The Role of Emission Reduction Measures for Carbon Neutrality & the Scenarios for Japan

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Introduction

Climate change is a serious issue and should be tackled with global cooperation. The Paris Agreement has long-term mitigation goals of 2°C or 1.5°C above the pre-industrial levels and net-zero emissions of global greenhouse gas (GHG) in the second half of this century. The world is seeking a significant reduction in emissions to reach net zero by the middle of this century to meet the 1.5°C goal to avoid dangerous climate change. All countries and sectors have to reduce their GHG emissions drastically to meet the targets.

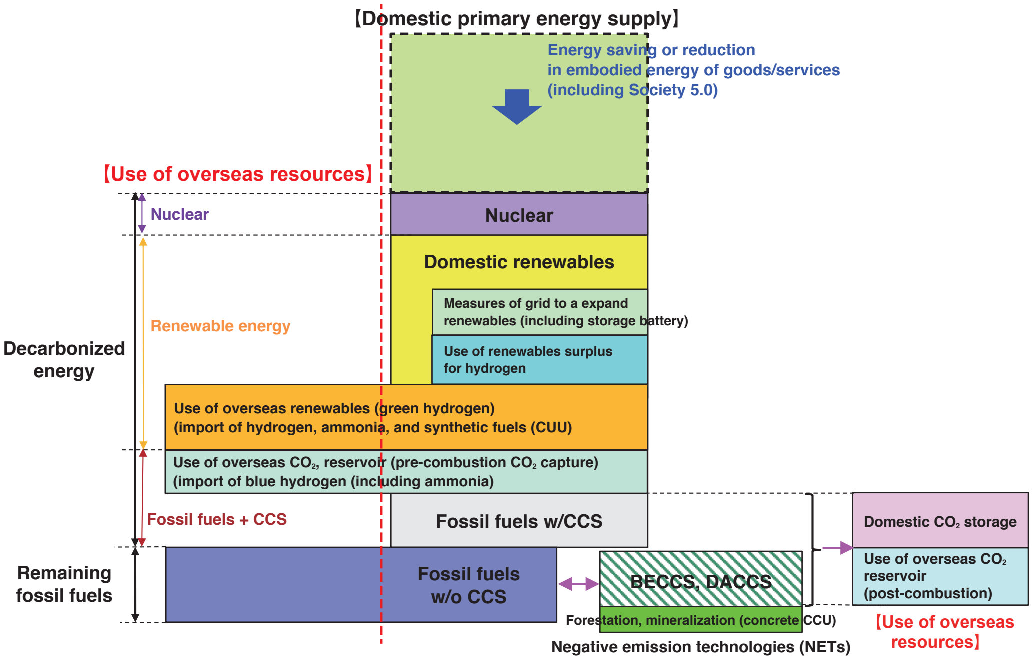
In the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C (SR15) in 2018, four kinds of emission reduction pathways are categorized for the 1.5°C target in which global CO_2 emissions reach net zero by around 2050. Typically, the P1 scenario assumes low energy demand and low dependencies on carbon dioxide removal (CDR) technologies such as bioenergy with CO_2 capture and storage (BECCS) and direct air CO_2 capture and storage (DACCS), and the P4 scenario assumes high dependencies on CDR. High dependency on CDR means, in turn, that CO_2 emissions without CCS can be economical even under net-zero emissions. The IPCC scenarios gathered from broad peer-reviewed papers on the scenarios developed by integrated assessment models (IAMs) rather depend largely on CDR. On the other hand, the International Energy Agency provided its net-zero emission scenario in 2021 (IEA, *Net Zero by 2050: A Roadmap for the Global Energy Sector*), and it considers relatively small amounts of CDR measures (around 1 $GtCO_2$/yr in 2050) compared with the IPCC scenarios, and assumes a large share of renewable energy and high share of electricity consumption in final energy consumption. It will be required to recognize that there are several opportunities to achieve net-zero emissions (carbon neutrality).

Overview of Required Energy Systems for Carbon Neutrality

Chart 1 shows the overview of energy supply systems to achieve

CHART 1

Overview of achieving net-zero emissions (in Japan)



Source: RITE

net-zero emissions including the roles of CO_2 capture and utilization (CCU) and CDR (or negative emission technologies, NETs). Basically, renewable energy, nuclear power, and fossil fuels with CO_2 capture, utilization and storage (CCUS) are required as primary energy sources. Meanwhile, CDR can serve as an opportunity to offset the emissions without CCUS. At the country level, there are also opportunities for secondary energy imports from overseas, and there are opportunities for imports of hydrogen and hydrogen-based secondary energy sources as well as electricity and biomass. In Japan, there are no international power grid connections, and therefore it will be more important to utilize hydrogen and hydrogen-based energy sources than in other countries that have international grid connections.

For individual countermeasures, deployment levels will be economically determined based on the outlooks on future improvements of technologies and the relative competitiveness of each technology. The economics of many kinds of CCU technologies are determined by the production costs of hydrogen etc., and the hydrogen costs are determined by the costs of renewables etc. The systems are complex.

In end-use sectors, electrifications are required in general, because it will be relatively easy to achieve zero emissions in electricity compared to non-electricity secondary energy sources. On the other hand, it will be difficult and costly that all final energy shifts to electricity. Hydrogen, hydrogen-based energy sources, such as ammonia, synthetic methane, and synthetic liquid fuels, and bioenergy will be also important. Furthermore, the residue emissions from fossil fuel combustions or other non-CO_2 GHGs will be offset by CDR.

Renewable Energy

Renewable energies, particularly of wind power and solar photovoltaics (PV), will play a key role for carbon neutrality. The costs of wind power and solar PV as variable renewable energies (VRE) have been greatly reduced in the world, and are so far competitive with fossil fuel power in many countries. However, in many countries, there still exist supporting schemes, such as Feed-In Tariff (FIT) and Feed-In Premium (FIP), to deploy renewable energies having relatively high costs. Japan also has FIT schemes and will introduce FIP in 2022.

In Japan, electricity generation from renewable energy or VRE per unit flat land area is the largest among countries *(Chart 2)*. Japan is facing the challenges of installing larger installation of VRE than the current levels due to the limitations of cheaper and appropriate land avoiding conflict with other land-use purposes.

The expansion of offshore wind power is expected and planned in Japan. In Japan, most sea areas are deep, and floating offshore wind power will be required. Further development of floating offshore wind power will be required for cost reductions and safe operation even during typhoons. In addition, the capacity factor will be around 30-35% which is smaller than around 50-60% in the North Sea in Europe. Therefore, the expected kWh costs will be higher than those in Europe.

Furthermore, the grid integration costs will be expected to increase according to increases in the share of VRE. There is relatively large potential for offshore wind power in Hokkaido, Tohoku, and the northern area of Kyushu. Large demand areas, such as Kanto (typically Tokyo), Chubu (Nagoya), and Kansai (Osaka), are long distances from these areas, and the power grid capacity is limited between them. In order to avoid large constraints on VRE outputs and then to avoid large increases in kWh costs, the expansion of power grids including Direct Current power cables will be necessary in Japan.

Bioenergy is also important because it can serve the flexibilities in electricity supply, but large deployments would increase conflicts with land-use, and biodiversity. Bioenergy also faces higher costs compared with other countries due to limitations of flat land areas.

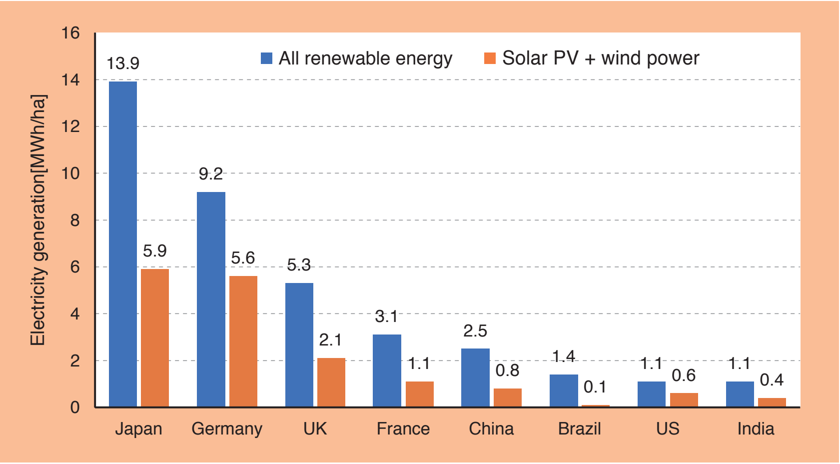
Batteries, Hydrogen & Demand Responses

For a large share of VRE, batteries are also required in order to balance supply and demand, but they still have high costs. Plug-in hybrid electric vehicles (PHEVs) and pure battery electric vehicles (BEVs) will contribute to carbon neutrality and could also help balance them for a large share of VRE. In addition, heat-pump hot water supply systems, for example, could also contribute.

Furthermore, hydrogen (“green hydrogen”) and hydrogen-based energies such as ammonia, synthetic methane, and synthetic liquid fuels will help in large deployments of VRE. For cost-efficient measures, batteries and hydrogen are important. For example, distributed hydrogen-based cogeneration systems on the energy demand-side will be able to help reduce some of the requirements of power grid expansions for VRE. But they also bring about cost increases, and therefore the targets for the share of renewables should be carefully considered.

CHART 2

Electricity generation of renewable energy per unit flat land area across countries



Source: Ministry of Economy, Trade and Industry (METI)

For the use of hydrogen, hydrogen-use direct reduced iron (DRI) will also be an important option as well as fuel-cell electric vehicles (FCEVs), hydrogen power stations and the cogeneration systems; however, their development including affordable steel production as well as the technology proven will be very challenging.

CCUS & CDR

CO_2 capture and storage (CCS) is also an important option, and the typical costs are approximately US$100/t$CO_2$ in Japan so far, and expected to be around $50/t$CO_2$ by 2050. Fossil fuel power serves a stable power grid operation including inertial forces. CCS helps with nearly zero CO_2 emissions. Japan also has large potential to store geological reservoirs technologically. However, realistic potentials, or economically possible or socially acceptable potentials, could be limited. These uncertainties would increase investment risks for implementation by private companies, and the role of the government will be important to reduce these risks particularly in the initial stages.

CCS-based “blue hydrogen” including ammonia will make an important contribution to carbon neutrality and the transition, due to the distributed potentials of CO_2 geological storage across countries. So far, the cost of “blue hydrogen” is cheaper than that of “green hydrogen”, while the cost of “green hydrogen” will be expected to reduce more rapidly than that of “blue hydrogen”.

As well as synthetic fuels, the other CCU opportunities include enhanced weathering (EW), including sequestration of CO_2 into concrete. EW will also play an important role, but the CO_2 sequestration potential of EW will be limited compared with current CO_2 emissions.

Synthetic methane and liquid fuels should be recognized as one option of hydrogen use, but they are also are one of the CCU options. These energy sources will be able to avoid new infrastructure of both energy supply and end-use, while they require CO_2 capture and synthesis of hydrogen and CO_2. In addition, these energy sources will also help with a good transition of jobs toward carbon neutrality.

Particularly for net-zero emissions, CDR technologies will contribute greatly. DACCS is one of the key measures. DACCS requires smaller land areas than BECCS; however, DACCS does require large energy to capture CO_2 from air of low-density CO_2 (approximately 400 ppm), while BECCS can serve energy. So far, the costs of DACCS are high and will be over $500/t$CO_2$, and be expected to reduce to around $100-150/t$CO_2$ by 2050. The combinations of residue energy from VRE into the required energy of DACCS would reduce the costs of DACCS. DACCS can help offset residue emissions not only of CO_2 but also of other greenhouse gases, and serve as a backstop type technology. Thanks to CDR, carbon neutrality can be achieved, even if PHEVs or Internal Combustion Engine Vehicles (ICEVs), for example, remain. Energy consumption varies widely across countries and sectors, and these types of technologies will contribute to carbon neutrality.

Nuclear Power

Nuclear power is also one of the key measures to achieve carbon neutrality. Nuclear power can produce carbon-free energy with high intensity that means small required land and relatively low costs. However, in many countries, public acceptance issues exist. In Japan, after the Fukushima Dai-Ichi nuclear power disaster in 2011, the restarts of reactors have been limited, and there are no clear policies on replacements and new construction. If the lifetime of all reactors were limited to 40 years, only three reactors would exist in 2050. This will make it difficult to achieve carbon neutrality by 2050. It will be desirable for many of the existing reactors that have economic potential to expand their lifetime to 60 years which is allowed as the maximum under the current law. However, even if all the reactors were expanded to 60 years, only eight would be operational in 2060. Public acceptance of nuclear power is still a big issue, but progress in discussions on new construction and/or replacement of nuclear power plants will be required to reduce the total risks, including the issues of climate change, energy security, and economy.

Small modular reactors (SMRs) may increase safety, and reduce construction time. They may induce an increase in public acceptance and a reduction in costs. The possibility of installing SMRs should also be discussed as well as their development.

Energy Saving Induced by Digital Transformation

Even for achieving carbon neutrality, several kinds of energy-saving technologies are needed because all of the carbon neutral energy sources have limitations as discussed above. Digital transformation including improvements of IoT, AI and big data will induce increases in capacity factor of several products and services with sharing- and circular-economies. For example, the average capacity factor of private passenger vehicles is around 5%, food losses are around 30% globally, and about 50% of newly produced apparel is not used. Thus, they would have large opportunities to reduce energy consumption in such products and services, and contribute not only to CO_2 emission reductions but also to multiple achievements of the Sustainable Development Goals (SDGs). In addition, the learning rate in cost reductions of end-use and granular technologies is usually higher than that of energy supply and lumpy technologies. Higher cost reductions in end-use and granular technologies are expected according to the increase in cumulative installations. On the other hand, high diffusion barriers (or high implicit costs) are observed in end-use technologies. Digitalization technologies will help to reduce these diffusion barriers or implicit costs. In addition, rebound effects could be expected, and responding policies should also be considered.

Comprehensive & Quantitative Scenario Analyses

Using a global energy systems model DNE21+ (Dynamic New Earth 21 plus), the emission reduction measures for carbon neutrality by 2050 can be analyzed. DNE21+ is a global model with consistencies across countries and regions and intertemporal years (“Climate change mitigation measures for global net-zero emissions and the roles of CO_2 capture and utilization and direct air capture”, by Keigo Akimoto et al., *Energy and Climate Change*, Vol. 2, 2021). The salient

TABLE

Assumed scenarios for carbon neutrality by 2050 in Japan

Scenario		GHG emission reduction in 2050	Cost of renewable energy	Ratio of nuclear power	Cost of hydrogen	CCUS (Storage potential)	Fully autonomous driving (car- & ride-sharing)
Offset emission credits of overseas (The latest-cost measures in the world = Equal marginal abatement costs among nations)		1.5C target; domestic emission reductions are endogenously determined.	Standard cost	Max. 10%	Standard cost	Domestic storage: max. 91MtCO$_2$/yr; Overseas transportation: max. 235MtCO$_2$/yr	Standard assumption: no fully autonomous cars
Reference Case		**▲100%** (For other than Japan, ▲100% for each Western country, and ▲100% for the others as a whole)					
Assuming high share of RE under standard cases	**1. Renewable Energy 100%**			0%			
Assuming each technology is further accelerated or expanded.	**2. Renewable Energy Innovation**		Low cost	Max. 10%			
	3. Nuclear Power Utilization		Standard cost	Max. 20%			
	4. Hydrogen Innovation			Max. 10%	Hydrogen production such as water electrolysis, hydrogen liquefaction facility cost: halved		
	5. CCS Utilization				Standard cost	Domestic: max. 273MtCO$_2$/yr; Overseas: max.282 MtCO$_2$/yr	
	6. Synthetic Fuel Utilization		Low cost			Domestic: max. 91Mt, Overseas: 0Mt	
	7. Demand Transformation		Standard cost			Domestic: max, 91MtCO$_2$/yr; Overseas max. 235MtCO$_2$/yr	Realization and diffusion of fully autonomous driving and expansion of car- & ride-sharing after 2030, and decrease in material production due to reduction of the number of automobiles.

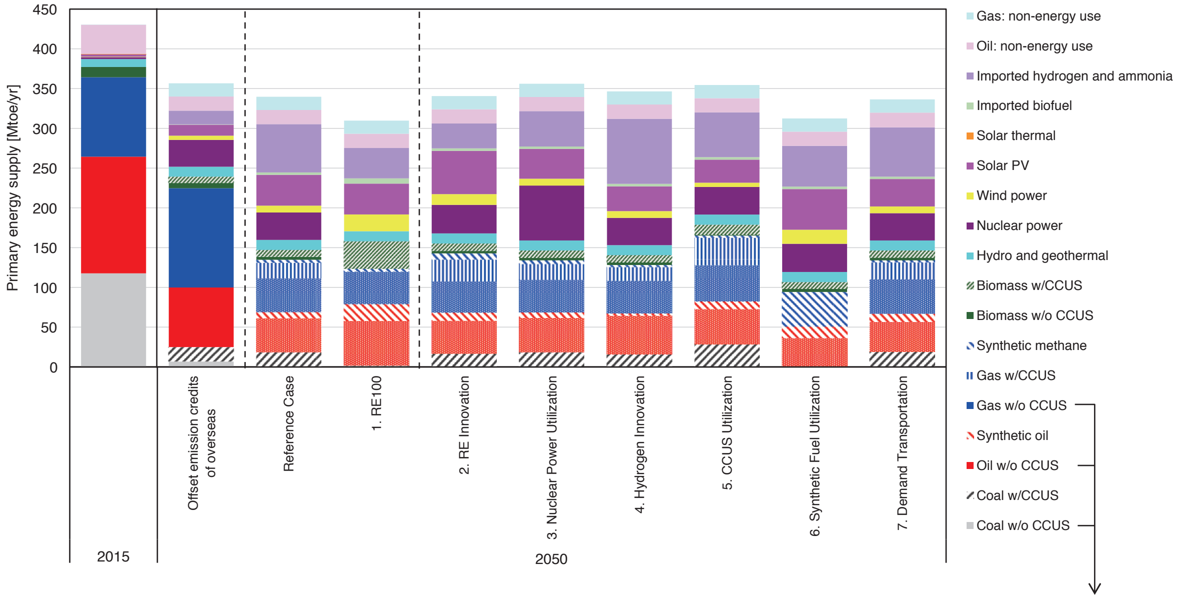
Source: RITE

features of the model are that (1) regional differences between 54 regions of the world can be considered while maintaining common assumptions and interrelationships, (2) global warming response measures for approximately 500 specific technologies can be evaluated in detail, and (3) facility replacements over the entire period can be considered explicitly. This article shows only the quantitative scenarios for Japan. There are several kinds of uncertainties in technology improvements, social constraints, etc., and several scenarios shown in the *Table* are considered for the achievement of carbon neutrality by 2050 in Japan (see also *Scenario Analyses for 2050 Carbon Neutrality in Japan* provided by the Research Institute of Innovative Technology for the Earth (RITE) to the Advisory Committee for Natural Resource and Energy, 2021).

Chart 3 shows primary energy supply in Japan for carbon neutrality by 2050. If DACCS is not considered, there were no feasible solutions for all of the assumed scenarios here. Energy savings are required, but increases in energy for CCUS and CDR are also observed. The net energy saving is around 25% across the assumed scenarios. In all of the scenarios, the increases in renewable energy and deployments of CCS are observed. The shares of renewable energy in total electricity supply are approximately 54% and 63% in the reference scenario and the renewable energy innovation scenario, respectively. Nuclear power is economical to meet the maximum assumed share in all the scenarios under the net-zero emission target. As well as these carbon neutral energies, imports of hydrogen, ammonia, and synthetic fuels are also economical due to domestic availability at affordable costs, and will contribute to the achievement of carbon neutrality in Japan. Thanks to CDR such as DACCS, some amounts of fossil fuels without CCS can be acceptable. In addition, when we consider the global least-cost measures to achieve carbon neutrality, it is more cost-effective to conduct CDR outside of Japan, where there is cheaper access to CO$_2$ geological reservoirs and residue VRE required for DACCS. Large deployments of hydrogen, ammonia, and synthetic fuels (both gas and liquid) are cost effective for carbon neutrality in Japan. These secondary energy sources will be expected to be used in several sectors, and in particular, hydrogen, ammonia, synthetic methane, and synthetic liquid fuels are expected for the iron and steel, power, end-use gas demand, and transportation sectors, respectively.

CHART 3

Primary energy supply in Japan for carbon neutrality by 2050



All are offset with CDR in ▲100% scenarios

Note 1) Conversion rates of primary energies correspond to IEA statistics. Renewable energies except biomass: 1TWh=0.086 Mtoe, nuclear: 1TWh=0.086/0.33 Mtoe

Note 2) Fossil fuels without CCS are offset with NETs, thus serving carbon-neutral fossil fuels.

Source: RITE

Emission Reduction Costs

Carbon neutrality will be technologically possible. On the other hand, emission reduction costs should be more seriously considered. While the CO_2 marginal abatement cost (MAC) in the least-cost scenarios with equal MAC across countries is approximately $168/$tCO_2$, the MACs for achieving net-zero emissions of GHGs in Japan are approximately $525/$tCO_2$ in reference cases. Global cooperation for emission reductions will be important for cost efficiency. The MAC ranges for below 1.5°C summarized by the IPCC SR15 are $245-14,300/$tCO_2$. The estimated MACs here are smaller than those cost ranges reported by the SR15, mainly because of the consideration of DACCS. CDR including DACCS would play a key role in the cost-efficient achievement of net-zero emissions, while too high expectations of CDR may be dangerous. The increases in total energy system costs of Japan in 2050 in the reference scenario compared to those in a no-climate policy scenario will be approximately $200 billion per year, and those in the renewable 100% scenario will be approximately $300 billion per year. Further technological and social innovations as considered in these scenarios will be required for such achievement.

The marginal cost of electricity supply will increase by about $100/MWh for carbon neutrality in Japan. If renewable energy was 100%, the estimated marginal cost would increase by about $360/MWh due to the increases in the grid integration costs. Balanced measures considering several kinds of technologies, and various technological and social innovations will be required.

Conclusion

Several kinds of emission reduction measures should be considered, bearing cost-efficiency in mind, to increase the possibility of carbon neutrality, because there are no silver bullet technologies. Renewable energies and electrification will play a key role in the achievement of net-zero emissions, but it would be very challenging to achieve carbon neutrality only by renewables and electrification, and be very costly. CCUS and nuclear power are also important. All of the measures in primary energy are limited in Japan due to costs and potential, and social constraints, hydrogen and hydrogen-based energy sources such as ammonia and synthetic fuels will also be significant for achieving carbon neutrality. CDR such as DACCS would also play a key role in carbon neutrality to offset residue emissions. Energy saving including social changes induced by improvements in digitalization will also be significant.

There are opportunities in technology to achieve net-zero emissions as discussed, but most technological options will increase the costs of our energy systems. They could bring distortions in international competitiveness, particularly in energy-intensive industries. Therefore, global cooperation will also be a key both in the development of technological global energy systems and globally coordinated emission reduction targets to avoid serious carbon leakages.

Keigo Akimoto is a group leader and chief researcher at the Research Institute of Innovative Technology for the Earth (RITE). His areas of expertise are energy and environmental system analysis, and policy analysis for global warming issues.