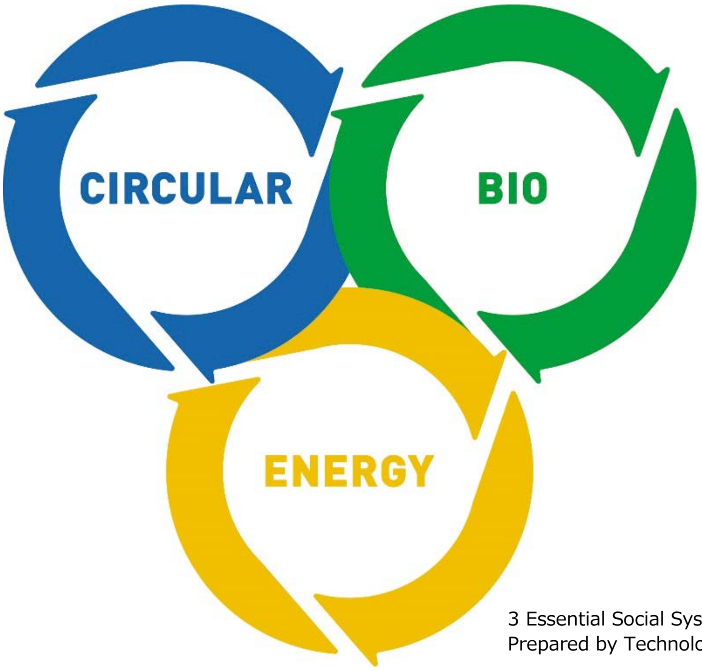
Technology Strategy Center Report

TSC Foresight

Comprehensive R&D Principle for Sustainable Society 2020

February 2020



3 Essential Social Systems for Sustainable Society
Prepared by Technology Strategy Center, NEDO (2020)

New Energy and Industrial Technology Development Organization
Technology Strategy Center (TSC)

Executive Summary

Chapter 1 Toward Realizing Sustainable Society

●Vision of Future

NEDO aims to build a future in which the international society is economically rich, environmentally friendly, coexists with nature, maintains and develops nature and ecosystem diversity, and creates a better society for future generations while satisfying the social needs of the current generation. To achieve this vision, climate change is a challenge to be overcome and it is required to pursue the realization of a sustainably developing society.

●Movement for Realizing Decarbonized Society

The Paris Agreement in 2015 requires the parties to limit the global average temperature increase to well below 2℃ (*the 2℃ target*) as well as to pursue efforts to limit the temperature increase to 1.5℃ (*the 1.5℃ non-binding target*), in order to realize a *decarbonized society* in the second half of the 21st century.

Based on the Long-term Strategy under the Paris Agreement (approved by the Cabinet in June 2019), the Environment Innovation Strategy was established in January 2020 with an aim to establish innovative technologies to achieve global carbon neutrality as well as CO_2 reduction on stock basis (*beyond zero*) by 2050.

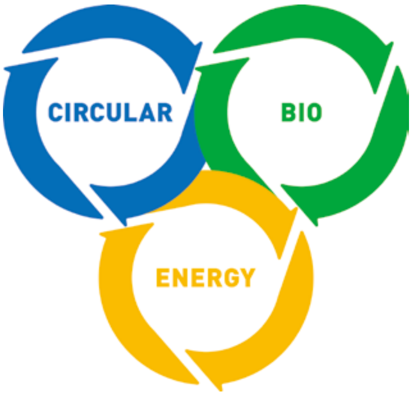
It is very important to address technical development for realizing a *decarbonized society* and the social implementation toward resolving the issue of climate change.

●3 Essential Social Systems for Sustainable Society

A key to realizing a sustainable society is the integrated and organized promotion of 3 Essential Social Systems:

◆ Circular Economy,
◆ Bioeconomy, and
◆ Sustainable Energy.

It is important to get an integral perspective on these 3 Essential Social Systems to bring about discontinuous innovation and to realize the social implementation with economic rationality.



3 Essential Social Systems for Sustainable Society

●Objective of this Comprehensive Principle

For integrated and organized promotion of 3 Essential Social Systems and identification of innovative technologies contributing to resolution of climate change issues, this Comprehensive Principle, with an eye toward 2050, has a purpose of helping assess innovative technologies to be developed and demonstrated by proposing to conduct general objective evaluation of technologies effective in CO_2 reduction and by providing specific estimations along their grounds for several of those innovative technologies. It should be noted that this Principle begins discussion with emission reduction of CO_2, which is the highest GHG emission contributor.

Chapter 2 GHG Emissions and Total Abatement Cost

The marginal abatement cost to achieve GHG emission reduction by about 40 $GtCO_2$ would be more than \$1,000/tCO_2 only with an extension of conventional technologies. This means that about \$10 trillion would be annually needed as the total abatement cost to achieve just a 40 $GtCO_2$ reduction and, furthermore, an even higher abatement cost would be needed to achieve carbon neutrality.

This huge annual total abatement cost cannot be lowered to a globally acceptable level only with an extension of conventional technologies. It is indispensable to bring out discontinuous innovation.

Chapter 3 Evaluation of Innovative Technologies

With an eye toward 2050, this Comprehensive Principle proposes to conduct general objective evaluation of technologies effective in CO_2 reduction and provides *CO_2 reduction potential* and *CO_2 reduction cost* estimates along their grounds, which are needed for the evaluation, for several of those innovative technologies.

These estimates may vary depending on technical factors such as technology development speed and discontinuous innovation as well as social environment variations including government policies for introducing technologies and social acceptability. Therefore, it is indispensable to verify such estimates by gathering findings from those concerned.

Chapter 4 Expectation toward Creation of Framework for Facilitating Innovation

To realize a sustainable society, it is also indispensable to develop a scheme to encourage innovation in technical fields for resolving the issue of climate change and accelerate the social implementation.

To this end, Japan should develop attractive research schemes and environments where industry and academia can intensively put together their knowledge and wisdom under significant technical themes, promote international cooperation for technical development, and offer support programs to implement innovative technologies. It is important to have continual nationwide discussion on how the country can develop these institutional environments/schemes and to improve them as appropriate.

Chapter 5 Conclusion

To realize a *decarbonized society*, discontinuous innovation is indispensable. For integrated and organized promotion of 3 Essential Social Systems to realize a sustainable society, it is important to have discussion for determining innovative technologies to be developed and demonstrated based on quantitative evaluation of *CO_2 reduction potential* and other factors.

Efforts to be addressed in the future include the consideration of items that have not been subject to estimation in this Principle and discussion on the possibility of improving CO_2 reduction effects by merging/integrating different technologies.

Working hand-in-hand with the Government and related institutes, NEDO, as one of the parties to the series of efforts and also as an *innovation accelerator*, is committed to continuously trying to develop innovative technologies, contributing to global GHG emission reduction.

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Introduction

The world's average ground-level atmospheric temperature has continuously increased since the commencement of the Industrial Revolution in the second half of the 18th century and the increase from 1880 to 2012 is about 0.85℃ (Figure 1).

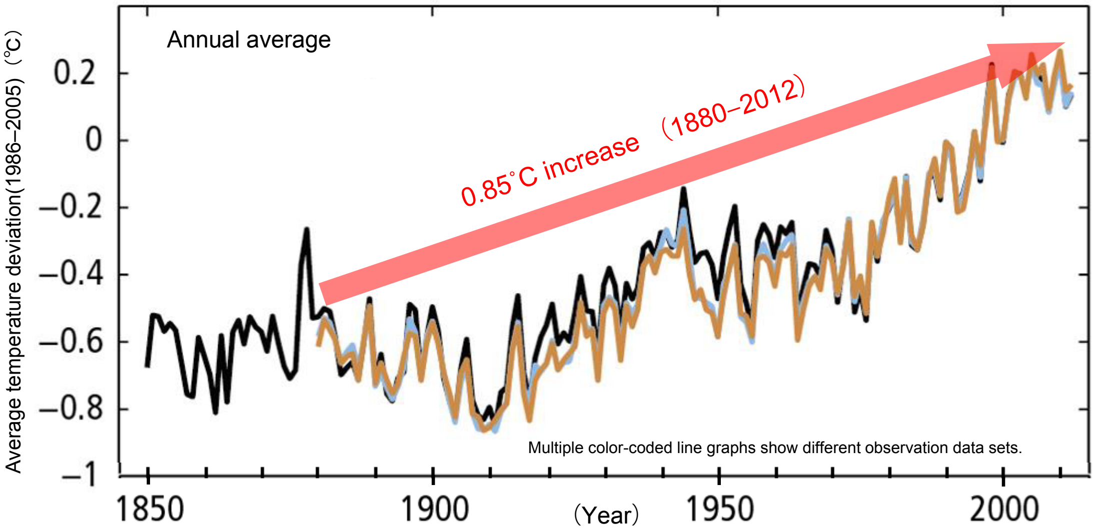

Figure 1 World's average ground-level atmospheric temperature (land and sea) deviation (1850 to 2012)
Source: Prepared by Technology Strategy Center, NEDO, 2020, based on Climate Change 2014 Synthesis Report Figure SPM.1 (a) (IPCC, 2014)

According to the Intergovernmental Panel on Climate Change (IPCC), this temperature increase is very likely attributable to human-induced emission of greenhouse gases (GHGs). It is pointed out that, if GHGs continue increasing as they are, the temperature may increase by up to 4.8℃ by the end of the 21st century[1]. Furthermore, this temperature increase may induce aggravation and/or prolongation of heavy rain and heat waves that have brought serious impacts throughout the world and would be even more serious at the end of the 21st century.

Climate change due to human-emitted GHGs is a challenge for the entire world. It is necessary for the international society to make a concerted effort to substantially reduce the global GHG emissions and try to achieve carbon neutrality. Today, the concept of global sustainability, not limited to climate change, has gradually become popular in international society as is seen in, for example, the unanimous adoption of Sustainable Development Goals (SDGs) and establishment of common goals toward 2030 for the international society in the United Nation's Summit in 2015.

Japan is now required to properly identify the global trend toward these environmental issues and promote implementing discontinuous innovation that can help resolve global environmental issues while bringing them into agreement with SDG elements other than the issue of climate change, thereby actively contributing to GHG reduction both at home and abroad.

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[1] Climate Change 2014 Synthesis Report (IPCC,2014)

Chapter 1 Toward Realizing Sustainable Society

- Addressing technical development to build a *decarbonized society* and realizing the social implementation by 2050 including the establishment of an innovative technology to achieve *beyond zero* are very important for resolving the issue of climate change. Discussion here begins with emission reduction of CO_2, which is the highest GHG emission contributor.
- To realize a sustainable society, it is indispensable to ensure integrated and organized promotion of 3 Essential Social Systems: Circular Economy, Bioeconomy and Sustainable Energy.

1-1 Vision of Future

The human future is infinite.

・To keep the international society economically rich, environmentally friendly and coexisting with nature after a hundred years, two hundred years and even thereafter;
・To ensure that nature and ecosystem diversity are maintained and continuously developed in the future;
・To meet the social needs of the current generation and not impede on the social needs of future generations, rather, to pass on a better society to future generations;

Climate change is a challenge that humans have to overcome. Even if considerable difficulty exists, humans need to aim at building a society where they can overcome the issue of climate change, ensure harmonization among the environment, economy and society, continue creating new values, and keep evolving in a sustainable way, namely, a *sustainable society*.

1-2 Movement for Realizing Decarbonized Society

In the 21st Session of the Conference of the Parties to the United Nations (UN) Framework Convention on Climate Change (COP21) held in Paris in 2015, the Paris Agreement was adopted on the basis of the scientific findings about climate change presented by the Intergovernmental Panel on Climate Change (IPCC). The Paris Agreement requires the participating countries to limit the global average temperature rise to well below 2℃ compared to pre-industrial levels (*the 2℃ target*) as well as to pursue efforts to limit the temperature increase to 1.5℃ (*the 1.5℃ non-binding target*). To this end, the Paris Agreement calls for the parties to aim at achieving an equilibrium between emissions from human-induced GHG sources and GHG removal (i.e., global carbon neutrality) in the second half of the 21st century.

In Japan, the Council for Science, Technology and Innovation (CSTI) established the National Energy & Environment Strategy for Technological Innovation toward 2050 (NESTI 2050) in 2016 accompanied by a list of technologies for which research and development should be promoted even more intensively along with their challenges, in order to achieve drastic global GHG emission reduction by around 2050 from a long-term point of view. According to this NESTI 2050, *the 2℃ target* cannot be achieved unless the global GHG emissions are reduced to about 24 $GtCO_2$ by 2050.

In 2018, IPCC published a Special Report describing what effects and risks would be expected in case of global warming of 1.5℃. The report forecasts that health, living, food and security risks associated with climate change would be aggravated in the global warming scenario of 1.5℃ and more seriously aggravated in the scenario of 2.0℃. It also predicts that human-induced CO_2 emissions need to be *zero net* around 2050 if they are released through the GHG emission routes that were exemplified to limit the temperature increase to 1.5℃.

With the increasingly severer prospects for future climate change risks, the Cabinet of Japan approved the Long-term Strategy under the Paris Agreement. Proclaiming a *decarbonized society* as the ultimate goal, the Long-term Strategy aims at ambitiously realizing a *decarbonized society* as early as possible during the second half of this century by setting a long-term target of 80% GHG emission reduction by 2050. Based on the Long-term Strategy, the "Environment Innovation Strategy" was established in January 2020 in order to implement discontinuous innovation in the energy and environment sectors, to determine the socially implementable cost, and to diffuse it throughout the world. With an aim of establishing an innovative technology to achieve global carbon neutrality and global CO_2 reduction on stock basis (*beyond zero*) by 2050, the Strategy set out to realize the social implementation toward the goals set in the Strategy itself.

In addition, the concept of global sustainability, not limited to the issue of climate change, has become popular in international society. The 2015 United Nation's Summit unanimously adopted Sustainable Development Goals (SDGs) and established common goals toward 2030 for international society. Under such situation, it is required to promote climate change measures in agreement with other SDG elements. In addition, many countries are more active in addressing environmental issues including climate change. For example, European countries including the U.K., France and Germany announced a policy of banning the sale of internal combustion engine cars. Investment in companies with considerations given to environmental, social and cooperate governance issues (*ESG investment*) is expanding. In addition, recent global trends including development of a sharing economy, problems caused by high-volume introduction of renewable energy, and marine pollution with plastic debris are also a significant point.

With these circumstances taken into account, addressing technical development to realize a *decarbonized society* and the social implementation is very important in the process toward resolving the issue of climate change. NEDO understands that it is its own duty to accelerate innovation in this field to realize a *sustainable society.*

1-3 Social System from Viewpoint of Carbon Cycle

In terms of CO_2, which makes up the majority of GHG emissions, it is important to aim to realize a society where the whole social system is sustainable from the viewpoint of carbon cycle. The concept of carbon cycle embraces emission reduction, storage/immobilization, and recycling.

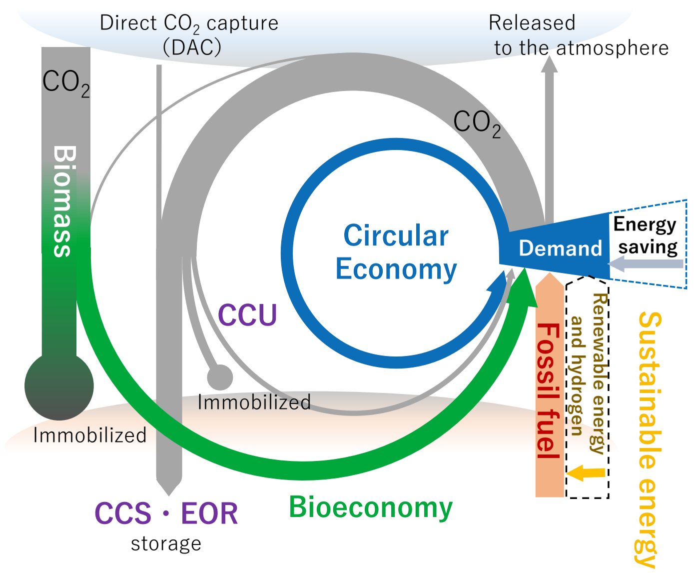

Figure 2 Conceptual Image of Social System from Viewpoint of Carbon Cycle
Source: Prepared by Technology Strategy Center, NEDO, 2019

Then, the conceptual image of a social system from the viewpoint of carbon cycle shown in Figure 2 was created. Based on the image, a roadmap to build a sustainable society was discussed. The figure indicates that CO_2 emissions from the energy demand sector shown in blue can be reduced by improving energy saving. CO_2 emission reduction can also take place when the fossil fuel usage is reduced by the use of renewable energy and hydrogen as well as the utilization of biomass energy. Thus, it is essential to implement a sustainable energy-based social system that can maximize the use of sustainable energy including the promotion of energy saving, in order to achieve lower CO_2 emissions.

Secondly, it is important to capture CO_2 released during energy consumption as much as possible and then to store it underground through CCS[2] and EOR[3] as well as reuse it for chemicals through CCU[4]. Moreover, CO_2 can be separated and stored through Direct Air Capture, mineralization or other technology. These technologies can be used to substantially reduce CO_2 emissions in the atmosphere and to reduce the energy/material demand through recycling or sharing. Thus, it is essential to implement a circular economy-based social system that can maximize recycling of material resources, in order to reduce CO_2 emissions.

Furthermore, atmospheric CO_2 can be immobilized in plants through photosynthesis. Using carbon-neutral biomass as energy or for material production will also allow for CO_2 emission reduction. Thus, it is essential to implement a bioeconomy-based social system that can make the most of biomass and reduce atmospheric CO_2, in order to reduce CO_2 emissions.

The discussion above has now provided an overview of social systems from the viewpoint of carbon cycle. In summary, for lower CO_2 emissions, it is essential to implement 3 Essential Social Systems: Sustainable Energy, Circular Economy, and Bioeconomy.

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[2] Carbon dioxide Capture and Storage
[3] Enhanced Oil Recovery
[4] Carbon dioxide Capture and Utilization

1-4 3 Essential Social Systems for Sustainable Society

As mentioned in the previous section, on the basis of the movement for realizing a *decarbonized society*, it is indispensable to continuously develop 3 Essential Social Systems: (1) Circular Economy, (2) Bioeconomy, and (3) Sustainable Energy. It is important to get an integral perspective on 3 Essential Social Systems, to bring about discontinuous innovation, and to realize the social implementation with economic rationality. Figure 3 represents how the 3 Essential Social Systems, which are indispensable to realizing a sustainable society, can continue developing, relate with each other, affect each other, and are optimally harmonized. The following explains these 3 Essential Social Systems.

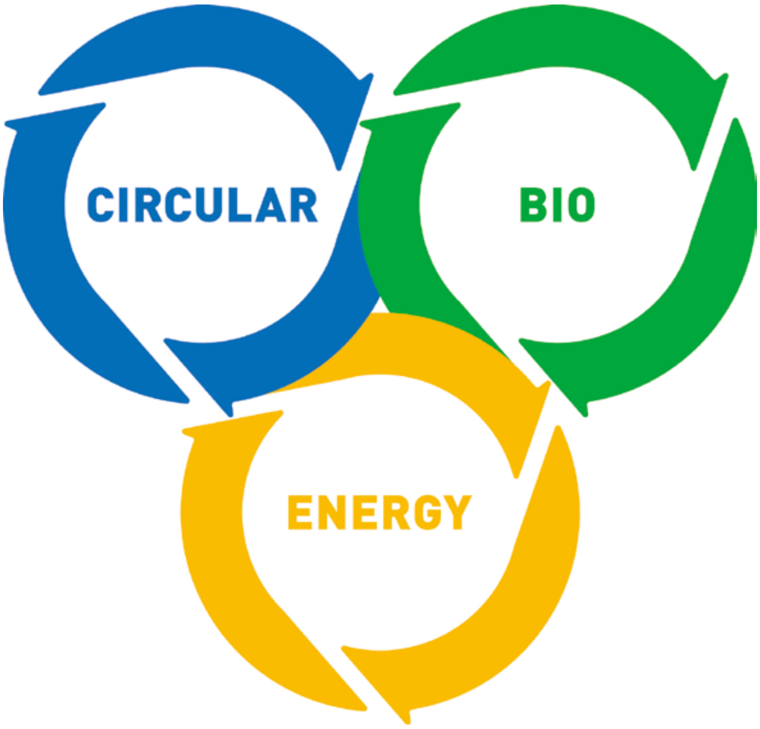

Figure 3 3 Essential Social Systems for Sustainable Society
Source: Prepared by Technology Strategy Center, NEDO, 2020

(1) Circular Economy (Blue)

Humans use various material resources existing on the Earth to carry out socioeconomic activities. Circular Economy refers to a social system in which recycling of material resources is maximized and consumption thereof is minimized. Even embracing the concept of a sharing economy, a Circular Economy has a goal of maximizing utilization of material resources produced from the Earth. The figure expresses Circular Economy in blue that symbolically represents the Earth.

Typical measures of Circular Economy include Reduce, Reuse and Recycle (3Rs). It was originally intended to mainly pursue resource saving, resource security and waste reduction, but recent attention has been paid to the 3Rs and the sharing economy as potential reduction measures in the manufacturing sector where radical CO_2 emission reduction is more difficult than in the power sector. For example, material recycling can lead to CO_2 reduction by around 80% for plastic and around 90% for aluminum, according to an estimate[5]. With their effect of reducing material/product production, the 3Rs are expected to be effective CO_2 emission reduction measures in the steel, cement, chemical and non-ferrous metal manufacturing sectors involving high-volume CO_2 emissions. Another potential CO_2 reduction measure is *carbon recycling* that recovers CO_2 and reuses it as various carbon compounds based on an idea that CO_2 is a carbon resource. Besides these, some other CO_2 reduction measures based on new business models on the demand side, including the sharing economy, are being studied for their effects. In this way, CO_2 reduction by, for example, optimizing transportation systems during the phase of material/product consumption, in addition to during the phase of production thereof, is also expected to be a potential measure[6].

(2) Bioeconomy (Green)

Besides the human race, other various forms of life live on the earth. These organisms coexist with each other as they produce materials useful to others in their life-support activities. Bioeconomy is a social system in which the use of materials produced by these organisms are maximized and the load on the ecosystem is minimized. The objective of Bioeconomy is to maximize the ecosystem performance and the contribution of biological resources. The figure expresses Bioeconomy in green that symbolically represents organisms.

In 2009, the Organization for Economic Co-operation and Development (OECD) published a report titled "The Bioeconomy to 2030", projecting that the biotechnology industry would expand to account for 2.7% of the gross domestic product (GDP) (about $2.0 trillion scale) in 2030 (less than 1% in the 2000s). Since then, many countries have drafted their own Bioeconomy strategy. In Japan, Biotechnology Strategy 2019 was approved in the Integrated Innovation Strategy Promotion Council in June 2019. The Strategy considers Bioeconomy as an indispensable element of the new sustainable socioeconomic system and describes how such Bioeconomy can be implemented.

Bioeconomy can help reduce CO_2 emissions by replacing petroleum-derived materials/products with organic ones and by using biomass into which atmospheric CO_2 has been immobilized by photosynthesis (considered as carbon neutral). Biotechnology has the potential for producing innovative approaches including discontinuous innovation. It could also capture and store CO_2 that has been released in the biomass utilization process, contributing to negative emissions[7].

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[5] The Circular Economy–A Powerful Force for Climate Mitigation (SITRA, 2018)

[6] ITF Transport Outlook 2017 (OECD,2017)

[7] Negative emission technologies refer to capture and immobilize or store CO_2 released to and accumulated in the atmosphere. Specifically, they include Bio-Energy with Carbon dioxide Capture and Storage (BECCS) that promotes plantation to immobilize CO_2 in plants or capture and store CO_2 released during biomass power generation and Direct Air Capture (DAC) that directly recovers CO_2 from the atmosphere and then immobilize or store it.

(3) Sustainable Energy (Orange)

Besides fossil fuel, there exist on the Earth many other natural energy sources based on the solar radiation to the Earth or the Earth's internal heat, such as sunlight, wind, geothermal heat and oceans. The sustainable energy-based social system means that the use of these natural energy sources is maximized and the load on the global environment is minimized. The purpose of such society is to implement long-term stable energy supply and consumption. The figure expresses it in orange that symbolically represents energy.

Since the Industrial Revolution, most of the rapidly increasing energy demand has been met by fossil fuels including coal, petroleum and natural gas. These are depleting resources that produce a large amount of GHGs when they are exploited or burnt. Therefore, the conventional energy supply system using fossil fuels needs to be converted to a sustainable energy system in order to realize a sustainable society. Specifically, it is important to promote development of *renewable energy utilization technologies* in terms of primary energies, *secondary energy technologies* to convert, transport and store the primary energies, *energy management technologies* to integrate the secondary energy technologies for optimal energy utilization, and *energy saving technologies* to use energy as efficiently as possible, thereby achieving cost reduction and preparing the way for the social implementation as early as possible.

1-5 Objective of This Comprehensive Principle

This Comprehensive Principle was established based on the idea that it is very important to ensure integrated and organized promotion of 3 Essential Social Systems (Circular Economy, Bioeconomy and Sustainable Energy) and to address technical development for globally *achieving carbon neutrality* and realizing the social implementation, toward the resolution of the issue of climate change.

To identify innovative technologies that can contribute to resolution of the issue of climate change, it is needed to get a bird's eye view of technologies related to Circular Economy, Bioeconomy or Sustainable Energy and to quantitatively assess which technologies can achieve how much CO_2 reduction at what cost and at which timing. It is particularly important to have quantitative discussion with an eye toward the future based on estimations of *CO_2 reduction potential* and *CO_2 abatement cost* of technologies that can contribute to CO_2 reduction.

Then, with an eye toward 2050, this Principle has a purpose of helping assess innovative technologies to be developed and demonstrated by proposing general objective evaluation of technologies effective in CO_2 reduction and by providing specific estimates along their grounds for several of those innovative technologies. It should be noted that this Comprehensive Principle begins discussion with emission reduction of CO_2 which is the highest GHG emission contributor.

As stated in the "Environment Innovation Strategy", many technologies other than those discussed in this Principle need to be discussed in order to establish innovative technologies that can realize global carbon neutrality as well as global CO_2 reduction on stock basis (*beyond zero*) by 2050. These technologies helping resolve the issue of climate change should be subjected to quantitative evaluation including *CO_2 reduction potential* assessment according to this Principle so that they can be further narrowed down. The resulting Japanese original innovative technologies are expected to be widely spread and used throughout the world, contributing to resolution of the issue of climate change.

NEDO has brought about innovation through a variety of technical developments and demonstration projects so far. By presenting and newly issuing what should be a *guideline* for use in discussing domestic efforts for innovation toward the resolution of the Earth's environment issues, NEDO will strengthen its own role as an *innovation accelerator* to further help resolve global challenges.

Chapter 2 GHG Emissions and Total Abatement Cost

- In discussing the relationship between GHG reduction measures and their cost efficiency, assume that about 40 $GtCO_2$ must be reduced annually. In this case, it costs more than $1 thousand to reduce 1 ton of CO_2.
- This means that about $10 trillion would be needed annually as the total abatement cost to reduce 40 $GtCO_2$.
- To lower this huge total abatement cost to a globally acceptable level, discontinuous innovation is indispensable.

2-1 Current Status of GHG Emissions

The global greenhouse gas (GHG) emissions in 2010 were about 49 $GtCO_2$. Of these, 76% is attributable to CO_2, followed by CH_4 (16%), N_2O (6%) and fluorine gases including CFC[8] (2%) (Figure 4). Figure 5 shows Japan's GHG emissions in FY2013, although the year is different from that of the global data[9].

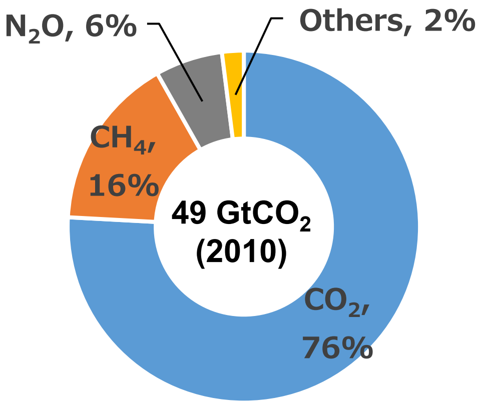

Figure 4 Global GHG emissions
Source: Prepared by Technology Strategy Center, NEDO, 2020, based on Climate Change 2014 Synthesis Report (IPCC, 2014)

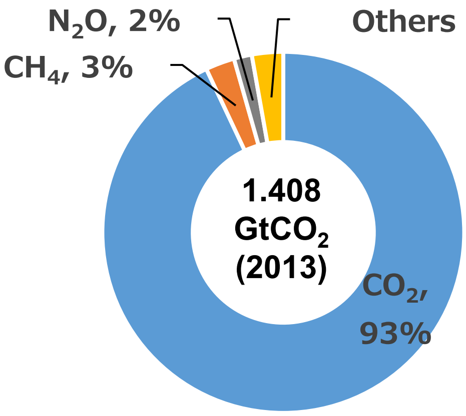

Figure 5 Japan's GHG emissions[10]
Source: Prepared by Technology Strategy Center, NEDO, 2020, based on the Ministry of Environment's Annual Report on the Environment, the Sound Material-Cycle Society and Biodiversity in Japan 2015

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[8] Many fluorine-containing gases including alternative CFCs are included in the controlled substance list of the Montreal Protocol on Substances that Deplete the Ozone Layer. Promoting the development of refrigerants with low Global Warming Potential (GWP) will contribute to GHG reduction.

[9] The reference year for setting 2030 targets was set to 2010 by IPCC or 2013 by Japan. The global GHG emissions have increased by 6% in 2013 and by 7% in 2016 from the 2010 level. (CLIMATEWATCH, https://www.climatewatchdata.org/)

[10] Japan's GHG emissions have decreased. The total GHG emissions in FY2017 were 1.292 $GtCO_2$. (Ministry of the Environment, Annual Report on the Environment, the Sound Material-Cycle Society and Biodiversity in Japan 2019)

CO_2 accounts for 93% (about 1.3 $GtCO_2$) of the total GHG emissions, which is higher than the global average. Japan's GHG emissions only account for a relatively small fraction of the global emissions, but it is very important for the country to contribute to lower GHG emissions not only domestically but also globally as climate change issues are a global scale concern[11]. This Comprehensive Principle mainly discusses reduction of CO_2 emissions, which account for about 80% of the total GHG emissions, although reduction of other GHGs than CO_2 is also a future significant challenge.

2-2 Prospects for GHG Emissions

Since there is climate sensitivity uncertainty about the relationship between future GHG emissions and the earth's average temperature, it should be noted that the prospects for GHG emissions vary greatly. International research institutes have assumed various scenarios based on several GHG emission routes and have analyzed energy consumption, CO_2 emissions, abatement cost and other factors for each scenario.

This Comprehensive Principle mainly analyzes ETP 2017[12] scenarios presented by the International Energy Agency (IEA). ETP 2017 provides three scenarios limited to CO_2: Reference Technology Scenario (RTS), 2℃ Scenario (2DS) and Beyond 2℃ Scenario (B2DS). Among these, RTS is to promote CO_2 reduction by improving and proliferating renewable energy and energy saving technologies. This scenario assumes that the global CO_2 emissions will be about 40 $GtCO_2$ in 2050, which is based on an estimation that about 15 $GtCO_2$ reduction in 2050 will be achieved through proliferation of conventional technologies from the level achieved with the 6℃ Scenario (6DS) in which no special measures are taken[13]. For 2DS and B2DS, further CO_2 emission reduction will take place with economic rationality because of technical development. These scenarios are shown in Figure 6.

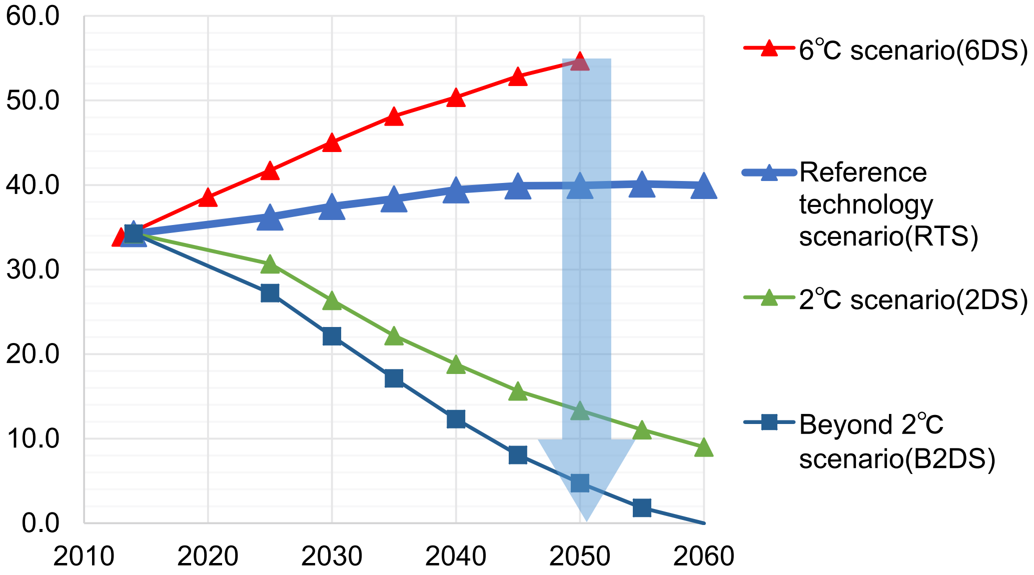

Figure 6 Typical IEA Scenarios

Source: Prepared by Technology Strategy Center, NEDO, 2020, based on Energy Technology Perspectives 2016 and Energy Technology Perspectives 2017

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[11] This means that when a country emits or reduces CO_2, it will affect the whole world.

[12] Energy Technology Perspectives 2017

[13] Business As Usual (BAU) scenario included in Energy Technology Perspectives 2016

2-3 Estimations of Marginal Abatement Cost and Total Abatement Cost

International research institutes working on climate change issues have simulated several scenarios to present the relationship between CO_2 emissions (or GHG emissions) and marginal abatement cost. The term *marginal abatement cost* refers to the cost incurred to reduce an additional 1 ton of CO_2 emissions expressed in the unit of $/t$CO_2$. This marginal abatement cost represents how high the hurdle for CO_2 reduction from a given emission level is from the viewpoint of economic rationality. It is an important index for setting a target of technical development for future CO_2 reduction (for more information, see Chapter 3).

To get a bird's eye view of global average marginal abatement cost, this section covers estimations of global GHG emissions and marginal abatement cost published by some international research institutes, i.e., the United Nations Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA) and Japan's Research Institute of Innovative Technology for the Earth (RITE). Based on the estimations, regression analysis has been made and the results are shown in Figure 7[14]. As indicated by approximate values on and around the blue line, as the GHG emissions decrease, the marginal abatement cost exponentially increases and exceeds $1 thousand/t$CO_2$ before achieving 40 GtCO_2 reduction.

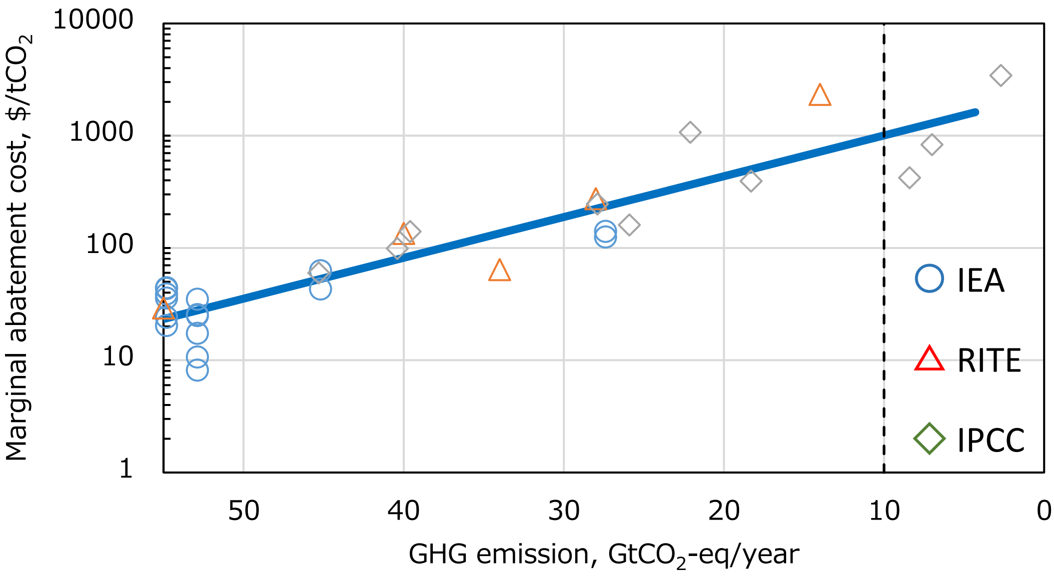

Figure 7 Relationship between GHG Emissions and Marginal Abatement Cost
Source: Prepared by Technology Strategy Center, NEDO, 2020, based on Global warming of 1.5˚C (IPCC, 2018),World Energy Outlook 2018 (IEA, 2018), and Analyses on Japan's GHG Emission Reduction Target for 2050 in light of the 2˚C Target Stipulated in the Paris Agreement (RITE, 2017).

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[14] Any cost data by the research institutes that is based on different reference years has been corrected with the relevant inflation rate. The IEA data, which is limited to CO_2, has been added with estimated valued for other GHGs than CO_2 based on the IPCC data on GHG emissions released from multiple emission routes.
The relationship between marginal abatement cost and GHG emissions can be approximately expressed by the equation:
Marginal abatement cost [$/t$CO_2$] = exp (-0.008363G + 7.748); G: GHG emissions [0.1 GtCO_2]

The cost borne by the whole world for abatement measures (hereinafter, referred to as the *total abatement cost* and expressed in the unit of \$/year) can be determined as the area under the line indicating the marginal abatement cost. Figure 8 shows the relationship between the total abatement cost and GHG emissions. According to the figure, the global total abatement cost to reduce emissions to 40 $GtCO_2$ is about \$10 trillion/year. The total abatement cost to achieve 0 (zero) emissions, which can be determined through extrapolation, is estimated to be \$27 trillion/year.

A \$10 trillion/year scale of total abatement cost is equivalent to 12% of the world's GDP[15]. This means that the total abatement cost being discussed is too high for society to accept, implying an extremely high hurdle for the implementation. Therefore, discontinuous innovation to lower this huge cost to a globally acceptable level is indispensable.

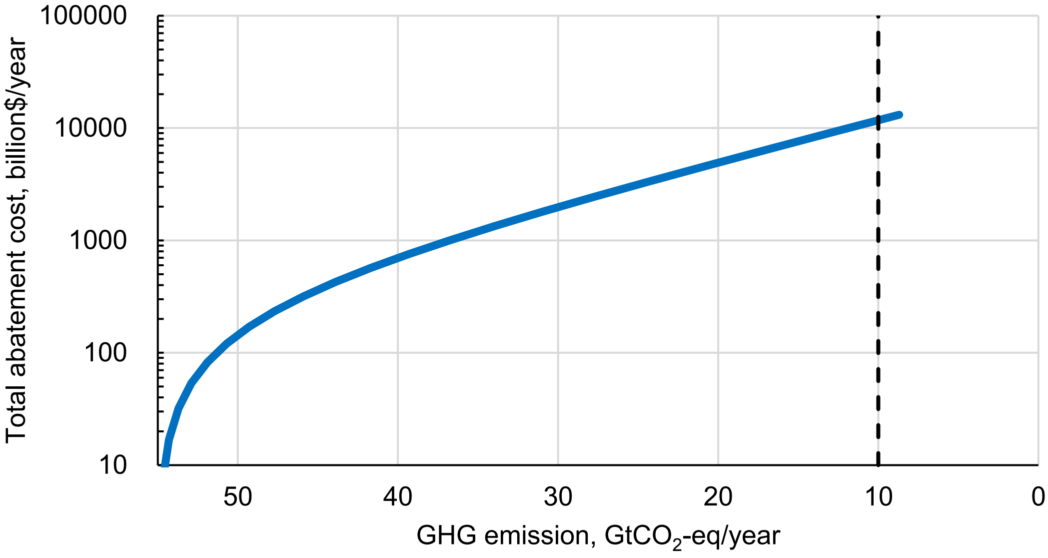

Figure 8 Relationship between GHG Emissions and Total Abatement Cost
Source: Prepared by Technology Strategy Center, NEDO, 2020, based on the analysis results in Figure 7

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[15] The global GDP (2018) was \$84,825.6 billion. (Source: IMF, World Economic Outlook Database)

Chapter 3 Evaluation of Innovative Technologies

- *CO_2 reduction potential* and *CO_2 abatement cost* are two important *evaluation factors* for the objective assessment of technologies across various fields.
- NEDO has estimated the CO_2 reduction potential and CO_2 abatement cost of each innovative technology which NEDO can measure their impacts.
- It is important to continuously validate these estimations by applying various stakeholders' insights since these figures may go up or down depending on changes to the environment, such as implementation policies or social acceptance, as well as technical factors.

3-1 Approach for Evaluating Innovative Technology

In order to evaluate technologies by their contribution to reducing CO_2 emissions, both *CO_2 reduction potential* and *CO_2 abatement cost* must be measured quantitatively.

In this Chapter, NEDO has estimated the CO_2 reduction potential and CO_2 abatement cost of each innovative technology, with a focus on the approaches that NEDO is familiar with their research and development efforts and for which it is equipped to measure their impacts. These estimates have helped further discussion over the "Environment Innovation Strategy." In this estimation, the CO_2 reduction impact of each technological approach in the "Environment Innovation Strategy" has been calculated based on the social implementation of innovative technologies, together with the development of next-generation innovative technologies and their social implementation. Since NEDO's goal is to solve the social issues by driving technological development, it has also estimated the *CO_2 reduction potential* portion of next-generation innovative technologies that need to be developed further. Figure 9 shows part of the CO_2 reduction estimates for the technological approaches that are discussed in this Principle.

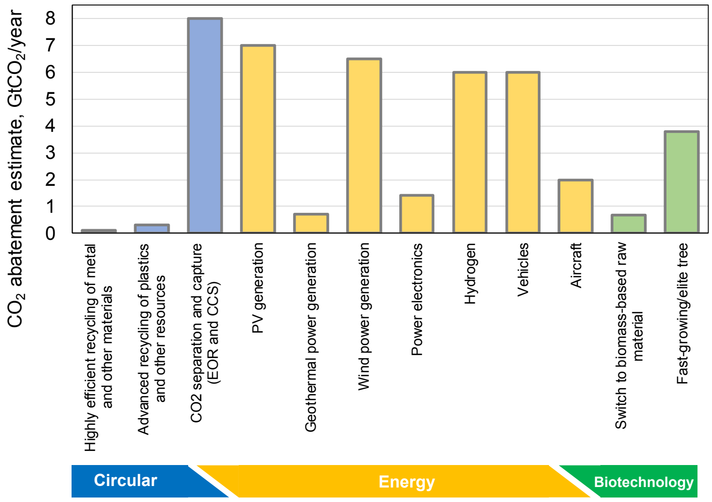

Figure 9 CO_2 reduction potentialspotential of technological approaches in the "Environment Innovation Strategy" (excerpted)

Source: Prepared by Technology Strategy Center, NEDO, 2020, based on the "Environment Innovation Strategy" (the Cabinet Office, 2020)

3-2 Methods for Estimating CO_2 Reduction Potential and CO_2 Abatement Cost

The innovative technologies discussed in this Principle are at different levels of perfection and have different social contexts. Based on these differences, the CO_2 reduction potential of these target technologies has been estimated using the following four methods.

A) Calculation based on estimated penetration of each technology
B) Calculation based on estimates by specialist institutions
C) Calculation based on targets and outlooks set out by the government and industries
D) Calculation based on the maximum penetration of technology or installation of equipment

CO_2 reduction potential may go up or down depending on changes to the environment, such as implementation policies or social acceptance, as well as technical factors such as speed of technological evolution and disruptive innovations. In cases where these uncertainties can be predicted, NEDO used different scenarios for penetration and other relevant elements for each technology and applied the following formula for estimating the CO_2 reduction potential in 2050.

$$\begin{aligned}&\text{CO}_2\text{ reduction potential [tCO}_2\text{]}\\&=\text{introduction amount [specific unit*]}\\&\quad * \text{ (emission intensity of traditional technology} - \text{emission intensity of innovative technology) [tCO}_2\text{/specific unit*]}\end{aligned}$$

*Specific unit: Wh, J, t, and so on

Appendix shows the estimated CO_2 reduction potential of the innovative technologies discussed in this Principle, together with the basis of the calculation.

The total figure for CO_2 reduction potential derived in this Principle must be handled carefully since the target technologies have different levels of perfection and may compete with each other in some areas. As already mentioned, these estimations are also limited to the technologies that NEDO could comprehend their research and development status and calculate their impact. Not all the technologies that can help reduce CO_2 are covered in this Principle.

Nevertheless, the CO_2 reduction potential of each technology discussed here can be high at 0.1–10.0 Gt, indicating that CO_2 emissions can be dramatically reduced by promoting technological development.

CO_2 abatement cost is the price for reducing one ton of CO_2 emissions, measured in the unit of ¥/tCO_2. In this Principle, the CO_2 abatement cost for socially implementing innovative CO_2 reduction technologies developed in the future has been estimated using the formula below.

$$\text{CO}_2\text{ abatement cost [¥/tCO}_2\text{]} = \frac{\text{innovative technology's unit price} - \text{traditional technology's unit price [¥/specific unit*]}}{\text{Traditional technology's CO}_2\text{ emission intensity} - \text{innovative technology's CO}_2\text{ emission intensity [tCO}_2\text{/specific unit*]}}$$

*Specific unit: kWh, GJ, t product, and so on

Technological development can sufficiently lower the cost of innovative technologies, accelerate their social implementation, resulting in a dramatic reduction of CO_2 emissions.

The innovative technologies discussed in this Principle have varying degrees of perfections and different social backgrounds, as well as differences in their CO_2 reduction potential. Each CO_2 abatement cost is estimated based on the following patterns.

A) Based on past learning curves: next-generation photovoltaics
B) Based on the target and outlook set out by the government and industries: hydrogen power generation
C) Based on estimates by specialist institutions: CCS and plastics recycling
D) Other patterns: next-generation battery for EV

3-3 Example of CO_2 Reduction Potential Estimation

① Next-generation photovoltaics (PV)

Innovative PV technologies' CO_2 reduction potential at 2050 is estimated at around 7.0 Gt. This figure is also quoted in the "Environment Innovation Strategy."

IEA ETP 2017 estimated that a deeper penetration of innovative technology will result in up to 3,345 TWh worth of PV introduced by 2050. This introduction amount and the CO_2 intensity in 2050 are the basis for estimating the CO_2 reduction potential of 2.2 Gt.

Next, based on 2DS[16] and other figures in IEA ETP 2017, the total power generation capacity of PV and other next-generation innovative technologies in 2050 are estimated at 8,000 TWh. The 4,655 TWh difference between these 8,000 TWh and 3,345 TWh figures are assumed to be the additional power supply coming from next-generation PV technologies, leading to the 3.0 Gt estimate for their CO_2 reduction potential.

Further advances in technology, next-generation PV modules that are, among their properties, super-light, super-efficient, and have high-quality design can bring them to building walls and production plant roofs, places that have been thought impossible with traditional technologies. Advanced installation methods can also open ways to PV modules placed on water or farmland. PV introduction amount can be expected to grow dramatically in the future through these innovations in technology. Estimates for the introduction amount of next-generation PV by application in 2050 are 2.02 TW for floating, 1.68 TW for side wall, 3.01 TW for farmland, and 0.56 TW for vehicle-mounted systems, with the total CO_2 reduction of almost 4.8 Gt. Adding this to the 2.2 Gt already mentioned results in 7.0 Gt reduction across all innovative technologies. By developing offshore facilities, solar road, electric aircraft, and other new applications, as well as introducing policy measures such as setting rules for net-zero energy buildings (ZEB), the CO_2 reduction potential may grow even larger.

② Hydrogen power generation

Hydrogen technology can theoretically reduce CO_2 emissions dramatically because this material that does not emit CO_2 during its usage can replace fossil fuel. Since some hydrogen production methods generate CO_2, technologies must be developed for capping total CO_2 emissions from production to consumption. "Hydrogen scaling up" (Hydrogen Council, 2017) says that 6.0 $GtCO_2$ reduction can be achieved in the future by extensively using hydrogen in utility, transportation, and other industries. This section will discuss hydrogen power generation as an example of technologies leveraging hydrogen.

According to IEA, the global supply of electricity generated by natural gas power stations in 2050 will be 10,586 TWh/year. By assuming that 5.0–15% of this amount can be replaced by hydrogen power generation, the CO_2 reduction potential can be 0.19–0.58 Gt. Note that this estimation is only for final consumption of hydrogen. The CO_2 emissions for producing, transporting, storing, and supply hydrogen have not been calculated in this Principle.

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[16] IEA World Energy Outlook 2018

③ Next-generation battery for EV

A next-generation battery can help reduce CO_2 emissions dramatically by storing electricity with low CO_2 emission intensity and extending its usage. In the "Environment Innovation Strategy," the reduction of CO_2 emissions from vehicles and aircraft are estimated at 6.0 Gt and 2.0 Gt respectively, after all measures, including electrification and switching to low-carbon fuels, are applied. The next-generation battery has higher energy density per weight as well. Electric vehicles (EV) carrying a 100 kilogram pack of next-generation batteries are expected to have a range of around 500 kilometers per charge, mostly on par with gasoline cars. Usages for next-generation batteries outside driving mobility machines may include power supply adjustment. Still, the CO_2 reduction potential of these batteries on passenger EVs was chosen for estimation.

According to IEA ETP 2017's RTS, the total driving distance of light duty vehicles (LDV) stocks per year will be 63.9 trillion kilometers in 2050, with the CO_2 emissions set at 5.47 Gt. The components of each passenger car stock in this RTS are 12 percent for EVs (including plug-in hybrid (PHEV) and fuel-cell (FCEV) types) against 88 percent for cars with internal-combustion engines (ICEV, including hybrids (HV)). By assuming that 40–60% of ICEV are replaced by EV with a next-generation battery, the esitimated CO_2 reduction potential will be 0.27–0.91 Gt.

④ Enhanced oil recovery (EOR), CO_2 capture and storage (CCS)

This is a technology for separating, capturing, and storing CO_2 emissions from power stations, steel mills, and other facilities generating CO_2 with higher concentration. EOR plants have already been commercially operational as this method has an economic advantage over CCS, which simply stores CO_2. There will be further social implementations for EOR in sites with better conditions (such as high CO_2 concentrations or favorable locations). Nevertheless, innovative technologies for separating, capturing, transporting, and storing CO_2 must be developed to offer introduce this method at affordable costs in disadvantaged sites with lower concentration or geographical limitations for deeper penetration.

In this Principle, the maximum possible amount that can be deduced from multiple IEA scenarios is taken as the basis for the CO_2 reduction potential estimate of 8.0 Gt.

⑤ Plastic recycling

Burning used plastics emits almost the same amount of CO_2 generated by all the processes combined from raw material extraction and product manufacturing. Recycling these plastics can dramatically reduce CO_2. While plastics are already being recycled, many processes still involve methods that are not efficient for reducing CO_2. Developing innovative technologies for each process, from sorting to material recycling, chemical recycling, and retrieving energy can be expected to have a large CO_2 reduction potential.

By assuming that, with the annual plastic production (for PE, PP, PET, and PS) reaching 0.4 Gt[17] in 2050, of which 0.04–0.12 Gt (10–30 percent) recycled with innovative technologies, the CO_2 reduction potential is estimated at 0.11–0.32 Gt. This figure covers the burning as well as production processes of plastics.

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[17] The future of Petrochemicals (IEA, 2018)

⑥ Bioplastic

Bioplastics derived from biomass-based raw material are carbon neutral since they have no impact on atmospheric CO_2 levels even when burned. The Ellen MacArthur Foundation report, "The New Plastics Economy: Rethinking the Future of Plastics," estimates the plastic production in 2050 at 1.124 Gt. The report also says that, by switching from oil-based to biomass-based plastics, CO_2 can be reduced by 140–200 percent in terms of weight.

By assuming that 20–30 percent of globally produced plastics can be switched to biomass-based types in 2050, and also assuming that CO_2 reduction impact can be as high as 200 percent of weight, then the CO_2 reduction potential can be estimated at 0.45–0.67 Gt.

3-4 Examples of CO_2 Abatement Cost Estimation

① Next-generation PV

More PV systems are being installed in Japan as mega-solar (commercial use) and rooftop applications. The cost of generating power has been steadily falling, coming closer to the government target of ¥14/kWh by 2020 and ¥7/kWh by 2030. The power generation cost after 2030 is expected to achieve generation parity (¥7/kWh, on par with base load power sources). Simultaneously, new research and development activities for next-generation PV technologies giving the panels dramatically higher efficiency, lighter weight, flexibility, and many advanced properties, are expected to bring new applications in diverse fields such as side wall systems for ZEB and vehicle systems. Figure 10 shows examples of CO_2 abatement cost estimations for commercial applications as well as side wall and car-mounted systems. The expectation for side wall and car-mounted applications is that they will be introduced to the market in 2030, followed by a steady drop in power generation cost (CO_2 abatement cost) with advances in technology and mass-production effects. The power generation cost for side wall systems, projected at ¥129/kWh in 2030, will drop to ¥14/kWh in 2050, lowering the CO_2 abatement cost from ¥336,000/tCO_2 to −¥4,000/tCO_2, For car-mounted systems, the power generation cost of ¥98/kWh in 2030 will drop to ¥14/kWh in 2050, bringing down the CO_2 abatement cost from ¥217,000/tCO_2 to −¥33,000/tCO_2. These figures must be handled carefully since the estimations are dependent on implementation requirements and many other conditions.

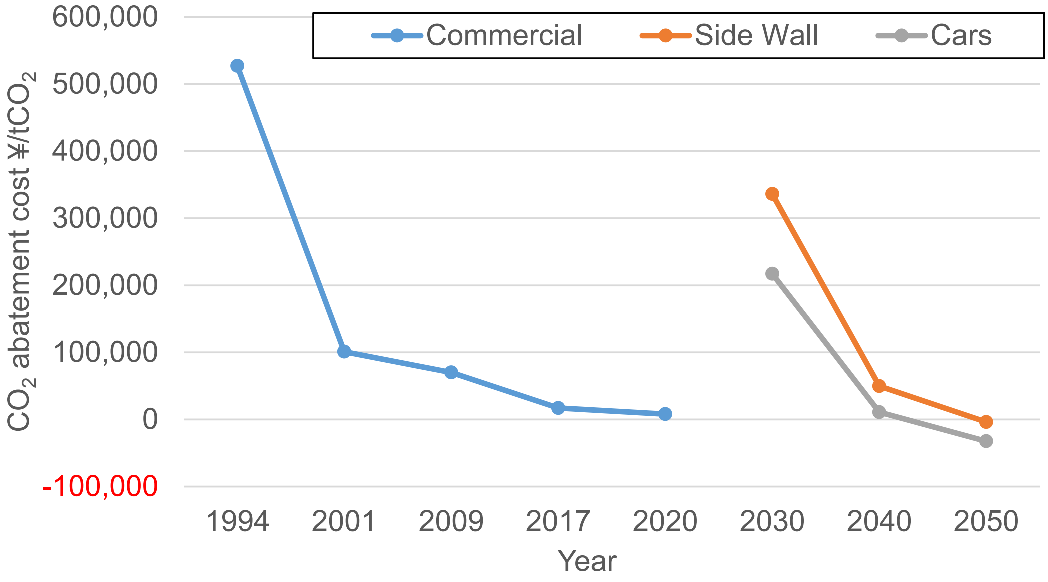

Figure 10 Drop in PV CO_2 abatement cost (estimate)

Source: Prepared by Technology Strategy Center, NEDO, 2019

In this section, the CO_2 abatement cost for PV in Japan is estimated. The CO_2 abatement cost outside Japan cannot be calculated in a uniform manner, since different countries have different power generation costs, energy compositions, or CO_2 emission intensities. The expectation is that Japan and other countries will all follow identical trajectories, with generation parity achieved for commercial and rooftop PV in most areas of the world by 2030. Even in areas where innovative technologies are required, such as ZEB, floating, farmland, and car-mounted systems, the grid parity is projected to be achieved by 2050. It is therefore reasonable to set the cost target per kWh for 2050 below the cost levels of current power sources. PV has large CO_2 reduction potential. Its role will be dramatically wider by lowering the cost for next-generation PV technologies through technological innovation. Note that grid connection and battery costs for introducing PV are not included in this estimation, since PV systems are used in different environments and for different purposes in different parts of the world.

② Hydrogen power generation

In the “Strategic Roadmap for Hydrogen and Fuel Cells” (revised March 2019, METI), relevant goals are set as follows: “¥30/Nm^3 has been set as a target for the cost of hydrogen (plant delivery) to be achieved by around 2030, with plans to further reduce costs to around ¥20/Nm^3 in the future.” In terms of power generation costs, they are translated as ¥17/kWh and ¥12/kWh respectively. This policy targets have been used to forecast the CO_2 abatement cost for hydrogen power generation in Japan (see Table 1), which will be nearly ¥14,700/tCO_2 in 2030. In the future (2050), if the traditional LNG power generation is to be switched to hydrogen power generation, the power generation cost for the latter must be on par with the former. This means that by the time the hydrogen cost of ¥20/Nm^3 (power generation cost of ¥12/kWh) is achieved, the CO_2 abatement cost will be as low as ¥0/tCO_2.

In order to achieve this, development of not only hydrogen power generation technology (advanced combustion chambers and much higher efficiency), but also of supplying hydrogen (production, transportation, or storage, for example) is important. It must be also noted that, if renewable energy-based electricity is used for producing hydrogen with water electrolysis, then the hydrogen cost will be highly sensitive to the cost of that renewable energy-based electricity.

Table 1 Example of estimated CO_2 abatement cost for hydrogen power generation

Type	Hydrogen power generation		LNG thermal (referenced traditional technology)
	¥30/Nm^3 *1 (2030 target)	¥20/Nm^3 *1 (future target)	
Power generation cost (¥/kWh)	17.0 *2,3	12.0 *2,3	12.0
Hydrogen cost (¥/Nm^3)	30	20	-
CO_2 emissions (g/kWh)	0 *4	0 *4	340 *5
CO_2 abatement cost (¥1,000/tCO_2)	14.7	0	-

*1 “Strategic Roadmap for Hydrogen and Fuel Cells” (METI, 2019)
*2 The cost for hydrogen power generation does not cover port facilities or any other infrastructures, land, or technology developments.
*3 The energy efficiency of hydrogen power generation is set at 59 percent (LHV), with costs other than the fuel being on par with LNG thermals (Power Generation Cost Validation WG)
*4 The CO_2 emissions from hydrogen power generation is set at zero, with only the emissions inside Japan being considered. The CO_2 emissions from producing, transporting, or storing hydrogen are not included.
*5 From “Higher Efficiency for Fossil-fuel Power Stations” (METI, 2015), used during the 18th meeting of the Strategic Policy Committee of the Advisory Committee for Natural Resources and Energy

Source: Prepared by Technology Strategy Center, NEDO, 2020

③ Next-generation battery for EV

In this section, the CO_2 abatement cost for EV has been estimated based on the assumption that traditional vehicles will be replaced by EV. In this calculation, the EV CO_2 abatement cost is defined as the additional cost for replacing traditional vehicles with EV divided by the amount of CO_2 emissions reduced. In the following formula for calculating the CO_2 abatement cost for EV, "ICEV" stands for traditional vehicles with internal-combustion engines (including HV).

$$\begin{aligned}&\text{CO}_2\text{ abatement cost}\\&=\frac{(\text{Difference between energy costs (for electricity and fuel) for running on electricity and fuel for total driving distance})+(\text{Difference between EV and ICEV purchasing prices})}{(\text{Difference between CO}_2\text{ emissions for running on electricity and fuel for total driving distance})+(\text{Difference in CO}_2\text{ emissions during EV and ICEV production})}\\&=\frac{\text{Total driving distance}*\left\{\left(\frac{\text{Electricity mileage}}{\text{Battery charging efficiency}}*\text{Electricity price}\right)-(\text{Fuel mileage}*\text{Fuel price(tax excluded)})\right\}+(\text{EV purchasing price}-\text{ICEV purchasing price})}{\text{Total driving distance}*\left\{(\text{Fuel mileage}*\text{CO}_2\text{ emission coefficient for fuel})-\left(\frac{\text{Electricity mileage}}{\text{Battery charging efficiency}}*\text{CO}_2\text{ emission coefficient for electricity}\right)\right\}+(\text{CO}_2\text{ emissions during ICEV production}-\text{CO}_2\text{ emissions during EV production})}\end{aligned}$$

In this formula, the numerator, actually the additional cost incurred when ICEV are replaced by EV, is the sum of *the price of electricity used by EV over the total driving distance subtracted by the price of fuel consumed during that time* (*tax excluded*) and *EV purchasing price subtracted by ICEV purchasing price*. The denominator, which is the CO_2 emission reduction when ICEV are replaced by EV, is the sum of *the total CO_2 emissions from ICEV for covering the total driving distance subtracted by the total CO_2 emissions from EV for covering the same distance* and *the CO_2 emissions from ICEV production subtracted by the CO_2 emissions from EV production*.

Table 2 shows all the assumptions behind this estimate. The future ICEV fuel mileage and EV electricity mileage are taken from the IEA report, putting them at 19.6 km/L for HV and 5.3 km/kWh (battery charging efficiency set at 95 percent) for EV in 2018[18]. The fuel cost is based on the IEA RTS figure of ¥86/L[19] (with ¥100 for one US dollar). The electricity price comes from Japan's level of ¥24/kWh[20], which is close to the median value for electricity price in 10 major countries (¥10–¥35) in 2016 as reported by the Central Research Institute of Electric Power Industry (CRIEPI). The total driving distance of 200,000 kilometers[21] is the maximum range used for calculations by Volkswagen. The (*EV purchasing price−ICEV purchasing price*) in the formula can be anywhere between zero to ¥1,000,000 because, while the price remains higher for EV than ICEV, battery prices are dropping, closing the price gap between both types of vehicle. As for the (*CO_2 emissions during ICEV production−CO_2 emissions during EV production*) part, the fact that EV production emits more CO_2 than ICEV, mostly because of CO_2 emissions for producing batteries, had to be taken into account. For the estimation in this Principle, the value has been factored in as a range between −5.0 t to 5.0 t, with the bottom range taken from the Volkswagen report stating that one EV emits 5.0 t more CO_2 than ICEV[21], while the top range comes from the assumption that this will be reversed when the CO_2 emissions from battery production dropped in the future, with EV production process emitting 5.0 t less CO_2 than ICEV.

Figure 11 shows the estimation results. The CO_2 abatement cost is dependent on the differences between purchasing prices and CO_2 emission during production, having a ¥2,000/tCO_2–¥146,000/tCO_2 range.

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[18] Global EV Outlook 2019

[19] Energy Technology Perspectives 2017

[20] Data comparing electricity prices in different countries, 2018

[21] Volkswagen website (https://www.volkswagenag.com/en/news/stories/2019/04/from-the-well-to-the-wheel.html)

Table 2 Assumption behind estimations for CO_2 abatement cost of EV

Assumption	Value	Description
ICEV fuel mileage	19.6 km/L	HV data for 2018 in IEA report[18] was used as the future average.
EV electricity mileage	5.3 km/kWh	EV data for 2018 based on battery charging/discharging efficiency of 95 percent[18] was used.
Fuel price	¥86/L	IEA RTS model value[19] is used, at the rate of ¥100 to one US dollar.
Electricity price	¥24/kWh	Japan's electricity price is used because it was close the median value for ten major countries (¥10–¥35) in the 2016 CRIEPI report[20].
Total driving distance	200,000 km	The maximum running distance of 200,000 kilometers used by Volkswagen for calculation[21] is used.
EV purchasing price －ICEV purchasing price	¥0–¥1,000,000	This figure is adopted to account for the fact that EV price is still higher than ICEV even though the gap is closing because of the dropping battery price.
CO_2 emissions for ICEV production －CO_2 emissions for EV production	－5–＋5 t	This figure is adopted taking into account the Volkswagen report claiming that one EV emits 5.0 t more CO_2 than an ICEV[21].

Source: Prepared by Technology Strategy Center, NEDO, 2020

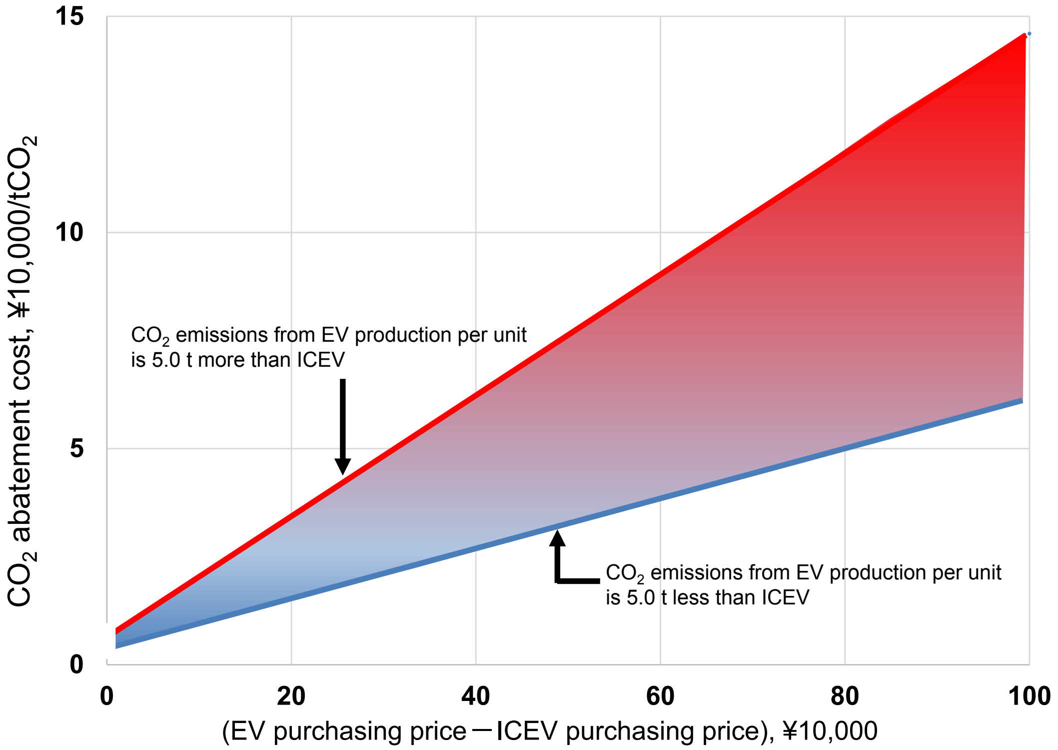

Figure 11 Example of CO_2 abatement cost when switching from ICEV to EV
Source: Prepared by Technology Strategy Center, NEDO, 2020

④ CCS

Table 3 shows extracts from the Global CCS Institute report offering a detailed analysis on the CO_2 abatement cost of CCS. Excluding the ammonia production with a particularly high level of CO_2 concentration and accompanying gases, the current CO_2 abatement cost level is ¥7,050–¥12,400/t CO_2[22] (at ¥100 to one US dollar), which is expected to go down by 20–30 percent in the future through technological development.

Table 3 CO_2 abatement cost by emission source[23] (\$/tCO_2)

	Power generation				Manufacturing			Accompanying gas
	Supercritical pulverized coal	Supercritical oxy-fuel combustion	IGCC	NGCC	Steel	Cement	Ammonia	
Traditional technology	78.5	70.5	97.0	89.0	77.0	124.0	25.4	21.5
Future	55.0	52.0	46.0	43.0	65.0	103.0	23.8	20.4

Source: Prepared by Technology Strategy Center, NEDO, 2020, based on “Global costs of carbon capture and storage 2017”

⑤ Plastic recycling (recycling and reusing)

According to an EU estimate[24], the costs of various measures for recycling plastics to reduce CO_2 can be relatively low, ranging from −¥10,000/tCO_2 to ¥5,700/tCO_2 (at ¥100 to one US dollar). The method with the lowest cost is the reuse of agricultural wrapping at −¥10,000/tCO_2, followed by chemical recycling at ¥5,500/tCO_2 and reuse of container packaging at ¥5,700/tCO_2. Retrieving and reusing plastic products without additional chemical synthesis or forming processes will cost less than producing them from virgin plastic (a conventional method), and the reduction cost will be negative value by definition. This means that this approach can reduce CO_2 while maintaining economic rationality.

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[22] The target in “Roadmap for Carbon Recycling Technologies” is ¥1,000/tCO_2 or less after 2050 just by CSS.

[23] Inside the USA, assuming pipeline transportation and CSS.

[24] The Circular Economy–A Powerful Force for Climate Mitigation（SITRA, 2018）

3-5 Promoting Strategical Development of Innovative Technology

As described in the previous Chapter, the marginal CO_2 abatement cost of reducing CO_2 emissions by 40 Gt solely by traditional methods will exceed the level of ¥100,000/tCO_2, burdening the world with a cost of $10 trillion. This is the reason why CO_2 abatement cost must be reduced quickly.

Figure 12 shows the relationship between the CO_2 abatement cost of a target technology (red line) and the marginal CO_2 abatement cost of its counterpart traditional technology (blue line). With the introduction of innovative technologies, the CO_2 abatement cost as well as marginal CO_2 abatement cost can be dramatically lowered. This, in turn, will enable the social implementation schedule to be brought forward, helping dramatically reduce action costs. Figure 12 is just an example for one innovative technology. In order to reduce CO_2 emissions by 40 Gt, innovations must be achieved for many more innovative technologies.

The key to future technological developments is to have higher performance, lower cost, reliability, better safety, and other basis for competitive industry in scope, with additional analysis of factors such as CO_2 reduction potential, CO_2 abatement cost, introduction timeline, and effectiveness of technological development to make comprehensive judgments, culminating in a focused and strategic approach.

Still, a *decarbonized society* cannot be realized single-handedly by Japan. It is important to socially implement innovative technologies already available in Japan while helping them be introduced to other parts of the world in need of those technologies. Japan is expected to help move the entire world toward a sustainable society by developing advanced technologies.

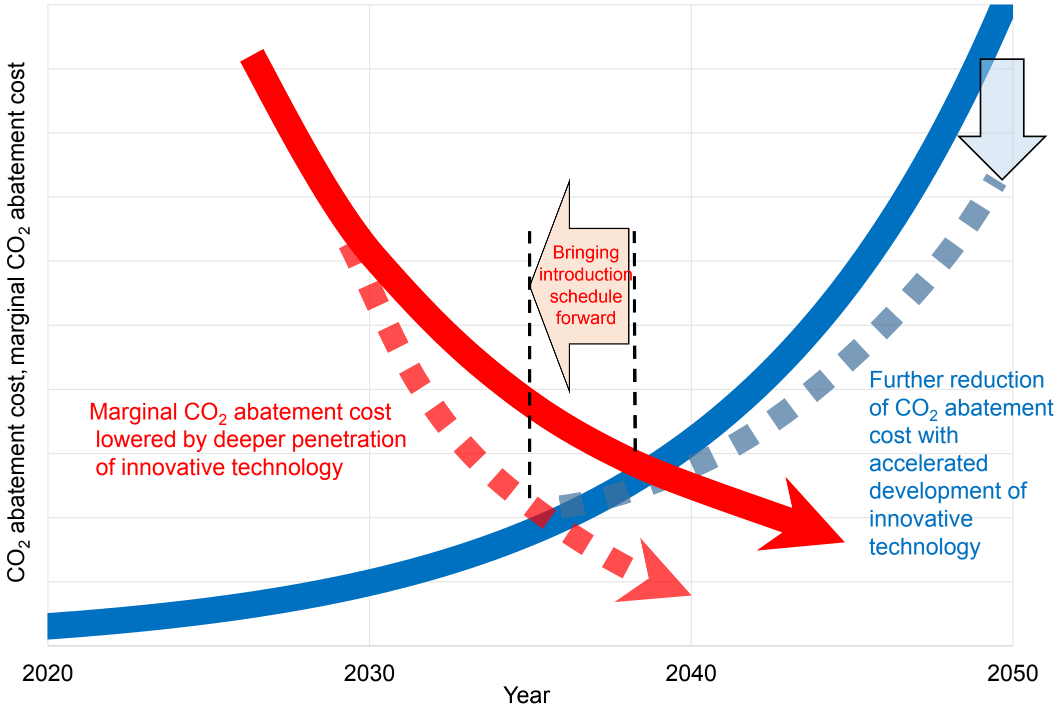

Figure 12 Relationship between technological development and cost reduction
Source: Prepared by Technology Strategy Center, NEDO, 2019

Chapter 4 Expectation toward Creation of Framework for Facilitating Innovation

- A sustainable society cannot be built without creation of a framework for facilitating technological innovations aimed at solving climate change challenges as well as accelerating their social implementation.
- It is important that Japan mobilize the entire nation to continuously discuss how to systematically establish a favorable and attractive research environment and programs for advancing an innovative technology agenda through concerted and focused efforts by businesses and academia, improving them as required, together with promoting international partnerships for developing, as well as supporting the implementation of, those innovative technologies.

In order to solve climate change challenges and build a sustainable society, initiation and social implementation of disruptive innovation is indispensable. For this to be realized, programs for triggering accelerated innovation, such as a comprehensive and objective evaluation system to identify promising technologies for solving climate change issues, will become vital. At the same time, for ensuring that the disruptive innovation thus realized is socially implemented, frameworks and systems for supporting the social implementation of innovative technologies also need to be built.

There are technology agendas that need to be tackled globally and quickly, such as climate change issues. Those challenges should be addressed by continuously developing programs and environment for research where all businesses' and academia's resources can be concentrated.

Climate change is a global challenge that should be countered by initiating, leveraging, and introducing innovative technology throughout the world. This requires a continuous tracking of trends in technology and the status of their development. Japan must be fully aware of its role in the global society and promote international partnerships.

The key to addressing these challenges is that all government, industry, and academia stakeholders steadily play their parts. Furthermore, since a sustainable society cannot be built without addressing serious challenges to the society, of which climate change is the most typical, promoting united efforts by industry, government, and academia will be equally crucial. The government and other public authorities are expected to play a significant role to drive this concerted effort that must involve all members of society.

In January 2020, the government of Japan authorized the "Environment Innovation Strategy," with the aim of making the most of its strength in the fields of energy and environment to initiate disruptive innovation in these areas, make them affordable for social implementation so that they can be introduced globally, with action plans based on the "Long-term Strategy under the Paris Agreement" and "Integrated Innovation Strategy 2019." All stakeholders must steadily work together in line with these Strategies. Also important is continuous discussions on building a framework for encouraging disruptive innovations so that systems can be continuously updated.

Chapter 5 Conclusion

The aim of this "Comprehensive R&D Principle for Sustainable Society 2020" is to offer a comprehensive and objective assessment of technologies that can effectively reduce CO_2. To that end, this Principle has estimated the essential *CO_2 reduction potential* and *CO_2 abatement cost* for a number of innovative technologies, provided the estimates with their underlying logic, in order to help further evaluation of innovative technologies that should be developed and tested.

The world must solve its common issue of climate change caused by greenhouse gas, if it is to remain a prosperous and eco-friendly society living together with its natural environment. As the United Nation's Sustainable Development Goals (SDGs) adopted by the 2015 Summit shows, focusing on sustainability has now become mainstream in the international society. For the purpose of resolving global environment issues while balancing SDGs requirements other than global climate change, Japan is expected to drive developing technologies that can initiate disruptive innovation, leading the way in creating a sustainable society.

The key to building a sustainable society is to facilitate the establishment of the *three social systems* (*circular economy, bioeconomy, and sustainable energy*) in a unified and organic manner, manage these technologies comprehensively, toward their social implementation with economic rationality in mind.

The cost estimate for CO_2 reduction shows that relying solely on traditional methods for offsetting 40 $GtCO_2$ emissions will still incur some $10 trillion every year. This cost cannot be lowered without developing innovative technologies that can trigger innovation.

Another critical condition for a creating a sustainable society is the development of a framework that can accelerate innovation and facilitate its social implementation. It is important that Japan engage all its citizens in continous discussions on how to systematically establish a research environment and programs for advancing key technology agenda through concerted and focused efforts by businesses and academia, improving them as required, together with promoting international partnerships for developing, as well as supporting the implementation of, those innovative technologies.

The next steps will begin with evaluating the data that was not part of this Principle's estimation, while the estimates already available will also be updated in steps. For this purpose, the latest technological developments in Japan and elsewhere will be tracked and partnerships with external institutions will be built, so that the evaluation methods offered can be improved and made more objective. Also important is to consider the potential for further CO_2 reduction through merging and combining different technologies. While this Principle has focused on reducing CO_2, which is 80 percent of greenhouse gas, reduction potential for other emissions such as CH_4 or N_2O must also be estimated.

NEDO will use these evaluation criteria in its technology strategies and other projects for quantitative assessment, so that results and methods acquired through these efforts can be applied for evaluation in many different fields. The institution will also leverage this Principle for supporting its various research and development projects, from embryonic initial-stage researches to initiatives for fast-tracking social implementation.

Lastly, NEDO will continue to play its role as an *innovation accelerator* that can actually deliver innovation to the society and strive to *solve global climate change challenges* as well as *help build a sustainable society*.

Appendix

Table. Examples of CO_2 reduction potential and underlying logic

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Aluminum recycling	0.07–0.1	A	(7.2 tCO_2/t−0.3 tCO_2/t Aluminum) * 0.0106–0.0147 Gt/year = 0.07–0.1 $GtCO_2$/year a) 0.3 tCO_2/t Aluminum b) 7.2 tCO_2/t Aluminum c) 0.0106–0.0147 Gt/year d) Emission intensity values are for post-distribution stages. The emission intensity value for traditional technology include impacts of efficiency improvement and fuel de-carbonization (currently 12 tCO_2/t, 7.2 tCO_2/t in 2050, Emission intensities based on “The Circular Economy 2018” (SITRA)). Aluminum demand estimate of 0.211 Gt for 2050 is based on 2017 result and also the annual growth rate of 2.41% derived from 2040 forecast in World-Aluminum website (http://www.world-aluminium.org/). Introduction amount is based on the assumption that innovative technology will increase the usage of manufactured material by 5.0–7.0%.
Plastic recycling	0.11–0.32	A	(4.48 tCO_2/t−1.85 tCO_2/t plastic) * (0.04–0.12 Gt/year) = 0.11–0.32 $GtCO_2$/year a) 1.85 tCO_2/t plastic b) 4.48 tCO_2/t plastic c) 0.04–0.12 Gt/year d) 25% of retrieved plastics is assumed to be sent to material recycling, another 25% to chemical recycling, with the remaining 50% going to energy recycling. Emission intensities of innovative technologies (1.27, 0.48, and 2.83 tCO_2/t) are weighted averages based on the above percentage for each method. Emission intensities of traditional technologies (3.72, 3.28, and 5.46 tCO_2/t) are calculated using the same logic (The basic emission intensity for each method is based on NEDO-TSC estimate). The introduction amount range of 0.04–0.12 Gt is equal to 10–30% of 0.4 Gt/year, the projected plastic output (PE, PP, PET, and PS) for 2050 in “The future of Petrochemicals” (IEA, 2018).
EOR and CCS	8.0	B	d) Based on reduction potential estimates in the following literature. 8.0 Gt/year is taken as the maximum potential for CO_2 reduction, based on several scenarios presented in IEA ETP 2017 for estimating reduction impact. The maximum cumulative storage capacity has been set at 360 $GtCO_2$, after the “Storing CO_2 through enhanced oil recovery” by IEA. It will take 51 years to exhaust this reserve when emissions are stored at the rate of 7.0 $GtCO_2$/year.

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Next-generation PV	7.0	A, B	644.7 gCO_2/kWh * 3,345 TWh/year = 2.2 $GtCO_2$/year 644.7 gCO_2/kWh * 4,655 TWh/year = 3.0 $GtCO_2$/year 644.7 gCO_2/kWh * 6,700 TWh/year + 300 gCO_2/kWh * 1,620 TWh/year = 4.8 $GtCO_2$/year a) 0.0 gCO_2/kWh b) 644.7 gCO_2/kWh (floating and farmland); 300 gCO_2/kWh (wall and car) c) 11,665 TWh/year d) • 2.2 Gt: ETP 2017 RTS puts PV power supply at 3,345 TWh • 3.0–4.8 Gt 3.0 Gt: ETP 2017 2DS and other figures formed the basis for assuming 8,000 TWh from PV in 2050, including the impact of next-generation innovative technologies. The difference of 4,655 TWh between this 8,000 TWh and 3,345 TWh in RTS is understood to be the potential of next-generation innovative technologies. 4.8 Gt: By assuming further advances in technology and introduction of next-generation PV systems, the following figures are derived: 2.02 TW for floating; 3.01 TW for farmland; 1.68 TW for side wall; 0.56 TW for car-mounted. Facility utilization rates are set at 15.2% for floating and farmland combined, 9.6% for side wall, and 8.7% for car-mounted.
Next-generation wind power generation	6.5	B	644.7 gCO_2/kWh * 10,123 TWh/year = 6.5 $GtCO_2$/year a) 0.0 gCO_2/kWh b) 644.7 gCO_2/kWh c) 10,123 TWh/year d) • 3.4 Gt: ETP 2017 RTS sets wind power at 5,252 TWh. • 1.9–3.1 Gt 1.9 Gt: The 2,927 TWh gap between the 8,179 TWh wind power forecast for 2050 in ETP 2017 2DS and the 5,252 TWh in RTS is assumed to be the potential of next-generation innovative technologies. 3.1 Gt: "Floating Offshore Wind: Market and Technology Review" (2015) sets that Japan, Europe, and the US may potentially introduce floating offshore wind farms with total capacity of 6,950 GW. 20% of this potential is the assumed target of this innovative technology, with facility utilization estimated at 40%.
Next-generation geothermal power generation	0.7	B	644.7 gCO_2/kWH * 1,094 TWh/year = 0.7 $GtCO_2$/year a) 0.0 gCO_2/kWh b) 644.7 gCO_2/kWH c) 1,094 TWh/year d) • 0.4 Gt: ETP 2017 RTS sets geothermal power at 621 TWh • 0.2–0.3 Gt 0.2 Gt: The 310 TWh gap between the 931 TWh geothermal power forecast for 2050 in ETP 2017 2DS and the 621 TWh in RTS is assumed to be the potential of next-generation innovative technologies. 0.3 Gt: The bottom line is the projected 355 TWh for Deep EGS in GeoVision 2019 (https://www.energy.gov/sites/prod/files/2019/06/f63/GeoVision-full-report-opt.pdf). On top of this, it is also assumed that around 50 more 300,000 kW-class Deep EGS or supercritical geothermal power stations will be built in Japan, Europe, and other locations.

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
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C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit) – specific units are kWh, GJ, kg, t, and so on; d) description.
Ocean energy power generation	0.25–0.38	B	644.7 gCO_2/kWh * 381–590 TWh/year = 0.25–0.38 $GtCO_2$/year a) 0.0 gCO_2/kWh b) 644.7 gCO_2/kWh c) 381–590 TWh/year d) 0.25 Gt: The 381 TWh gap between the 478 TWh ocean power forecast for 2050 in ETP 2017 2DS and the 97 TWh in RTS is the assumed potential of this technology. 0.38 Gt: According to "Powering Homes Today, Powering Nations Tomorrow" (2018), ocean energy may provide 1,181 TWh worldwide by 2050. 50% of this capacity is assumed to be actually introduced.
High efficiency thermal power generation	0.86–1.32	A	((0.363 $kgCO_2$/kWh－0.295 $kgCO_2$/kWh) * 3,176–5,082 TWh/year) ＋((0.835 $kgCO_2$/kWh－0.650 $kgCO_2$/kWh) * 3,481–5,293 TWh/year) = 0.86–1.32 $GtCO_2$/year a) 0.295 $kgCO_2$/kWh for LNG and 0.650 $kgCO_2$/kWh for coal b) 0.363 $kgCO_2$/kWh for LNG and 0.835 $kgCO_2$/kWh for coal c) 3,176–5,082 TWh/year for LNG and 3,481–5,293 TWh/year for coal d) With mass introduction of renewable energy, future thermal power plants must be equipped with innovative technologies for improving their performance with features such as agility and partial or minimum load operations. Based on the LNG and coal technologies described in "Technology Roadmap for Next-Generation Thermal Power Generation," the emission intensity of innovative technology for LNG is from the average of GTCC and GTFC (with 60% efficiency) while that of coal is from the average of IGCC and IGFC (50% efficiency). The emission intensity value for traditional technology is taken from ETP 2017 RTS. ETP 2017 RTS estimates are 10,586 TWh for LNG thermal and 11,604 TWh for coal thermal. The introduction amount has been derived by assuming that 30–50% of these capacities will be replaced by innovative technologies. Note that impact from performance improvements in areas such as agility or partial/minimum load operations are not accounted for in this estimation, although they will result in more fluctuating renewable energy sources such as PV being introduced.
Hydrogen power generation	0.19–0.58	A, C	0.363 $kgCO_2$/kWh * 529.3–1,587.9 TWh/year = 0.19–0.58 $GtCO_2$/year a) 0 $kgCO_2$/kWh (only for when hydrogen is used) b) 0.363 $kgCO_2$/kWh c) 529.3–1,587.9 TWh/year d) The "Environment Innovation Strategy" sets the total CO_2 reduction potential of hydrogen at nearly 6.0 Gt for production, transportation, storage, usage, and power generation combined (based on "Hydrogen scaling up" by Hydrogen Council, 2017). The above estimate covers just the power generation stage. The emission intensity of hydrogen power generation is assumed to be 0 $kgCO_2$/kWh. The emission intensity of traditional technology is taken from the LNG thermal figure in ETP 2017 RTS. Power produced by LNG thermal in 2050 (without CCS) is estimated at 10,586 TWh/year (RTS). Of this capacity, 5.0–15% is assumed to be replaced by hydrogen power generation (529.3–1,587.9 TWh/year). CO_2 emissions from hydrogen production, transportation, or storage are not included.

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Fuel cell vehicle	0.06–1.2	A, C	(86 gCO_2/km－15–75 gCO_2/km) * 5,620–16,900 Gkm/year = 0.06–1.2 $GtCO_2$/year a) 15–75 gCO_2/km b) 86 gCO_2/km c) 5,620–16,900 Gkm/year (total driving distance of fuel cell vehicles) d) The "Environment Innovation Strategy" sets the total CO_2 reduction potential of hydrogen at nearly 6.0 Gt for production, transportation, storage, usage, and power generation combined (based on "Hydrogen scaling up" by Hydrogen Council, 2017). The above estimate covers only the passenger types of fuel cell vehicles (FCV). The emission intensity figures for FCV have been adopted from the "Hydrogen scaling up" (Hydrogen Council, 2017): 15 gCO_2/km for green or clean hydrogen (based on renewable energy) and 75 gCO_2/km for hydrogen produced by reforming LNG. The emission intensity of traditional technology is the average figure derived from ETP 2017 RTS data for light duty vehicles (LDV), putting their CO_2 emissions at 5.47 Gt/year and total driving distance at 63,900 Gkm/year. Of the total LDV stock (2.4 billion units), 88% are ICEV (including HV) and 12% are EV (including PHEV and FCEV). In this estimation, ICEV are assumed to be replaced by EV. The total driving distance for the ICEV to be replaced is 56,200 Gkm/year. Another assumption underlying the total driving distance of FCV is that their penetration will be 10–30% of ICEV. (Total driving distance of all FCV) = (total driving distance of ICEV per year) * (FCV penetration) 5,620–16,900 Gkm/year = 56,200 Gkm * 10–30%

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential GtCO_2/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
EV Next-generation battery for EV	0.27–0.91	A	(86 gCO_2/km－59–74 gCO_2/km) * (22,500–33,700 Gkm/year) = 0.27–0.91 GtCO_2/year a) 59–74 gCO_2/km b) 86 gCO_2/km c) 22,500–33,700 Gkm/year (total driving distance of EV with next-generation fuel cell) d) The “Environment Innovation Strategy” estimates that CO_2 emissions can be reduced by 6.0 Gt after taking all actions, such as electrification and fuel de-carbonization. The target of this Principle’s estimate for the CO_2 reduction potential of the next-generation battery is passenger type EV. The emission intensity figure for EV is based on electricity used per unit distance by EV in 2018, 0.19–0.24 kWh/km (with 5.0% battery charging loss, see “IEA Global EV Outlook 2019”), and the emission intensity of electricity, 0.309 kgCO_2/kWh (ETP 2017 RTS). (EV emission intensity) = (electricity used per unit distance by EV)* (emission intensity of electricity) The emission intensity of traditional technology is the average figure derived from ETP 2017 RTS data for light duty vehicles (LDV), putting their CO_2 emissions at 5.47 Gt/year and total driving distance at 63,900 Gkm/year. Of the total LDV stock (2.4 billion units), 88% are ICEV (including HV) and 12% are EV (including PHEV and FCEV). In this estimation, ICEV are assumed to be replaced by EV with next-generation battery. The total driving distance for the ICEV to be replaced is 56,200 Gkm/year. Another assumption underlying the total driving distance of EV with next-generation battery is that their penetration will be 40–60% of ICEV. (Total driving distance of all EV with next-generation battery) = (total driving distance of ICEV per year) * (penetration of EV with next-generation battery) 22,500–33,700 Gkm/year = 56,200 Gkm * 40–60%

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Next-generation power electronics	1.4	A	0.309 $kgCO_2$/kWh * 4,602 TWh/year = 1.4 Gt/year c) Global electricity reduction: 4,602 TWh/year d) The global electricity reduction in 2050 has been extrapolated from electricity reduction in Japan. Global electricity reduction = (electricity reduction in Japan) * (global power generation in 2050 by RTS) / (power generation in Japan in 2050) = 74.36 TWh/year * 45,000 TWh/year / 727 TWh/year = 4,602 TWh/year Electricity reduction in Japan （1）Household appliance (air conditioner and refrigerator): 3.16 TWh （2）Hybrid vehicle and EV: 64.86 TWh （3）Industrial inverter replacement: 1.1 TWh （4）Computer-related: 0.91 TWh （5）Uninterruptible power supply (UPS): 0.1 TWh （6）Inverter for distributed power source: 0.58 TWh （7）Further introduction of inverter: 3.65 TWh （1）Household appliance (air conditioner and refrigerator) In order to calculate the level of power savings, electricity used by these appliances per unit in 2050 is estimated at 950 kWh for air conditioner and 520 kWh for refrigerator, while their stock volumes were set at 100 million units for air conditioner and 60 million units for refrigerator. Performance improvement rate with SI being replaced with SIC is estimated at 2.5% (“Next-Generation Energy Saving Device Technology Survey”, Research and Development Association for Future Electron Devices (FED), March 2008), while also assuming that the transition to SIC will be 100% by 2050. 3.16 TWh = (950 kWh * 100 million units + 520 kWh * 60 million units) * 2.5% （2）Hybrid vehicle and EV Maximum motor output is estimated at 60 kW (from the Toyota website, data for Prius battery capacity) with average power output of 40% (24 kW) for 500 hours of driving per year (FED 2004 research report and the 2005 NEDO survey and research on the introduction and acceptance strategy for SIC power electronics). From the total vehicle stock of 79 million units in 2050 (Automobile Inspection & Registration Information Association website, number of registered vehicles as of April 30, 2012), 60%, or 47 million units, is assumed to be next-generation cars (long-term energy supply and demand outlook by the Supply and Demand Committee of the Advisory Committee for Natural Resources and Energy, first announced in May 2008, revised in August 2008). In order to calculate the level of power savings, performance improvement rate achieved for next-generation vehicles by switching from SI to SIC is assumed to be 11.5% (“Next-Generation Energy Saving Device Technology Survey”, FED, March 2008), while also assuming that the transition to SIC will be 100% by 2050. 64.86 TWh = 24 kW * 500 hours * 47 million units * 11.5% * 100%

Table. Examples of CO_2 reduction potential and underlying logic (continued)

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Next-generation power electronics (continued)	1.4	A	(3) Industrial inverter replacement Power demand in 2010 was some 350 GkWh for industrial and some 200 GkWh for commercial usages (actual power demand in 2010 by the Federation of Electric Power Companies of Japan, April 2012). Almost 70% of the former and 60% of the latter are presumably used by motors ("Survey on the Current Status and Near-Future Development of Power Consumption by Electric Devices and Equipment," Fuji Keizai Group, March 2009). Based on these data, the amount of electricity used by motors ("Survey on the Current Status and Near-Future Development of Power Consumption by Electric Devices and Equipment," Fuji Keizai Group, March 2009) is estimated at 365 GkWh. Since 15% of generic three-phase motors can be assumed to have inverters, the amount of electricity used by inverter-equipped motors is set at approximately 55 GkWh. In order to calculate the level of power savings, performance improvement rate achieved for motors by inverters is assumed to be 2.0% ("Next-Generation Energy Saving Device Technology Survey," FED, March 2008), while also assuming that the transition to SIC will be 100% by 2050. 1.1 TWh = 55 GkWh * 2.0% * 100% (4) Computer-related Production volume is estimated at 21.5 million units, their stock volume at 65 million with a three-year life cycle, 150 W power consumption, and 2,000 hours of annual usage. In order to calculate the level of power savings, performance improvement rate achieved by switching from SI to SIC is assumed to be 4.7% ("Next-Generation Energy Saving Device Technology Survey," FED, March 2008), while also assuming that the transition to SIC will be 100% by 2050. 0.91 TWh = 0.15 kW * 2,000 hours * 65 million units * 4.7% * 100% (5) Uninterruptible power supply (UPS) Basic assumption for UPS is that it uses 300 W power, is used 8,760 hours per year, around 200,000 units are built each year (from METI production volume statistics), and last five years, resulting in a stock level of one million units. In order to calculate the level of power savings, performance improvement rate achieved by switching from SI to SIC is assumed to be 4.1% ("Next-Generation Energy Saving Device Technology Survey," FED, March 2008), while also assuming that the transition to SIC will be 100% by 2050. 0.1 TWh = 0.3 kW * 8,760 hours * 1.0 million units * 4.1% * 100% (6) Inverter for distributed power source The capacity of PV facilities is estimated at 28,000,000 kW and their utilization rate at 12%. In order to calculate the level of power savings, performance improvement rate achieved by switching from SI to SIC is assumed to be 2.0% ("Next-Generation Energy Saving Device Technology Survey," FED, March 2008), while also assuming that the transition to SIC will be 100% by 2050. 0.58 TWh = 28,000,000 kW * 365 days * 24 hours * 12% * 2.0% (7) Further introduction of inverter As in the case of industrial inverter replacement (see (3) above), motor power usage is estimated at 360 GkWh. Switching from SI to SIC has a benefit of making devices smaller, which can be an incentive for introduction of inverters to small pumps. Building upon the current inverter penetration of 15%, the potential for further inverter penetration is estimated at 20% ("Survey on the Current Status and Near-Future Development of Power Consumption by Electric Devices and Equipment," Fuji Keizai Group, March 2009), of which 5.0% is assumed to be SIC inverters in 2050. 3.65 TWh = 365 GkWh * 20% * 5.0%

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Next-generation battery for aircraft	0.072–0.17	A	(0.195–0.455 $GtCO_2$/year) * (1.0－(381 gCO_2/kWh / 603 gCO_2/kWh)) = 0.072–0.17 $GtCO_2$/ year a) 381 gCO_2/kWh b) 603 gCO_2/kWh c) 0.195–0.455 $GtCO_2$/year d) The “Environment Innovation Strategy” sets CO_2 reduction potential in the aviation sector at 2.0 Gt (METI estimate) when the measures based on IATA long-term targets, such as electrification and fuel decarbonization, are implemented. In this section, the impact of electrified aircraft is estimated, based on an operation model for electric aircraft using next-generation batteries for domestic flight. These batteries, once connected to the grid and charged, can let the aircraft cover a distance of around 1,000 km without any other energy source. In order to ensure that the energy used for flight is taken into account, the energy used by the electric aircraft is assumed to be the same as conventional aircraft. The emission intensity of electric aircraft has been calculated based on the emission intensity of electricity, 0.309 $kgCO_2$/kWh (ETP 2017 RTS), while assuming that the electric aircraft’s energy efficiency will be 81% (by also assuming the motor efficiency of 95%, energy conversion efficiency of 95%, and battery discharge efficiency of 90%). (Emission intensity of electric aircraft) = (emission intensity of electricity) * (energy efficiency of electric aircraft) The emission intensity of traditional aircraft is set at 0.0671 tCO_2/GJ, based on the carbon emission intensity of jet fuel, 0.0183 tC/GJ (Ministry of the Environment document at https://www.env.go.jp/council/16pol-ear/y164-04/mat04.pdf). The energy efficiency of jet engine is assumed to be 40%, with a conversion rate of 0.278 Wh/kJ. (Emission intensity of traditional technology) = (emission intensity of jet fuel) / (energy efficiency of jet engine) / 0.278 Wh/kJ Estimate for CO_2 emissions from jet fuel in 2050 is based on the official statement from EU in September 2019 (https://www.europarl.europa.eu/RegData/etudes/ATAG/2019/640169/EPRS_ATA (2019) 640169_EN.pdf) quoting the 2016 ICAO agreement that said the emissions are “expected to increase by a further 300-700%” against 2005 levels, and IATA data putting the CO_2 emissions from jet fuel in 2005 at 0.65 Gt (“IATA Airline Industry Economic Performance,” https://www.iata.org/publications/economics/Reports/Industry-Econ-Performance/Central-forecast-mid-year-2018-tables-v1.0.pdf, 2018) CO_2 emissions from jet fuel in 2050 will reach between 1.95 $GtCO_2$/year, if rate of increase from 2005 is 300%, and 4.55 $GtCO_2$/year if this rate is 700%. The assumption behind the energy consumption of 10% is that electric aircraft will be used only for domestic flights, and then only for 25% of them. The energy consumption rate for domestic flights is set at 40% of the total energy consumption (2017 IATA report, https://www.iata.org/pressroom/pr/Pages/2017-09-06-01.aspx). (CO_2 emissions from jet fuel to be replaced) = (CO_2 emissions from jet fuel in 2050) * (penetration of electric aircraft) 0.195–0.455 $GtCO_2$/year = 0.65 $GtCO_2$/year * (300–700%) * 10%

Table. Examples of CO$_2$ reduction potential and underlying logic (continued)

*Estimation pattern
A: calculation based on estimated penetration of each technology
B: calculation based on estimates by specialist institutions
C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO$_2$ reduction potential GtCO$_2$/year	Estimation pattern (*)	Basis for estimating CO$_2$ reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO$_2$ per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Bio-jet fuel for aircraft	0.64–1.5	A	(0.0671 tCO$_2$/GJ−0.0302 tCO$_2$/GJ) * 17.5–40.7 EJ/year = 0.64–1.5 GtCO$_2$/year a) 0.0302 tCO$_2$/GJ b) 0.0671 tCO$_2$/GJ c) 17.5–40.7 EJ/year d) The “Environment Innovation Strategy” sets CO$_2$ reduction potential in the aviation sector at 2.0 Gt (METI estimate) when the measures based on IATA long-term targets, such as electrification and fuel de-carbonization, are implemented. In this section, the impact of bio-jet fuel is estimated, based on the assumption that bio-jet will be widely used and power all international flights (mixture rate 100%) in 2050 (making up 60% of total consumption, according to 2017 IATA data in https://www.iata.org/contentassets/9faa9f69011d46c484d93e6dd97a7f52/passenger-analysis-jul-2017.pdf). The CO$_2$ emission intensity of bio-jet fuel is based on CO$_2$ emission intensity of existing jet fuel, 0.0671 tCO$_2$/GJ, and assumed to be 45% of this figure. Since Japan has yet to define regulatory values for reducing CO$_2$ emission from bio-jet fuel, the maximum CO$_2$ emission allowed for bio-methanol, which is 45% of fossil-based fuel, has been applied. The CO$_2$ emission intensity of current jet fuel is set at 0.0671 tCO$_2$/GJ, based on the carbon emission intensity of jet fuel, 0.0183 tC/GJ (Ministry of the Environment document at https://www.env.go.jp/council/16pol-ear/y164-04/mat04.pdf). Estimate for CO$_2$ emissions from jet fuel in 2050 is based on the official statement from EU in September 2019 (https://www.europarl.europa.eu/RegData/etudes/ATAG/2019/640169/EPRS_ATA(2019)640169_EN.pdf) quoting the 2016 ICAO agreement that said the emissions are “expected to increase by a further 300-700%” against 2005 levels. This 300–700% range has been directly applied here. This means that CO$_2$ emissions from jet fuel, 0.65 GtCO$_2$/year in 2005 (https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---2018-mid-year---table/), in 2050 will reach between 1.17 GtCO$_2$/year if rate of increase from 2005 is 300%, and 2.73 GtCO$_2$/year if this rate is 700%. When the CO$_2$ emission intensity of 0.0671 tCO$_2$/GJ is applied, the energy consumption will be 17.5–40.7 EJ/year.
Cellulose nanofiber	0.22–0.27	A	1.5 tCO$_2$/unit * (1.8–2.2 billion units) / 12.44 years = 0.22–0.27 GtCO$_2$/year d) The “Environment Innovation Strategy” estimates that CO$_2$ emissions can be reduced by 6.0 Gt after taking all actions, such as electrification and fuel de-carbonization. This section has estimated the CO$_2$ reduction potential of light-weight composite material produced from cellulose nanofiber (CNF) and plastic. According to research data, CO$_2$ emissions of a vehicle throughout its lifecycle can be lowered by 1.5 tCO$_2$ per unit (J. Jpn. Inst. Energy, 95, 8, 2016), with a vehicle’s lifetime set at 12.44 years. A PricewaterhouseCoopers forecast puts the number of vehicles in 2050 at 2.01 billion units. Allowing for variances of 0.2 billion units in both directions has resulted in the 1.8–2.2 billion range.

Table. Examples of CO_2 reduction potential and underlying logic (continued)

*Estimation pattern
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C: calculation based on targets and outlooks set out by the government and industries
D: calculation based on the maximum penetration of technology or installation of equipment

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for estimating CO_2 reduction potential a) emission intensity of innovative techs; b) emission intensity of traditional techs (tCO_2 per specific unit); c) introduction amount (specific unit)–specific units are kWh, GJ, kg, t, and so on; d) description.
Bioplastic	0.45–0.67	A	1.124 Gt/year * 20–30% * 2.0 tCO_2/t plastic = 0.45–0.67 $GtCO_2$/year c) 20–30% d) The Ellen MacArthur Foundation report “The New Plastics Economy: Rethinking the future of plastics” estimates plastic production level in 2050 at 1.124 Gt/year, while Japan Organics Recycling Association’s projection for CO_2 emission reduction impact from switching to petroleum-based plastics to biomass-based types is around 140–200% of the plastics’ weight. Assumption behind the CO_2 reduction potential of 0.45–0.67 $GtCO_2$ is that, by 2050, 20–30% of all plastics are switched to biomass-based material, and also that the CO_2 reduction will be 200% of the plastics’ weight.
Forestation	3.6–3.8	B	d) These estimates are taken from study by the Mercator Research Institute on Global Commons and Climate Change and other researchers (Environ. Res. Lett., 13, 2018), and another study by the United Nations Environment Programme (UNEP) (The Emissions Gap Report 2015).

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TSC Foresight

Comprehensive R&D Principle for Sustainable Society 2020

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