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SPECIAL FEATURE: ORIGINAL ARTICLE

Energy Scenarios for Long-Term Climate Change Mitigation in Japan

Beyond Japanese NDC: energy and macroeconomic transitions towards 2050 in emission pathways with multiple ambition levels

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Abstract

Japan has set greenhouse gas emissions reduction targets for 2030 and 2050, as stated in the nationally determined contribution (NDC) and in the long-term strategy for decarbonization (LTS) submitted to the UNFCCC in 2020, respectively. While upgrading these targets is needed to realize the global climate goals (2 °C and 1.5 °C), the implications of the target for the period in-between remains unclear. This study assesses the energy and macroeconomic impacts of enhancing the ambition of 2040 and 2050 emission reduction targets in Japan by means of a computable general equilibrium (CGE) model. In addition, we analyze the implications on the speed of energy efficiency improvement and low-carbon energy penetration along with macroeconomic impacts, and the shift from the current LTS goal (80% emissions reduction by 2050) to a full decarbonization one. The study shows that, compared to the current ambition (53% reduction by 2040 compared to 2005), enhancing ambition of the 2040 (63% reduction by 2040 compared to 2005) and 2050 targets (zero emissions by 2050) rises the share of low-carbon energy supply more drastically than the decreases in energy intensity, and increases macroeconomic costs by 19–72%. Moreover, meeting these targets demands accelerating considerably the reductions in carbon intensities through expansion of renewables and CCS beyond historical trends and beyond current efforts towards the 2030s NDC. Enabling larger low-carbon supplies and energy efficiency improvements makes full decarbonization by 2050 possible at costs equivalent to current ambition. Further analyses are needed to clarify at a finer detail the implications of changes in these enablers by sectors, technologies and policies. This kind of analysis offer key insights on the feasibility of Japan's emission reduction targets for the formulation of new commitments for the next cycle of the Global Stocktake under the Paris Agreement.

Keywords Enhanced mitigation ambition · Mitigation scenario · Long-term strategy · Japan · Computable general equilibrium

Introduction

Current targets for greenhouse gas (GHG) emission reduction set by countries for the near term (2030) under the Paris Agreement of the United Nations Framework Convention for Climate Change (UNFCCC) (UNFCCC. Conference of the Parties (COP) 2015), are regarded insufficient for realizing the global goals for climate mitigation, namely, to keep global warming below 2 °C and pursuing efforts for it by 1.5 °C within this century (United Nations Environment Programme and United Nations 2016; Hof et al. 2017). Therefore, mitigation targets for the near term need to be enhanced to avert dangerous climate change. The formulation of the forthcoming nationally determined contribution (NDC) (which will target the period five or ten years after 2030 depending on the pending discussions on the

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Paris Rulebook), and of the long-term strategy (LTS) aiming for decarbonization by mid-century by countries under the PA, are expected to foster more ambitious mitigation targets. Moreover, the Global Stocktake (GST), a process established by the PA to periodically review and enhance the ambition of the current and upcoming targets set by the parties, is expected to contribute to close the gap between national contributions and global climate targets.

As the world's fifth largest emitter (Crippa et al. 2019), and the third largest economy (World Bank 2019), increasing the mitigation ambition set by Japan can bring strong signals to other parties on the need to step up actions towards climate change mitigation (Kuriyama et al. 2019). Following the adoption of the PA in 2015, Japan submitted its NDC including a target for reducing GHG emissions by 26% in 2030 compared to 2013 (Cabinet Office 2015). In 2019, Japan submitted its LTS for decarbonization, including a goal of 80% emission reduction by 2050 without specifying the base year (The Government of Japan 2019). In March 2020, Japan submitted its NDC update keeping the same target of the 2015 submission (The Government of Japan 2015). More recently, in October 2020 the new head of government announced the goal of net zero GHG emissions by 2050 (Prime Minister's Office of Japan 2020). This move justifies the consideration of the next NDC cycle, likely to be 2040 based on the position of Japan towards the "common timeframe" under the Paris Agreement (The Government of Japan 2018).

The possibility of increasing ambition depends on the speed of long-term changes in the major drivers of emissions and the associated economic impacts. For the case of Japan, as well as for many other countries, it is essential to evaluate the changes in the supply and consumption of energy, as they are the major sources of emissions. Moreover, careful consideration of alternative pathways and measures that lessen economic impacts and promote benefits is needed. For example, the feasibility of enhanced mitigation ambition can improve by enabling a larger availability of low-carbon energy supply, such as renewable energy sources and carbon capture and storage (CCS), as well as by enabling lower energy intensity of energy consumption, by means of technologies and measures accelerating energy efficiency improvements in end use sectors (Kuramochi et al. 2017). Global assessments have included expansion of these aspects (low-carbon energy supply and energy efficiency) into their scenario designs (Liu et al. 2018).

The literature on long-term mitigation scenarios for Japan shows that meeting 2030 and 2050 targets is possible with drastic changes in the supply and demand of energy (Kuramochi et al. 2017; Sugiyama et al. 2019). The share of low-carbon energy supply, including renewables, nuclear and energy supply (both fossil fuel and biomass) coupled with carbon capture and storage (CCS), needs to be scaled up to unprecedent levels, as the current share of these options is minor (15% as of 2016). Mitigation scenarios also show that energy intensity must decrease faster than historical trends. These changes demand large investments in low-carbon technologies and energy efficiency improvements, and result in mitigation costs equivalent to a GDP loss of few percentage points by 2050 (Silva Herran et al. 2019). In contrast, benefits are expected in terms of improved energy security, due to lower dependence on imported fuels, and increased diversity of energy supply options (Oshiro et al. 2016; Matsumoto and Shiraki 2018; Silva Herran et al. 2019). Also, there are cost savings from the reduction in fuel imports (Oshiro et al. 2016).

With respect to enhancing the mitigation ambition, national and global studies assess the gap of current NDCs with emissions levels consistent with the 2 °C goal, either focusing on the implications of the effort sharing scheme for allocating global emissions budgets to countries (Kuramochi et al. 2016; Pan et al. 2017; Xunzhang et al. 2017; van den Berg et al. 2020), of the socioeconomic assumptions (Hof et al. 2017), or of the current policies (Roelfsema et al. 2020). Some Japanese studies include a more ambitious near-term target (compared to the current NDC by 2030), and an immediate shift in emissions towards the 2050 goal, and zero emissions goal by 2050, but lack any assessment of macroeconomic impacts (Oshiro and Masui 2015; Oshiro et al. 2017b). To the best of our current knowledge, the assessment of the energy transitions together with the macroeconomic impacts associated to multiple levels of ambition by 2040 along with 2030 and 2050 for Japan, and the corresponding implications on the speed of transformations compared with historical trends, are missing in the literature. To fill this gap, this paper conducts the assessment of emission pathways with multiple ambition levels for 2040 and 2050, and analyses the implications on low-carbon energy supply, energy intensity, and macroeconomic impacts, with a general equilibrium modeling framework. The contribution of this study lies on the following: (1) the assessment of energy transitions in emission pathways for Japan up to 2050 including macroeconomic impacts; (2) the consideration of multiple levels of mitigation ambition (i.e. emissions reduction targets) for multiple periods (2040 in addition to 2030 and 2050); (3) the analysis of the speed of change in key decarbonization indicators against historical trends.

This study is part of the Stanford Energy Modeling Forum (EMF) Japan Model Intercomparison Project (EMF35 JMIP), a multi-model inter-comparison project for Japan climate policy assessment focusing on the 2050 target (Sugiyama et al. this special issue). While the EMF35 JMIP includes scenarios assuming enhanced ambition (zero emissions by 2050, and enhanced ambition of the 2030 target), this paper further complements the project assessment with additional scenarios and analysis.

Methods

In this study, a computable general equilibrium (CGE) model is applied to assess the feasibility of enhanced levels of mitigation ambition in Japan, with scenarios considering alternative targets for GHG emission reduction by 2030, 2040 and 2050. We analyze the implications on energy supply, energy consumption, and the macroeconomic impacts, and the effect of enabling larger shares of low-carbon energy supply and lower energy intensity (i.e. higher energy efficiency improvements).

Model

The Asia–Pacific Integrated Assessment Model Hub-Japan (AIM/Hub-Japan) model is applied for the case of Japan. The model is used to assess climate mitigation scenarios in Japan (Silva Herran et al. 2019). The AIM/Hub (previously known as AIM/CGE) is a CGE model covering all economic activities and a full set of GHGs and air pollutants (Fujimori et al. 2012, 2017). It is a recursive dynamic model which assumes investment decisions are based on the outcomes of the previous period and the prices of the current modelling period, without any foresight. It includes 45 production sectors and has a detailed description of the energy sector, the agricultural sector and land use activities on an annual basis. The energy sector includes energy resources, conversion technologies, and end uses by final energy sources and services (trade of energy covers fossil fuels and bioenergy). Features of energy resources and technologies (including CCS), such as efficiency and costs technologies, are based on IEA (IEA 2013) and relevant studies (Silva Herran et al. 2016; World Energy Council 2016; Fujimori et al. 2017; Hasegawa et al. 2017). The additional cost of integrating a variable supply from wind and solar power is included (daily/hourly supply/demand are not handled by the model) (Dai et al. 2017). Mitigation policies are evaluated by means of a carbon price, which is levied on activities emitting GHGs. We run the AIM/Hub model in this study as a single national model (Chunark et al. 2017). Additional details are included in the supplement of this paper, and the overview paper of the EMF35 JMIP (Sugiyama et al. 2021).

Scenarios

The scenarios in this study consider a combination of two dimensions; namely climate policy (emissions reduction targets) and energy related assumptions (covering low-carbon energy supply and energy efficiency). We consider these dimensions to assess: (1) the level of ambition of the mitigation targets (2030, 2040 and 2050); and (2) the effect of "enablers" of enhanced mitigation ambition. For the first aspect, we consider six policy scenarios using the default energy-related assumptions (see Tables 1 and 2 for details). For the second aspect, we consider 12 scenarios based on the policy scenarios that assume enhanced mitigation ambition (three policy scenarios), and using four combinations of energy-related assumptions (default, high low-carbon energy supply, high energy efficiency, and high for both low-carbon energy supply and energy efficiency).

The policy dimension (see Table 1) includes a business as usual (*BaU*) scenario without any climate mitigation policies, and five emissions reduction scenarios with different levels of ambition during the first half of the century. The level of mitigation ambition is represented by the emissions reduction target (covering carbon dioxide, methane and nitrous oxide) by 2040 and 2050. The reference scenario is the *NDC_80by2050*, which represents the current near-term (by 2030 as in the NDC) and long-term (by 2050 as in the LTS) ambition (25.4% reduction by 2030 and 80% reduction by 2050 compared to 2005,

Table 1 Description of climate policy assumptions in the scenarios (GHG emissions reduction relative to 2005, including carbon dioxide, methane and nitrous oxide, but excluding F-gases)

Scenario name	Code	Emissions reduction relative to 2005 values		
		2030	2040[a]	2050[b]
No policy	BaU	NA	NA	NA
Reference	NDC_80by2050	25.4%[c]	53%	80%[d]
Stagnant ambition	NDCextend_80by2050	25.4%[c]	48%	80%[d]
Enhanced ambition 2040	NDCtoZero_80by2050	25.4%[c]	63%	80%[d]
Enhanced ambition 2040/2050	NDCtoZero_100by2050	25.4%[c]	63%	100%
Immediate decarbonization	2020toZero	36%	68%	100%

[a]Emissions by 2040 calculated as linear interpolation of emission trajectories reflecting the values for 2020, 2030 and 2050

[b]As of the time of writing, the Japanese government has not specified the base year for the 2050 target

[c]Based on Japanese NDC (Cabinet Office 2015)

[d]Based on Japanese LTS submission (The Government of Japan 2019)

Table 2 Description of energy-related assumptions in the scenarios

Scenario name (code)	VRE potential	CCS	Nuclear	AEEI (%/year)
Default	Solar PV 1.2 EJ/year, onshore wind 5.4 EJ/year Shiraki et al. (2021) and Silva Herran et al. (2019)	Start from 2030, 50–200 USD/tCO_2 IEA (2013)	Plant life 60 years, no new plants, restart idle plants progressively from 2020 to meet NDC target (20–22% of power supply by 2030). Silva Herran et al. (2019)	1.00
Low-carbon energy supply (LowC)	Double of Default	Start from 2022, 28 USD/tCO_2 IEA (2013)	Same as default but with 3 new plants Silva Herran et al. (2019)	1.00
Energy efficiency (EE)	Same as default	Same as default	Same as default	1.25
Combined (LowC_EE)	Same as LowC	Same as LowC	Same as LowC	1.25

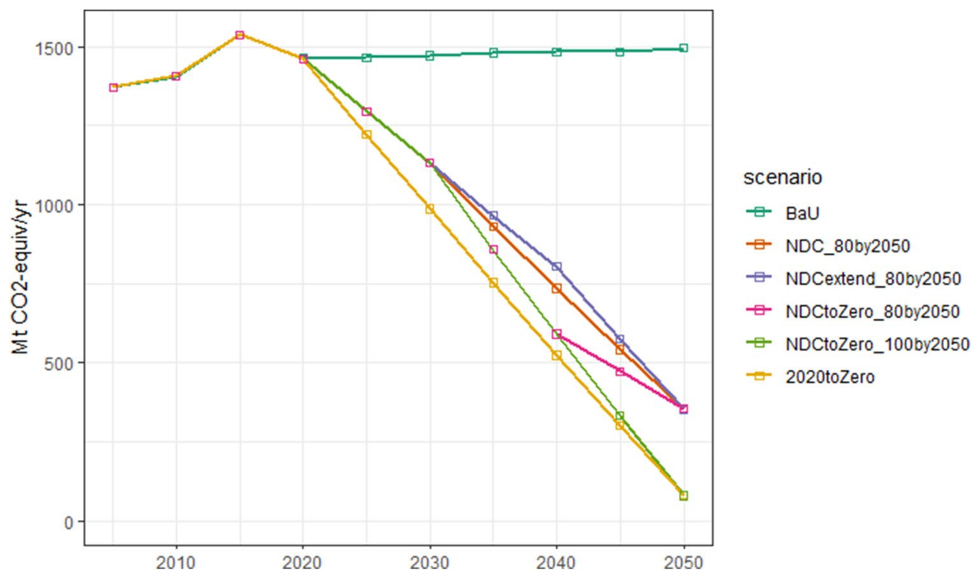

Fig. 1 Emission pathways (GHGs including carbon dioxide, methane, nitrous oxide, and F-gases) assessed in the study

respectively). Two scenarios are defined to evaluate the effect of stagnant (*NDCextend_80by2050*) and enhanced (*NDCtoZero_80by2050*) ambition by 2040. The stagnant ambition scenario assumes emissions decrease by 2040 at the same rate needed to reach the 2030 target (i.e. linear extrapolation of the emissions trend in the *NDC_80by2050* scenario after 2030). The enhanced ambition scenario assumes emissions between 2030 and 2040 are aligned to a pathway towards zero emissions by 2050. These two scenarios assume the same level of ambition by 2050 of the *NDC_80by2050* scenario. The fourth mitigation scenario (*NDCtoZero_100by2050*) assumes shifting towards zero emissions from 2030 and enhancing the LTS target to a full decarbonization target by 2050. The last scenario (*2020toZero*) assumes an immediate shift towards zero emissions in 2050 (a linear pathway towards zero emissions between 2020 and 2050). The emission scenarios, presented in Fig. 1, result in 2040 emissions reduction targets ranging from 48 to 68% compared to 2005 levels.

The energy-related assumptions dimension (see Table 2) includes default and optimistic (high) assumptions for low-carbon energy supply and energy efficiency. They reflect the uncertainty in future trends of factors related to these aspects (such as resource and technology availability, and technological progress). Although optimistic outcomes can result from additional costs or efforts put on top of current policies, this study excludes such analysis. Low-carbon supply (LowC) assumptions cover the size of the economic potential for variable renewable energy (VRE), namely solar and wind, the starting year of availability of CCS and its cost, and the availability of nuclear power supply. Energy efficiency (EE) assumptions are represented in terms of the rate of autonomous energy efficiency improvement (AEEI), which represents the contribution of technological progress (and excludes any policy-induced effects).

Socioeconomic assumptions (population, GDP, technology progress, etc.) in all scenarios follow the SSP2 narrative of the Shared Socioeconomic Pathways (SSP) framework

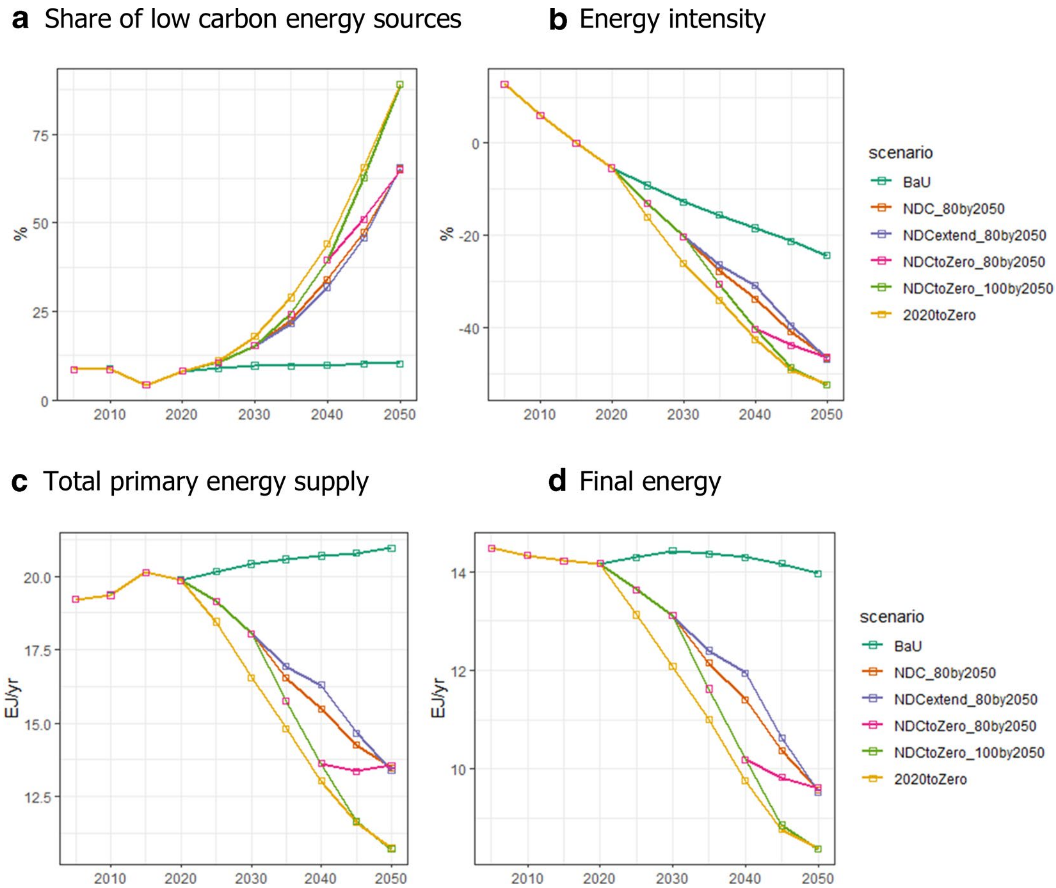

Fig. 2 Results for energy aspects across emission scenarios: **a** low-carbon energy supply (share), **b** energy intensity (difference from 2015), **c** total primary energy supply, **d** final energy

(O'Neill et al. 2014; Riahi 2016), and described in detail in Fujimori et al. (2017).

Assessment indicators and other settings

In this study we evaluate two aspects, energy and macroeconomic impacts. For the energy aspect we evaluate two indicators. Low-carbon energy supply refers to the share of renewable energy, nuclear power and CCS (both fossil and biomass). Energy intensity refers to the total final energy consumption per unit of GDP. The macroeconomic aspect is evaluated with the carbon price and the GDP loss (expressed as a percentage reduction compared to the *BaU* scenario).

Results and discussion

BaU and reference (*NDC_80by2050*) scenarios

The outcomes of the scenarios for energy indicators and macroeconomic impacts are presented in Figs. 2, 3, and 4, respectively. The long-term (towards 2050) energy transformations in the *NDC_80by2050* scenario are characterized by a decrease in total energy supply and consumption, a drastic shift from fossil fuels to low-carbon energy in the energy supply side, and by continuous decline in energy intensity. Primary energy supply in the *NDC_80by2050* scenario decreases compared to the base year (2005) by 19% and 29% in 2040 and 2050, respectively. In contrast, in the *BaU* scenario it increases by 8% and 9% in 2040 and 2050, respectively. The *NDC_80by2050* scenario results in a low-carbon supply share (Fig. 2a) jumping from 8% in 2020 to 33% in 2040 and to 64% in 2050, while in the *BaU* scenario the share remains stagnant at 10% in both periods. Energy intensity (Fig. 2b) in the *NDC_80by2050* scenario declines to 59% and 47% of the base year levels in 2040 and 2050, respectively. In the *BaU* scenario, the decline is smaller (72% in 2040 and 67% in 2050).

Energy implications of enhanced ambition

Here we analyze the effect of enhanced mitigation ambition on the share of low-carbon energy supply and energy intensity (presented in Fig. 2). Overall, the level of ambition

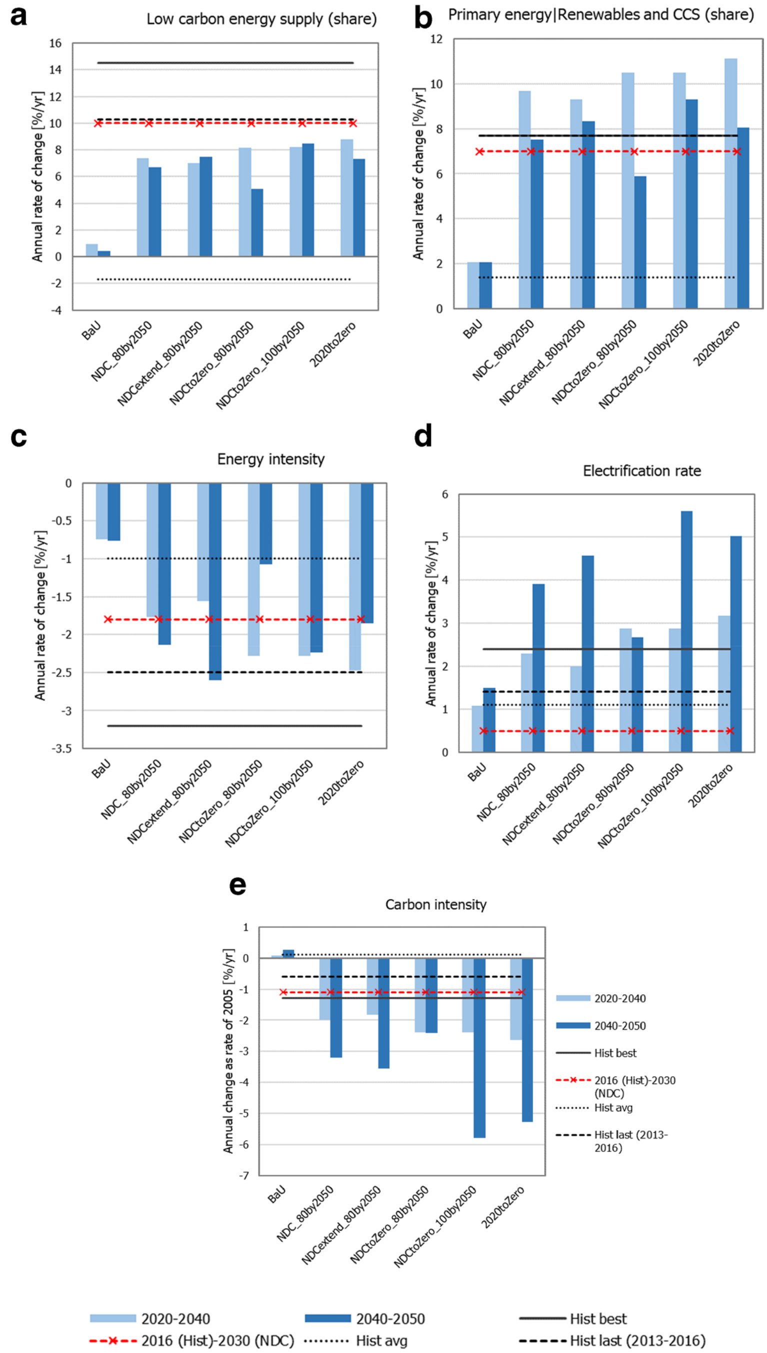

Fig. 3 Annual rate of change between 2020–2040 and 2040–2050 for key energy indicators: **a** share of low-carbon energy supply in primary energy supply, **b** share of renewables and CCS in primary energy supply, **c** energy intensity, **d** electrification rate (share of electricity in final energy consumption), **e** carbon intensity of final energy consumption (as average annual difference relative to 2005). "Hist best" corresponds to the largest average annual rate of change (highest for low-carbon supply and electrification rate, lowest for energy intensity and carbon intensity) for selected historical timeframes covering 1960–2016 (for details see Kuriyama et al. 2019). "Hist avg" corresponds to the average of the historical data. "2016 (Hist)—2030 (NDC)" corresponds to the rate of change based on the 2016 historical data and the assumptions in Japan's NDC

affects the speed at which changes occur between the target periods (i.e. 2030, 2040, 2050), and the outcome in each of these periods is determined by the level of ambition (emission target) set for that period. Compared to the *NDC_80by2050* scenario, enhancing the mitigation ambition by 2040 (as in the *NDCtoZero_80by2050* scenario) increases the share of low-carbon supply by 16% (equivalent to increase in the share of 5 percentage points) and lowers energy intensity by 10% in 2040. The outcome by 2050, however, is almost the same as the *NDC_80by2050* scenario (which has the same emission target by 2050). In the scenario with the highest ambition (*2020toZero*) the share of low-carbon supply increases faster than in any other scenario, resulting in values 10 and 24 percentage points higher than the *NDC_80by2050* scenario in 2040 and 2050, respectively (equivalent to shares of 43% and 87%). Energy intensity in 2040 and 2050 for this scenario is 15% and 11% lower than the *NDC_80by2050* scenario, respectively.

The speed of changes in key energy indicators across the scenarios, presented in Fig. 3, are analyzed below, along with the "best" values of annual average change from selected timeframes in the past (spanning 3–13 years depending on

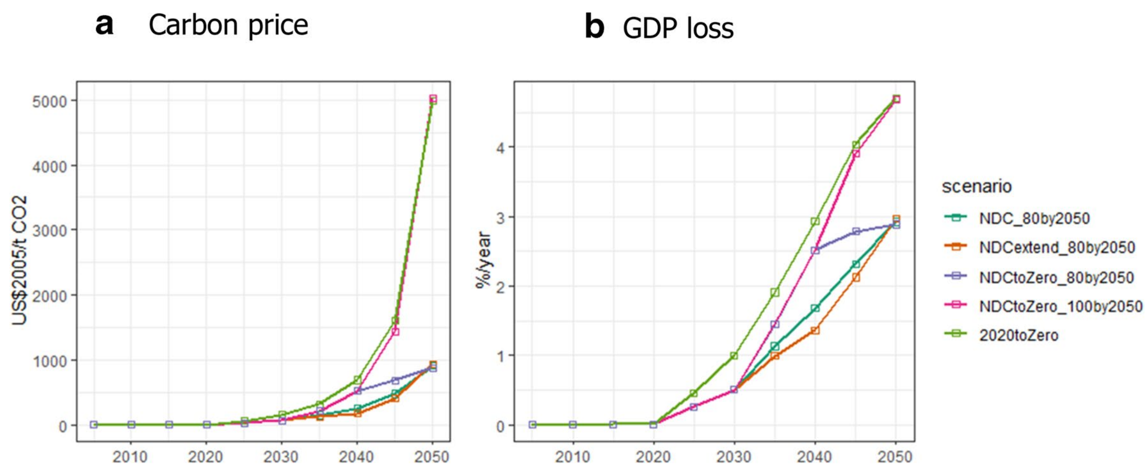

Fig. 4 Results for economic impacts across emission scenarios: **a** carbon price, **b** GDP loss rate compared to the *BaU* scenario

the timeframe). This value is different from the largest value within each timeframe. The timeframes reflect historical milestones relevant to energy policy in Japan (such as the oil crisis in 1973, the financial crisis in 1991 and 2007, and the 2011 East Japan great earthquake, among others) following Kuriyama et al. (2019). The analysis focuses on 2020–2040 and 2040–2050 periods, as most scenarios (four out of six) assume the same emissions trajectory until 2030. Compound annual growth rates are used for low-carbon energy supply, energy intensity, electrification; average annual difference is used for carbon intensity of energy consumption. Compared to the *NDC_80by2050* scenario, enhanced ambition by 2040 (*NDCtoZero_80by2050*) slightly accelerates the penetration of low-carbon energy supply towards 2040, but slows it towards 2050 (Fig. 3a). Enhancing the 2050 target results in almost the same rate of change in the whole timeframe (up to 2050). Although in all mitigation scenarios changes are lower than both the values observed historically, and the trend towards the NDC assumption (2016–2030), a detailed analysis by specific technologies demonstrates that enhanced efforts are needed for expanding the use of renewables and CCS to meet long-term mitigation, due to the uncertain role of nuclear power in Japan.

Nuclear power has a significant role in past trends of low-carbon energy supply. The historical best performance ("Hist best" in Fig. 3a) was achieved in 1973–1986 through the fast buildup of nuclear power to tackle the oil crisis. Under the current situation, scale up of nuclear power in Japan is uncertain due to increased restrictions to nuclear power operation in response to the 2011 disaster, which stopped plans for new installations (World Nuclear Association 2020). Moreover, the trend in low-carbon energy supply shown in Fig. 3a between 2013 and 2016 (10.3%/year), which is similar to the rate expected for the 2030 NDC (2016–2030), is largely influenced by the growth in nuclear power supply from very low levels following the progressive restart of nuclear plants after 2011.

The share of renewables and CCS (Fig. 3b) towards 2040 grows at a pace at least 26% faster than the best historical performance, achieved in 2013–2016, and 38% faster than the trend towards the NDC. Enhanced ambition by 2040 and 2050 further accelerates the penetration of renewables and CCS. Therefore, meeting long-term mitigation goals require efforts beyond the current schemes promoting renewables through feed-in-tariff policy.

In terms of energy intensity (Fig. 3c), enhancing ambition by 2040 results in a faster change by 2040, but in the lowest rate of change by 2050 across all scenarios. In contrast, keeping ambition stagnant (*NDCextend_80by2050*) results in a considerably larger rate of change towards 2050 compared to any other scenario. Enhancing ambition from 2020 (*2020toZero*) has the largest rate of change towards 2040, and levels towards 2050 similar to the rate of change towards 2040 in the *NDC_80by2050* scenario. Rates of change are lower than historical trends, and the current ambition (*NDC_80by2050*) is aligned to the trend towards the NDC (2016–2030). Similar to the changes in low-carbon supply, the fastest historical trend corresponds to the time of the oil crisis (1973–1986). Also, the latest trend (2.5%/year in 2013–2016) is faster than all scenarios considering increased ambition (only the *NDCextend_80by2050* scenario has slightly higher values in 2050). This points to the importance of continuing the achievements in energy savings and efficiency improvements promoted after the 2011 disaster.

The speed of electrification (Fig. 3d) seems very sensitive to the level of ambition. Enhancing ambition by 2040, increases the rate of change moderately towards 2040. Towards 2050, the rate of change remains at a level similar up to 2050, in contrast to the *NDC_80by2050* scenario where electrification accelerates sharply after 2040. Enhancing ambition towards full decarbonization almost doubles the speed of electrification after 2040 compared to the enhanced ambition by 2040. All scenarios, except the one assuming enhanced ambition by 2040, reach rates of change towards 2050 considerably higher than the maximum historical value (2.4%/year in 1973–1986) and recent trends (1.4%/year in 2013–2016), highlighting the need for long-term innovations to electrify final energy supply much faster than ever experienced. Moreover, the model in this study seems to be optimistic in terms of the expansion of electrification, given that the NDC assumption results in a very slow rate of change (0.5%/year between 2016 and 2030).

The speed of decarbonization (Fig. 3e), measured in terms of the carbon intensity of final energy consumption (which is presented as the difference in a given period compared to 2005 emissions), is around two times larger than the historical maximum trend and the NDC assumption when ambition of the 2040 target is considered. Also, values before and after 2040 become almost equal, in contrast with other scenarios where changes are more drastic after 2040. Decarbonization speed is even higher in scenarios assuming enhancement of the 2050 target to zero emissions. This outcome demonstrates the gap between the current short-term (i.e. towards 2030) decarbonization effort and what is needed in the longer term (2040 and 2050).

Economic implications of enhanced ambition

The carbon prices (Fig. 4a) for the *NDC_80by2050* scenario in 2040 and 2050 are 247 and 905 USD/tCO_2, respectively. These values are similar to those reported in other studies assessing the 80% reduction goal in Japan (Oshiro et al. 2017a; Silva Herran et al. 2019). The GDP loss compared to the *BaU* scenario (Fig. 4b) in the *NDC_80by2050* scenario in 2040 and 2050 are 1.7% and 2.9%, respectively. Enhancing mitigation ambition increases economic impacts, especially when the 2050 target is upgraded to zero emissions (*NDCtoZero_100by2050* and *2020toZero*), as shown in Fig. 4. Similar to the outcomes on energy indicators, the effect of enhanced ambition on carbon prices and on GDP loss is evident only in a period where the emission target is changed. For example, the level of ambition by 2040 has no considerable influence on the outcome by 2050.

Enhancing the ambition in 2040 increases carbon prices by 111% and GDP loss by 50% (in 2040) compared to the *NDC_80by2050* scenario. In contrast, enhancing the ambition in 2050 results in carbon prices in 2050 more than 5 times larger, and GDP losses in 2050 60% larger than in the *NDC_80by2050* scenario (equivalent to a reduction in annual average GDP growth from 0.81% in the *BaU* scenario to 0.71% in the *2020toZero* scenario). This additional mitigation ambition brings down cumulative emissions (between 2011 and 2050) from 41.8 to 36.6–38.8 Gt CO_2. The extremely high carbon price is partially due to the lack of backstop technologies, such as direct air capture, in the model. The model should be expanded to include this kind of technology in the future. By sectors, the outcomes compared

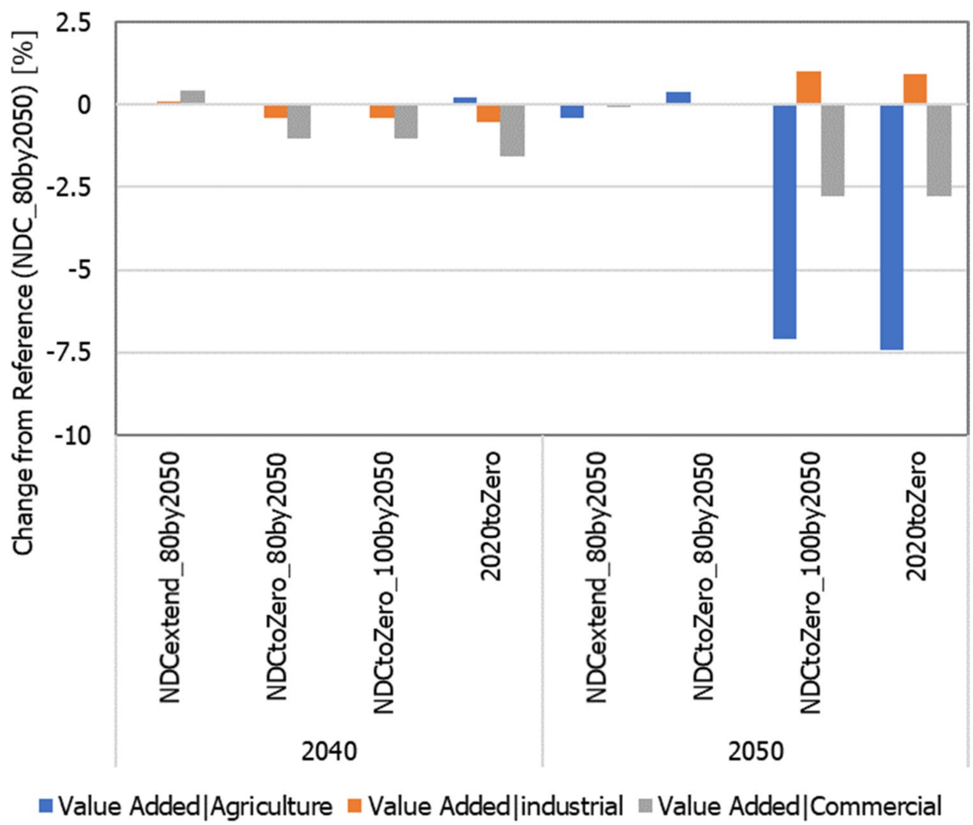

Fig. 5 Economic impacts by sectors across emission scenarios. Values indicate the percentage change in value added compared to the *NDC_80by2050* scenario

to the *NDC_80by2050* scenario, presented in Fig. 5, show that increasing 2040 ambition leads to losses for commercial and industry sectors in 2040, but almost no change in 2050. Upgrading the 2050 ambition boosts these gains for the industrial sector (due to more aggressive expansion of low-carbon industry, such as those deploying CCS and electrification from low-carbon sources), in contrast to the agricultural and commercial sectors which see losses amplified considerably due to the impact of higher energy prices on consumption of intermediate outputs. Those kind of negative impacts driven by mitigation policy are also mentioned in the literature (Fujimori et al. 2019a).

Enablers for enhanced ambition in the energy system

Overall, the outcomes of the study show that enhanced ambition results in lower cumulative emissions via faster energy transformations and higher costs in the near term (2030–2040), and slow (and stagnant for some aspects) changes for the long term (2040–2050). In contrast, if the near-term (2030–2040) ambition remains stagnant (as in the *2030extended_80by2050* scenario) the effect on energy and macroeconomic indicators is lessened. Then, there is a clear tradeoff between the mitigation cost and the cumulative emissions irrespective of the path chosen. Although this fact undermines the feasibility of enhanced ambition from the macroeconomic perspective, it must be noted that: (1) this study only assesses macroeconomic impacts and excludes evaluation of the benefits (direct as well as co-benefits) granted by climate change mitigation; (2) the rationale for enhancing ambition is grounded on the need to close the gap between current efforts and the global climate targets agreed under the Paris Agreement, which will in turn diminish the risks from climate change impacts (while obviously Japanese independent efforts to reduce cumulative emissions would not largely change the global temperature outcomes, as the fifth largest emitter these efforts are a strong signal

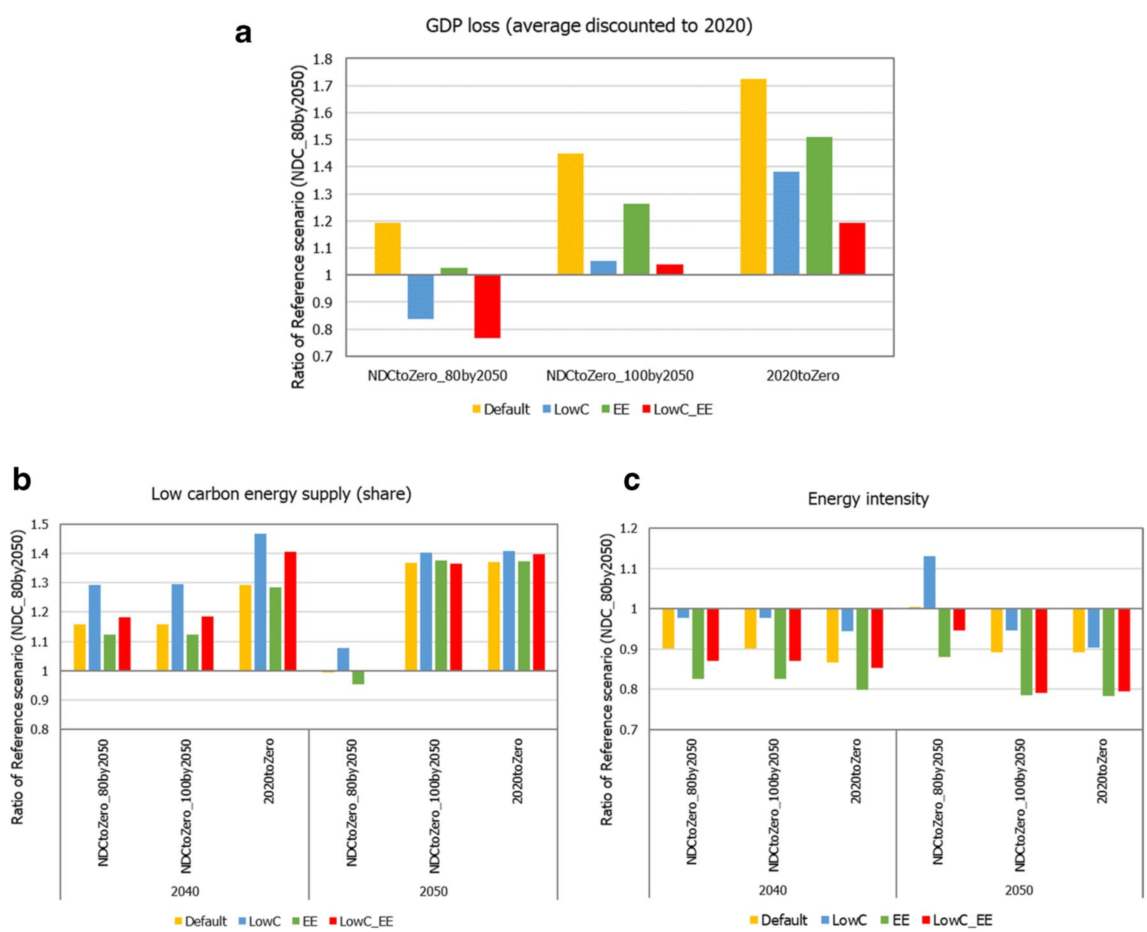

Fig. 6 Effect of enabling expanded availability of low-carbon energy supply (LowC) and energy efficiency improvements (EE) on economic and in energy indicators (expressed as relative values to the *NDC_80by2050* scenario) ("Default" refers to scenarios assuming default values for low-carbon energy supply and energy efficiency): **a** GDP loss (average 2020–2050 discounted at 5% annual rate); **b** share of low-carbon energy supply across scenarios; **c** energy intensity

to incentivize other countries). Therefore, it is important to explore how the trade-off between mitigation costs and cumulative emissions can be overcome to enable enhanced ambition.

In this section we analyze the effect of expanded availability of low-carbon energy supply and of faster energy efficiency improvements, on the feasibility of enhanced ambition. Although these two "enablers" of enhanced mitigation are not the only factors affecting the feasibility of mitigation targets (Hof et al. 2017), at the macro level they encapsulate the aggregated effects of multiple mitigation measures at the country level. The effect of these factors, which is also analyzed in global scenario assessments (Liu et al. 2018), is presented in Fig. 6. To better represent the macroeconomic impacts, the GDP losses are expressed as the average of values between 2020 and 2050 discounted at 5% annual rate. Expressed this way, the impact for the *NDC_80by2050* scenario is 26.6 billion USD. Rising the level of mitigation ambition under the default assumptions can bring cumulative emissions down from 42 $GtCO_2$ in the *NDC_80by2050* scenario by 4% to 12%, but increases GDP losses by 19% to 72%.

Enabling low-carbon energy supply (LowC) can realize the enhanced ambition by 2040 (*NDCtoZero_80by2050*) at 16% lower costs than the current ambition (*NDC_80by2050* scenario), and the long-term ambition (*NDCtoZero_100by2050*) at similar costs. Compared to scenarios under the default assumptions, GDP losses are smaller (− 16 to 38% compared to the *NDC_80by2050* scenario), with shares of low-carbon supply moderately higher by 2040, and very similar by 2050. However, energy intensity increases compared to the default assumptions, due to the expanded availability of cheaper low-carbon electricity supply, which in turns facilitates electrification across all sectors. The assumptions for low-carbon supply affect the timing rather than the scale of low-carbon supply. Enabling energy efficiency improvements lowers the GDP losses compared to the default assumptions (2–51% larger than the *NDC_80by2050* scenario), although at a smaller scale than expanding low-carbon supply, and with considerable reductions in energy intensity in both 2040 and 2050. Enhanced ambition by 2040 (*NDCtoZero_80by2050*) is achieved at similar costs to the current ambition. Also, the effect of energy efficiency assumptions has almost no influence on the share of low-carbon energy sources in 2040 and 2050. Enabling simultaneously the improvements in low-carbon energy supply and energy efficiency, reduces even further the economic impact by 2050. For example, enhanced ambition of 2040 and 2050 targets (*NDCtoZero_100by2050*) can be achieved at the same mitigation cost of the current level of ambition, and still secure 9% less cumulative emissions (2010–2050). In the case of shifting to a path of immediate decarbonization (*2020toZero*), these improvements can cut cumulative emissions by 14% at similar mitigation costs as enhancing ambition only for 2040 under default assumptions.

Feasibility of enhanced ambition

Enhanced mitigation ambition must be evaluated against the possibility to close the gap with the carbon budgets consistent with global climate targets (i.e. 2 degree target). Carbon budgets depend on the scheme for allocating emissions allowances (Kuramochi et al. 2016). Emissions pathways in this study result in cumulative emissions larger than the national carbon budgets under a cost-optimal allocation of emissions allowances suggested by the median outcomes from global models that applied global carbon budget constraints (Oshiro et al. 2020). Only the scenario assuming the highest level of ambition (*2020toZero*) is within the range indicated by the median of global models (31–36 $GtCO_2$ between 2011 and 2050). The energy system transformations by 2050 suggested by the median values of global models are more moderate than in this study. For example, low-carbon energy supply shares in global models are 41–58%, while values in this study were 62–92%. Median values for the reduction in final energy consumption (relative to 2010) in global models were 20–26%, while they were 33–42% in this study. This difference comes from diverging technologies' assumptions and approaches among models. For example, the limited role of nuclear power under the current circumstances of Japan is not reflected in all global models, and, as a result, shares in primary energy supply by 2050 (7–12%) are around two to three times larger than in this study (3%). Also, CGE type of models tend to result in higher energy and economic impacts than bottom-up models which use a partial equilibrium approach (Fujimori et al. 2019b).

While other studies focusing on Japan's mitigation up to 2050 emphasize the role of low-carbon energy supply, the role of lowering consumption by means of energy efficiency improvements is not equally treated. As many of these assessments are based on bottom-up models, they have limited capability to represent energy savings driven by changes in socioeconomic structure. Moreover, circumstances unique to Japan (such as energy improvement rates and savings motivated by the rolling power blackouts in the aftermath of the 2011 earthquake) may not be always reflected.

Although this study shows that enhancing Japan's ambition, including the upgrading of near- (2030), mid- (2040) and long-term (2050) mitigation targets, is feasible from the modeling perspective, challenges are expected in terms of the speed of socioeconomic transformations, of costs, and of decision-making attitudes. While the speed of change needed for enhanced ambition in the share of low-carbon energy supply is lower than what has been observed in Japan in the past decade, the uncertain role of nuclear power in the country (involving decisions on the restart of idle plants and construction of new ones) calls for stepped up efforts for expanding other low-carbon energy sources. Therefore, the energy infrastructure must transform so that technologies, such as VRE and CCS, dominate the share of supply (which was at most 6% between 2000 and 2007). At the same time, solutions to issues related to nuclear power (safety, local acceptance, waste disposal among others) are needed in the short and long terms. In contrast, for the energy intensity improvement, enhancing ambition requires changes in the long term greater than those consistent with the current ambition (2.0%/year) and observed in the past (2.5%/year between 2013–2016 and at most 3.2%/year between 1973–1986). Evaluating feasibility relying solely based on these kind of aggregated indicators is not adequate, especially in the case of low-carbon energy supply which relies on radical innovations in addition to incremental ones (e.g. CCS, solar and wind power). Thus, consideration of indicators related to transformations in specific technologies and economic sectors is necessary.

Enhancing mitigation will undoubtedly increase the costs, but it will also reduce the risks posed by climate change and amplify the co-benefits from mitigation measures, such as improved air quality due to less combustion of fossil fuels, increased employment due to higher labor intensity in certain low-carbon technologies, among others (Zusman et al. 2012; Springmann et al. 2016; Takakura et al. 2017; Xie et al. 2018; Matsumoto 2019; Matsumoto et al. 2019; Saari et al. 2019). Evaluating these aspects is another area of further research. In addition, mitigation costs can be alleviated by expanding low-carbon energy supply and energy efficiency improvements, as shown in this study. Research is needed to identify and evaluate specific measures related to these two enablers based on existing practices within and outside Japan, including the additional cost incurred by implementing relevant policies. The effectiveness of existing policies and practices in addition to climate policies is highlighted in recent studies (Kriegler et al. 2018; Roelfsema et al. 2018).

Now that the Japanese government expressed its aim for achieving net-zero emissions by 2050, attention has concentrated into the feasibility of this goal. Although this study excluded a comprehensive assessment of this goal, the discussion points raised above about the feasibility of enhanced ambition are equally relevant. According to the results of this study, the GDP loss, which is one of the several possible feasibility indicators, of reaching zero emissions by 2050 (as indicated by the *NDCtoZero_100by2050* scenario in Fig. 6a) can be considerably lowered if both low-carbon energy supply and energy efficiency are expanded. This outcome can be realized by several means. Firstly, by expanding existing low-carbon technologies and developing new ones through aggressive policies and measures fostering technology and system innovations. Secondly, by measures removing barriers to the penetration of low-carbon technologies and innovations, for example through the improvement of regulations and infrastructure that hinder flexible power supply in decentralized schemes (such as bi-directional supply in power distribution networks), the revision of the process and criteria that complicates the approval of large scale renewable energy installations (such as wind farms and potential carbon storage sites), among others. Thirdly, by diverting investments and subsidies from fossil fuels towards low-carbon technologies and enhancement of carbon sinks (such as afforestation and direct air capture), while limiting the deployment of fossil fuel CCS to applications where no other options are available. Fourthly, by promoting lifestyle changes with higher preference for less energy and carbon intensive products and behaviors.

Finally, achieving more ambitious emissions reduction is ultimately driven by decision-making, thus, the role of policy makers is fundamental. Scenario analyses such as those found in this study can inform policy makers about the multiple mitigation pathways available and their implications, and help them to evaluate potential synergies and tradeoffs between enhanced mitigation ambition and other goals in current development agendas. Moreover, including scenario analyses in the discussions and documents forming the long-term climate policy in the country improves the transparency of the policy process. Reference to scenario analysis has been missing in past processes in Japan, including the 2015 NDC and 2019 LTS submitted to the UNFCCC. More recently, in March 2020, Japan submitted its latest NDC, but without any revision from the 2015 submission, excluding any reference to scenarios (The Government of Japan 2015). Since the LTS explicitly mentions that further ambitious efforts will be considered in future revisions of the mitigation target, scenario analysis will be needed actively and openly for the next NDC submission. Moreover, further studies based on scenario analysis are needed to elucidate the measures and transformation pathways enabling the net-zero emissions ambition recently declared by the Japanese government.

Conclusion

This study assessed the feasibility of enhancing the mitigation ambition of Japan by considering alternative pathways with GHG emission reduction goals for 2040 (48–68% reduction compared to 2005) and 2050 (80% and 100% reduction compared to 2005), with emphasis on the implications by 2040 in addition to those by 2050.

Overall insights include:

- Enhanced ambition brings more drastic changes in the share of low-carbon supply, compared to the reductions in energy intensity; economic impacts (GDP loss) increase by 19–72% compared to current levels of ambition.

- Unless the 2050 target is unchanged, increasing ambition will not affect significantly either the energy system or the economic impacts by 2050.
- Expansion of low-carbon supply for achieving 2040 and 2050 mitigation targets should step up efforts in renewables and CCS beyond the 2030 NDC assumption and past experiences, without relying on nuclear power given its uncertain role in Japan.
- Accelerating reductions in carbon intensity of final energy consumption during 2020 and 2040 is needed, given that current efforts assumed in the 2030 NDC are insufficient to achieve 2050 targets.
- Improvements in low-carbon energy supply and energy efficiency reduce considerably the economic impact by 2050. Therefore, these two enablers can eliminate the tradeoff between mitigation costs and cumulative emissions reductions.
- Realizing these improvements altogether can enable enhanced ambition of 2040 and 2050 targets at the same mitigation cost of the current level of ambition, and still secure lower cumulative emissions. Shifting to a path of immediate decarbonization further reduces cumulative emissions at similar mitigation costs as enhancing ambition only for 2040.

The insights from the scenario analysis in this study (as well as those in this special issue) provide concrete quantitative insights to inform the revision of current mitigation policies and the formulation of new commitments. For instance, the study presents the speed of change in key decarbonization indicators (carbon intensity, share of low-carbon energy supply, energy intensity) needed for realizing different levels of mitigation ambition by 2030/2040/2050. Therefore, scenario analysis should be explicitly referenced in the relevant discussions in Japan to improve the effectiveness of climate policy. The discussion on the enhancement of long-term mitigation targets should account for the uncertainties in multiple socioeconomic aspects of decarbonization. Although this study only addresses a part of these uncertainties (low-carbon energy supply availability and energy efficiency improvements), research such as that conducted in the EMF35 JMIP project offer valuable insights. A systematic analysis of the implications at higher levels of detail across economic sectors, technologies and policies is needed to complete the picture of the feasibility of enhanced ambition, in particular of the net-zero emissions goal by 2050.

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