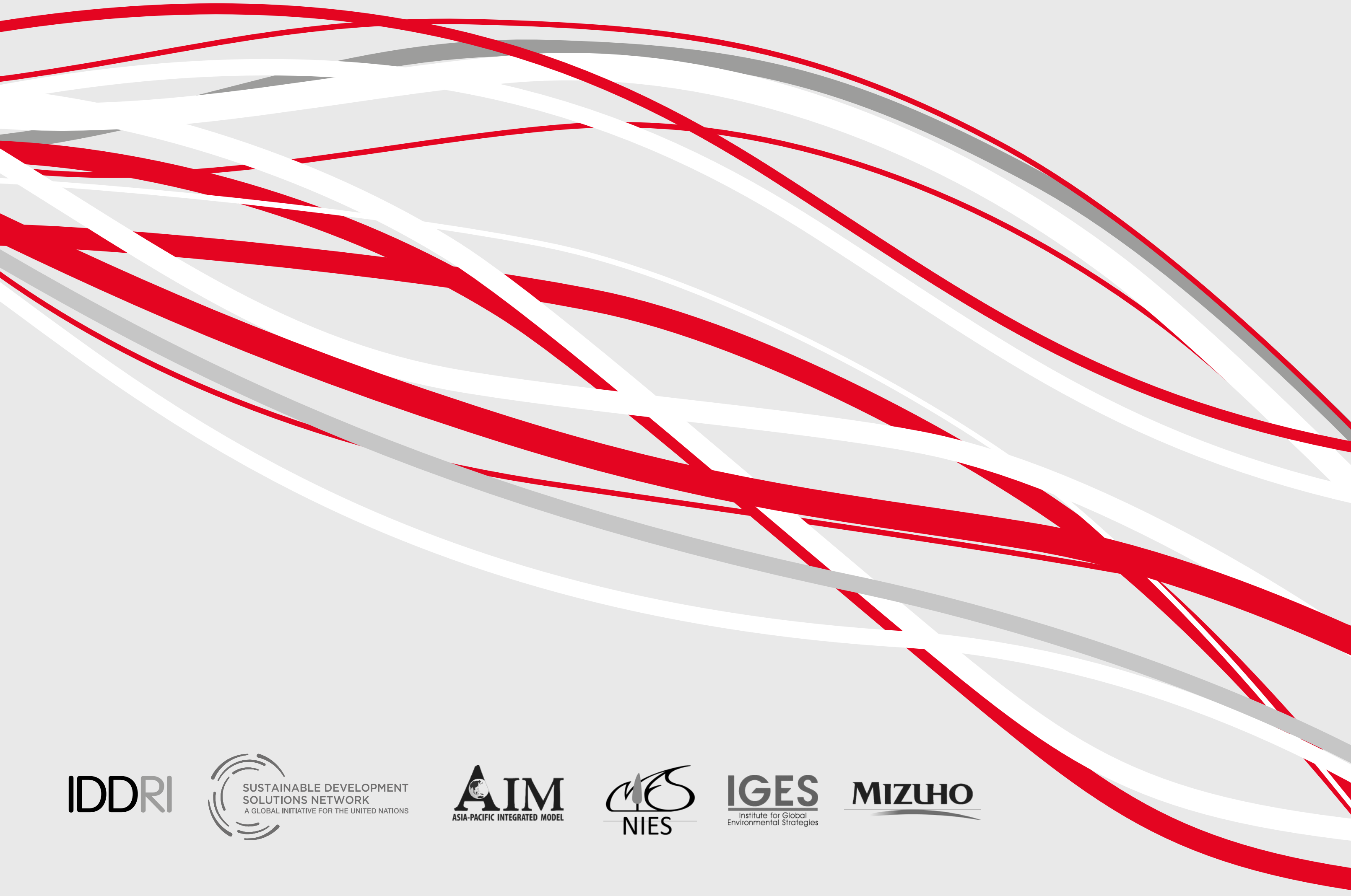
JP 2015 Report

pathways to deep decarbonization *in Japan*



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AIM
ASIA-PACIFIC INTEGRATED MODEL

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pathways to
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Executive summary

To achieve the political mitigation target of reducing 80% of greenhouse gas (GHG) emissions by 2050 with reduced nuclear dependence, Japan must conduct an ambitious transformation built on two major components: i) reduction of energy demand through deployment of highly energy-efficient technologies, and ii) increase of low-carbon energies, such as renewable energies and fossil fuels with carbon capture and storage (CCS). In this study, three Deep-Decarbonization Pathways are defined for Japan, each meeting the 2050 mitigation target, while considering different assumptions regarding the availability of low-carbon technologies. The assessments of these scenarios, using AIM/Enduse and AIM/CGE models, demonstrate that they correspond to realistic transformations and help to identify the conditions for their implementation.

In Japan's **Mixed Scenario**, the long-term GHG emission reduction target is achieved by large-scale energy demand reduction by end users and decarbonization of power generation through a massive deployment of CCS. Total final energy consumption in 2050 decreases substantially to reach approximately half of the 2010 level despite a continuation of economic growth at an average annual rate of 1.0%. This means that this scenario demonstrates the feasibility of a 68% decoupling between energy demand and economic activity thanks to extensive diffusion of energy efficiency. Achieving the carbon target requires an additional effort to decarbonize the energy supply, notably with electricity. Given the assumption of an almost complete phase-out of nuclear power, the diffusion of both renewable energy and CCS by 2050 plays a crucial role. The share of renewable energy (including hydropower) and CCS-equipped plants reaches approximately 60% and 35% of total electricity generation, respectively, ensuring that the carbon intensity of electricity falls to nearly zero in 2050. In end-use sectors, CO_2 emissions are substantially reduced by large-scale energy efficiency improvements and a shift to low-carbon electricity.

We also considered an alternative pathway (**No-Nuclear Scenario**) with a complete phase-out of nuclear power by 2050 (compared with a remaining 5% share in the Mixed Scenario). In this scenario, an 80% emission reduction in 2050 is still feasible with additional deployment of renewable energy and natural gas equipped with CCS. However, a major challenge identified in this transition scenario is higher carbon intensity experienced where coal and gas operate temporarily without CCS to compensate for the gap caused by the phase-out of nuclear.

Finally, to address the uncertainties regarding the scale of CO_2 storage potential, a third pathway is considered that assumes limitations on CCS deployment (**Limited CCS Scenario**). Here again, it is still possible to achieve the long-term emission-reduction target through a substantial increase of renewable energy, particularly solar PV and wind power. In this scenario, the share of intermittent renewable energies account for about 64% in electricity generation in 2050, imposing a further challenge for integration into the electricity system.

In the last two scenarios, energy efficiency also plays an important role and final energy demand in 2050 is almost at the same level as in the Mixed Scenario since most energy efficiency measures are already introduced even in the Mixed Scenario.

With large-scale diffusion of low-carbon technologies, Japan's long-term GHG emission reduction target is technically feasible, even if the availability of nuclear power and/or CCS is limited. But deep decarbonization in Japan poses a number of challenges. Particularly, avoiding a lock-in of devices and infrastructure that have high carbon intensity, as well as promoting of energy efficiency and low carbon technologies, such as diffusion of renewable energies and energy efficiency in buildings, could be essential to achieving deep decarbonization as a near-term priority. When considering economic implications, it must be noted that the effect of decarbonization on growth rate remains relatively small, and some early actions could entail additional benefits, such as the enhancement of energy security through the reduction of import dependency and fuel import costs.

The long-term analysis conducted in this analysis reveals that meeting the long-term goal of decarbonization in Japan requires the adoption of adequate short- and medium-term reduction strategies to make the long-term transformation possible. In particular, focusing on a level of GHG emissions reductions in the mid-term is not sufficient, but a certain degree of transparency in the content of the transformations is necessary in order to make explicit how actions on the three pillars of decarbonization – the improvement in energy efficiency, electrification, and decarbonization of electricity – can be implemented on different time horizons.

1 Introduction

1.1 Background

The Japanese economy is characterized by low domestic reserves of fossil fuels, which make it highly dependent upon imports (IEA, 2014b). This situation has raised important energy security concerns since the 1950s, when Japan turned from domestic coal and hydro to imported oil to support its rapid economic growth. After the first oil shock, Japan's energy policy priorities shifted to be framed around the three pillars of energy security, environmental protection, and economic efficiency. This strategy has led to the development of nuclear, liquefied natural gas (LNG), and imported coal to limit the dependency on oil and promote the diversification of the energy supply. The focus on energy security and climate change has favored the development of renewables and the domination of nuclear power, which was the most important energy source until the Fukushima Daiichi Nuclear Power Plant accident.

After the 2011 accident, Japan's mid- to long-term energy plan was revised since the previous plan published in 2010 assumed a dominant role for nuclear power, especially building 14 new plants by 2030 (METI, 2010). In the revised Strategic Energy Plan in Japan published in April 2014 (METI, 2014), the availability of nuclear power is mentioned just qualitatively and remains quantitatively still uncertain in the future. Large-scale deployment of energy-efficient technologies and low-carbon energy from renewables or fossil energy with carbon capture and storage (CCS) would become important in light of uncertainties on the availability of nuclear power in the low-carbon transition.

Developing renewables is also important for energy security purposes since it is the major option to increase the share of domestic sources in the primary energy supply from its low 4% value in 2010 (IEA, 2014a). However, the development of this energy poses an important challenge for regional electricity exchange. Indeed, the potential of renewable energies is unevenly distributed, and the major renewable-energy capacity is not located in the major electricity-demand regions (e.g. Kanto area) but in rural areas such as Hokkaido and Tohoku. Given currently low electricity interconnection capacity between regions in Japan, the strengthening of interconnection and the development of adequate infrastructure is therefore crucial to incorporating potentially high levels of renewable energies.

1.2 Why we need to stay below 2°C

IPCC reports that "Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks" (IPCC, 2014b).

The impacts of climate change have been becoming visible in many parts of the world. In Japan, many urban areas, mountainous settlements, and remote islands are suffering from torrential rain and landslide damage every year on a scale not previously experienced. Moreover, various impacts of climate change are becoming apparent in fields such as water resources, ecosystem, agriculture, coastal areas, and health (S-8 project, 2014). If the global mean temperature increase exceeds 2°C, more severe impacts could happen, and should be prevented.

In the G8 L'Aquila Summit in 2009, leaders recognized the scientific view on the need to keep the global temperature increase below two °C above pre-industrial levels, and agreed on an 80% or more reduction goal for developed countries by 2050. As a national long-term GHG reduction target in the Fourth Basic Environment Plan (Government of Japan, 2013), Japan aims to reduce GHG emissions by 80% by 2050. Japan's Intended Nationally Determined Contribution (INDC), published in July 2015, sets a target to reduce GHG emissions by 26% by 2030 with respect to the 2013 level; the INDC also mentions that this target in 2030 is consistent with the goal of developed countries to reduce GHG emissions in aggregate by 80% or more by 2050 (the Government of Japan, 2015). One can, however, question whether these two targets are consistent given the huge challenges that would remain to achieve the long-term target after 2030.[1]

This report illustrates deep-decarbonization pathways for Japan and analyzes the feasibility to achieve the GHG emission target of 80% reduction in 2050 with respect to 1990 levels. This objective notably translates into a level of energy-related CO_2 emissions around 2,1 tCO_2/cap in 2050 (down from 8,8tCO_2/cap in 2010), which is around the average reached in the most ambitious decarbonization scenarios across the 16 DDPP country analyses.

Box 1: What will happen if the climate exceeds 2°C?

It is predicted that climate change affects a variety of fields in Japan throughout 21st century. The impacts of disaster related to extreme weather, health effects such as heat stress, impacts on water resources, agricultural and ecological changes, are expected to be wide in scope and extent, affecting: 1) national health, safety and security; 2) national life quality and economic activity; and 3) ecosystems. Table 1 indicates severe impacts will occur as climate change moves beyond 2°C as an example (S-8 Project, 2014).

Table 1. Potential impacts of moving beyond 2°C in Japan

Area of Impact	Potential impacts of moving beyond 2°C
Flood and landslide	The damage cost of floods is projected to be large in urban areas, while landslides inflict significant damage on hilly areas of urban neighborhoods.
Ecosystem	Pinus pumila is a dwarf conifer that is dominant in the Japanese alpine zone, ranging from the Chubu region to the north. The area of potential habitats is projected to decrease to 489-8,517 km^2 under IPCC RCP scenarios. The distribution area of Aedes albopictus covers approximately a little less than 40% of Japan's total land area under existing condition, but RCP8.5 of the end of 21st century anticipates that it will reach approximately 75-90%e of the Japanese landmass.
Agriculture	The distribution is largely skewed between areas with yield increase and those with yield decrease, and thus indicates that unsuitable areas for rice production will be further polarized along with temperature change.
Human health	Heat stress excess mortality (if not adapted) and the number of heat stroke patients transported by ambulance drastically increases according as climate change progress.

1.3 Japanese GHG emissions: current levels, drivers and past trends

Total GHG emissions in 2010 (excluding LULUCF and NF_3, based on the GWPs subjected to IPCC SAR) amounted to 1,256 $MtCO_2eq$ of which CO_2 represented a large majority (1,191 $MtCO_2$ or 94.8%) (Figure 1 (left)) (GIO, 2014a). The sectoral decomposition shows that three activities were dominantly responsible for these CO_2 emissions (Figure 1 (right)): power generation, notably because the power sector was largely fueled by imported coal and LNG (even in 2010 before nuclear was partly removed from the power generation mix); industry, because industrial sectors play a very important role in the Japanese economy notably for exports with a share of energy-intensive industry such as iron and steel that remains still large; and transport, as notably triggered by the constant increase of the freight traffic (+12% from 1990 to 2010). Direct CO_2 emissions in commercial and residential sectors are moderate, notably because electricity plays a dominant role in these activities since the main driver of associated emissions is related to increasing distribution of electrical appliances.

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[1] See for example an analysis of Japan INDC at: http://www.blog-iddri.org/2015/07/27/japans-indc-afirst-analysis/

Figure 2 shows a historical trend of energy-related CO_2 emissions by sector. Emissions from the industry sector have reduced continuously since 1990, and those from the transport sector have reduced since 2000. The trends demonstrate a continuous but moderate increase of total CO_2 emissions over 1990-2007 (+14%) before recent drastic changes (-8% between 2008 and 2010 after the economic crisis and +7% between 2010 and 2012 because the closure of nuclear plants after Fukushima triggered a temporary increase of fossil importations). During the 1st commitment period of Kyoto Protocol, GHG emissions increased by 1.4% compared to the level of Kyoto Protocol Base Year (KPBY). On the other hand, if the carbon sink of LULUCF and credit of Kyoto Mechanism are included, the GHG emissions during the 1st commitment period amount to 1,156 $MtCO_2eq$, a 8.4% decrease from KPBY (GIO, 2014b).

In Figure 3, the decomposition of drivers of changes in CO_2 emission from fuel combustion over 1990-2012 demonstrates that the Japanese economy has experienced a continuous diffusion of energy efficiency after 2000s permitting an average 0.7% annual decrease of energy intensity of production, which is significant, especially when considering the high initial efficiency of the Japanese economy. The other Kaya drivers did not have such a continuous effect during that period. Until 2007, growth of GDP per capita has been the major driver push-

Figure 2. Historical energy-related CO_2 emissions by sector

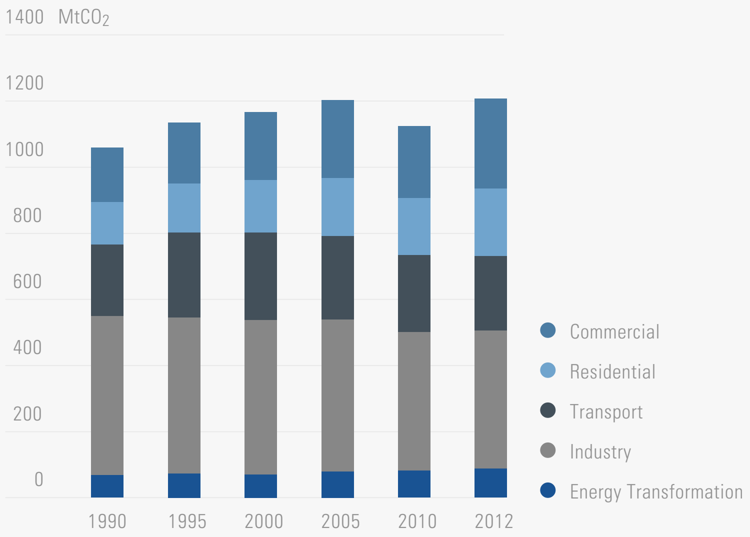
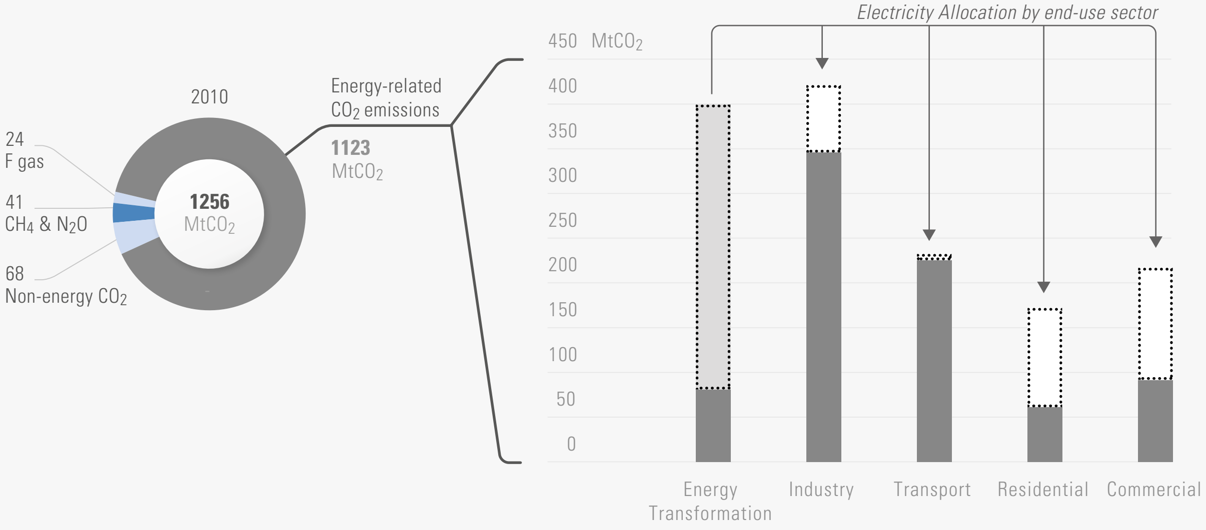


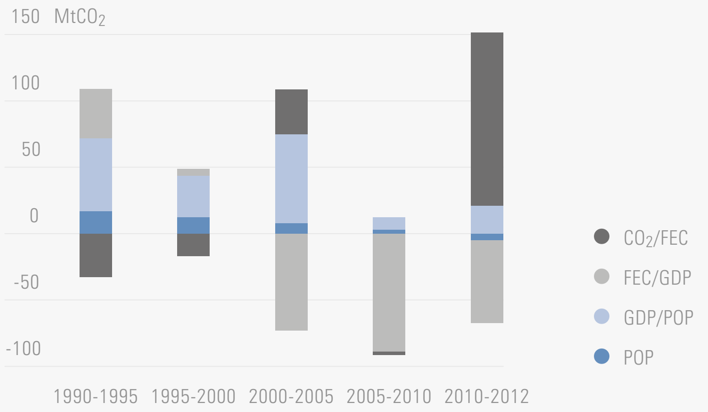
Figure 1. GHG Emissions and Energy-related CO_2 Emissions in 2010



ing CO_2 emission upwards (except in 2008 and 2009 during the global economic recession). The combination of economic growth and increase of carbon intensity more than offset efficiency gains over 2000-2005 causing an absolute increase in energy-related CO_2 emission over this period. This trend was reversed over 2005-2010 due mainly to switch from oil to LNG in primary energy.

In 2011 and 2012, the dramatic increase of carbon intensity was the major reason for a new increase of emissions, as a direct consequence of the suspension of nuclear plants after the Great East Japan Earthquake in 2011 and the resulting comeback of fossil fuels.

Figure 3. Decomposition of historical energy-related CO_2 emission



2 Methodology

2.1 The AIM family of models

The Asian Pacific Integrated Model (AIM) is a large-scale computer simulation model developed by the National Institute for Environmental Studies, Kyoto University and Mizuho Information & Researh Institute in collaboration with several research institutes in the Asian-Pacific region. The AIM assesses policy options for stabilizing the global climate, particularly in the Asian-Pacific region, with the objectives of reducing greenhouse gas emissions and avoiding the impacts of climate change.

The AIM is a family of models consisting of three different parts: GHG emission, climate, and impacts. The two main models of the emissions part are AIM/Enduse (mutli-sectoral, bottom-up model of energy technology selection), used at global, national and subnational scales, and AIM/CGE (general equilibrium model used to estimate economic impacts) ,used at global and national scales[2] (Kainuma et al., 2000; Masui, 2005). AIM models have been extensively used for analysis of low carbon and other climate policy actions, and have provided inputs to policy makers at the levels of regions, countries and cities (Kainuma et al. 2003; Matsuoka, 2012; Low-Carbon Asia Project, 2012; Masui, 2015).

2.2 AIM/Enduse Model

AIM/Enduse model is a dynamic recursive, technology selection model for the mid-to long-term mitigation policy assessment, which has already been applied to assess the long-term mitigation target in Japan (Fujino et al. 2008). The model covers both end-use sectors (transport, industrial,residential and commercial) and energy supply sector[3]. In each sector, service demand (eg, steel

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[2] A third tool in the AIM family of models, AIM/ExSS (Extended Snapshot tool), is mainly used for local scale planning such as a city and a prefecture by providing a comprehensive and consistent picture of GHG emission trends and reduction plans.

[3] Non-energy sectors (e.g. agriculture, industrial process, waste) are also included, and non-CO_2 gases include CH_4, N_2O, hydrofluorocarbon (HFC), perfluorocarbon (PFC), and SF_6 (these emissions are converted into CO_2-equivalents based on GWP from GIO (2014a)).

production in Mt, lighting demand in buildings in lumen-hour or passenger transport demand in person-km) are given exogenously and technologies are selected in order to minimize total system cost (annualized capital cost (with discount rate from 10%-33%), energy cost and carbon price). End-use and supply-side (notably power generation) sectors are mutually interlinked: technology selection in power generation sector is implemented subject to electricity demand derived from end-use sectors and the carbon intensity of electricity affects technology selection in end-use sector when including explicit carbon price.

The model used in this study is a multi-region version of AIM/Enduse model of Japan, in which 10 regions are explicitly distinguished with their regional differences in renewable-energy potential and energy-demand characteristics. These 10 regions coincide with the business areas of 10 public power supply firms (Oshiro and Masui, 2015).

2.3 AIM/CGE model

In order to assess the economic impacts of deep-decarbonization pathways in Japan, we adopt the multi-region[4], computable general equilibrium model with recursive dynamics model AIM/CGE (Masui, 2005). It assesses the economic trajectories, notably GDP levels, consistent with the technological trajectories of the DDPP scenarios. In each region, total supply and demand for each commodity and production factor are in equilibrium through the price mechanism, and each commodity market is linked to those in other regions. The final demand sector holds capital and labor force, and receives income by providing them to the production sectors. This income is split between final consumption to maximize utility, and savings used for investments. Each production sector produces the goods using capital, labor, energy, and other materials to maximize profit. Investments and production are linked through the evolution of the capital stock, which defines the characteristics of the production function consistently with the dynamics of technologies, including the deployment of advanced energy-saving technology.

2.4 Technical Options and Assumptions for National Deep Decarbonization

A wide range of low-carbon technologies are taken into account and explicitly represented in the AIM/Enduse model. Table 2 summarizes the list of major low-carbon technologies considered in the analysis.

Table 2. List of major low-carbon technologies

Sector	Technologies
Electricity	Efficiency improvements of power generation (e.g. switch from conventional LNG plant (efficiency: 40%) to combined cycle (57%)); coal and gas with CCS; reduced T&D (transmission & distribution) line losses; nuclear power; wind power; solar PV; geothermal; bioenergy; reinforcing electricity interconnection
Transport sector	Energy-efficiency improvements (fuel economy improvement of LDV: more than 20% compared with current level); gas-powered HDVs; vehicle electrification; fuel-cell electric vehicles
Residential and commercial sectors	Improvement of the energy-efficiency performance of buildings; high-efficiency equipment and appliances; electric heat pump water heaters (COP: 6.0); energy-management systems
Industrial sector (incl. agriculture)	Energy-efficiency improvements; electrification where possible; natural gas use; CCS for iron making and cement lime; fuel economy improvements of agricultural machines; bioenergy use; nitrogen fertilizer management

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[4] Because of the limitation of data availability for the CGE model, the number of regions in this CGE model is set to be nine.

3 Scenarios

3.1 Three Deep-Decarbonization Scenarios

The three deep-decarbonization scenarios are developed to analyze effects that result from different technology choices to achieve the 80% reduction of GHG emissions by 2050 with respect to 1990 levels. This objective notably translates into a level of energy-related CO_2 emissions around 2,1 tCO_2/cap in 2050 (down from 8,8 tCO_2/cap in 2010), which is around the average level reached in the most ambitious decarbonization scenarios across the 16 DDPP country analyses.

(1) Mixed Scenario:
The Mixed Scenario achieves deep decarbonization under continued economic growth through strong action on the three pillars of decarbonization: i) large-scale energy demand reduction permitted by the deployment of various energy-efficiency measures (high-efficiency home and office appliances, high-efficiency boilers and furnaces, and improvement in the fuel economy of vehicles), combined with a decline of population triggering absolute reduction of energy service demand in the end-use sector; ii) strong decarbonization in the power-generation sector notably thanks to large deployment of CCS (approximately 97% reduction in carbon intensity of electricity compared with the 2010 level) and renewable energies; and iii) extensive diffusion of low-carbon electricity in end-uses, reaching up to 45% of final energy (compared with less than 25% in 2010). The scenario considers a partial phase-out of nuclear under the assumption that all plants are operated for no more than 40-50 years, translating to a share of nuclear in electricity generation of 19% in 2030 and 5% in 2050.

(2) No Nuclear Scenario (No-Nuclear):
Contrary to the Mixed Scenario, the No-nuclear scenario assesses the robustness of the decarbonization process under a complete phase-out of nuclear, following the assumption that no nuclear plant is restarted over the entire period of estimation after 2014. This scenario acknowledges that, although Sendai Nuclear Power Station has passed the safety inspection by the Nuclear Regulation Authority and restarted in August 2015, and nuclear plants are assumed to restart by 2030 in Government's INDC[5], the availability of nuclear plants is still uncertain, and there is today widely diffused opposition to nuclear power.

(3) Limited CCS Scenario (Limited CCS):
Carbon Capture and Sequestration plays a prominent role in the Mixed Scenario, but strong uncertainties remain regarding the scale of its potential. It will notably depend on the technical development of this solution (which is currently non-commercially available), the regulations concerning short- and long-term responsibilities for storage, as well as economic incentives. Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of CO_2 storage in seismic areas as well as transport risks. (IPCC, 2014a). This is why this alternative Limited CCS scenario is developed to assess the robustness of decarbonization to lower sequestration levels reaching only 100 $MtCO_2$/year, i.e. half of those considered in the Mixed Scenario.

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[5] In 2030, nuclear power accounts for 20-22% of total electricity supply in the Government's INDC

3.2 Assumptions for national deep-decarbonization scenarios

Population and GDP

Population and GDP assumptions are common to all three decarbonization scenarios assessed in AIM/Enduse (Table 3). The impact on GDP in each scenario is then analyzed by implementing the technical changes forecasted and derived from AIM/Enduse into the AIM/CGE model (see Section 6)[6]. In line with a declining birthrate and a growing proportion of elderly people, both total and active Japanese populations will significantly decrease between 2010 and 2050, by 24% and 39% respectively (IPSS, 2012). Despite the decline in population, the continuous rise of GDP per capita is projected to be sufficient to ensure a steady rise of total GDP at around 1% annual growth on average over 2010-2050 (Central Environmental Council, 2012). Table 3 also gives some energy service demand drivers as illustration of the assumptions on the dynamics of major end-use sectors (buildings, industry, and transport).

Nuclear power

Except in the No-Nuclear Scenario, which considers that no nuclear power is used (see detailed explanation above), electricity generation from nuclear plants and the availability of nuclear power in the Mixed and Limited CCS Scenarios is assumed based on the assumptions of the New Policies Scenario of World Energy Outlook 2013 (IEA, 2013). This means that the lifetime of nuclear plants is limited to 40 years for plants built before 1990 and 50 years for all other plants, and during 2013 to 2035 an additional 3 GW nuclear plants capacity is included (compared with installed nuclear capacity in 2011, at around 46 GW).

Geologic carbon storage potential

CCS technologies are assumed to be available from 2025 and, in the Mixed Scenario, annual CO_2 storage volume is assumed to increase linearly from zero in 2024 up to 200 Mt-CO_2/year in 2050, consistent with assessments by the Central Environmental Council (2012). Given estimations of potential capacity around 5 Gt-CO_2, this means that about half of the total storage capacity would be used by 2050. CCS technology can be applied to both power generation and industrial sectors. In the power-generation sector, both coal plants and natural gas plants can be equipped with CCS technology, but bioenergy with CCS (BECCS) is excluded in this analysis because it entails specific risks and uncertainties associated with large-scale provision of biomass, especially given limited domestic resources. For industrial use, CCS technologies are available in iron and steel and cement sectors. A maximum capture rate of CO_2 by CCS technologies is assumed to be 90% for all CCS technologies (IEA 2008).

Integration of variable renewable energies: Electricity interconnection and demand-side management

In Japan, the regions with a large potential for renewable energy are different from the ones with large electricity consumption, while interconnection capacity between the business areas of 10 public power supply firms is insufficient. Thus, reinforcement of interconnection capacity would be helpful to facilitate more effective use

Table 3. Assumptions of macroeconomic indicator and activity level in 2050

	2010	2050
Population (Millions)	128	97
Real GDP (Trillion USD)	4.65	7.04
Household (Millions)	53	44
Commercial floor area (Msqm)	1,834	1,896
Crude steel production (Mt)	111	85
Passenger transport (Gpkm)	1,264	1,140

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[6] In other words, the two models are not fully integrated, but are used in a soft-linking approach.

of local renewable sources. Particularly, Hokkaido and Tohoku have large wind power potential compared with their electricity demand.

In order to integrate large-scale variable renewable energies (VREs) such as solar PV and wind power into the electricity grid, demand-side management as well as supply-side measures such as pumped hydropower would be essential in the long term. In the AIM/Enduse model used in this analysis, a variety of demand-side management strategies common to all scenarios are considered, such as the deployment of battery electric vehicles (BEV), heat pump water heaters, and converting electricity into hydrogen. These technologies permit peak shifting and change the pattern of the future electricity load curve, hence providing flexibility to the electricity system (see discussions in section.5.2)

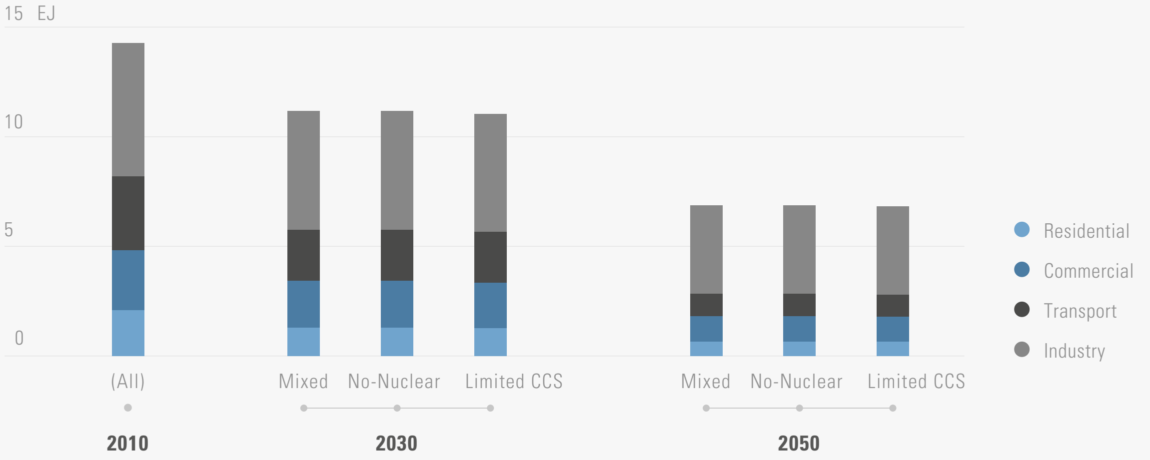
4 Results: High-level summary

This section summarizes the high-level results of this analysis across the three decarbonization scenarios.

4.1 Final energy demand

The total final energy demand in 2050 decreases by more than 50% compared with the 2010 level in all scenarios (Figure 4). The difference in energy demand between three DD scenarios is negligible in 2050, because energy-efficiency technologies are almost fully introduced commonly in all scenarios and measures to reduce activity levels are not considered. In the Mixed Scenario, energy demand by 2050 is reduced 68% in the residential sector, 58% in commercial, 68% in transport, and 37% in industrial. The smaller energy demand reduction in the industrial sector compared with the other sectors is explained by the absence of drastic change to the industrial structure in the scenario assumptions and the very efficient initial industrial processes, which limit the potential for improvement.

Figure 4. Final energy demand by case



4.2 Emissions

In all scenarios, energy-related CO_2 emissions are decreased by approximately 84% in 2050 compared with the 2010 level (Figure 5), and the 80% reduction target in 2050 for GHG emissions is achieved in all scenarios.

Decarbonization wedges in 2050

Figure 5 identifies the sources of these emission reductions in the three scenarios by analyzing decarbonization wedges in 2050 compared with the Reference Scenario based on Kaya Identity (Kaya, 1990). “Reduction by energy efficiency” measures the contribution of reduced energy demand compared with the Reference Scenario. The contribution of carbon intensity improvement compared with the Reference case is separated into two wedges. “Reduction by CCS” refers to the captured CO_2 emissions in electricity and the industrial sector, and the rest is shown as “Reduction by shift to low-carbon sources.”[7] In Mixed and No-Nuclear Scenarios, energy efficiency, energy transformation, and CCS play a similar role, each accounting for about one-third of CO_2 emissions reductions. Note that these two scenarios are identical at the 2050 horizon, but would be rather different in the transition (see discussion below). In the Limited CCS Scenario, the unavailability of CCS is compensated for with the additional deployment of renewable energies, as shown by the larger “Reduction by shift to low-carbon sources” wedge.

Time profile of emissions reductions and their drivers

We deconstruct the Kaya drivers of emissions in the different decades to identify the main determinants of emissions reductions over time. Figure 6 presents the result for the Mixed Scenario. The results for the two scenarios are qualitatively similar, although we will comment on the difference in the magnitude of the effects.

Figure 5. CO_2 emissions by case and decarbonization wedges for the three scenarios

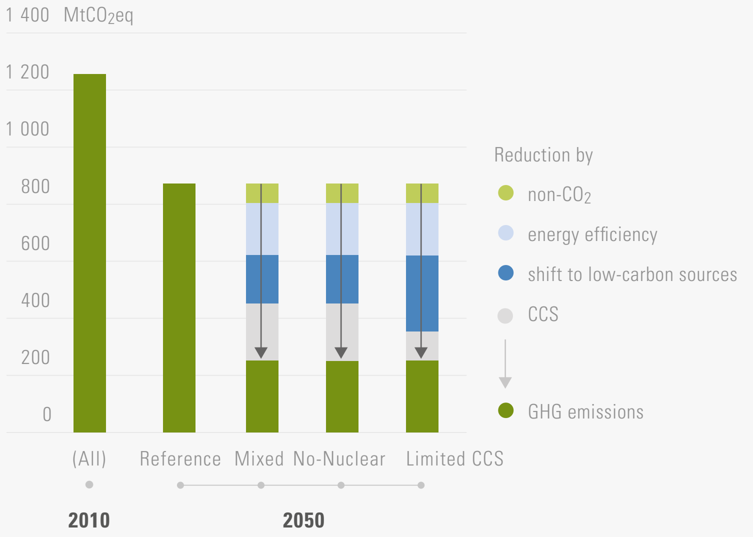
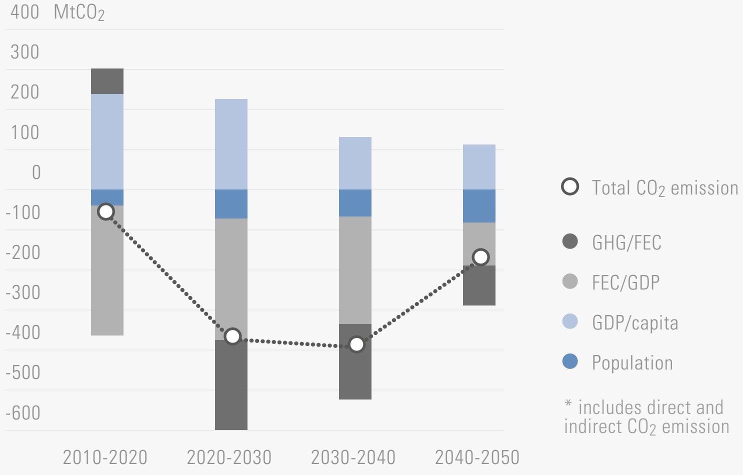


Figure 6. Breaking down the change in CO_2 emission* by decade in Mixed Scenario



* includes direct and indirect CO_2 emission

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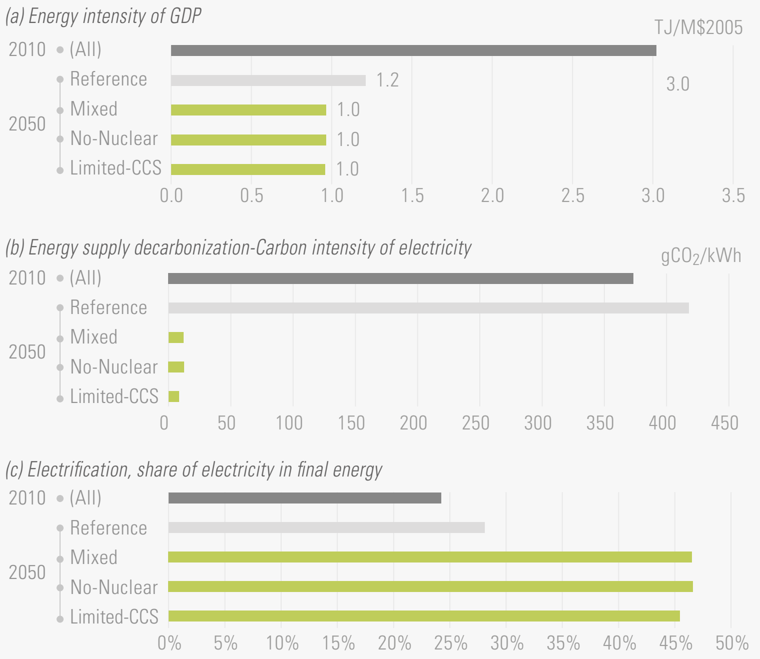
[7] Note that structural change is identical in all scenarios, which explains why we do not consider a wedge associated with this transformation. “Reduction by low-carbon energy” includes emissions reductions by a shift to low-carbon sources (e.g. electricity, renewables) and by decarbonization of the types of energy themselves (particularly in the power sector).

In all scenarios, population and GDP per capita have the same impact on emissions, and push emissions downwards and upwards respectively, given the constant decrease of population and increase of GDP/cap in all scenarios. Now we turn to consider the two other Kaya drivers, i.e. energy per unit of GDP and emissions per unit of energy.

In the Mixed Scenario, the reduction of final energy consumption per unit of GDP is the major driver of decarbonization over all decades thanks to the continued large-scale deployment of energy-efficiency measures (Figure 6). While emissions per energy increases in the first decade due to the suspension of nuclear power, this indicator then steadily decreases after 2020 and contributes to a similar amount of emissions reductions as energy efficiency by 2050.

The trends are similar in the No-Nuclear scenario, but a noteworthy difference concerns the trends of the carbon intensity of energy. The increase over the first decade is more pronounced than under the Mixed Scenario because even existing nuclear plants do not contribute to power generation, in turn forcing more use of fossil fuels in the short term; this leads to an additional 30 $MtCO_2$ in 2020. But interestingly, the reduction of carbon intensity over the next decade provides more important emission reductions than in the Mixed Scenario thanks to more aggressive diffusion of renewable energy and natural gas equipped with CCS in the long term; this ensures additional emissions reductions of around 30 $MtCO_2$ between 2020 and 2040 compared with the decarbonization of energy in the Mixed Scenario. Finally, it is suggested that the impact of a nuclear phase-out is relatively small in the long term because nuclear power represents a very small share of the electricity supply in 2050 even in the Mixed Scenario. Finally, in the Limited CCS Scenario, the short-term increase of the emissions intensity of energy is even more pronounced, causing an increase of emissions to around 135 $MtCO_2$ (vs. “only” 64 in No-Nuclear Scenario). Indeed, this scenario is by far the most aggressive in terms of renewables in the long-term, but the integration of a large amount of variable renewable energies (VREs) into the electricity system raises challenges causing delays in their diffusion. The consequence is that this Limited CCS scenario is the only one where carbon emissions increase between 2010 and 2020. The other side of it is that the decrease of carbon intensity is much more important after 2020 than in the two other scenarios, once renewables start playing a dominant role.

Figure 7. Indicative metrics for the three main decarbonization strategies compared to 2010



4.3 *The pillars of decarbonization*

Figure 7 summarizes the characteristics of the three decarbonization scenarios according to the three pillars of decarbonization, as defined in the general DDPP methodology and approach.

As shown in Figure 7(a), energy consumption per GDP is decreased substantially in 2050 regardless of technology availability in the energy supply sector. It illustrates that energy demand reduction is essential even if the technologies in the energy supply sector are fully available.

The carbon intensity of electricity increases about 1.13 times in the Reference Scenario in 2050 compared with 2010 because of an increase in coal consumption in place of nuclear power. As the use of fossil fuel energy without CCS is reduced to almost zero in the decarbonization scenarios, their carbon intensities are reduced drastically to reach levels around 10gCO_2/kWh in all scenarios (compared with 370 gCO_2/kWh in 2010) (Figure 7(b)).

Low-carbon electrification is essential in Japan's decarbonization scenarios. In all scenarios, a share of electricity in total final energy consumption is almost doubled and accounts for more than 45% in 2050 (Figure 7 (c)). Notably, electric vehicles in the transport sector and heat pumps in the buildings sector play important roles in order to electrify energy demand in Japan.

5 Results: Energy trajectories and CO_2 emissions

5.1 Primary energy supply

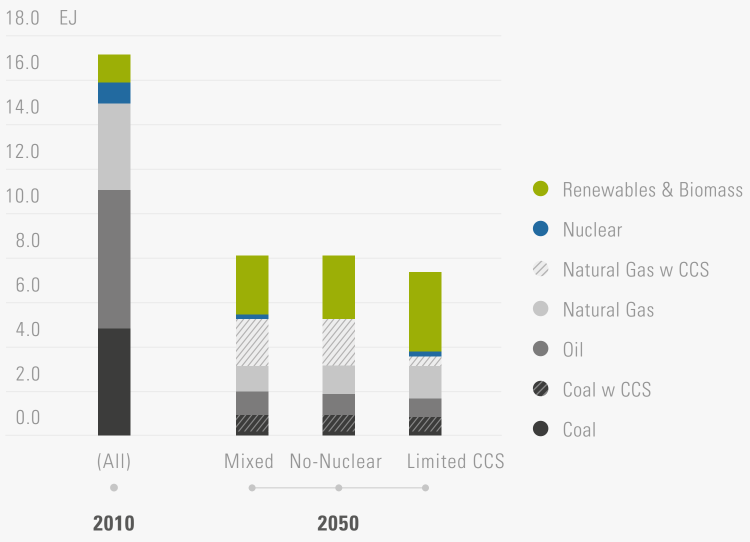
In all scenarios, dependency on fossil fuel is reduced substantially compared with the 2010 level thanks to the combination of a drastic reduction in energy demand and the deployment of non-fossil options on the supply-side, notably renewable energy. By 2050, fossil fuel consumption falls by approximately 60% compared with the 2010 level in all scenarios (Figure 8).

The structure of the energy supply varies significantly across scenarios. In all cases, the share of renewable energy (including hydropower) in primary energy significantly increases, but the magnitude depends on the scenario considered. Renewables indeed account for approximately 35% of the total primary energy supply in 2050 in the Mixed and No-Nuclear Scenarios, and significantly more in the Limited CCS Scenario (49%), to compensate for the limitation of CCS for the decarbonization of electricity. Among fossil fuels, residuals of natural gas and oil (including non-energy use) remain in 2050 mainly in the industry and freight transport sector, while coal almost phases out (excluding residual uses in heavy industry) thanks to switching to renewables and natural gas.

5.2 Electricity

The role of nuclear power is significantly decreased in the Mixed Scenario and the Limited CCS Scenario, whereas renewable energy (including hydropower) increases over the mid- to long-term, reaching approximately 59% and 85%, respectively, of total electricity generation in each

Figure 8. Primary energy supply



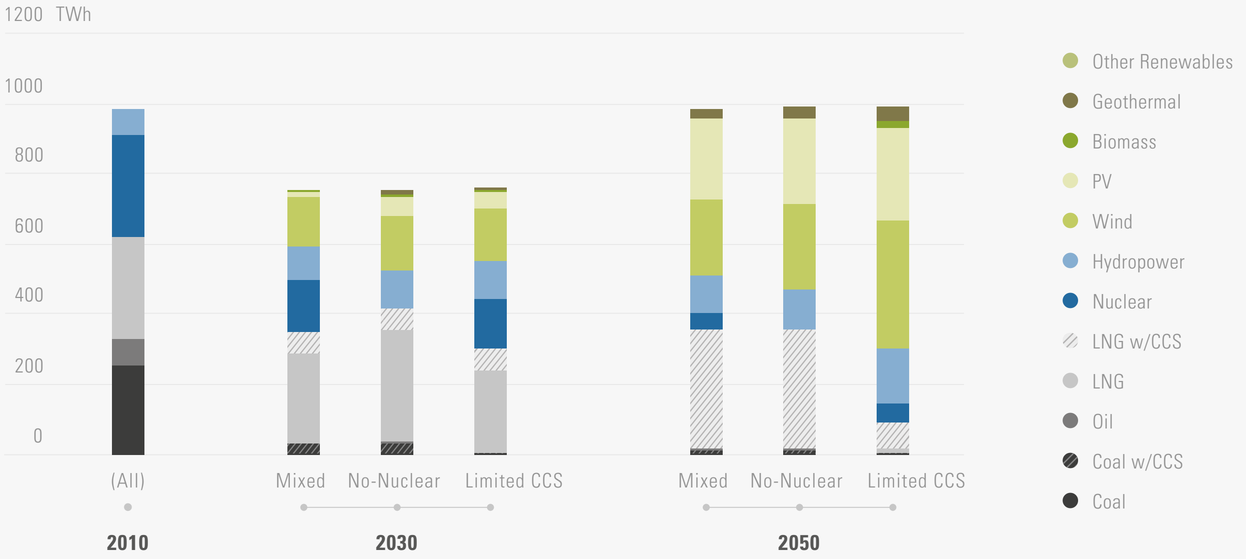
scenario by large-scale deployments of solar PV and wind power. In the No-Nuclear Scenario, natural gas and renewables take an even more important role than in the other scenarios in order to compensate for the absence of nuclear power, notably in the mid-term. In addition, the share of electricity generation from natural gas equipped with CCS rises after 2030 and reaches about one-third of total electricity generation in 2050 in the Mixed Scenario and the No-Nuclear Scenario, while that without CCS falls from around a third in 2030 to a tiny fraction of the electricity supply in 2050. Hence, LNG power plant without CCS acts as a bridge technology in all DD Scenarios. Electricity generation from coal without CCS is entirely phased out by 2050 because of its high carbon intensity. Due to large-scale deployments of renewable energy and/or natural gas equipped with CCS, carbon intensity of electricity falls to nearly zero in 2050 in all scenarios. (Figure 9).

In the AIM/Enduse model used in this study, electricity supply and demand are balanced every 3 hours in a day in each region in order to take into account the intermittency of the electricity supply derived from solar PV and wind power (for more detail about the model structure, see Oshiro and Masui (2015)). Figure 10 shows the hourly electricity supply in the Mixed Scenario. The share of PV energy increases during daytime, providing 60% of electricity from 10:00 to 16:00. LNG with CCS serves to back up the intermittent sources (wind and PV), which reach up to 75% of production between 10:00 and 15:00, and plays the dominant role before 6:00 and after 16:00, providing 40% to 50% of electricity.

5.3 Energy demands and their driving forces in end-use sectors

In this section, the sectoral details of energy demand and their drivers are shown. As energy demands in all deep decarbonization scenarios are very similar as shown in Figure 4, only the numbers from the Mixed Scenario are presented here.

Figure 9. Annual electricity supply



5.3.1 Buildings

In the buildings sector, energy consumption decreases substantially, with final energy demand being reduced by approximately 60%-70% in 2050 compared with the 2010 level, notably thanks to the decrease in final energy demand per capita by almost 45% in 2050 across all deep-decarbonization scenarios (Figure 11 (left)). In addition to energy-efficiency improvement, the share of electricity increases from about 50% in 2010 to about 93% in 2050 in all deep-decarbonization scenarios (Figure 11 (right)). These drastic changes in DD scenarios are obtained mainly through the diffusion of technologies that electrify space heating and water heating in the buildings sector, such as heat pump water heaters and air conditioners, as well as electricity demand for lighting and appliances. As a result of electrification in heating demand, pipeline gas and liquid fossil fuel consumption are substantially decreased in 2050 compared with the 2010 level. Due to electrification and electricity decarbonization, CO_2 emissions in the buildings sector (both residential and commercial) reaches almost zero in 2050.

5.3.2 Transportation

In the transport sector, CO_2 emissions in 2050 are reduced by 82% compared with the 2010 level. This is obtained under a 33% increase in passenger-km per capita, leading to a 10% decrease of overall passenger mobility given the decrease in population, and a 28% increase of total freight mobility in tons-km and a 22% decoupling of freight transport versus GDP.

Figure 11. Energy efficiency (demand/capita) and energy demand in the building sector for Mixed scenario

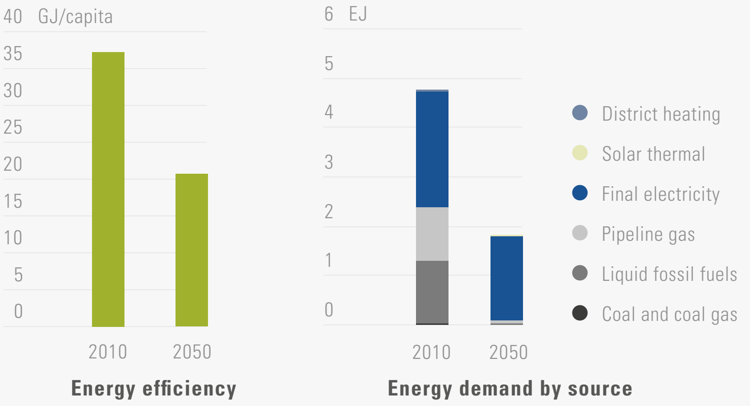


Figure 10. Example of hourly electricity supply in Mixed Scenario

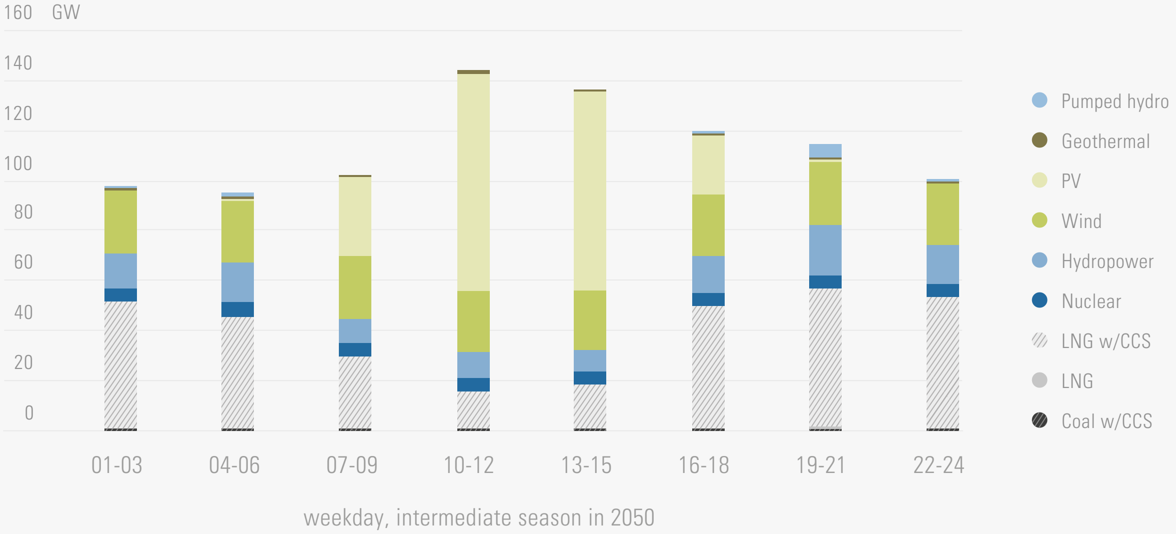
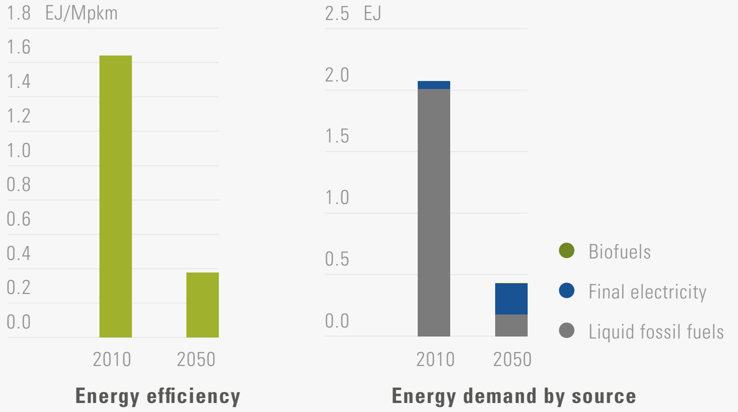


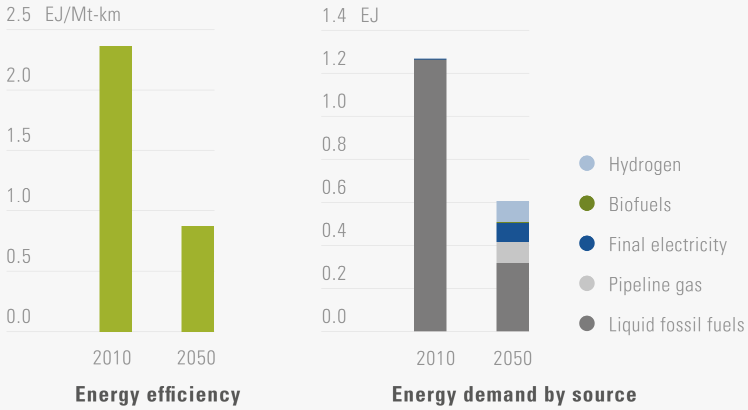
Figure 12. Energy efficiency and energy demand by source in the passenger transport



Energy efficiency

Energy demand by source

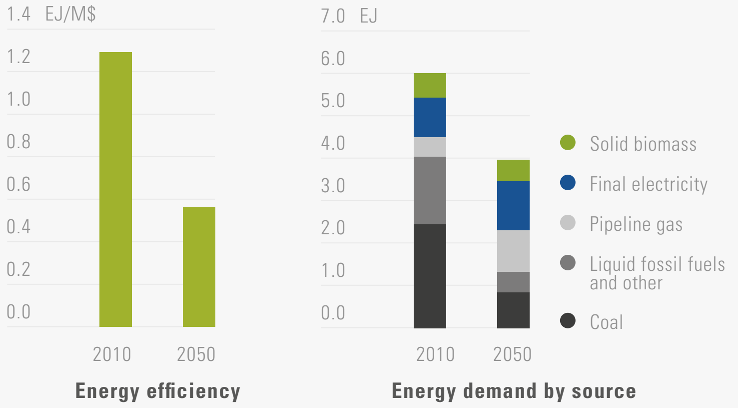
Figure 13. Energy efficiency and energy demand by source in the freight transport



Energy efficiency

Energy demand by source

Figures 14. Energy efficiency (energy demand/GDP) and final energy demand by source in the industrial sector



Energy efficiency

Energy demand by source

A major driver of this drop in emissions is the 69% reduction of energy demand in aggregate for transport resulting from the diffusion of efficient vehicles leading to 77% and 63% less energy content in passenger and freight transport respectively. These efficiency gains are associated with the switch from fossil fuel to electricity and hydrogen. Electrification plays an important role, and electricity accounts for about half of total final energy consumption in passenger transport sector. In freight transport, electrification in 2050 is relatively moderate because heavy trucking is not assumed to adopt EV in this study. However, demand for liquid fossil fuel is substantially decreased thanks to improvements in fuel economy and a switch to hydrogen and natural gas (Figures 12 and 13).

5.3.3 *Industrial*

The industrial sector is by far the largest source of residual emissions in 2050, representing almost 60% of energy-related emissions by that time. This can be explained because fuel demand for high-temperature heat is hard to replace using low-carbon sources.

In the industrial sector, energy consumption in 2050 is decreased by about 35% compared with the 2010 level despite GDP growth, thanks to the deployment of energy-efficiency measures. However, the improvement of energy efficiency is relatively moderate compared with other sectors, since industrial processes are already efficient in Japan and energy-intensive heavy industry keeps an substantial share of total industry in 2050 (given the assumption of constant industrial structure and activity level across all scenarios). In heavy industry, the deployment of renewable energy and CCS contribute to improving carbon intensity in the middle to long term. In the non-heavy industry subsectors, in addition to the improvement in energy intensity, a switch from coal to electricity and pipeline gas also contributes to reductions in CO_2 emissions (Figure 14).

6 Results: Costs

6.1 Investment and Energy Savings

Figure 15 shows annual average incremental investments and energy savings in the energy sector compared with the Reference Scenario, under assumptions for energy prices from Energy Technology Perspectives (IEA, 2012). From 2025 to 2030, annual average investments reach around 4 trillion JPY, or about 0.5%-0.7% of GDP in 2030, with marginal benefits in terms of energy savings (notably because of the delay before efficiency measures reach their full magnitude) inducing a net cost in the three scenarios. However, on a longer time horizon, the increase of investments to 6 trillion JPY (representing the same order of magnitude at 0.7% of GDP) is totally compensated by a surge of energy savings leading to zero or negative costs in the Mixed Scenario between 2045 and 2050. The aggregate result of very low or even a negative energy system cost is valid in the three scenarios but with significantly different patterns. Notably, in the Limited CCS Scenario, average investments are increased compared with the Mixed Scenario due to additional deployment of renewable energies in the long term, but energy savings are also significantly higher because of lower costs for fossil fuel imports (cf energy supply in Figure 8).

Figure 16 summarizes the average additional investments compared with the Reference Scenario by sectors. In the period of 2025 to 2030, most additional investments go to the energy-transformation sector because of the significant cost of the initial deployment of renewable energies. In the period of 2045 to 2050, investment in energy transformation sector remains large, particularly in the Limited CCS Scenario due to additional renewable energy deployment. Additionally, investment in the transport sector is also increased due to the introduction of Battery Electric Vehicles (BEV) and Fuel-Cells Electric Vehicles (FCEV).

6.2 Fuel import cost and energy security

A crucial feature of the deep decarbonization for Japan is the reduction of the dependency on imported fossil fuel. The cost of fuel imports to the Japanese economy continuously decreases over time in parallel with the strengthening of deep decarbonization, reaching a 56% to 65% reduction in 2050 compared with 2010 levels. The effect is most pronounced in the Limited CCS Scenario, which imposes an even more ambitious reduction of fossils use (and hence imports) in the electricity sector and favors the diffusion of domestic renewable energy (Figure 17).

6.3 Economic Impacts

Figure 18 compares the GDP growth rates in the different scenarios by decade. We use the Reference Scenario as the basis for comparison, which experiences 0.95% average annual growth rate from 2010 to 2050, with a progressive decline over time that reflects the progressive stabilization of the Japanese economy (1.57%; 1.34%; 0.5% and 0.33%, decade by decade).

The deep-decarbonization scenarios feature a small decrease in the average growth rate over the period, which is similar across scenarios at 0.02pt, leading to an average growth rate around 0.93% from 2010 to 2050.

The average growth rate under the No-Nuclear Scenario is 1.53% from 2010 to 2020, which is lower than in the other scenarios. However, it becomes higher than in other mitigation scenarios by 2050. It implies that the No-Nuclear Scenario has an impact on the economy during the first decade because of the limited availability of a low-carbon electricity. However, in the long-run, efforts taken in the early period to introduce renewable energies will mitigate the economic impact.

Figure 15. Average investments and energy savings for three scenarios

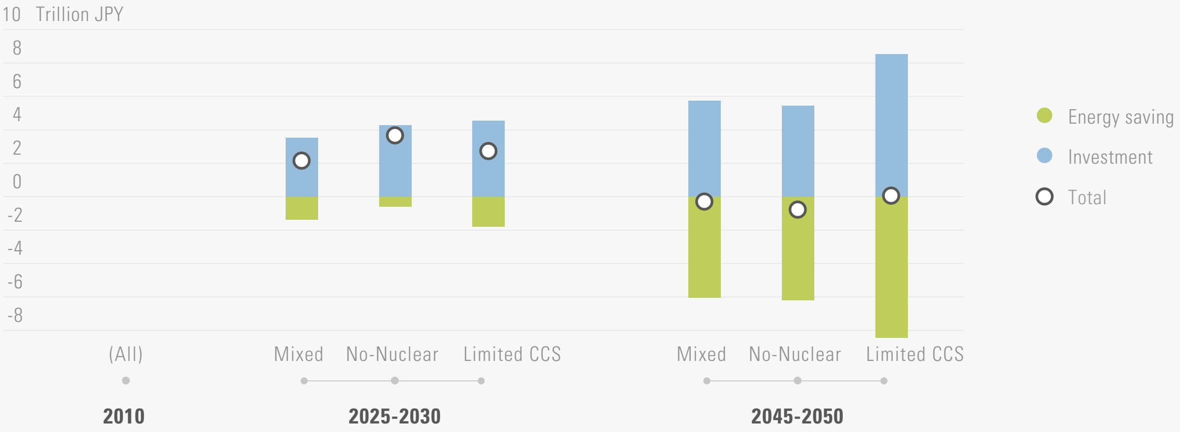


Figure 16. Average investments by sector

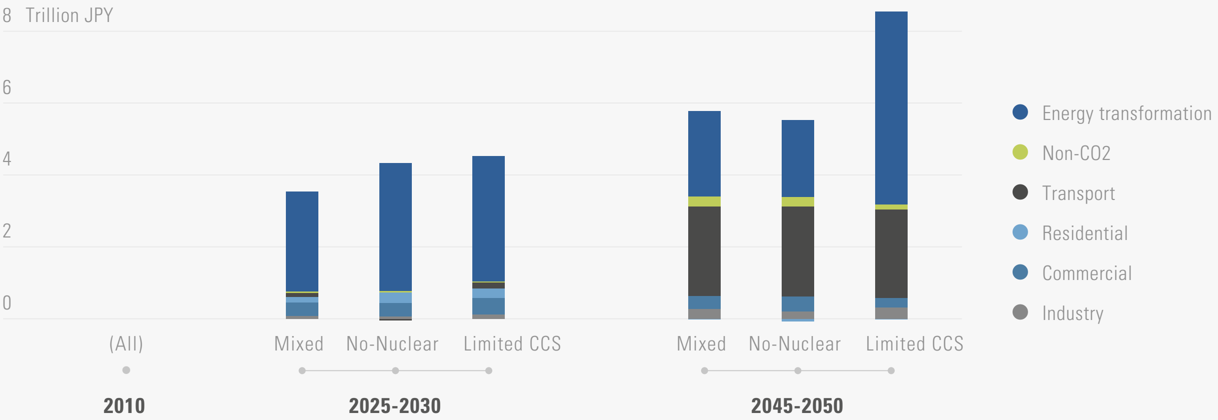


Figure 17. Fuel import cost

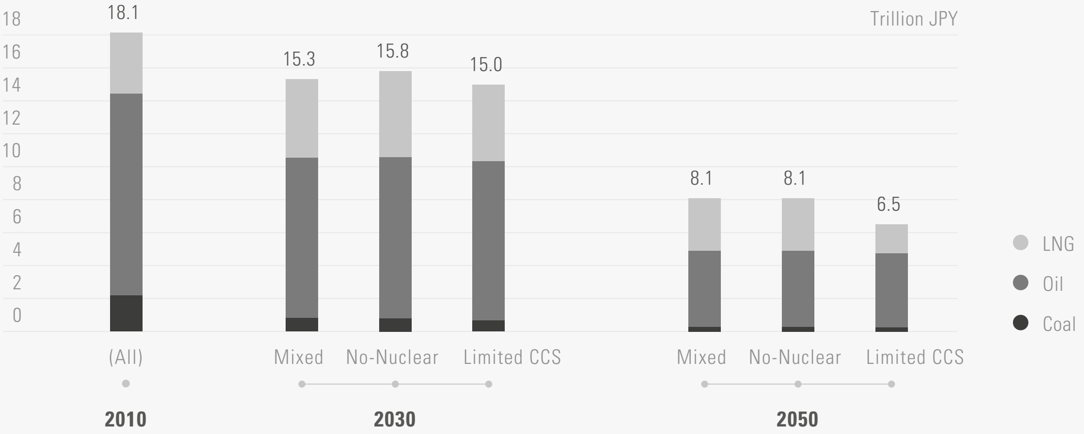
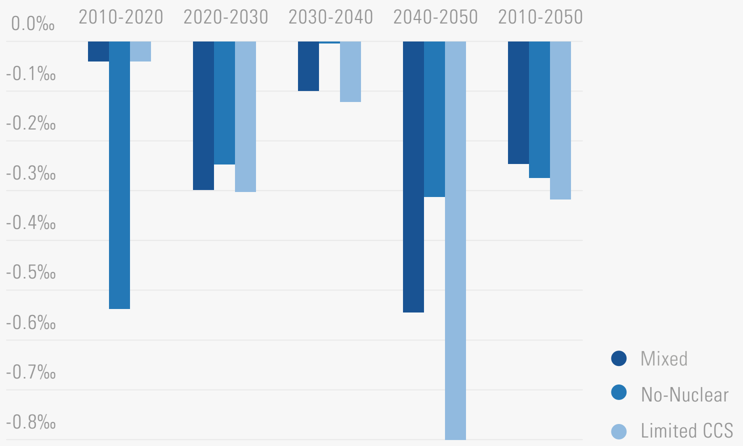


Figure 18. GDP change among the scenarios



In the Limited CCS scenario, the economic impact is the largest among the three mitigation scenarios in the long-term as it starts to appear after 2040, anticipating the results if the analysis was continued after 2050, i.e. that the limitation of CCS would bring more severe economic damage if implemented under the assumptions adopted under the DDPP analysis.

An important caveat of this analysis is that we use a recursive dynamics CGE model with myopic expectations, so that future severe CO_2 reductions and technology constraints are not anticipated in the early stages of the scenarios. If the intertemporal optimization model is applied, the economic impacts would be mitigated.

7 Additional measures and deeper pathways

The following measures should be considered for deeper decarbonization.

Further development and diffusion of innovative low-carbon technologies

The technologies listed in Table 2 are proven energy-saving technologies. On the other hand, further improvement in the energy efficiency of low-carbon technology beyond the levels assumed in the scenario analysis as well as the development of innovative technology would provide additional potential to reduce emissions, especially in the industrial sector. In addition, system technologies such as the reinforcement of electricity interconnection and a demand-side management system would be helpful for effective deeper decarbonization by allowing further introduction of variable renewables sources.

Changes in lifestyles to reduce energy service demand while maintaining standards of living

Substantial change in lifestyles and a reduction in energy service demand are not considered in this analysis. However, changes in behavioral patterns, organizations or preferences have important potential to reduce energy demand while maintaining standards of living. For example, the material stock in developed countries is likely to saturate, and developing countries will also catch up with developed countries in the future. The enhancement of the service economy or stock economy will be able to reduce the material demand, and as a result, energy demand will decline. Analyzing these effects could help with more refined assessments of deeper pathways.

Changes of material demand and its energy service demand

Substantial change in material production is not considered in this study. However, with existing stock levels of infrastructure and a future population decline, a small amount of material production is likely to be sufficient to maintain the stock level. For example, the stock of steel in developed countries is estimated to be 4.9 tons to 10.6 tons per capita (Kawase and Matsuoka, 2013). If the quantities of material production are controlled, the energy service demand in the industrial sector could be reduced further, and as a result, CO_2 emissions also could be reduced.

Redevelopment of cities designed to consume limited energy

Further reductions in emissions and energy demand in cities can be achieved by changes in urban forms favoring an even more important shift from private vehicles to public transport and the reuse of waste heat. In addition, mitigation actions in cities often provide multiple co-benefits.

Relocation of industrial firms where unused energies are easily available

Though reinforcement of electricity interconnection is taken into account as an option in the scenario analysis, relocation of industrial firms would contribute to the more effective use of heat from renewable sources and waste heat. In particular, at present most of the low-temperature heat is goes to waste Though the locations of various industries and locations between industries and residential areas are well organized, there is a potential to improve energy efficiency and utilization of heat by reorganizing the locations, thereby further reducing CO_2 emissions.

Box 2: Experiences of Tokyo Metropolitan Government on emissions reduction schemes*

In 2006 Tokyo Metropolitan Government (TMG) has decided a target of reducing GHG emissions by 25% by 2020. To reduce emissions from buildings, which emit nearly 70% of total GHG in Tokyo, TMG has introduced Cap & Trade, a Carbon Reduction Reporting Program, and a Green Building Program.

Cap & Trade is setting cap on emissions from 1,400 large-scale entities (mainly commercial buildings) that account for 20% of Tokyo's total emissions. Under the cap, each building is obligated to reduce emissions by 6% in the 1st period and by 15% in the 2nd period, and they can utilize a trading system to fulfill their obligations. This is accompanied by an incentive scheme that granted entities a 50% cut in emissions-reduction obligations if they submit their reports.

The Carbon Reduction Reporting Program for Small and Medium-Size Facilities is a scheme that requires entities to report the amount of energy they used in a year to TMG. Again, there are incentive schemes whereby entities can gain tax exemptions and priority on obtaining loans from TMG when they introduce energy-saving facilities. TMG also provides entities with feedback so entities can acknowledge their emissions levels compared with other similar entities in Tokyo.

For newly constructed buildings, there is the Green Building Program and the District Plan for Energy Efficiency, which require owners of large buildings to submit their plans about emissions reductions and energy-efficiency improvements (Figure 18).

As a result of implementing such schemes, TMG has succeeded in reducing emissions significantly. Entities under Cap & Trade have achieved a 22% reduction in total in both 2011 and 2012 from baseline emissions (the baseline is the average amount from 3 successive selected from 2000-2007 by each entity) (Figure 19). Also, energy consumption in Tokyo has declined by 15% in 2011 compared with 2000.

Figure 20. Tokyo cap-and-trade: results to date

Remarkable reductions in 3 years

Total CO_2 emissions from factilties covered by C&T dropped drastically

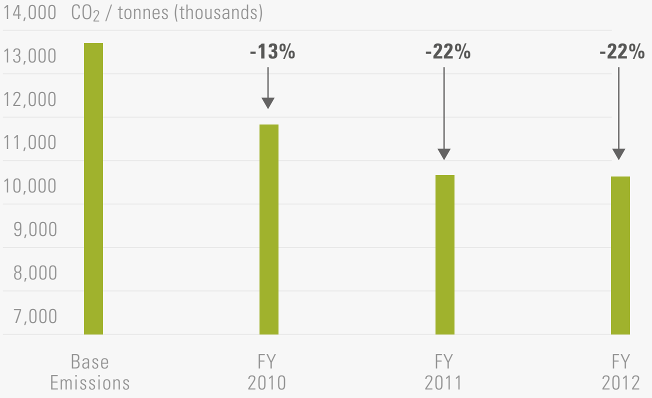
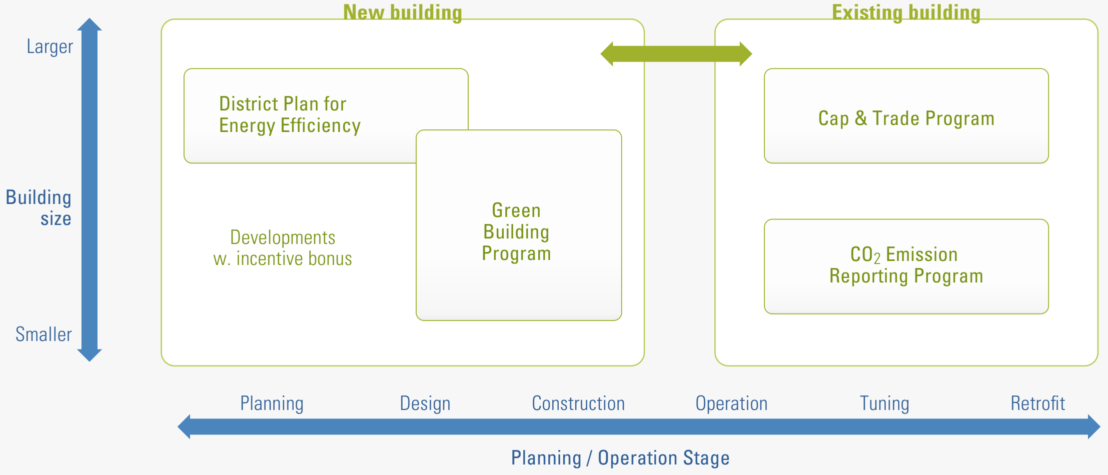


Figure 19. Emissions Reduction Schemes for Buildings in Tokyo



* http://www.kankyo.metro.tokyo.jp/en/climate/index.html

8 Challenges, opportunities, and enabling conditions

Energy system transformation

Deep decarbonization in Japan requires a large-scale transformation in the energy system. In particular, there is a huge challenge to integrate VRE, such as solar PV and wind power, into the electricity system. Additional plants that can provide flexibility, such as pumped hydro storage, are built to complement large-scale deployment of VREs in the scenario analysis. In addition, demand-side management would be an effective option but may not be implemented by market mechanisms alone. Therefore, additional policy instruments such as dynamic pricing of electricity would be needed.

Promoting public acceptance of deep decarbonization pathways

The pace of deploying low-carbon technology is strongly influenced by public acceptance. In general, higher discount rates provide further opportunity to diffuse low-carbon technologies. Public acceptance of technologies may also involve social issues as well as economic barriers, because there are a wide range of possible co-benefits and adverse side effects that can be caused by the diffusion of low-carbon technologies.

Decarbonization in industrial sector

The analysis shows that emission reductions in the industrial sector are lower than in other sectors, because energy use in this sector is already efficient in Japan and fuel demand for high-temperature heat is hard to replace using low-carbon sources. Therefore, huge challenges for decarbonizing the industrial sector would remain in 2050 and thereafter. However, further options such as a reduction in service demand, as mentioned in the previous section, and development and deployment of innovative technologies could have additional potential to decarbonize the industrial sector.

Benefits from deep decarbonization

The analysis focusing on economic aspects shows that deep-decarbonization scenarios feature several opportunities for economic benefits. The effect of decarbonization on the growth rate is estimated to be relatively small at 0.02pt compared with the average growth rate of around 0.93% between 2010 and 2050. But, notably, additional investments for low-carbon options are almost offset by energy savings on fossil fuel imports in the long term, and the reduction of fossil fuel imports contributes to the enhancement of energy security, a crucial political objective in Japan's energy policy (e.g. lower import dependency and the alleviation of vulnerability to oil prices' volatility).

Opportunities for early actions

Though it is difficult to compare the DD Scenarios in this analysis and the Japan's INDC published in July 2015, because some assumptions on socio-economic indicators and energy mix (particularly regarding nuclear power) are different, the decarbonization pathways analyzed here have important implications for actions to be deployed until 2030. Indeed, by adopting a long-term perspective to 2050, the DD scenarios reveal the set of measures that must be implemented in the short-term in order to put the Japanese economy on track to meet the 80% GHG reduction target by 2050. For instance, unabated coal-fired plants are largely replaced by low-carbon electricity coupled with the substantial reduction of electricity demand by 2030 in DD Scenarios, mainly via renewables, while the share of coal is still considerable in the Government's INDC (approximately 26% of the total electricity supply in 2030). These early actions could help avoid a lock-in of infrastructure with high-carbon intensity and help achieve robust pathways to deep decarbonization in the long term.

9 Near-term priorities

Avoiding lock-in of high-carbon-intensity infrastructure

Some infrastructure such as power plants and buildings entail considerable lock-in risks because the majority of those introduced in the near term will remain until 2050. As some gas combined-cycle plants as well as coal plants have to be equipped with CCS in 2050, newly built plants should be CCS-ready, as well as employing the best available technology.

Continuation of electricity savings

After the Great East Japan Earthquake in 2011, electricity use had been reduced in order to avoid blackouts due to the Fukushima accident and the suspension of other damaged power plants. Continuing these actions is a key pillar for deep decarbonization.

Reducing the near-term impact of energy import prices

Since 2011, fossil fuel import values have increased in Japan due mainly to the depreciation of the Japanese Yen and the suspension of nuclear plants. Immediate actions for deep decarbonization that decrease fossil fuel demand can contribute to reducing the impact on the economy in the near term.

10 Next Step

Detailed analysis in the electricity sector

As the model used in this study cannot consider short-term intermittency on a time scale of seconds or minutes, large-scale deployment of PV and wind power would need further advancement to stabilize the supply-and-demand balance of electricity in real time. However the model used in this study considers aggregated back-up of intermittent renewable energy. For a more detailed assessment of the electricity supply-and-demand balance, application of the electricity-oriented detailed model would be needed.

Considering additional decarbonization options

There are additional decarbonization opportunities through the implementation of some measures that are not treated in this analysis, such as service demand control by modal shifts to pubic transport, effective urban planning, and the structural change of industries. The policy instruments exposing the potential of these measures would also be important for cost-effective emissions reductions.

Suggestion for mid-term emissions reductions strategy

The DDP analysis provides a framework for elaborating Japan's mid-term actions (which are the core focus of international negotiations in the lead-up to COP21, but also after) by ensuring a vision consistent with the long-term reduction target. The analysis reveals notably that setting a target level of GHG emissions in the mid-term itself is not sufficient, and that the content of the transformation and the strategy to trigger it must be made explicit, focusing on the key pillars of energy-efficiency improvements, electrification and the decarbonization of electricity. As a next step of DDP analysis in Japan, the discussion should turn to which mid-term actions would be required to reach the long-term target.

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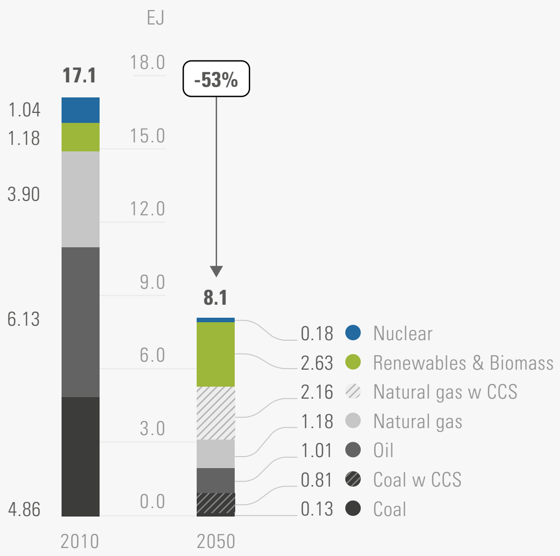
Standardized DDPP graphics for Japan scenarios

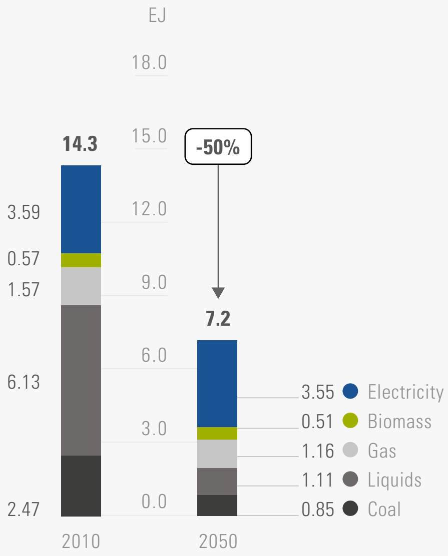
JP – Mixed
JP – No Nuclear
JP – Limited CCS

JP – Mixed

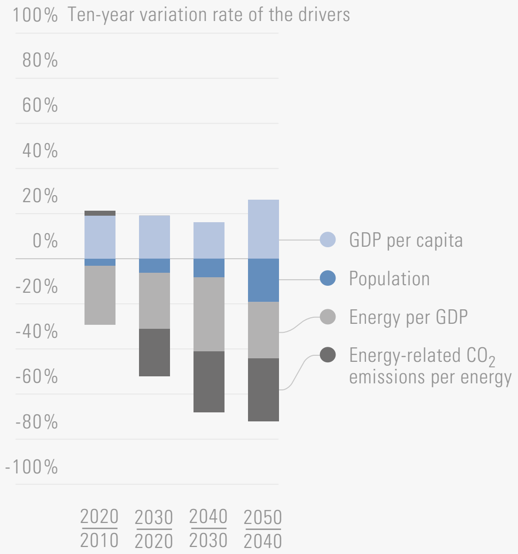
Energy Pathways, Primary Energy by source



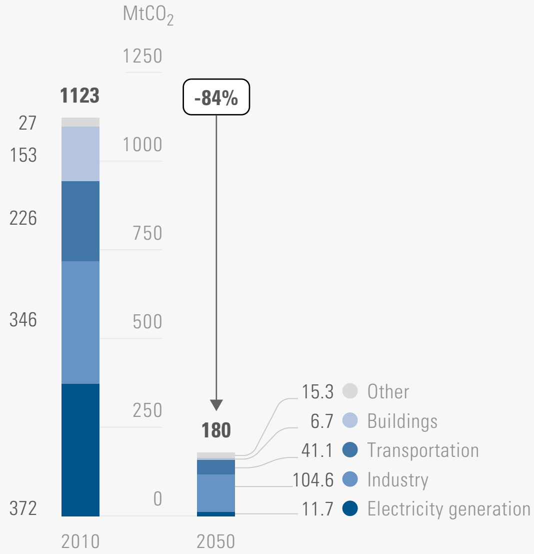
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050

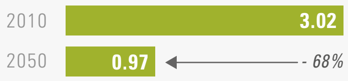


Energy-related CO_2 Emissions Pathway, by Sector



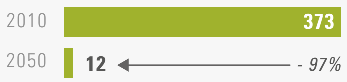
The Pillars of Decarbonization

Energy efficiency



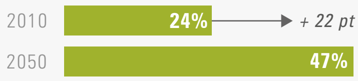
Energy Intensity of GDP, MJ/$

Decarbonization of electricity



Electricity Emissions Intensity, gCO_2/kWh

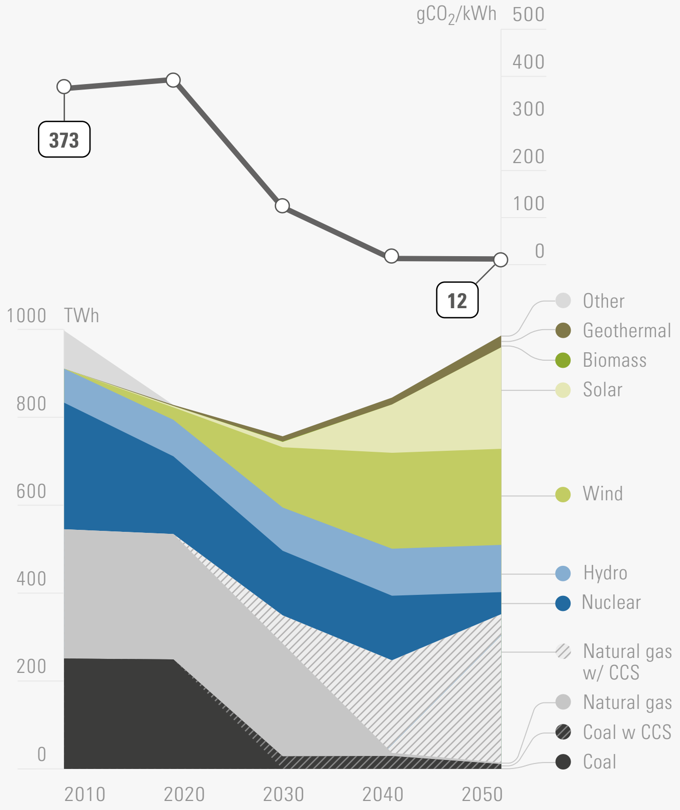
Electrification of end-uses



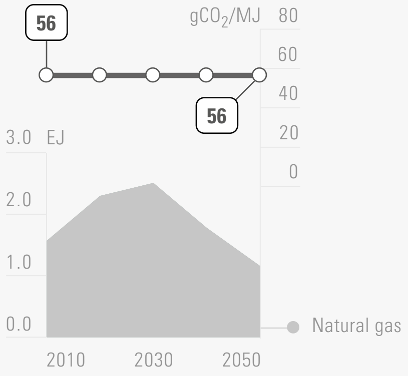
Share of electricity in total final energy, %

Carbon intensity

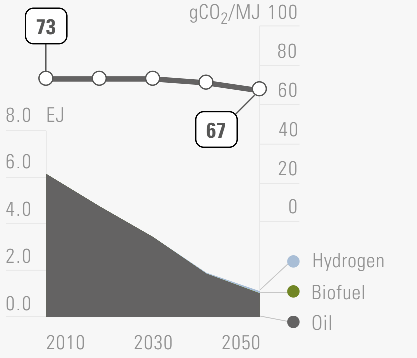
Energy Supply Pathways, by Resource



Electricity

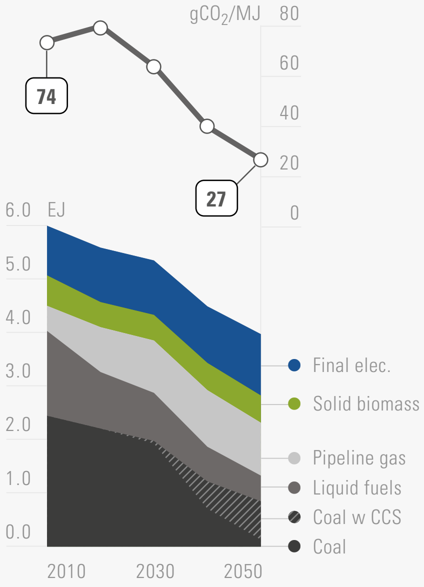


Pipeline gas

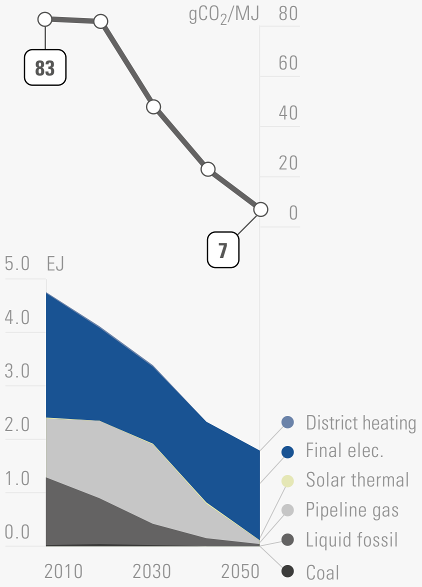


Liquid Fuels

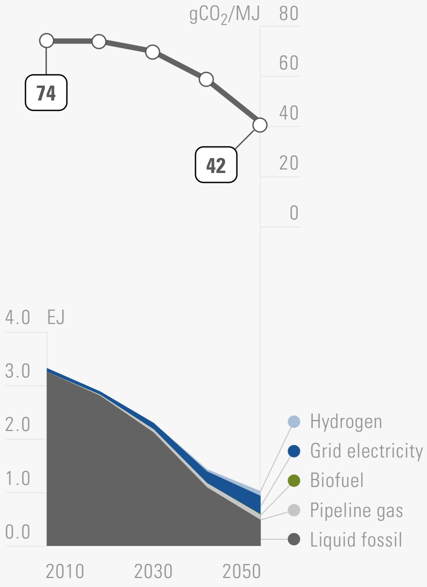
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



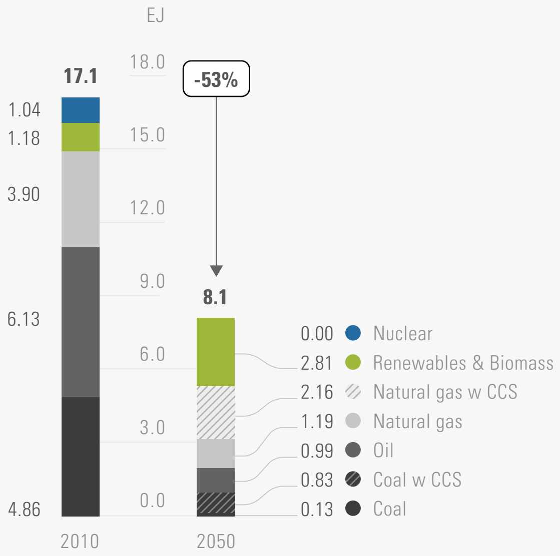
Buildings



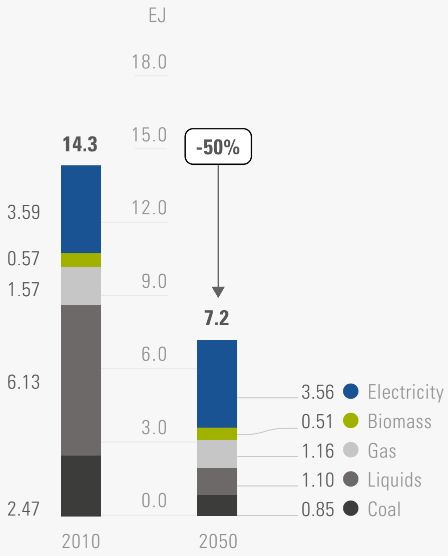
Transportation

JP – No Nuclear

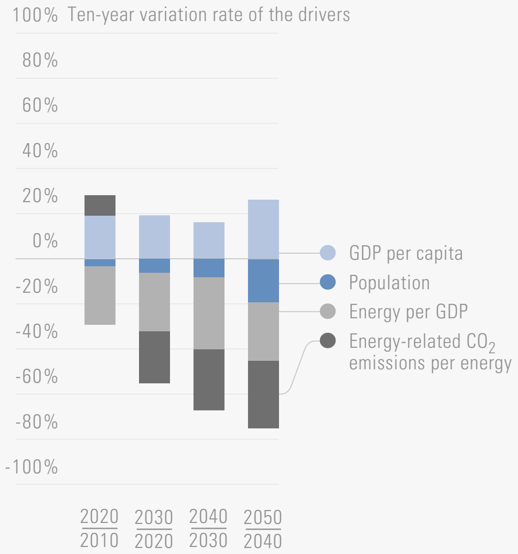
Energy Pathways, Primary Energy by source



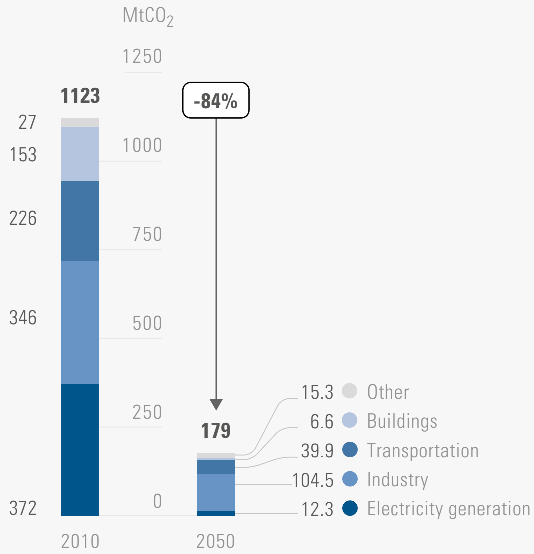
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector

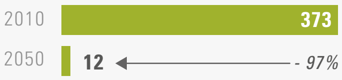


The Pillars of Decarbonization

Energy efficiency

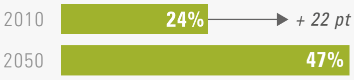
Energy Intensity of GDP, MJ/$

Decarbonization of electricity



Electricity Emissions Intensity, gCO_2/kWh

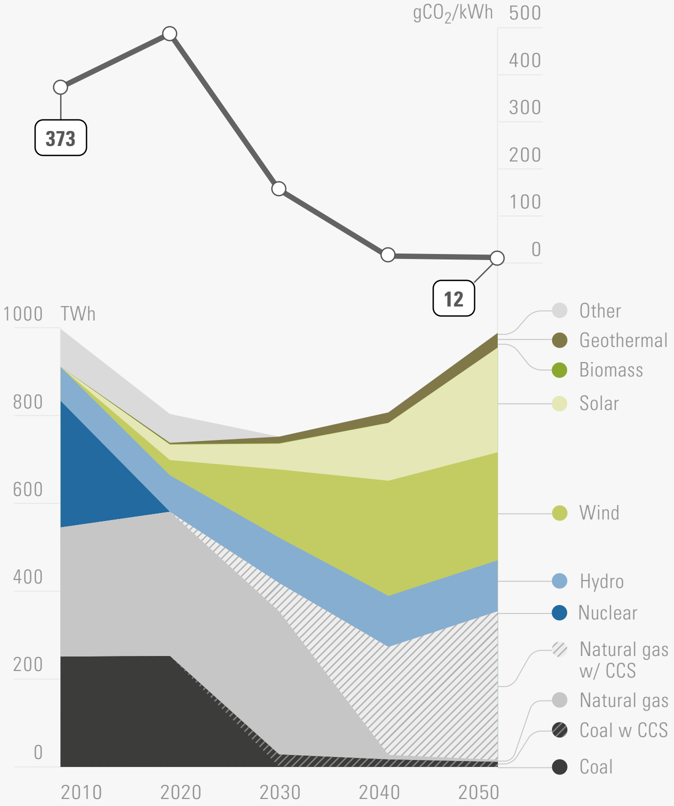
Electrification of end-uses



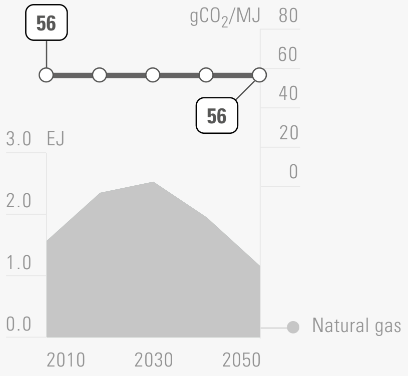
Share of electricity in total final energy, %

Carbon intensity

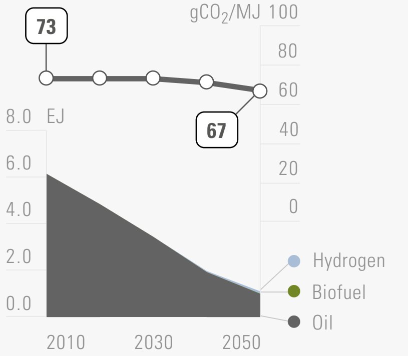
Energy Supply Pathways, by Resource



Electricity

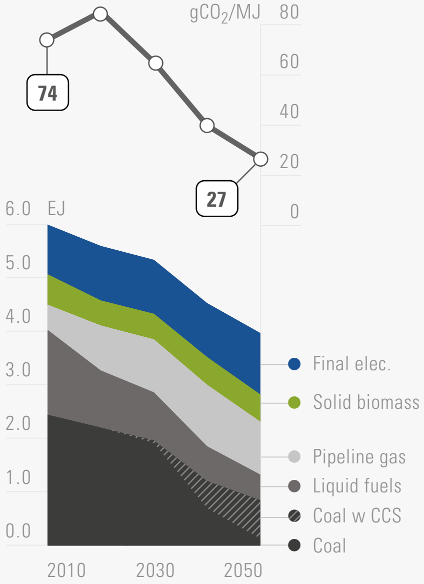


Pipeline gas

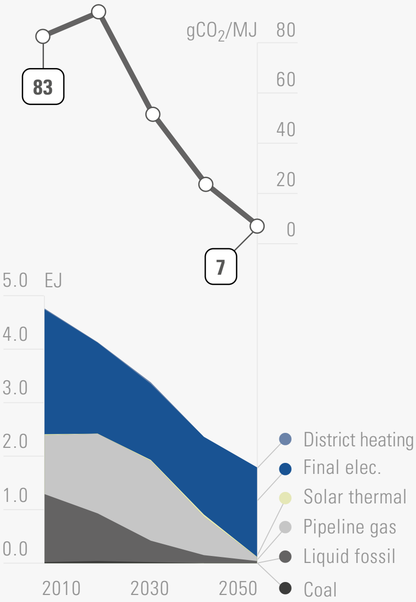


Liquid Fuels

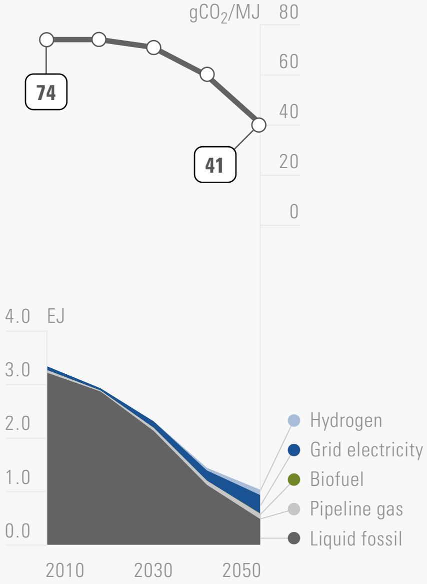
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



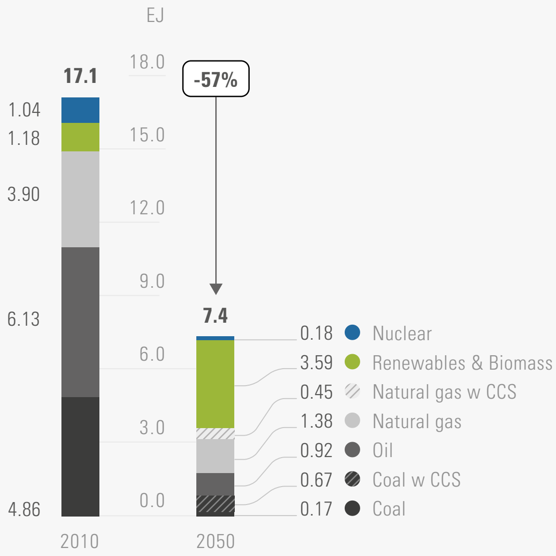
Buildings



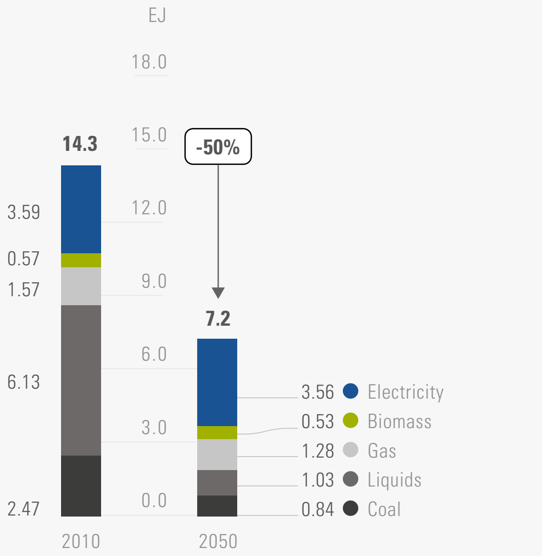
Transportation

JP – Limited CCS

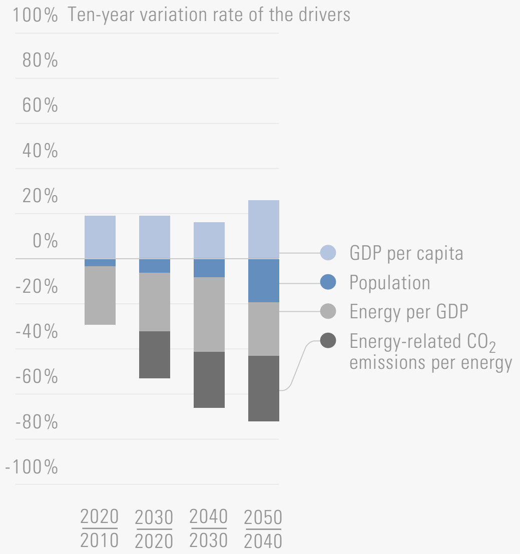
Energy Pathways, Primary Energy by source



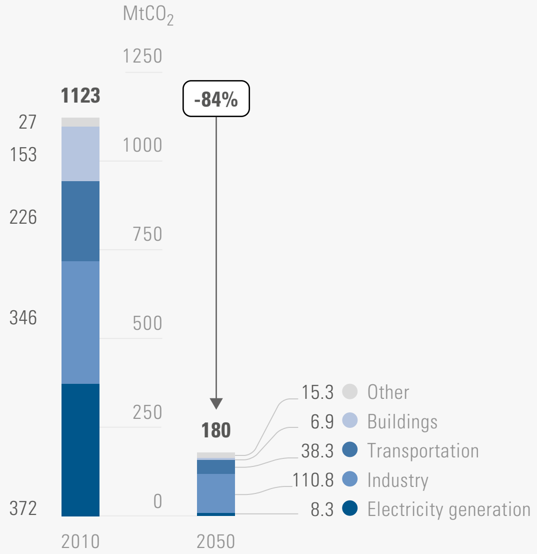
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector

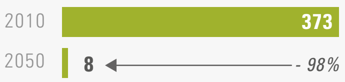


The Pillars of Decarbonization

Energy efficiency

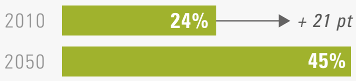
Energy Intensity of GDP, MJ/$

Decarbonization of electricity



Electricity Emissions Intensity, gCO_2/kWh

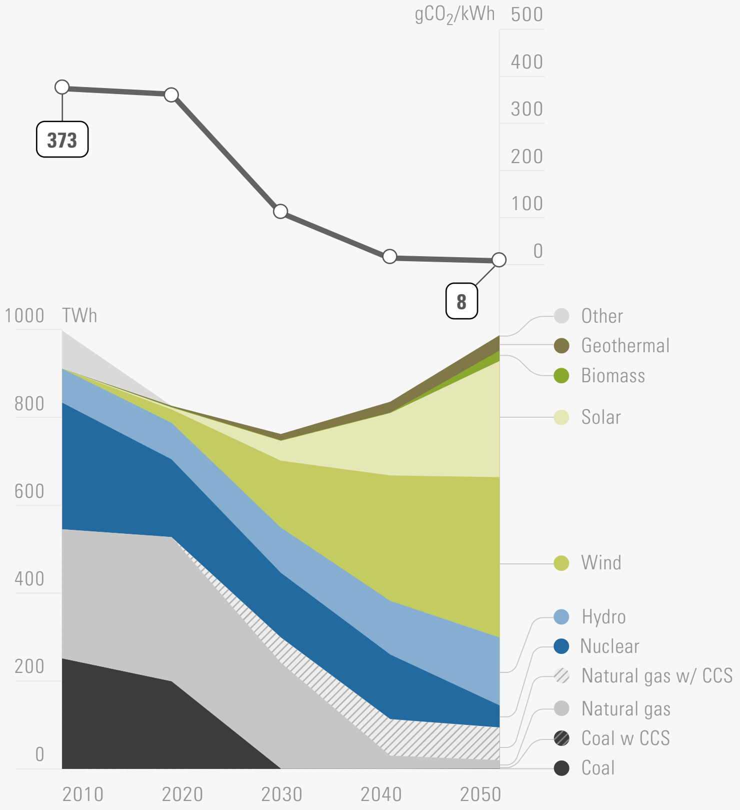
Electrification of end-uses



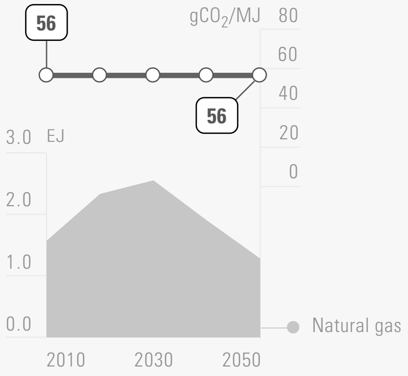
Share of electricity in total final energy, %

Carbon intensity

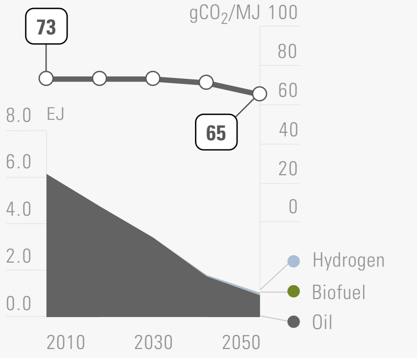
Energy Supply Pathways, by Resource



Electricity

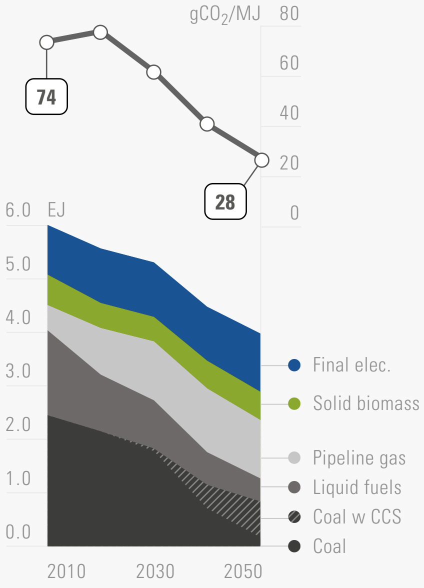


Pipeline gas

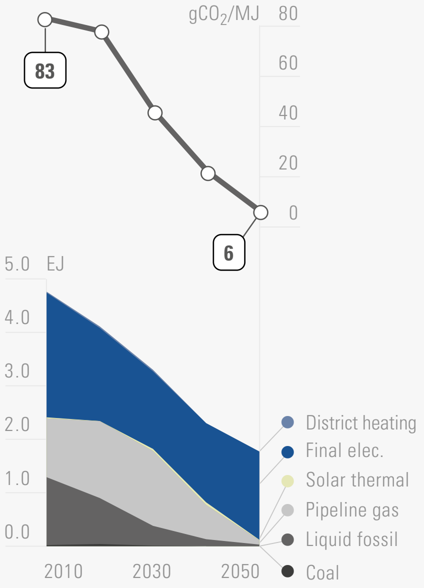


Liquid Fuels

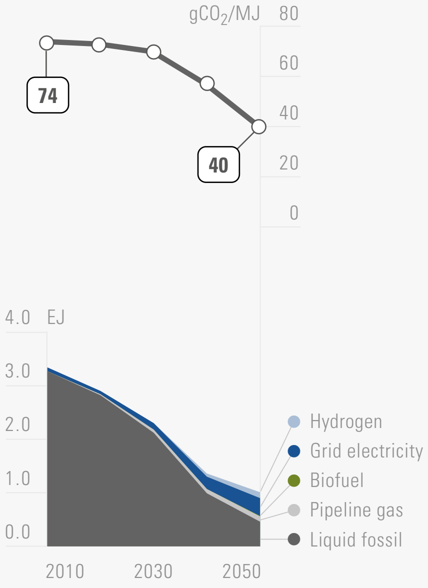
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



Buildings



Transportation