: Ahn J, et al., editors. Reflections on the Fukushima Daiichi nuclear accident: toward social-scientific literacy and engineering resilience. Springer International Publishing; 2015. http://doi.org/10.1007/978-3-319-12090-4_5.

[31] Akimoto K, Sano F, Homma T, Oda J, Nagashima M, Kii M. Estimates of GHG emission reduction potential by country, sector, and cost. Energy Pol 2010;38(7):3384–93. http://doi.org/10.1016/j.enpol.2010.02.012.
[32] Sato O. A study on long-term energy scenarios for Japan, JAERI-Research, 2005-012. 2005. http://doi.org/10.11484/jaeri-research-2005-012 [in Japanese].
[33] Matsuo Y, Yanagisawa A, Yamashita Y. A global energy outlook to 2035 with strategic considerations for Asia and Middle East energy supply and demand interdependencies. Energy Strategy Reviews 2013;2(1):79–91. http://doi.org/10.1016/j.esr.2013.04.002.
[34] Kurosawa A, Hagiwara N. Long term energy system analysis of Japan after March 11, 2011. In: 3rd IAEE Asian conference, February 21, 2012, Japan; 2012.
[35] Loulou R, Remne U, Kanudia A, Lehtila A, Goldstein G. Documentation for the TIMES model - PART I. 2005. http://iea-etsap.org/docs/TIMESDoc-Intro.pdf.
[36] Clarke LE, Fawcett AA, Weyant JP, McFarland J, Chaturvedi V, Zhou Y. Technology and US emissions reductions goals: results of the EMF 24 modeling exercise. Energy J 2014;35(SI1):9–21. http://doi.org/10.5547/01956574.35.SI1.2.
[37] Knopf B, Chen YHH, De Cian E, Förster H, Kanudia A, Karkatsouli I, Keppo I, Koljonen T, Schumacher K, van Vuuren DP. Beyond 2020—strategies and costs for transforming the European energy system. Clim Change Econ 2013;4(supp01):1340001. http://doi.org/10.1142/S2010007813400010.
[38] Sano F, Akimoto K, Homma T, Tokushige K. Evaluations of the Japan's greenhouse gas emission reduction target for 2030. J Jpn Soc Energy Resour 2016;37:51–60. http://jser.gr.jp/journal/journal_pdf/2016/journal201601_7.pdf [in Japanese].
[39] UNFCCC. Greenhouse gas inventory data - detailed data by party. 2017. http://di.unfccc.int/detailed_data_by_party. [Accessed 5 January 2018].
[40] Ministry of the Environment. National greenhouse gas inventory report of Japan 2017. 2017. Retrieved from, http://www-gio.nies.go.jp/aboutghg/nir/2017/NIR-JPN-2017-v3.1_web.pdf.
[41] Fawcett AA, Clarke LE, Weyant JP. Introduction to EMF 24. Energy J 2014;35(SI1):1–8. http://doi.org/10.5547/01956574.35.SI1.1.
[42] Clarke L, et al. Assessing transformation pathways. In: Edenhofer O, et al., editors. Climate change 2014: mitigation of climate change. Contribution of working group III to the Fifth assessment report of the intergovernmental Panel on climate change. Cambridge and New York: Cambridge University Press; 2014. https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter6.pdf.
[43] Keidanren. Recommendations for the future global warming countermeasures. 2017. Retrieved from, http://www.keidanren.or.jp/policy/2017/077_honbun.pdf [in Japanese].
[44] Renewable Energy Institute. Recommendation: transition to energy policy to realize a decarbonized society–not to make a mistake in discussing the basic energy plan and the long-term low emission development strategies–. 2018. Retrieved from, https://www.renewable-ei.org/activities/reports/img/pdf/20180130/20170130_ProposalEnergyBasicPlan_JP.pdf [in Japanese].
[45] Endo M. Mid-term targets of global warming countermeasures. Issue brief No. 645. National Diet Library; 2009. Retrieved from, http://www.ndl.go.jp/jp/diet/publication/issue/0645.pdf [in Japanese].
[46] Kawasaki Heavy Industries. CO_2-free hydrogen energy supply-chain technology research association commences operations —Multi-company effort takes a step toward the future of hydrogen energy. 2016. Press release on April 1, 2016. Retrieved from, https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20160401_4614.
[47] Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Hartmann J, Khanna T, Lenzi D, Luderer G, Nemet GF, Rogelj J, Smith P, Vicente-Vicente JL, Wilcox J, del Mar Zamora Dominguez M. Negative emissions—Part 1: research landscape and synthesis. Environ Res Lett 2018;13:063001.
[48] Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum DL, Rao ND, Riahi K, Rogelj J, De Stercke S, Cullen J, Frank S, Fricko O, Guo F, Gidden M, Havlík P, Huppmann D, Kiesewetter G, Rafaj P, Schoepp W, Valin H. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 2018;3:515–27.
[49] Luderer G, Pietzcker RC, Carrara S, de Boer HS, Fujimori S, Johnson N,, Arent D. Assessment of wind and solar power in global low-carbon energy scenarios: an introduction. Energy Econ 2017;64:542–51.
[50] Allen MR, Stainforth DA. Towards objective probabalistic climate forecasting. Nature 2002;419(6903):228.
[51] Tebaldi C, Knutti R. The use of the multi-model ensemble in probabilistic climate projections. Phil Trans Roy Soc Lond A: Math Phys Eng Sci 2007;365:2053–75.
[52] Oshiro K, Gi K, Fujimori S, van Soest HL, Bertram C, Després J, Masui T, Rochedo P, Roelfsema M, Vrontisi Z. Mid-century emission pathways in Japan associated with the global 2°C goal: National and global models' assessments based on carbon budgets. Climatic Change 2018 [in review].
[53] Kimura K, Zissler R. Comparison of solar PV cost between Japan and Germany: why is solar PV in Japan costly? (Niohon to Doitsu-ni okeru Taiyōkō Hatsuden no Kosuto HIkaku: Nihon no Taiyōkō Hatsuden wa Naze Takaika?). Renewable Energy Institute; 2016. Retrieved from, https://www.renewable-ei.org/images/pdf/20160113/JREF_Japan_Germany_solarpower_costcomparison.pdf [in Japanese].
[54] Study Group on Enhancing Solar PV Competitiveness (Taiyōkō Hatsuden Kyōsōryoku Kyōka Kenkyūkai). Report of Study Group on enhancing solar PV competitiveness. Japan: Ministry of Economy, Trade, and Industry; 2016. Retrieved from, http://www.meti.go.jp/committee/kenkyukai/energy_environment/taiyoukou/pdf/report_01_01.pdf [in Japanaese].
[55] Kimura K, Kitakaze R. A study on the cost of wind power in Japan. (Nihon-no Huryoku Hatsuden Kosuto-ni Kansuru Kenkyu). Renewable Energy Institute; 2017. Retrieved from, https://www.renewable-ei.org/activities/reports/img/20170614/20170614_JapanWindPowerCostReport.pdf [in Japanese].
[56] Krey V, Luderer G, Clarke L, Kriegler E. Getting from here to there–energy technology transformation pathways in the EMF27 scenarios. Climatic Change 2014;123(3–4):369–82. https://doi.org/10.1007/s10584-013-0947-5.
[57] Pietzcker RC, Longden T, Chen W, Fu S, Kriegler E, Kyle P, Luderer G. Long-term transport energy demand and climate policy: alternative visions on transport decarbonization in energy-economy models. Energy 2014;64:95–108. https://doi.org/10.1016/j.energy.2013.08.059.
[58] Creutzig F, Jochem P, Edelenbosch OY, Mattauch L, van Vuuren DP, McCollum D, Minx J. Transport: a roadblock to climate change mitigation? Science 2015;350(6263):911–2. http://doi.org/10.1126/science.aac8033.
[59] Sugiyama M, Akashi O, Wada K, Kanudia A, Li J, Weyant J. Energy efficiency potentials for global climate change mitigation. Climatic Change 2014;123(3–4):397. http://doi.org/10.1007/s10584-013-0874-5.
[60] World. World crude steel output increases by 5.3% in 2017. Press release, World Steel Association; 2018. Retrieved from, https://www.worldsteel.org/en/dam/jcr:b4df255e-59e3-47e3-8f74-d2e36caf94ca/2017+World+Crude+Steel+Production+Press+Release_vfinal.pdf.
[61] International Energy Agency (IEA). Digitalization and energy. Paris: OECD/IEA; 2017.
[62] NRC (National Research Council). Climate intervention: carbon dioxide removal and reliable sequestration. National Academies Press; 2015. http://doi.org/10.17226/18805.
[63] Davis Steven J, Lewis Nathan S, Shaner Matthew, Aggarwal Sonia, Arent Doug, Azevedo Inês L, Benson Sally M, Bradley Thomas, Brouwer Jack, Chiang Yet-Ming, Clack Christopher TM, Cohen Armond, Doig Stephen, Edmonds Jae, Fennell Paul, Field Christopher B, Hannegan Bryan, Hodge Bri-Mathias, Hoffert Martin I, Ingersoll Eric, Jaramillo Paulina, Lackner Klaus S, Mach Katharine J, Mastrandrea Michael, Ogden Joan, Peterson Per F, Sanchez Daniel L, Sperling Daniel, Stagner Joseph, Trancik Jessika E, Yang Chi-Jen, Caldeira Ken. Net-zero emissions energy systems. Science 2018;360(6396):eaas9793. http://doi.org/10.1126/science.aas9793.
[64] Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P,, Le Quéré C. Betting on negative emissions. Nat Clim Change 2014;4(10):850–3. http://doi.org/10.1038/nclimate2392.
[65] Smith Pete, Davis Steven J, Creutzig Felix, Fuss Sabine, Minx Jan, Gabrielle Benoit, Kato Etsushi, Jackson Robert B, Cowie Annette, Kriegler Elmar, van Vuuren Detlef P, Rogelj Joeri, Ciais Philippe, Milne Jennifer, Canadell Josep G, McCollum David, Peters Glen, Andrew Robbie, Krey Volker, Shrestha Gyami, Friedlingstein Pierre, Gasser Thomas, Grübler Arnulf, Heidug Wolfgang K, Jonas Matthias, Jones Chris D, Kraxner Florian, Littleton Emma, Lowe Jason, Moreira José Roberto, Nakicenovic Nebojsa, Obersteiner Michael. Biophysical and economic limits to negative CO2 emissions. Nat Clim Change 2016;6(1):42–50. http://doi.org/10.1038/nclimate2870.
[66] Solano Rodriguez B, Drummond P, Ekins P. Decarbonizing the EU energy system by 2050: an important role for BECCS. Clim Pol 2017;17(sup1):S93–110. http://doi.org/10.1080/14693062.2016.1242058.
[67] Sanchez DL, Nelson JH, Johnston J, Mileva A, Kammen DM. Biomass enables the transition to a carbon-negative power system across western North America. Nat Clim Change 2015;5(3):230–4. http://doi.org/10.1038/nclimate2488.
[68] Kraxner F, Aoki K, Leduc S, Kindermann G, Fuss S, Yang J,, Obersteiner M. BECCS in South Korea—analyzing the negative emissions potential of bioenergy as a mitigation tool. Renew Energy 2014;61:102–8. https://doi.org/10.1016/j.renene.2012.09.064.
[69] Mizuno Y, Ishimoto Y, Sakai S, Sakata K. Economic analysis on international hydrogen energy career supply chains. J Jpn Soc Energy Resour 2017;38:11–7 [in Japanese with an English abstract].
[70] Fujii Y, Yamaji K. Assessment of technological options in the global energy system for limiting the atmospheric CO2 concentration. Environ Econ Pol Stud 1998;1(2):113–39. https://doi.org/10.1007/BF03353897.
[71] Government of Japan. Strategic energy plan. 2018.