Implications of Japan’s long-term climate mitigation target and the relevance of uncertain nuclear policy

Abstract

Achieving long-term climate mitigation goals in Japan faces several challenges, starting with the uncertain nuclear power policy after the 2011 earthquake, the uncertain availability and progress of energy technologies, as well as energy security concerns in light of a high dependency on fuel imports. The combined weight of these challenges needs to be clarified in terms of the energy system and macroeconomic impacts. We applied a general equilibrium energy economic model to assess these impacts on an 80% emission reduction target by 2050 considering several alternative scenarios for nuclear power deployment, technology availability, end use energy efficiency, and the price of fossil fuels. We found that achieving the mitigation target was feasible for all scenarios, with considerable reductions in total energy consumption (39-50%), higher shares of low-carbon sources (43-72% compared to 15%), and larger shares of electricity in the final energy supply (51-58% compared to 42%). The economic impacts of limiting nuclear power by 2050 (3.5% GDP loss) were small compared to the lack of carbon capture and storage (CCS) (6.4% GDP loss). Mitigation scenarios led to an improvement in energy security indicators (trade dependency and diversity of primary energy sources) even in the absence of nuclear power. Moreover, preliminary analysis indicates that expanding the range of renewable energy resources can lower the macroeconomic impacts of the long term target considerably, and thus further in depth analysis is needed on this aspect.

Key policy insights

- For Japan, an emissions reduction target of 80% by 2050 is feasible without nuclear power or CCS.
- The macroeconomic impact of such a 2050 target was largest without CCS, and smallest without nuclear power.

- Energy security indicators improved in mitigation scenarios compared to the baseline.

Keywords: climate mitigation targets, macroeconomic impact, Japan, scenario

Introduction

Japan announced in its nationally determined contribution (NDC) under the Paris Agreement a target of 26% reduction of greenhouse gas (GHG) emissions by 2030 compared to 2013 (Government of Japan, 2015). The consistency of the NDC target with the global goal for keeping global temperature change well below 2 degrees Celsius within this century (known as the 2 degree target), will require further emission reductions in the long term. The government made public a statement on efforts to achieve an 80% reduction in emissions by 2050 (Government of Japan, 2013). This goal derives from the common vision agreed upon by countries in the G8 (of which Japan is a member) for reducing GHG emissions by 2050, and it is regarded as being in line with the 2 degree target (Kawase and Matsuoka, 2013). In 2014, GHG emissions in Japan reached 1.364 $GtCO_2eq$, with CO_2 from fossil fuels and industry being the largest source of emissions (90%) (Ministry of Environment of Japan, 2016). The power sector alone was a major contributor to total emissions, which have experienced a steep increase in the last decade after nuclear power supply was substituted by fossil fuels (initially mainly natural gas and oil, and later coal), after the events triggered by the Great East Japan Earthquake in 2011, including the disaster at the Fukushima nuclear power plant.

The particular socioeconomic situation of Japan poses several challenges for long-term climate mitigation in addition to the costs it entails. On the one hand, the availability and affordability of key low-carbon energy technologies remain uncertain, in particular for nuclear power, carbon capture and storage (CCS) and renewables. The 2011 earthquake and tsunami resulted in the shutting down of almost all nuclear power plants in the country, and rigorous verification was carried out on the safety of these facilities. Restarting the nuclear plants requires approval from local governments, and in some cases, district courts have challenged rulings that have favoured prefectural and national efforts to resume nuclear power generation (World Nuclear Association, 2018). Currently only five nuclear power plants in the country are operating (out of a total of nine units as of 2018) (METI/Agency for Natural Resources and Energy). This situation led to the revision of the national energy plan, the GHG mitigation targets, and the role of nuclear power in achieving those targets (IEA, 2016).

With respect to CCS, only two applications for power generation are ready at commercial scale in the world, and progress has been slower than expected (Global CCS Institute, 2017). Thus, considerable cost reductions and policy support, such as carbon pricing or subsidies, will be required to realize the potential for sequestering a meaningful amount of CO_2 emissions in the future (IEA, 2013; McCulloch, Keeling, Malischek, & Stanley, 2016). For renewables, several barriers to penetration remain, such as: the technical and economic capability of the energy system to incorporate large amounts of variable electricity supply (as in the case of solar and wind power plants); the limited amount of renewable resource potential (as in the case of biomass); the cost of the technology; and the lengthy environmental approval process (as in the case of wind and geothermal power) (IEA, 2016). While global renewable energy costs have decreased considerably in recent years, the costs in Japan remain higher compared to other countries, lowering expectations for cost reductions (IRENA, 2018). In addition, there are institutional barriers to the penetration of renewables. These barriers are rooted in the vertically integrated structure of the power sector whereby it is controlled in each region by a single private utility. However, recent regulations are promoting market liberalization, and will separate power transmission and distribution from supply and retail (IEA, 2016).

On the other hand, there are significant uncertainties related to energy efficiency improvements and energy security concerns. Energy intensity in Japan has consistently fallen due to the penetration of high efficiency technologies and devices into the industrial and residential sectors, but greater improvements may be cumbersome to realize (IEA, 2017a). With respect to energy security, Japan is highly dependent on fossil fuel imports, and lacks significant deployment of domestic renewable energy resources or grid interconnections with neighbouring countries. The share of energy supply from domestic sources (also referred to as energy self-sufficiency) was 8.3% in 2016, dropping from 20% in 2010 to a low of 6.4% in 2014 (Agency for Natural Resources and Energy, 2017) mainly as a consequence of nuclear power stoppage after the 2011 Fukushima disaster. Japan has taken measures to alleviate energy security risks, for example by diversifying the portfolio of fuel imports with gas from other countries, and promoting domestic renewable energy through feed-in-tariff policies.

There are several assessments of climate mitigation policies for Japan based on quantitative analysis of scenarios (Kuramochi, Asuka, Fekete, Tamura, & Höhne, 2016; Kuramochi, Wakiyama, & Kuriyama, 2017). Some of these studies have focused on the near-term implications of nuclear power supply uncertainty, motivated by the Fukushima disaster (Esteban and Portugal-Pereira, 2014; Esteban et al., 2018; Homma and Akimoto, 2013; McLellan, Zhang, Utama, Farzaneh, & Ishihara, 2013; Portugal Pereira, Troncoso Parady, & Castro Dominguez, 2014; Su, Zhou, Sun, & Nakagami, 2014; Takase and Suzuki, 2011). Analysis of the implications of the NDC in mitigation scenarios is still emerging, and studies evaluating Japan's NDC target in the context of long-term global mitigation targets are scarce (Akashi and Hanaoka, 2012; Masui, Oshiro, & Kainuma, 2015; Matsumoto and Shiraki, 2018; Oshiro, Kainuma, & Masui, 2016, 2017; Oshiro, Masui, & Kainuma, 2017; Sugiyama et al., 2019). Additionally, these studies lack any comprehensive insight into changes to the energy system or into the macroeconomic impacts of uncertain availability and performance of mitigation options in the power sector besides nuclear power, such as CCS and renewable energy technologies. Moreover, weighting the challenges to climate mitigation with respect to energy security in 2050 scenarios is only considered by Oshiro, et al. (2016).

The purpose of this paper is to assess the macroeconomic impacts of meeting the long-term climate mitigation goal of reducing emissions by 80% by 2050 in Japan, focusing on the relevance of nuclear policy relative to other uncertainties. We demonstrate this with diagnostic scenarios assuming various uncertainties in technological availability, end use energy efficiency, and the price of fossil fuels. In addition, the paper assesses the influence of climate policy on energy security, given the vulnerability of Japan's energy system to disruptions in fuel imports. For the analysis, a computable general equilibrium (CGE) model is applied to assess Japan's NDC and its long-term target of 80% emission reduction by 2050.

Methodology

In this study we design scenarios considering mitigation targets with different assumptions for the availability of key technologies, and assess the impacts on Japan's energy system and economy by means of a CGE model. In addition, we consider other scenarios to examine specific uncertainties related to the energy demand and energy security dimensions. The modelling approach and analysis covers only mitigation costs, and excludes any valuation of the costs of inaction in terms of climate change impacts.

Model

The Asia-Pacific Integrated Assessment Model CGE (AIM/CGE) model is applied for the case of Japan to assess a set of scenarios considering climate mitigation and technology constraints. The AIM/CGE is a computable general equilibrium model covering all economic activities and a full set of GHGs and air pollutants ((Fujimori et al., 2017; Fujimori, Masui, & Matsuoka, 2012). It is a dynamic recursive 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 40 economic 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 (International Energy Agency, 2012) and relevant studies (Fujimori, et al., 2017; Hasegawa, Fujimori, Ito, Takahashi, & Masui, 2017; Silva Herran, Dai, Fujimori, & Masui, 2016; World Energy Council, 2016). 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) (H. 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/CGE model in this study as a single national model (Chunark, Limmeechokchai, Fujimori, & Masui, 2017)).

Scenarios

An outline of the scenarios is presented in Table 1. Scenarios included a Reference scenario (*Reference*) without mitigation policy, and a set of mitigation scenarios (*NDC80*) considering several uncertainties. Mitigation scenarios assumed both the mid-term target represented by the NDC (25.4% emission reduction by 2030 compared to 2005 levels), and a long-term target (80% emission reduction by 2050 compared to 2005 levels). GHG emissions (CO_2, CH_4, N_2O, excluding fluorinated gases) throughout the timeframe of analysis are imposed exogenously (global warming potentials based on IPCC AR4 (IPCC, 2007) are assumed). Accordingly, carbon prices are determined by the model to match the emissions constraint.

TABLE_1_HERE

These mitigation scenarios were divided into two sub-sets. The first set considers a case with availability of all technologies (*Default_NDC80*), and cases focusing on uncertainties in energy supply technologies, including nuclear power, CCS, and renewable energy. The case restricting nuclear power (*Nuc_L_NDC80*) assumes a plant life of 40 years, and restarting of idle plants between 2020 and 2030 without new installations, resulting in phasing out by 2050. The case restricting CCS (*NoCCS_NDC80*) assumes CCS is not available at all (in the Default scenario

CCS is available from 2022). For renewable energy technologies (*RE_CostRed_L_NDC80*) we assume a scenario with a slower rate of cost reductions (25% smaller compared to the *Default_NDC80* scenario).

The second set of mitigation scenarios are defined to analyze the implications on energy security against the macroeconomic impacts. They focus on additional changes to nuclear power, and on aspects besides energy supply technologies, namely energy demand efficiency and energy security. For nuclear power, we test the feasibility of Japan's climate goals against extreme situations for nuclear power supply, by means of a high-level scenario assuming extension of plant life from 40 to 60 years, full restart of idle plants by 2020 and three new installations (*Nuc_H_NDC80*), and a scenario with complete phase-out from 2020 (*Nuc_no_NDC80*). The high-level scenario is consistent with well-known scenarios (IEA, 2017b; The Institute of Energy Economics, 2017). For energy demand efficiency and energy security, we include scenarios with low levels of end-use energy efficiency, in terms of the rate of autonomous energy efficiency improvement (*AEEI_L_NDC80*) and of prices of fossil fuel imports (*PrFossil_L_NDC80*).

Default assumptions for nuclear power supply are consistent with the NDC (20-22% of total power supply by 2030), projecting a decrease to 0.32 EJ/yr (89 TWh/yr) in 2050. This projection is equivalent to the average of nuclear power supply assuming high (*Nuc_H*) and low (*Nuc_L*) levels (see Table 2 for details on relevant assumptions, and Figure S-1 in the supplementary information for the trajectories of nuclear power supply). The underlying socioeconomic assumptions (population, GDP, etc.) were based on the SSP2 scenario, from the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014; Riahi et al., 2017), as they provide trajectories up to 2050 under a consistent framework (Government projections for GDP are only available up to 2030; the effect of population and GDP assumptions on key outcomes is provided in Table S-1 of the supplement). This pathway, which corresponds to a storyline picturing intermediate assumptions within the framework of the SSPs, results in the population decreasing to 109 million, and GDP increasing to USD_{2005} 6.2 trillion (for the non-mitigation cases) by 2050. Assumptions related to energy resources, technologies and other parameters are documented in previous analysis using the AIM/CGE model (Fujimori, et al., 2017; Fujimori, et al., 2012).

TABLE_2_HERE

Energy security analysis

Given the low self-reliance of Japan in terms of energy supply, we evaluate the scenarios in the study with respect to energy security. We evaluate two indicators: trade dependency as the share of imported fossil fuels in energy supply (nuclear fuel is regarded a domestic resource following IEA's definition (Jewell, 2011)), and the Shannon-Wiener index for energy diversity (Grubb, Butler, & Twomey, 2006; Jewell, Cherp, & Riahi, 2014; Kruyt, van Vuuren, de Vries, & Groenenberg, 2009). The former quantifies the vulnerability of energy supply to disruptions in trade of fuels, which are external to the national energy system. The latter quantifies the versatility of the energy system to balance changes in supply with increased variety of energy sources, and captures to some extent external and domestic disruptions to energy supply. It has to be noted that we are not aiming for a comprehensive evaluation of energy security, given that it has several interpretations and contexts, and, thus, multiple indicators to quantify it. The indicators evaluated have been selected because they are commonly used in mitigation scenario assessments; they can be estimated with the outcomes from the CGE model applied in the study, and they highlight representative aspects within the energy security dimension.

Results

Features of the Reference scenario.

In the *Reference* scenario, CO_2 emissions in Japan reached 1,458 Mt CO_2 in 2050, equivalent to a 7% increase compared to 2005. Energy supply, presented in Figure 1, showed a steady increase in total primary energy supply (TPES) reaching 21 EJ in 2050, an 8.6% increase compared to 2005. Fossil fuels covered most of the supply (85%), with oil taking the main share (36% of TPES). The mix of electricity supply by technologies, presented in Figure 1-b), remained dominated by fossil fuels, with increased amounts of renewables. The diminishing role of nuclear power assumed in the Reference scenario led to a share of 5% of power supply in 2050. Final energy supply, presented in Figure 1-c), was dominated by liquids (mainly transport fuels) and electricity with similar shares, accounting for 46% and 42% of the total in 2050, respectively.

FIGURE_1_HERE

Features of the Mitigation scenarios

Outcomes in the first group of Mitigation scenarios, presented in Figure 2, showed a decrease in energy consumption, higher shares of electricity in final energy supply, and the enhanced role of natural gas and renewables in the energy mix (see also Figure S-2 and Figure S-3 in the supplement). Compared to the Reference scenario, in the *Default_NDC80* scenario, TPES and final energy consumption in 2050 decreased by 36% and 39%, respectively. The share of fossil fuels fell considerably, but still covered more than half of the energy supply. Most of the renewable energy supply corresponded to biomass (13% of TPES), followed by solar and wind. In contrast, the electricity supply was dominated by renewables and fossil fuels with CCS, which in 2050 represented 48% and 31% of the total, respectively. As presented in Figure 3 (see also Figure S-2 in the supplement), a large reduction in emissions was enabled also by a larger share of electricity in the final energy supply (around 58% in 2050), which improved the energy conversion efficiency and carbon intensity (by replacing coal and oil with natural gas), and the penetration of carbon neutral technologies (such as PV and wind). Phasing out nuclear power in 2050 (*Nuc_L_NDC80* scenario) promoted a slight reduction in total energy supply compared to the *Default_NDC80* scenario. Changes in renewable technology costs (*RE_CostRed_L_NDC80* scenario) slightly affected total energy supply, with no significant changes in the energy mix. In the *NoCCS_NDC80* scenario, energy supply decreased considerably (71% compared to the *Default_NDC80* scenario) and biomass without CCS replaced biomass with CCS.

FIGURE_2_HERE

FIGURE_3_HERE

CCS had an important role in complementing the decarbonization of energy supply in the long term, along with renewables. Interestingly, the absence of CCS (*NoCCS_NDC80* scenario) did not result in greater use of renewable resources (besides a slight increase in biomass). Such inelastic behaviour of renewable supply in 2050 was also observed in other scenarios. We can identify three factors explaining this outcome. First was the relatively small resource potential of solar and wind assumed in the model (1.0EJ/yr and 0.5EJ/yr for solar PV and onshore wind, respectively (see Hancheng Dai, Silva Herran, Fujimori, & Masui, 2016; Fujimori, et al., 2017; Fujimori, et al., 2012; Silva, 2012; Silva Herran, et al., 2016) for relevant assumptions), which resulted in the system making full use of this potential to meet the mitigation target. In fact, even the resource potential with the highest unit supply costs (i.e., lowest quality) assumed in the model was deployed by 2050. We elaborate further on the role of energy potential assumptions below. The second factor was the maximum penetration rate of low-carbon technologies, which prevented faster penetration of renewables with available resource potential (such as biomass). Thirdly there was an increase in average electricity prices driven by the carbon price, which favoured energy demand reductions instead of larger penetration of renewables.

Table 3 shows the average electricity prices, the carbon prices, and the macroeconomic impact expressed as percentage GDP losses. All mitigation scenarios led to a considerable increase in electricity prices along with carbon prices, which reached similar values by 2050, except for the

NoCCS_NDC80 scenario. Therefore, the absence of CCS is a key factor in shaping the macroeconomic impact of achieving mitigation targets in Japan. GDP losses were between 3.4 and 6.4% in 2050. The largest impact was observed for the *NoCCS_NDC80* scenario (6.4%), followed by the scenario assuming changes in the rate of cost reduction of renewable energy (*RE_CostRed_L_NDC80*).

TABLE_3_HERE

Mapping mitigation scenarios in the energy security dimension

To get deeper insights into the robustness of the long-term mitigation target, we analyzed the implications on energy security against the macroeconomic impacts. We assessed an extended set of scenarios to elicit a response to uncertainties related to nuclear power availability and aspects beyond energy technology availability, namely energy demand and energy security (i.e. stability of energy supply). The outcomes of these scenarios were compared to the mitigation scenario assuming default conditions (*Default_NDC80*).

The largest macroeconomic impact of mitigation in terms of GDP losses was still for the *NoCCS_NDC80* scenario (6.4%), followed by the scenarios assuming low levels of renewable energy cost reduction *RE_CostRed_L_NDC80* (4.2%). GDP losses larger than that of the *Default_NDC80* scenario were within a close range of values (3.5 – 3.8%), and corresponded to those assuming challenging conditions for climate mitigation (e.g. *Nuc_L_NDC80*). It is worth noting that in the scenario assuming early phase-out of nuclear power (*Nuc_no_NDC80*), GDP losses were the same as for the default case. For this scenario, GDP losses were higher than the default scenario until around 2035 (see Figure S-4 in the supplementary information), demonstrating that the importance of macroeconomic impacts of early nuclear phase-out depends on the timeframe of analysis. In the absence of nuclear power, the penetration of other low-carbon technologies (which otherwise could not rapidly enter the market due to the long life of nuclear power installations), and the reduction in energy consumption (which scales down new investments), can lessen mitigation costs in the long term. This contrasting pattern between near and long-term impacts is also reflected in the energy system. While this issue is relevant for the assessment of Japan's climate mitigation policies, only a brief discussion is provided in the next section as it is out of the scope of this study.

The scenarios were mapped against the outcomes for the energy security indicators and the macroeconomic impacts (measured as GDP losses). The maps, presented in Figure 4, showed that energy security indicators improve considerably in mitigation scenarios. Among the scenarios, only the absence of CCS (*NoCCS_NDC80*) produced a clear difference in terms of fuel import dependency, while a marked distribution was observed for energy diversity. The *NoCCS_NDC80* scenario had the largest mitigation costs, but at the same time, showed the largest improvements in dependency in fuel imports. This outcome highlights the double role of CCS as a cost-effective option to achieve large emissions reductions in the long term, and as a barrier to shifting away from fossil fuels, which for a country like Japan translates into fewer opportunities for improving self-sufficiency. In terms of diversity of energy supply sources, lack of CCS resulted in the lowest improvement among mitigation scenarios. This was a result of an energy mix with more disparity in the shares of energy sources, driven by the larger importance of renewables and the very minor contribution of coal and oil compared to other scenarios. Availability of nuclear power had a small role in improving energy dependency, compared to improvements in energy demand efficiency and changes in fossil fuel prices. While the absence of nuclear power had an evident effect on the energy diversity indicator compared to other uncertainties, this effect was small compared to the effect of whether or not climate mitigation targets were implemented. Differences in the impacts of mitigation in terms of macroeconomic costs and energy security across scenarios became evident only in the long term (2050), while nuclear power availability and fossil fuel prices produced already marked differences in energy security in the near term (2030).

FIGURE_4_HERE

Preliminary analysis on the renewable energy resource assumptions

As mentioned above, the contribution of renewable energy in 2050 was almost uniform across all scenarios, in spite of the wide range of carbon prices indicated by the model. However, it is likely that high carbon prices allow for additional amounts of renewable energy from "low quality" resources (i.e., low capacity factors, high energy supply costs, low technical feasibility, etc.). To further explore the role of renewables we conducted a preliminary analysis by incorporating in the model the resource potentials of solar PV installed in vertical surfaces (e.g., building facades), and of offshore wind power. These renewable resources, currently not included in the model, were added to the energy potential with the highest unit supply costs (i.e., lowest capacity factors).

The outcomes for selected scenarios, presented in Table 4, showed that these two resources can add 5 EJ/yr to the energy supply, and could increase the share of renewables in the power mix up to 76% (compared to 22-67% in the scenarios in this study). In addition, the inclusion of these resources resulted in considerably lower carbon prices (29-57% lower than the original results) in 2050, as well as GDP losses (10-43% lower). It is worth noting that the revised assumptions on solar and wind power energy potentials, did not alter the findings of this research (i.e., lack of CCS has the largest macroeconomic impact, and nuclear phase out leads to a relatively small difference with the default scenario with all mitigation options). However, we acknowledge that this analysis shows only an approximated picture of the issue, therefore, further research on the role of scaling up renewable energy deployment is needed.

TABLE_4_HERE

Discussion

Some aspects relevant to this study remain unclear due to limitations of the model to deal with certain issues. Here we reflect further on the feasibility of mitigation targets under the uncertainties assessed (nuclear power policy, CCS availability, renewable energy, and end use energy efficiency) and the implications for energy security.

The role of nuclear power in Japan has been at the centre of discussions after the events following the earthquake and tsunami in March 2011. Currently, nuclear power deployment is still being considered as an energy source for the coming decades, and as an option for long-term climate mitigation, as presented in the latest national energy plan by the government (Government of Japan, 2018). According to our analysis, from a long-term perspective, phasing-out nuclear power is not a critical limitation to mitigation, but the short-term impacts of nuclear power deployment are complex. On the one hand, early phase-out will bring direct negative economic implications on the companies operating nuclear power plants. There are also rising concerns over stranded assets in nuclear power plants with several decades of potential operation, and over the labour market and supply chain associated with the maintenance and operation of facilities. Moreover, lack of nuclear power may increase dependence on fossil fuels imports, exacerbating the vulnerability of fuel supply in the country. On the other hand, shifting away from nuclear power may respond to concerns over the safety of facilities, the postponed issue of proper disposal of nuclear waste, and decreasing social acceptability. Such a shift would also make room for alternative local energy supply sources and efficiency measures, contributing to diversification of the energy portfolio and improvement of the country's resilience to energy supply shocks.

Reconciling the trade-offs between short and long-term perspectives for nuclear energy and climate policies requires leveraging different risks. Climate mitigation policies are motivated by a long-term perspective addressing the risks posed by climate change for present and future generations. The size and distribution of such risks are highly uncertain, but they are likely to have impacts that may be irreversible across several regions and sectors in multiple ways. Our analysis indicated that nuclear policy would have a small impact on the balance between the benefit and cost of climate mitigation by 2050. In contrast, nuclear energy policies are formulated to respond to energy demands for current generations. Thus, phasing out nuclear power brings impacts evident in the near term, and will require immediate measures for the affected stakeholders to adapt to the new situation. In fact, our analysis showed that an early phase-out scenario resulted in larger GDP losses by 2030. Given that this study focused on the long term (i.e., 2050) implications of climate policies, further analysis is recommended to better understand the trade-offs against short-term policy perspectives.

With respect to renewable energy, major challenges are adapting existing infrastructure to accommodate larger amounts of variable energy supply from solar and wind power, securing a stable supply of biomass resources for bioenergy supply, and realising the potential for renewable resources that are currently unaffordable. Policies favouring renewable energy in Japan, such as the feed-in-tariff system implemented since 2012, have increased the installed capacity of solar PV, wind power and biomass power. However, potential supply from new solar and wind installations has been constrained by the limits imposed by the electricity grid operators on the amount of variable power supply (Kimura, 2017). To overcome this issue, the power system will need to become more flexible by means of batteries, gas power and enhanced exchanges of electricity among regions in the national grid (Wakiyama and Kuriyama, 2018). Also, the sustainability of power supply from renewables without the support of feed-in-tariffs may be affected, in particular for biomass power plants, as they incur large fuel costs. Another concern is the effect of technology imports driven by renewable energy development on the domestic market (trade of energy technologies is not considered in this study). In spite of the above challenges, larger shares of renewable energy may be possible with untapped resource potentials through new technologies, such as solar panels on building facades and use of offshore wind, which are not handled by the model in this study (a preliminary analysis is included in the results section and Table 4).

As for CCS, investment, technical and safety barriers will need to be overcome in order to realize the level of penetration needed for long-term climate mitigation. Currently, in Japan there is one large-scale CCS project operating since 2016 and several other pilot scale projects (Global CCS Institute, 2017). Another issue is the CO_2 storage potential. According to some sources the potential in Japan may be as low as 5 $GtCO_2$ (Ricci and Selosse, 2013), or as high as 140 $GtCO_2$ (Consoli and Wildgust). Although cumulative CO_2 sequestration constraints were not considered in this study, scenario outcomes (less than 3 $GtCO_2$ by 2050) were below the low range of sequestration potentials in the literature. Other barriers to CCS penetration include risk perceptions by investors and the public. Investors have concerns that focus on the large scale of investments needed compared with uncertain prospects for profitable operation, along with the lack of robust economic incentives. The general public focuses on safety concerns, and regards it as more acceptable to redirect investments to less uncertain mitigation options such as renewables (Johnsson, Reiner, Itaoka, & Herzog, 2010; Leung, Caramanna, & Maroto-Valer, 2014).

The effect of improved energy efficiency has been recognized by industries and this has led to the diffusion of highly efficient appliances and practices in the residential and commercial sectors. Boosting rates of improvement may be challenging for many technologies and practices that are already highly energy-efficient, and where further improvements can be difficult or expensive. However, some industries in Japan with lower energy efficiency compared to other developed nations have the potential to improve their performance (Honma and Hu, 2014). Additionally, other measures can complement emissions reductions from the demand side, such as lifestyle changes, disruptive innovations (such as new technologies and practices creating or withdrawing the need for an energy service), or strong policies promoting energy saving.

With respect to the economic impacts, how well each outcome for these scenarios will be accepted differs among national stakeholders, given that these impacts will be distributed unevenly across sectors and points in time. Fossil fuel industries and carbon intensive activities bear the largest burden from climate policies introducing carbon prices. In addition, as highlighted by the analysis, electricity prices are likely to increase considerably in the long term, affecting energy expenditures in both households and businesses. In order to accommodate these transformations and lessen the negative impacts, considerable changes will be necessary. The structure of the economy will need a larger share of industries with low energy and carbon intensities, and more service-oriented activities. Consumption behaviour of end users will have to shift to low-carbon energy sources, adopt less energy-intensive (i.e., more efficient) technologies, and have lower total energy consumption. At the same time, the revenues from carbon markets will have to be efficiently allocated to facilitate a smooth transition across sectors.

Valuation and interpretation of the economic impact depends on the indicator and perspective considered. In this study, impacts in terms of the GDP loss (3.3%-6.3%) were close to the range indicated by IPCC global assessments for stringent scenarios (2%-4%) consistent with the 2 degree target (RCP2.6) (Clarke et al., 2014). The carbon price is another indicator commonly used in quantitative assessments of climate policies on national and global scales. Carbon prices by 2050 in the scenarios were considerably higher than in other studies. For example, Oshiro et al. (2017) reported values for 2050 below USD_{2005} 800/tCO_2. However, it has to be noted that the carbon price as an indicator has several limitations compared to GDP loss. The carbon price is sensitive to many assumptions, and it only captures part of the economic effect of climate mitigation, since other policies and measures can also affect total economic output. It can also take on much higher values when assuming stringent targets, as the marginal abatement curve becomes very steep for large values of emission reductions. A better indication of the equivalent value of future carbon prices in the present is provided by the discounted average value for the whole timeframe of analysis. Assuming a discount rate of 5%, average discounted carbon prices in this study were USD_{2005} 49-84/tCO_2, which are considerably higher than the carbon prices for meeting the 2030 target (USD_{2005} 20-29/tCO_2 discounted at 5%), and this illustrates the misalignment of the NDC target with the 2050 goal. Although these outcomes outweigh the carbon tax currently in place in Japan (USD 3/tCO_2), they are within the upper range of values reported by the IPCC assessments, and are similar to carbon prices implemented in some countries (e.g., USD 55/tCO_2 in France (World Bank and Ecofys, 2018)). Carbon prices and economic impacts may be lowered if a more ambitious mitigation target for 2030 (i.e., the NDC) is put in place, which will prevent locking in carbon intensive infrastructure and will realize existing mitigation potentials. Although it is not quantified in this study, we can anticipate lower economic impacts if mitigation capacity is boosted via faster improvements in energy efficiency on the supply and demand sides, and faster penetration and cost reductions of low-carbon energy technologies including CCS (see Table 4 in the results section for a description of a preliminary analysis including solar PV panels from vertical surfaces and offshore wind power resources).

Realizing climate mitigation targets for Japan is aligned with improved energy security goals. This finding is also confirmed by Oshiro et al. (2016), who reported values of trade dependency similar to this study using a bottom-up technology selection model, but without any indication of the macroeconomic impacts. Mitigation means shifting to a low-carbon and less intensive energy system, with more diversity of energy sources and less dependence on imported fuels. Therefore, mitigation costs can be seen as an investment to avoid not only the risks of climate change, but also those arising from sudden disruptions in fuel imports, or from impaired availability of certain technologies (e.g., nuclear power). It is worth noting that the energy security dimension is broad, and that this study only focuses on two indicators. Disruptions in the energy supply are manifold in nature, and as such they influence the role of each energy technology in different ways. With respect to nuclear energy, the energy security dimension also relates to the risks posed by radioactive waste, by the release of radioactive materials due to aging facilities, by human error in plant operation, and by attacks and natural disasters (such as earthquakes), among others.

Conclusion

This study showed that mitigation targets for the mid (NDC) and long term (80% emission reduction by 2050 compared to 2005 levels) for Japan are feasible under several scenarios from a macroeconomic modelling perspective, including early phase-out of nuclear power. We showed quantitatively that the lack of CCS has considerably larger impacts on the energy system and the macroeconomy, and that uncertain nuclear power policy had a secondary role, given that it can be substituted with other sources (mainly natural gas) and measures (reduction of energy consumption) to achieve long-term mitigation targets with lower GDP losses. In addition to scaling up low-carbon energy technologies, it could be seen that energy consumption reductions and higher electricity shares in the final energy supply had important roles in mitigation. Evaluation of technological uncertainties against changes in end use demand and energy security aspects revealed that lack of CCS and lower cost reductions for renewables produced the largest macroeconomic impacts, in comparison to pessimistic scenarios for energy efficiency improvements and fossil fuel prices.

Achieving climate targets improved energy security indicators. This was confirmed across all scenarios and multiple energy security indicators. CCS contributed to the largest improvements in energy dependency, but to the lowest benefits in diversifying energy supply. Also, the balance between mitigation costs and dependency in fuel imports was similar for other scenarios. In terms of energy diversity, even when this indicator was more affected by nuclear power availability than by other uncertainties, this indicator improved in all mitigation scenarios. As a whole, the analysis showed that the effect of technology and other uncertainties on energy security indicators is slightly different, but relatively small compared to the improvement induced by achieving mitigation targets (compared to a business as usual scenario).

In addition, preliminary analysis on the renewable energy resource potential showed that these assumptions have an important effect on the macroeconomic impact of mitigation goals, and therefore warrant further in depth research. Further analysis is also needed to clarify the differences in near-term (by 2030) and long-term (by 2050) perspectives for climate mitigation in Japan. There also needs to be careful consideration of alternative pathways that increase the ambition in mitigation policies for the country, given the growing significance of the gap between current commitments and the 2 and 1.5 degree targets. Moreover, conservative assumptions on the CGE model, such as having the same labour force supply across scenarios, need reconsideration to reflect possible changes stemming from stimulation of green industry, and the corresponding benefits to the macroeconomy. Analysis is also needed to weigh climate mitigation costs against climate change impacts. These issues are the challenges facing future studies in this area.

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Tables

Table 1 Features of the scenarios considered.

Scenario name	Description	Assumptions
Reference	Without mitigation policies.	Default values, levels of nuclear power supply are "Default" shown in Table 2 (includes 2030 level as in NDC).
Default _NDC80	Same as Reference but with mitigation targets.	NDC by 2030 and 80% reduction by 2050.
Nuc_L_NDC80	Same as *Default_NDC80*, but with low level of nuclear power supply.	Low level of nuclear power supply towards phase out in 2050 (see Table 2).
NoCCS_NDC80	Same as *Default_NDC80*, but with no CCS.	CCS unavailable.
RE_CostRed_L_NDC 80	Same as *Default_NDC80*, but with low level of renewable energy cost reduction.	25% slower than in default scenario.
Nuc_H_NDC80	Same as *Default_NDC80* but with high level of nuclear power supply.	High level of nuclear power supply (see Table 2).
Nuc_no_NDC80	Same as *Default_NDC80*, but with no nuclear power supply.	Nuclear power supply phase out since 2011.
AEEI_L_NDC80	Same as *Default_NDC80*, but with low level of autonomous energy efficiency improvement.	1.0% less annual improvement than in the default scenario.
PrFossil_L_NDC80	Same as *Default_NDC80*, but with low prices of fossil primary energy sources (coal, oil, gas).	Change linearly reaching 50% of the price of the default scenario in 2050

Table 2 Assumptions of nuclear power generation considered in the scenarios (the corresponding trajectories are plotted in Figure S-1 in the supplement).

	Capacity [a] [GW]			Generation [b] [TWh/yr]		
	2020	2030	2050	2020	2030	2050
Default [c]	25.4	31.5	12.8	178	221 [d]	89
High [e]	41.7	41.7	25.5	292	292	179
Low [f]	9.1	21.4	0	64	150	0

[a] Considers the age and operation status of existing plants and those under construction in Japan. The status considers whether plants have legally applied for restart of operation (Genanshin).

[b] Assuming capacity factor of 80% (utilization rates between 1990-2010 were 59%-84%) (Ministry of Environment of Japan, 2016).

[c] Default values calculated as average of high and low levels.

[d] Value for 2030 is in the range stipulated in the Japanese NDC (20-22% of total power supply).

[e] Assumes extension of plant life from 40 to 60 years, full restart of idle plants by 2020 and three new installations.

[f] Assumes plant life of 40 years and restart of idle plants between 2020 and 2030 without new installations.

Table 3 Macroeconomic impacts in 2030 and 2050 across scenarios. GDP loss only account for mitigation costs and exclude damages due to the impacts of climate change.

	Electricity price [USD_{2005}/GJ]		Carbon price [USD_{2005}/tCO_2]		GDP loss [%]	
	2030	2050	2030	2050	2030	2050
Reference	45	42	0	0	0	0
Default _NDC80	50	123	56	1,279	0.43	3.4
Nuc_L_NDC80	51	134	52	1,298	0.40	3.5
NoCCS_NDC80	50	265	56	2,854	0.43	6.4
RE_CostRed_L_NDC80	50	126	55	1,300	0.57	4.2
Nuc_H_NDC80	49	115	61	1,279	0.45	3.3
Nuc_no_NDC80	56	129	62	1,269	0.49	3.4
AEEI_L_NDC80	54	130	76	1,388	0.55	3.8
PrFossil_L_NDC80	49	123	67	1,437	0.62	3.8

Table 4 Outcomes in key indicators in 2030 and 2050 for selected scenarios with different assumptions for solar PV and wind energy resources.

	Share renewable energy in electricity supply [%]		Carbon price [USD_{2005}/tCO_2]		GDP loss [%]	
	2030	2050	2030	2050	2030	2050
Reference	15	22	0	0	0	0
Default _NDC80	28	48	56	1,280	0.43	3.4
Nuc_L_NDC80	28	52	52	1,298	0.40	3.5
NoCCS_NDC80	28	67	56	2,854	0.43	6.4
vreH_Reference	15	22	0	0	0	0
vreH_Default_NDC80	28	66	55	911	0.43	3.0
vreH_Nuc_L_NDC80	29	69	51	907	0.40	3.1
vreH_NoCCS_NDC80	28	76	55	1,233	0.43	3.6

Scenarios labelled with "vreH" include the total energy potential of "low quality" solar PV, and of offshore wind based on national assessments by the Ministry of Environment of Japan (Ministry of Environment of Japan, 2013, 2017). Low quality solar PV corresponds to the energy potential with lowest capacity factors (thus lowest unit electricity supply cost), which includes vertical surfaces (walls, facades) and surfaces with low exposure times to direct sunlight. Offshore wind energy potential was corrected by density of wind turbines to 5 MW/km^2 Silva Herran, et al. (2016) (instead of 10 MW/km^2 assumed in Ministry of Environment of Japan (2013)).

Figure captions

Figure 1 Outcomes for energy supply in the Reference scenario: a) primary energy supply by sources, b) electricity supply by technologies, c) final energy supply by carriers.

Figure 2 Outcomes for energy supply in 2050 in all scenarios: a) primary energy supply by sources, b) electricity supply by technologies, c) final energy supply by carriers.

Figure 3 Share of electricity in final energy supply

Figure 4 Mapping of scenarios with respect to the impact of climate mitigation on the macroeconomy (GDP loss relative to the *Reference* scenario) and on energy security (a) in terms of the dependency on imported fuels (trade dependency), and (b) in terms of the diversity of primary energy sources (Shannon-Wiener diversity index). Values for 2030 and 2050 are highlighted in grey and black, respectively. GDP loss only account for mitigation costs and exclude damages due to the impacts of climate change.

Figure 1

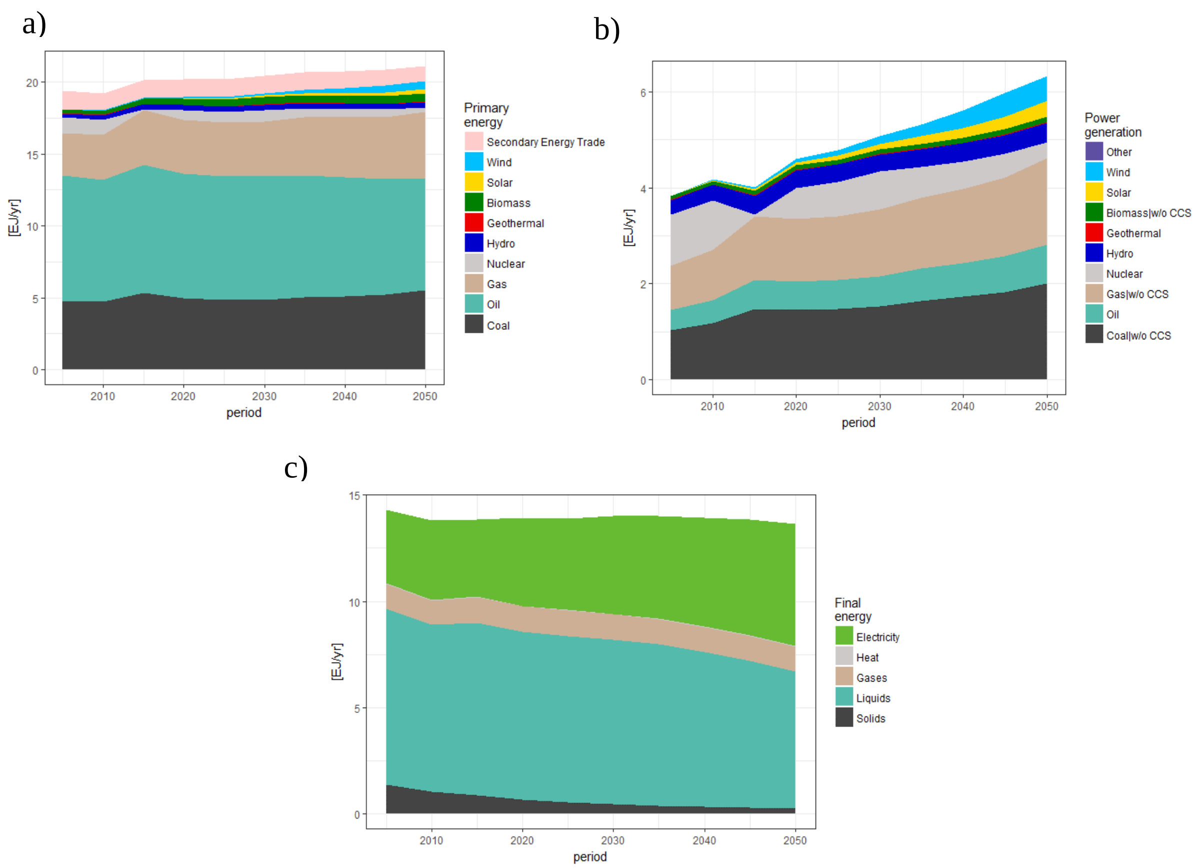


Figure 2

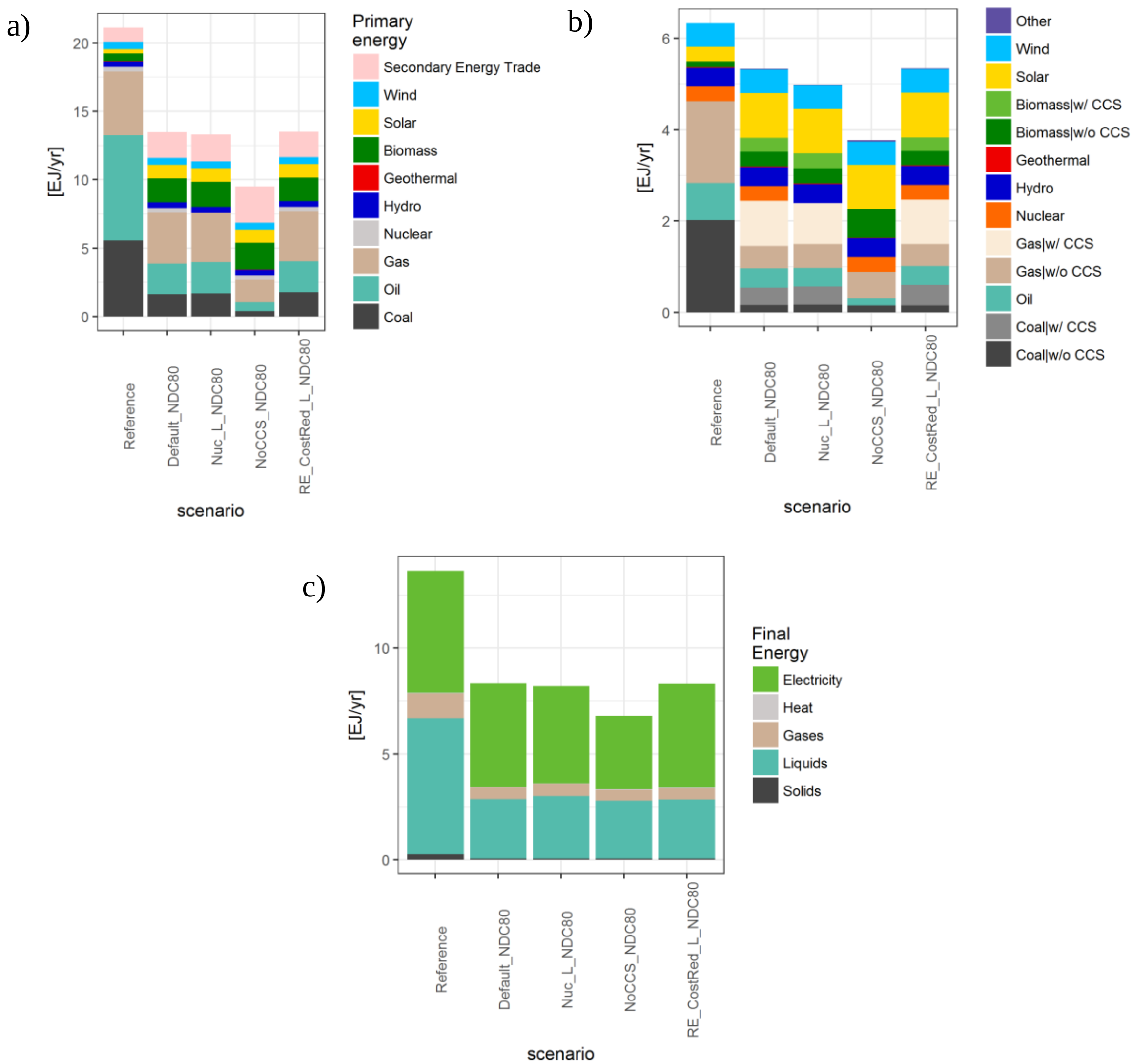

a)
[EJ/yr]
0
5
10
15
20
Reference
Default_NDC80
Nuc_L_NDC80
NoCCS_NDC80
RE_CostRed_L_NDC80
scenario
Primary energy
Secondary Energy Trade
Wind
Solar
Biomass
Geothermal
Hydro
Nuclear
Gas
Oil
Coal
b)
[EJ/yr]
0
2
4
6
Reference
Default_NDC80
Nuc_L_NDC80
NoCCS_NDC80
RE_CostRed_L_NDC80
scenario
Other
Wind
Solar
Biomass|w/ CCS
Biomass|w/o CCS
Geothermal
Hydro
Nuclear
Gas|w/ CCS
Gas|w/o CCS
Oil
Coal|w/ CCS
Coal|w/o CCS
c)
[EJ/yr]
0
5
10
Reference
Default_NDC80
Nuc_L_NDC80
NoCCS_NDC80
RE_CostRed_L_NDC80
scenario
Final Energy
Electricity
Heat
Gases
Liquids
Solids

Figure 3

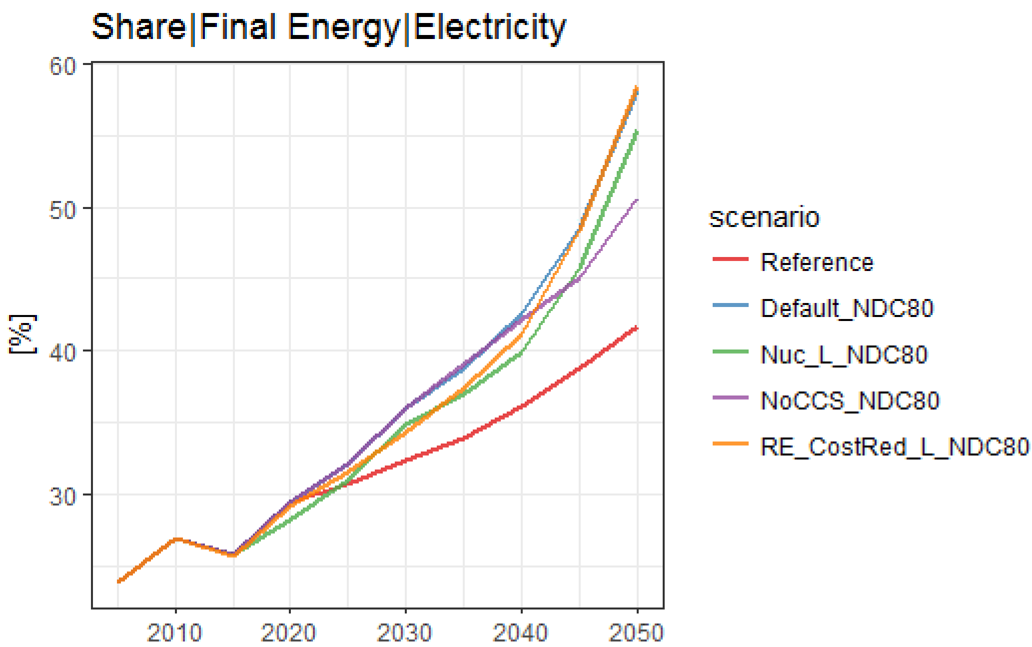
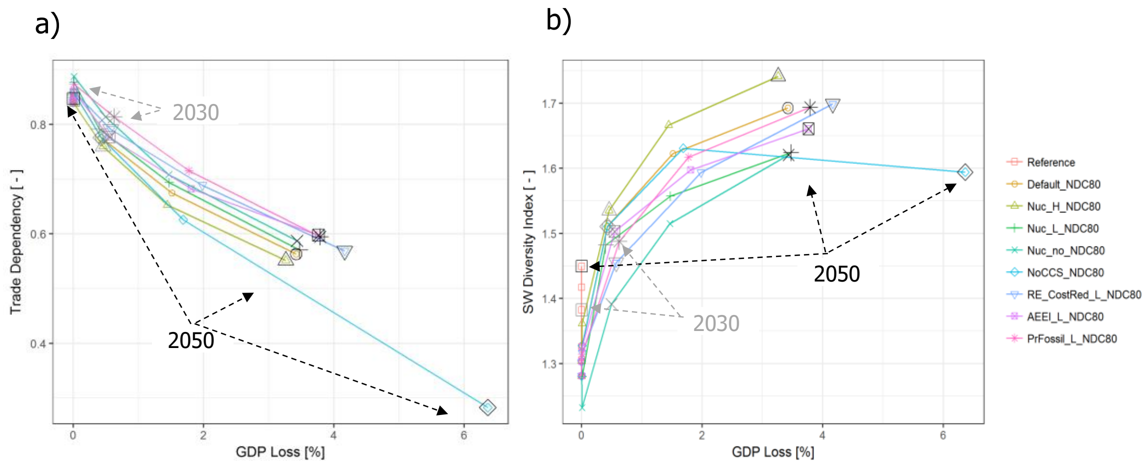

Share|Final Energy|Electricity
60
50
40
30
[%]
2010
2020
2030
2040
2050
scenario
Reference
Default_NDC80
Nuc_L_NDC80
NoCCS_NDC80
RE_CostRed_L_NDC80

Figure 4


a)
b)
Trade Dependency [-]
0.8
0.6
0.4
GDP Loss [%]
0
2
4
6
2030
2050
SW Diversity Index [-]
1.7
1.6
1.5
1.4
1.3
Reference
Default_NDC80
Nuc_H_NDC80
Nuc_L_NDC80
Nuc_no_NDC80
NoCCS_NDC80
RE_CostRed_L_NDC80
AEEI_L_NDC80
PrFossil_L_NDC80