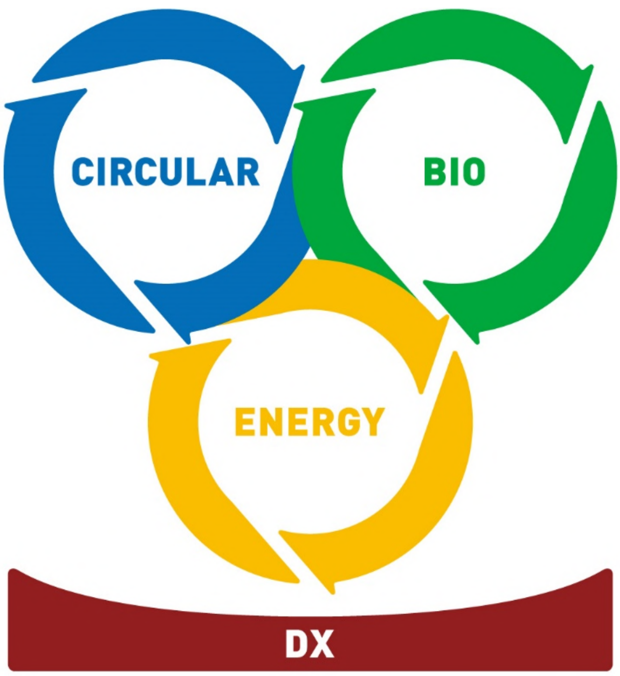
Technology Strategy Center Report

TSC Foresight

August 2023

Comprehensive R&D Principle for Sustainable Society 2023

3 Essential Social Systems for Sustainable Society



TSC is the abbreviation for Technology Strategy Center.

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

Executive **Summary**

<Chapter 1> Toward Realizing a Sustainable Society

● Vision for the Future

NEDO aims to build a future in which international society is economically rich, environmentally friendly, coexists with nature, maintains and develops diversity in nature and ecology, 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 overcome, so we need to help realize a sustainably developing society.

● Movement for Realizing a Decarbonized Society

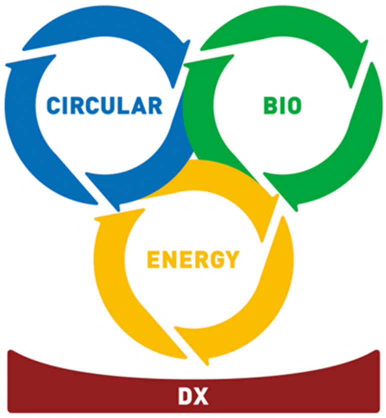
Climate change is becoming an ever more serious issue. Since this decade began, many countries around the world have announced greenhouse gas (GHG) reduction targets aimed at achieving carbon neutrality by 2050, and their efforts are accelerating rapidly. Japan, as well as other countries, announced its 2050 Carbon Neutrality Declaration in October 2020, and in February 2023 compiled the Basic Policy for the Realization of GX. The aim is to fulfill the 2050 Carbon Neutrality Declaration and other international commitments and at the same time achieve economic growth and enhanced industrial competitiveness. Furthermore, security risks in supply chains have become apparent as a social challenge to overcome.

Efforts to develop technologies to realize a decarbonized society and implement them in society are fundamental means for overcoming such social challenges and climate change, so further promoting these efforts is essential.

● 3 Essential Social Systems for Sustainable Society and Digital Transformation Fundamental to them

A key to realizing a sustainable society is promoting the following three social systems in an integrated manner:

- ◆ Circular economy
- ◆ Bioeconomy
- ◆ Sustainable energy



It is important to consider these three social systems in a comprehensive manner, apply them to technical innovation, and implement them in society in an economically rational manner. To develop these social systems in an integrated and continuous way,

- ◆ Digital transformation (DX)

is essential as a foundation to support them.

● Objective of Comprehensive Principle 2023

Comprehensive Principle 2023 is intended to give an overview of technologies related to the *3 Essential Social Systems for Sustainable Society and the Digital Transformation Fundamental to them*. The aim is to identify technologies that should be developed and are demonstrated to help alleviate climate change, and then recommend that their CO_2 reduction effects should be evaluated comprehensively and objectively with a view to achieving carbon neutrality by 2050. The intention is also to improve technologies considered to have increased importance based on the latest social and technological trends and offer specific estimates for some of them, thereby helping evaluate technologies that should be developed and demonstrated. Under the Comprehensive Principle, studies are focused on reducing CO_2 emissions, which are the largest component of GHG emissions.

<Chapter 2> GHG Emissions and Marginal Abatement Cost

The marginal abatement cost to achieve carbon neutrality would exceed ¥50,000/tCO_2 with conventional technologies. However, it is essential to innovate through discontinuous innovations and social implementation, as conventional technologies would not be able to reduce the marginal abatement cost to a globally acceptable level.

Specifically, as *key initiatives*, we need to promote *decarbonization of energy use; reduction of final energy consumption; introduction of negative emission technologies*; and *non-energy related GHG emissions reduction*.

<Chapter 3> Trends and Prospects for the 3 Essential Social Systems for Sustainable Society and the Digital Transformation Fundamental to them

Focusing on the *key initiatives* cited in Chapter 2 in order to identify technologies that should be developed to achieve carbon neutrality, Chapter 3 gives an overview of technologies related to the *3 Essential Social Systems for Sustainable Society and the Digital Transformation Fundamental to them*, considering the latest trends, and presents significant technologies.

The *key initiatives* cannot be implemented sustainably without collaboration among the *3 Essential Social Systems for Sustainable Society and the Digital Transformation Fundamental to them*.

<Chapter 4> Evaluation of Significant Technologies

Chapter 4 sets out the *CO_2 reduction potential* and *CO_2 abatement cost* estimated mainly for the technologies presented in Chapter 3, as well as the basis for the estimates.

These estimates may increase or decrease due to technical factors, including the speed of technological progress and innovation as well as changes in social environments, including introduction policies and social receptivity. Therefore, continuous verification is required with knowledge from those involved.

<Chapter 5> Expectations for Creating a Framework to Stimulate Innovation

Toward achieving carbon neutrality by 2050, heavy policy support that could bring research and development to the social implementation phase has been announced, mainly by developed countries. The time has come when corporate and national competitiveness depend directly on the success or failure of these efforts.

Japan also has announced many policies that encourage public and private investments in promoting carbon neutrality. As a foundation for such an effort, there is a need to build a comprehensive framework for creating research and development results and implementing them in society to drive innovation. In addition to having outstanding researchers, achieving this requires people who are able to promote rule-making in consideration of trends in business models, investments, and domestic and foreign policies and technologies. There are high expectations for the industrial, academic, and public sectors to fulfill their given roles step by step.

<Chapter 6> Conclusion

Innovation is essential for attaining carbon neutrality by 2050. Discussions based on quantitative evaluation (e.g., *CO_2 reduction potential*) are important for evaluating the technologies that should be developed and demonstrated in order to promote the *3 Essential Social Systems and Digital Transformation* for realizing a sustainable society in an integrated manner.

To identify technologies to work on, it is necessary to keep assessing technology based on the latest information and data, according to the approaches suggested in Comprehensive Principle 2023. To achieve this, improving evaluation techniques and their objectiveness in cooperation with external organizations is crucial, and we must strive to ensure that Comprehensive Principle 2023 is reflected in policies and so on.

To play a role in a series of initiatives toward carbon neutrality, the New Energy and Industrial Technology Development Organization (NEDO) will work with the government and relevant authorities to strengthen its role as an *innovation accelerator* that finds the seeds of innovation and implements them in society, and aim to *solve the issue of global climate change* and *contribute to realizing a sustainable society*, thereby contributing further to solve social challenges.

Table of Contents

Introduction

The global average temperature has been on the rise since the late 18th century, when the Industrial Revolution began. The Intergovernmental Panel on Climate Change (IPCC) suggests in the Sixth Assessment Report (AR6)[1] that the average temperature between 2011 and 2020 was higher than that between 1850 and 1900 by 1.09°C (Figure 1), and there is no doubt that human-caused GHG emissions are a cause of global warming. The climate change simulation results in this report show that the global temperature rise will exceed far beyond 1.5 to 2.0°C in the next several decades unless GHG emissions are significantly reduced[1]. Climate change, which is caused by GHG emissions from humans, is an urgent global issue, and the world must work together to achieve carbon neutrality.

In addition to climate change, the idea of emphasizing sustainability has prevailed in the international community. For example, the Sustainable Development Goals (SDGs) have become well established as international goals for 2030. In the discussions and agreements made at the 26th and 27th sessions of the Conference of the Parties to the United Nations (UN) Framework Convention on Climate (COP26 and COP27), efforts to support developing countries are required in addition to measures against climate change.

Japan must accurately grasp the global trends in these environmental issues, promote innovation that will contribute to solving global environmental issues while ensuring consistency with SDGs other than those related to climate change, and actively help to cut GHG emissions not only in Japan but also all over the world.

1 Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021) https://www.ipcc.ch/report/ar6/wg1/

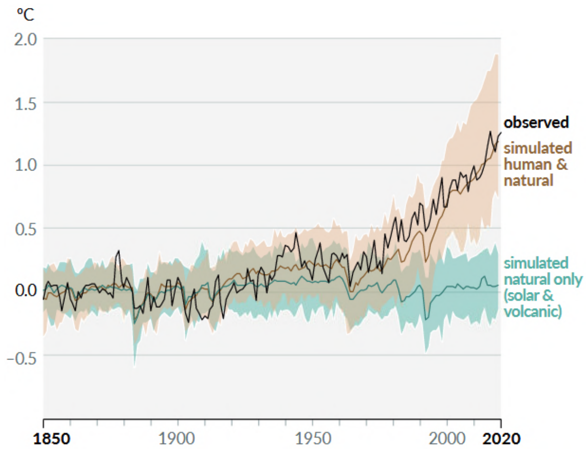


Figure 1 Changes in the global average temperature relative to 1850–1900

Source: Summary for Policymakers, IPCC AR6 WG1

Chapter 1 Toward Realizing a Sustainable Society

- The global warming goal for countries around the world to tackle has been raised to carbon neutrality by 2050, and their efforts are accelerating rapidly.
- In order to overcome climate change and realize a sustainable society, it is essential to promote the 3 Social Systems, namely *circular economy*, *bioeconomy*, and *sustainable energy*, in an integrated manner, as well as *digital transformation*, which will play a fundamental part in promoting the 3 Social Systems.
- Developing technologies to achieve carbon neutrality by 2050 and implementing them in society is extremely important for solving the issue of climate change. Comprehensive Principle 2023 focuses on technologies to reduce CO_2 emissions, which are the largest component of GHG emissions.

1-1 Vision for the Future

Our future is infinite, so climate change is a challenge we must overcome to:

- ensure that our society will continue to be one that is economically rich, is environmentally friendly, and coexists with nature even 100 and 200 years from now;
- ensure that diversity in nature and ecology is continuously maintained and developed in the future; and
- meet the social needs of the current generation, and at the same time hand over a better society to future generations without compromising the social needs of the future one.

Even if there are considerable difficulties, we should aim to overcome climate change; achieve harmony among the environment, economy, and society; continuously create new value; and realize a society that will develop in a sustainable manner, or realize a *sustainable society*.

1-2 Movement for Realizing a Decarbonized Society

Climate change is becoming an increasingly serious issue. To overcome this problem, in recent years efforts toward decarbonization have been accelerating rapidly around the world. Table 1 gives a summary of movements against climate change since the Paris Agreement. Especially after 2020, when the impact of the COVID-19 pandemic on the global economy became a serious concern, it was a significant turning point when climate change was regarded as a strategy for economic recovery and, what is more, economic growth afterwards. In the EU, Next Generation EU was announced in May 2020, and furthermore, Fit for 55[2] was announced in July 2021, which presented specific policies for the EU to achieve a CO_2 emission reduction of 55% by 2030. In the US, the Biden administration returned to the Paris Agreement in January 2021, and hosted the Leaders Summit on Climate (Climate Summit) in April 2021. At the Climate Summit, many countries presented their GHG reduction targets for achieving carbon neutrality by 2050 as a Nationally Determined Contribution (NDC)[3]. After that, international authorities, research institutions, and other organizations announced their scenarios based on the 2050 Carbon Neutrality goal. In May 2021, the International Energy Agency (IEA) announced a scenario aimed at achieving net-zero CO_2 emissions (Net Zero Emissions by 2050)[4], and the International Renewable Energy Agency (IRENA)[5] and other organizations announced scenarios of achieving net-zero emissions by around 2050. The IPCC released AR6 from 2021 to 2022, which again emphasized the importance of achieving the 1.5°C goal. At COP26, which was held in the UK between October and November 2021, the Glasgow Climate Pact was agreed on, which, from the scientific perspective suggested in the IPCC's AR6, shows a determination to set it as a long-term global goal that the world will continue efforts to reach the 1.5°C target. In addition to providing direction for problem solving through the acceleration of innovation, this Pact also emphasized the importance of support for developing countries and the need for cooperation at every level (e.g., countries, regions, communities, generations, genders, governments, non-governmental organizations, and the private sector). At COP27, which took place in Egypt in November 2022, the participating countries

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2 'Fit for 55' (European Commission, 2021)
https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

3 Reviewing the Climate Summit and Checking the New Emissions Reduction Goals (US) (Japan External Trade Organization (JETRO), 2021)
https://www.jetro.go.jp/biz/areareports/special/2021/0401/9ac24934b1ca2265.html

4 Net Zero by 2050 (IEA, 2021) https://www.iea.org/reports/net-zero-by-2050

5 World Energy Transitions Outlook (IRENA, 2022)
https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022

reaffirmed the importance of the 1.5°C goal based on the results of COP26. They agreed to strengthen the goal for 2030 in line with the target temperature in the Paris Agreement and also agreed to establish a fund for losses and damage caused by the adverse effects of climate change. Likewise, discussions are underway in the international community, not only on emissions reduction, but also on the impact of climate change.

Japan is also considering climate change as an urgent global issue and accelerating its efforts in this area. In October 2020, Japan declared that it would achieve carbon neutrality by 2050. In December of the same year, it formulated the Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (Green Growth Strategy), which is aimed at achieving a virtuous cycle of economy and environment, and established the Green Innovation Fund in March 2021. In April of 2021, before the Climate Summit, Japan announced its NDC aimed at achieving CO_2 emission reduction of 46% from the 2013 level by 2030, and in June, revised its Green Growth Strategy to present specific measures to achieve carbon neutrality by 2050. In October of the same year, Japan's Cabinet approved the Sixth Strategic Energy Plan, which presents a roadmap for the energy policies to ensure S + 3E (Safety + Energy Security, Economic Efficiency, and Environment) and achieve the GHG emissions reduction goals.

The growing momentum toward carbon neutrality has been affected by the invasion of Ukraine by Russia, which broke out in February 2022. Because of resource supply disruptions from Russia and Ukraine, as well as the paralysis of logistics arising from the COVID-19 crisis and other reasons, the world is encountering an unstable supply and rising prices of resources and materials, including fossil fuels. All of this has highlighted the importance of global energy security and security risks in supply chains. In particular, some European countries, which have depended heavily on energy resources from Russia, have stopped the supply of crude oil and natural gas from Russia, and instead, have extended the life of their nuclear power plants and restarted coal-fired thermal power plants. It is recognized that promoting a transition to clean energy to achieve carbon neutrality while accepting these realistic solutions as emergency measures will lead to ensuring energy security and fundamentally solving social challenges, such as climate change. Policies based on this recognition have been launched mainly in Europe. For example, the EU expanded and accelerated the above-mentioned Fit for 55 and moved up its schedule, and formulated REPowerEU[6]. REPowerEU includes measures

[6] REPowerEU (European Commission, 2022)
https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

aimed at both ensuring energy security and achieving carbon neutrality through the elimination of dependence of energy resources on Russia, promotion of energy saving; expansion of renewable energy use, and widespread use of hydrogen. This situation also requires the strengthening of the supply chain of valuable minerals and other materials essential to the transition to clean energy.

Under these circumstances, in February 2023, Japan's Cabinet approved the Basic Policy for the Realization of GX in order to simultaneously reduce emissions, achieve economic growth, and enhance industrial competitiveness, with the basic premise of ensuring a stable energy supply. Consequently the laws required to implement the basic policy, namely the Act on Promotion of a Smooth Transition to a Decarbonized Growth-Oriented Economic Structure (GX Promotion Act) and the Act for Partial Revision of the Electricity Business Act and Other Acts for Establishing Electricity Supply Systems for Realizing a Decarbonized Society (GX Decarbonized Power Supply Act), were enacted in May 2023.

Drawing on the Basic Policy for the Realization of GX, Japan will comprehensively push energy conservation and promote a transition to decarbonized power supplies such as renewable energy and nuclear power in order to eliminate excessive dependence on fossil fuels. It will also establish an energy supply-and-demand structure that can deal with crisis. The government has announced a specific scheme to provide up-front investment support amounting to around 20 trillion yen by using GX Economy Transition Bonds and introduce carbon pricing to strongly attract more than 150 trillion yen of investments over 10 years from companies interested in investing in green transformation.

Table 1 Movements against climate change since the Paris Agreement

Nov.–Dec. 2015	The Paris Agreement was adopted at COP21.
Apr. 2016	The National Energy & Environment Strategy for Technological Innovation towards 2050 (NESTI-2050) was formulated by the Council for Science, Technology and Innovation (CSTI), Cabinet Office of Japan.
Oct. 2018	The IPCC released the Special Report on Global Warming of 1.5°C.
Jun. 2019	The Long-term Strategy under the Paris Agreement was approved by the Cabinet of Japan.
Dec. 2019	The European Commission announced the European Green Deal.
Jan. 2020	The Environment Innovation Strategy was formulated.
Feb. 2020	NEDO released the Comprehensive R&D Principle for Sustainable Society 2020 (NEDO Comprehensive Principle 2020).
Mar. 2020	WHO declared that COVID-19 was pandemic.
May 2020	The European Commission announced the Next Generation EU, an initiative for economic recovery from the COVID-19 crisis. The recovery fund and long-term budget were approved by the European Council in July.
Oct. 2020	The 2050 Carbon Neutrality goal was declared.
Dec. 2020	The Ministry of Economy, Trade and Industry formulated the Green Growth Strategy Through Achieving Carbon Neutrality in 2050, aimed at achieving a virtuous cycle between the economy and the environment.
Jan. 2021	In the U.S., the Biden administration took office and rejoined the Paris Agreement.
Apr. 2021	Japan announced the NDC aimed at reducing CO_2 emissions by 46% in 2030 from the 2013 level.
Apr. 2021	The Leaders Summit on Climate was hosted by the US (Japan also emphasized its NDC).
May 2021	The IEA announced a scenario for achieving net-zero CO_2 emissions by 2050 (Net Zero by 2050). (It was also presented as a basic scenario for decarbonization in the WEO released in October 2021.)
Jun. 2021	The Ministry of Economy, Trade and Industry released a revised version of the Green Growth Strategy Through Achieving Carbon Neutrality in 2050. The Green Innovation Fund was established.
Jul. 2021	The European Commission announced Fit for 55, a comprehensive policy package for promoting the European Green Deal.
Aug. 2021	The IPCC released the Sixth Assessment Report (Working Group I: Physical Science Basis).
Oct. 2021	The Sixth Strategic Energy Plan was approved by the Cabinet of Japan.
Oct.–Nov. 2021	COP26 was held in the UK.
Feb. 2022	The IPCC released the Sixth Assessment Report (Working Group II: Impacts, Adaptation, and Vulnerability).
Feb. 2022	Russia invaded Ukraine.
Apr. 2022	The IPCC released the Sixth Assessment Report (Working Group III: Mitigation of Climate Change).
May 2022	The European Commission announced RepowerEU.
Nov. 2022	COP27 was held in Egypt.
Feb. 2023	The Basic Policy for the Realization of GX was approved by the Cabinet of Japan.
May 2023	The GX Promotion Act and GX Decarbonized Power Supply Act were enacted.

Note: The red text indicates the movements that took place in Japan.

1-3 Social Systems Viewed from the Perspective of Carbon Recycling

This section discusses the roadmap to significantly reduce CO_2, which accounts for a large proportion of GHG emissions, based on the social systems (Figure 2) viewed from the perspective of carbon recycling, which takes into consideration all of the reduction, storage, immobilization, and recycling of CO_2.

Regarding the energy demand indicated in blue, CO_2 emissions are reduced as initiatives to save energy make progress. CO_2 emissions can also be reduced by cutting the use of fossil fuels through the maximum utilization of sustainable energy, such as renewable energy, hydrogen, and biomass. As such, promoting *sustainable energy* is essential to reduce CO_2 emissions.

Also, CO_2 emissions from energy utilization can be separated and captured as much as possible by, for example, Direct Air Capture (DAC) and stored underground by Carbon Dioxide Capture and Storage (CCS), and stored, for example, in chemicals and minerals by Carbon Recycling (CR) technology. These technologies will make it possible to significantly reduce CO_2 emissions into the atmosphere and at the same time reduce demand for energy and materials through recycling and sharing. Thus, promoting the *circular economy*, which maximizes the recycling of material resources, is essential to reduce CO_2 emissions.

Also, CO_2 in the atmosphere can be immobilized in plants by photosynthesis. Furthermore, it will be possible to reduce CO_2 emissions by using carbon-neutral biomass as energy or for material production. As just described, promoting the *bioeconomy*, which makes the most of biomass to reduce CO_2 in the atmosphere, is essential for cutting CO_2 emissions.

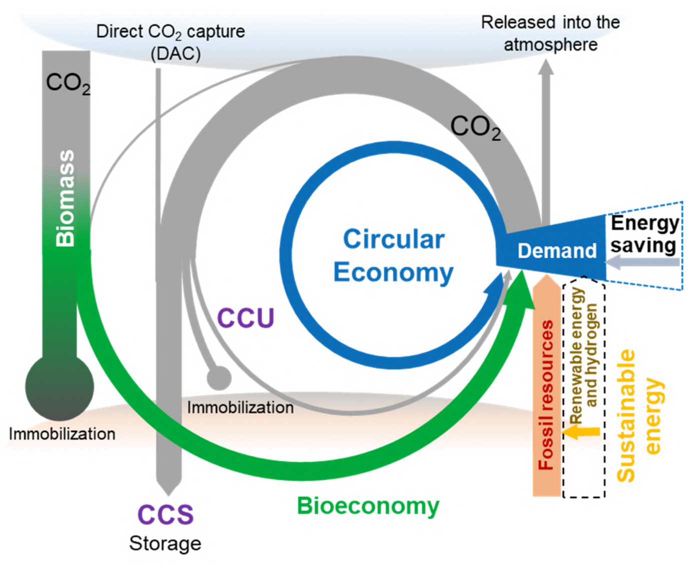

Figure 2 Social systems viewed from the perspective of carbon recycling

1-4 3 Essential Social Systems for Sustainable Society and Digital Transformation Fundamental to them

As described in the previous section, considering the movement toward realizing a decarbonized society, the continuous development of the three social systems, namely (1) the circular economy, (2) the bioeconomy, and (3) sustainable energy, is essential to realize a sustainable society. Also, it is important to consider these three social systems in a comprehensive manner, lead them to discontinuous innovation, and implement them in society in an economically rational manner.

To promote these three social systems in an integrated manner, (4) digital transformation (DX) is essential as a foundation for supporting them. Figure 3 shows that the three social systems, which are crucial for bringing about a sustainable society, are developing in a sustainable manner, relating to one another, influencing one another, and are in optimal harmony with one another. At the same time, they are supported by digital transformation as their foundation. The following describes the three social systems and digital transformation.

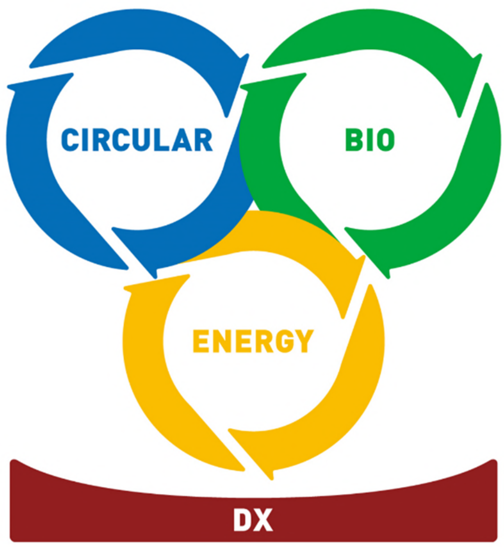

Figure 3 3 Essential social systems for sustainable society and digital transformation fundamental to them

(1) Circular economy (blue)

We use a variety of material resources on the planet to carry out economic and social activities. The circular economy is a social system where these material resources are recycled as much as possible and consumed as little as possible. Such an economy includes concepts for making the best use of material resources, such as promoting the sharing economy. In the figure, circular economy is represented in blue, which is the symbolic color of the Earth.

The circular economy had been originally considered important as a means of ensuring resource conservation and resource security, and reducing waste materials. However, its effectiveness in cutting CO_2 emissions by reducing new consumption is also important from the perspective of climate change measures. For example, the steel, cement, chemical, non-ferrous, and other material industries emit large amounts of CO_2 during production processes, and it is difficult to take drastic measures to curb them. 3R (Reduce, Reuse, Recycle) measures can reduce the consumption of materials, thereby contributing to CO_2 reduction. In addition, new demand-side business models such as sharing are expected to reduce the consumption of goods and products as well as reduce CO_2 emissions by optimizing transportation systems, etc[7]. Moreover, carbon recycling, in which CO_2 is considered as a carbon resource and recycled as various carbon compounds, is expected as a future way to cut CO_2 emissions. In addition, nitrogen oxides in exhaust gas are GHGs, and nitrogen recycling, which collects, detoxifies, and reuses nitrogen oxides, is expected as an effective measure against global warning. The nitrogen cycle, including nitrogen oxides in wastewater, is attracting attention from the perspective of solving planetary boundary issues.

(2) Bioeconomy (green)

Humans share the Earth with an enormous number of organisms, and these organisms have codependent relationships with one another where they produce foods and other materials useful to other organisms while sustaining their own lives. The bioeconomy is a social system where the materials these organisms produce are utilized as much as possible with a minimal load on the ecosystem formed by these organisms, with the aim of maximizing both the ecological function and the contribution of biological

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[7] ITF Transport Outlook 2017 (OECD, 2017)
https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2017_9789282108000-en

resources. In the figure, the bioeconomy is represented in green, which is the symbolic color of organisms.

Then bioeconomy enables increased production, utilization, conservation, and reproduction of biological resources through the application of relevant knowledge, science, technology, and innovation, thereby offering sustainable solutions (information, product, process, and service) on a global scale, including within and across economic zones[8] [9]. The bioeconomy also helps to reduce CO_2 emissions, especially when bioprocesses with low energy consumption are introduced. That is, it can lower the concentration of CO_2 in the atmosphere by efficient carbon fixation, i.e., the conversion of dilute CO_2 in the atmosphere into organic molecules through photosynthesis; and substitution of bioproducts made by appropriately applying biological resources (biomass) in which CO_2 has been fixed, from fossil fuel-based products. New and innovative technologies are being developed continuously, which could lead to new discoveries or become game-changers. The bioeconomy is also expected to help realize a society where both urban and rural communities thrive while enhancing economic, social, and ecological recovery.

(3) Sustainable energy (orange)

In addition to fossil fuels, the Earth is home to natural energy sources such as sunlight, wind, geothermal heat, oceans, and others derived from solar radiation and heat inside the Earth. When considered as a social system, sustainable energy is one where the use of these nature-based energy sources is maximized and the load on the Earth's environment is minimized. It is aimed at ensuring the long-term, stable supply and use of energy. In the figure, sustainable energy is represented in orange, which is the symbolic color of energy.

Most of the energy demand that has been expanding rapidly since the Industrial Revolution has been met by fossil fuels, such as coal, crude oil, and natural gas. However, they are depletable resources and emit large amounts of GHGs when mined and burned. This means that realizing a sustainable society requires a transition from conventional energy systems using fossil fuels to sustainable ones. Specifically, it is important to promote the development of the following: renewable energy utilization

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[8] The Bioeconomy to 2030 (OECD, 2009) https://www.oecd-ilibrary.org/economics/the-bioeconomy-to-2030_9789264056886-en

[9] Bioeconomy Strategy 2019 (Cabinet Office, 2019) https://www8.cao.go.jp/cstp/bio/index.html

technologies, where renewable energy will be considered as the primary form of energy generation; secondary energy technologies for converting, transporting, and storing the primary energy; energy management technologies aimed at consolidating these technologies and optimizing energy utilization; and energy saving technologies for using energy as efficiently as possible. The goal is to lower the cost of these technologies and implement them in society as soon as possible.

(4) Digital transformation (wine red)

Information technology (IT) has been advancing at breakneck speed since the end of the 20^{th} century. It has boosted people's convenience and affluence, and has made business more global, agile, and efficient. But for businesses to gain an advantage in the face of future changes that will happen around the world, they need to embrace digital transformation (DX). In the figure, digital transformation is represented in wine red below the three social systems because digital transformation is a foundation for embodying the three social systems and connecting them with one another.

Generally, digitization and digitalization are required to achieve digital transformation. Digitization is the process of changing physical and analog tasks to digital format to convert work partially or locally to digital format. Digitalization is the process of identifying organic links among the data obtained by converting tasks to digital format in order to switch entire work processes to digital format. Digital transformation is the process of transforming the form of business through digitization and digitalization to offer new value to society. Also, greening related to IT has been discussed as Green by IT, by which IT is used to achieve decarbonization, and Green of IT, by which the power consumption for IT itself is reduced. Green by IT can be broadly defined as the result of digital transformation.

1-5 Objective of Comprehensive Principle 2023

NEDO formulated the Comprehensive R&D Principle for Sustainable Society 2020 (hereinafter, Comprehensive Principle 2020) in February 2020 (Table 1) because promoting the three social systems, namely the *circular economy*, the *bioeconomy*, and *sustainable energy*, in an integrated manner and working on technology development and social implementation aimed at achieving carbon neutrality around the world, are crucial factors for solving the issue of climate change. Since then, concepts similar to the three social systems have appeared in development strategies and policies in various places, and similar ideas to solve the problem of climate change have been spreading[10] [11]. Since the situation surrounding climate change is becoming ever more serious, efforts based on the NDC aimed at achieving carbon neutrality by 2050 are accelerating all around the world.

Therefore, NEDO decided to formulate the Comprehensive R&D Principle for Sustainable Society 2023 (hereinafter, Comprehensive Principle 2023) based on the results of analysis of the current situation and technical trends. Comprehensive Principle 2023 follows the basic concept of comprehensively and objectively evaluating technologies effective at cutting GHG emissions in Comprehensive Principle 2020. Also, Comprehensive Principle 2023 presents technologies considered important for achieving carbon neutrality by 2050 and offers specific estimates for their GHG reduction effects as well as the basis for these estimates. With this, NEDO aims to help evaluate technologies that should be developed and demonstrated.

In order to present technologies that are important in overcoming climate change, it is necessary to develop an overview of the technologies related to the three social systems of the *circular economy*, the *bioeconomy,* and *sustainable energy*, as well as *digital transformation*, which supports these social systems, based on the latest social and technical trends, and quantitatively assess the following: the extent to which GHG emissions can be reduced by each technology; how much each technology costs; and when each technology can be realized. In Comprehensive Principle 2023, studies are focused on CO_2, which is the largest component of GHG emissions, and the other GHGs are evaluated based on CO_2-equivalent values. For technologies that will contribute to reducing CO_2 emissions, the *CO_2 reduction potential* and *CO_2 abatement cost* are estimated to fuel quantitative discussions with an eye to the future.

To achieve carbon neutrality by 2050 and mitigate climate change, studying other many technologies in addition to the technologies studied in Comprehensive Principle 2023 is necessary. Also, NEDO expects that Comprehensive Principle 2023 will enable it to identify technologies that should be tackled by quantitatively evaluating technologies that will contribute to solving climate change, such as their CO_2 reduction potentials. The

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10 Business Opportunities in BCG Economy Models, Smart Farming, and Biological Technologies in Thailand (Japan External Trade Organization, 2021)
https://www.jetro.go.jp/biz/areareports/2021/81285571d8e6c862.html

11 Opinion Exchange with Environment Minister Nishimura (Weekly Keidanren Times, No. 3579, 2023)
https://www.keidanren.or.jp/journal/times/2023/0216_01.html

goal is that technologies developed in Japan will spread throughout the world, thereby helping to solve the issue of climate change.

Chapter 2 GHG Emissions and Marginal Abatement Cost

- Considering the economic performance of GHG reduction technologies, the marginal abatement cost per tonne of CO_2 to achieve carbon neutrality is found to be above the level of ¥50,000.
- This marginal abatement cost has been reduced from that analyzed in Comprehensive Principle 2020, and is thought to reflect the lower unit costs of solar power and storage batteries as a result of technological developments.
- In order to lower the marginal abatement cost to globally acceptable levels, innovation is essential through discontinuous technology developments and social implementation.

2-1 Current Status of GHG Emissions

According to the IPCC Sixth Assessment Report Working Group (WG3) Report[12], the global GHG emissions were approximately 59 billion tonnes of CO_2-equivalent in 2019, and CO_2 accounted for 75% of the total GHG emissions, followed by CH_4 (18%), N_2O (5%), and fluorine gases such as chlorofluorocarbon (2%) (Figure 4). Since 1990, global GHG emissions have been continuously increasing. From 2010 to 2019, the rate of the increase slowed down but emissions are still rising nonetheless (Figure 6). According to the IEA's World Energy Outlook 2022[13] (WEO 2022), in 2020 the global CO_2 emissions dropped by 5.2% because the energy demand was stagnant due to the COVID-19 pandemic. In 2021, however, these emissions increased by 6.1% as GDP growth recovered. This suggests that enormous efforts would be required to achieve carbon neutrality.

Japan's actual GHG emissions are approximately 1.2 billion tonnes in 2019 and account for approximately 2% of overall global GHG emissions (Figure 5). They reached their peak and started to decline in 2013 (Figure 7). Although the percentage of Japan's

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[12] Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022) https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/

[13] World Energy Outlook 2022 (IEA, 2021) https://www.iea.org/reports/world-energy-outlook-2022

GHG emissions to the global total is relatively low, climate change is a global issue, so it is extremely important to reduce not only Japan's own GHG emissions but also the amount worldwide.

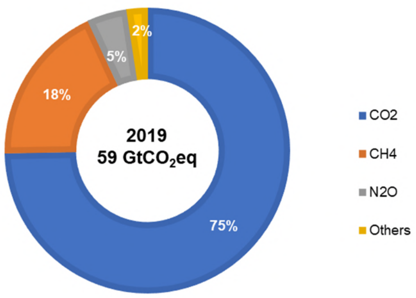

Figure 4 Global GHG emissions

Source: Prepared by NEDO's Technology Strategy Center based on the IPCC AR6 WG3 report (2022)

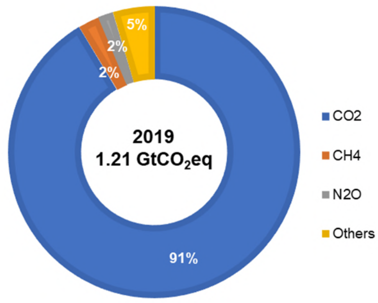

Figure 5 Japan's GHG emissions

Source: Prepared by NEDO's Technology Strategy Center based on the Japan's National Greenhouse Gas Emissions in Fiscal Year 2020 (Final Figures) <Executive Summary> (Ministry of the Environment, 2022) (2022)

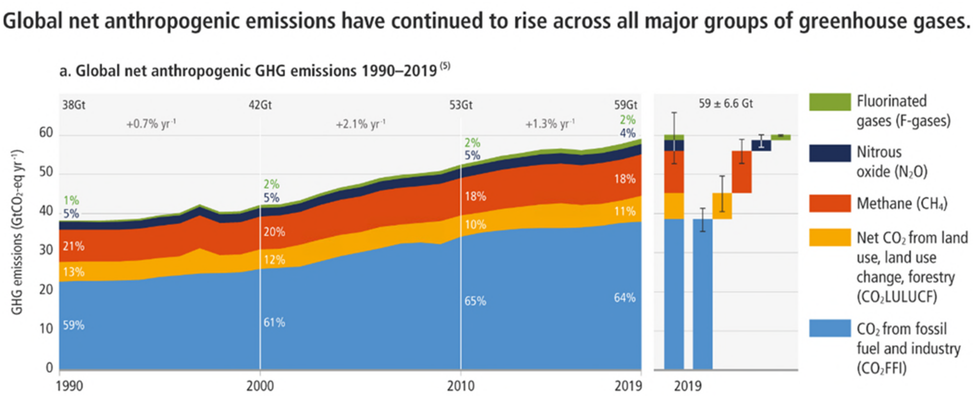

Figure 6 Trends in global GHG emissions

Source: IPCC AR6 WG3 report

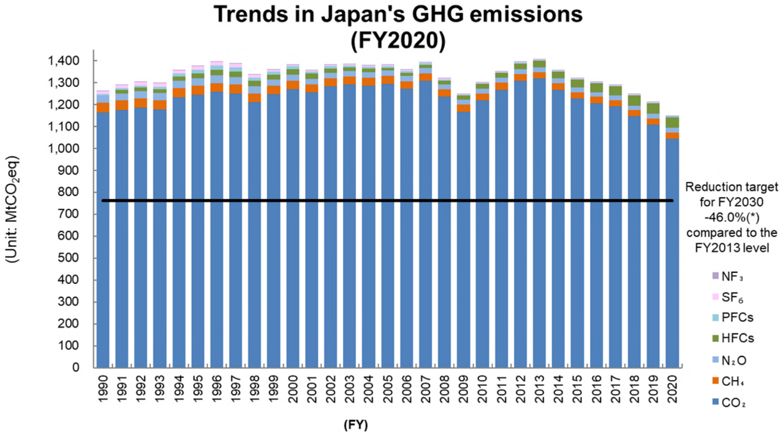

Figure 7 Trends in Japan's GHG emissions

Source: Japan's GHG emissions data (FY1990–2020, Final figures)
(National Institute for Environmental Studies, 2022)

2-2 Forecast of GHG Emissions

Many research institutes around the world have provided forecast scenarios based on various GHG emissions pathways, and the energy consumption, CO_2 emissions, and abatement cost have been analyzed for each scenario. The International Energy Agency (IEA) suggested scenarios for CO_2 emissions in its WEO 2022: Stated Policies Scenario (STEPS), where CO_2 emissions will be reduced based on the current policy, and Net-Zero Emissions by 2050 Scenario (NZE), where net-zero emissions will be achieved (Figure 8). In the STEPS scenario, the CO_2 emissions are expected to be approximately 32 billion tonnes in 2050, and decline by approximately 22 billion tonnes compared to the Pre-Paris baseline under which the measures will be implemented based on the policy before the Paris Agreement. However, to achieve net-zero emissions, another 32 billion tonnes of CO_2 emissions must be reduced from the STEPS scenario, so introducing economically rational, innovative technologies is vital for achieving the target.

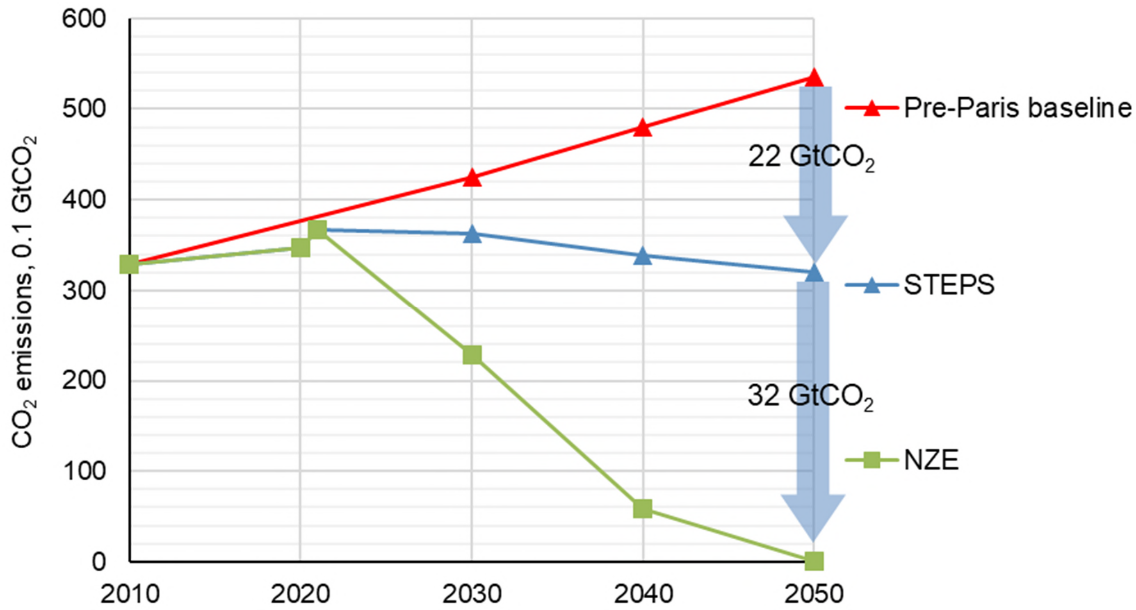

Figure 8 Representative scenarios by IEA

Source: Prepared by NEDO's Technology Strategy Center based on IEA WEO 2022 (2022)

2-3 Estimation of Marginal Abatement Cost

Research institutions around the world on climate change have conducted simulations based on multiple scenarios and presented relationships between GHG emissions (or CO_2 emissions) and marginal abatement cost. Marginal abatement cost refers to how much it will cost to reduce an additional one tonne of CO_2 emissions, and is represented as ¥/tCO_2 (or \$/tCO_2). Marginal abatement cost represents a hurdle to CO_2 reduction to a certain level of emissions in terms of economic rationality, and is a key indicator that serves as a goal of future technology development for reducing CO_2 (for details, refer to Chapter 4). After Comprehensive Principle 2020 was issued, the research institutes revised their scenarios because many countries have strengthened their measures against climate change and technology progressed.

In Comprehensive Principle 2023, we have analyzed the marginal abatement cost necessary to keep global warming below 1.5°C based on the IPPC AR6 WG3 report. In the AR6 WG3 report, 1,202 scenarios that have gone through the screening process are classified into eight categories (C1 to C8) according to the global warning predictions for the year 2100 (Table 2). Comprehensive Principle 2023 gives an analysis of the relationship between the estimated global GHG emissions and marginal abatement cost for the C1 and C2 scenarios where global warming will be kept below 1.5°C.

Table 2 Categories for GHG emissions scenarios in the AR6 WG3 report

Category	Global warming prediction	No. of scenarios
C1	1.5°C (no or low overshoot)	97
C2	1.5°C (high overshoot)	133
C3	2°C (> 67%)	311
C4	2°C (> 50%)	159
C5	2.5°C	212
C6	3°C	97
C7	4°C	164
C8	> 4°C	29

Source: Prepared by NEDO's Technology Strategy Center based on the IPCC AR6 WG3 report (2022)

Figure 9 shows the results of regression analysis[14]. As indicated by the blue approximate line, as GHG emissions decrease, the marginal abatement cost increases exponentially and exceeds ¥50,000/tCO_2 (1 USD = 100 yen) before carbon neutrality is achieved.

A comparison with the black dashed line, which is the approximate line obtained by conducting the same analysis as in Comprehensive Principle 2020, shows that the marginal abatement cost is lower around net-zero GHG emissions by result of this analysis. In the scenarios used in the AR6 WG3 report, continuous drops in the unit costs of photovoltaic power generation (85%), wind power generation (55%), and lithium-ion batteries (85%) from 2010 to 2019 have been mentioned. This is one of the factors causing the marginal abatement cost to drop around the point of carbon neutrality. Further innovation is therefore essential to lower the marginal abatement cost to globally acceptable levels.

[14] Differences in the base year for costs between research institutes have been adjusted for inflation. Regarding the IEA data, which has been created for CO_2 only, the values for the other GHGs estimated based on multiple emissions pathways presented by the IPCC have been added.
The relationship between marginal abatement cost and GHG emissions is expressed by the following approximation:
C1 + C2 Marginal abatement cost [$/t$CO_2$] = 665.42 × exp(-0.006G), G: GHG emissions [0.1 GtCO_2]
Comprehensive Principle 2020 Marginal abatement cost [$/t$CO_2$] = 2061.2 × exp(-0.008G), G: GHG emissions [0.1 GtCO_2]

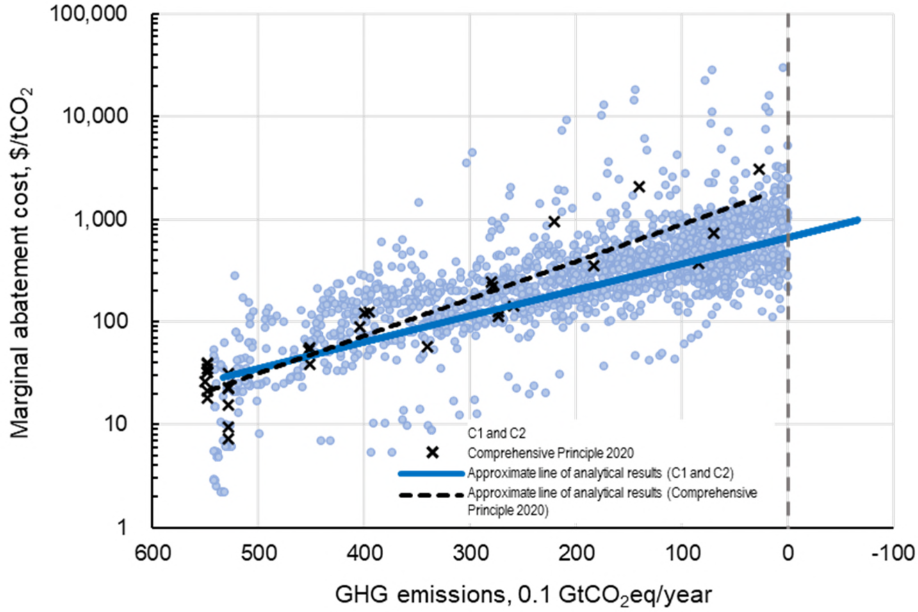

Figure 9 Relationship between GHG emissions and marginal abatement cost

Source: Prepared by NEDO's Technology Strategy Center based on the IPCC AR6 WG3 report and Comprehensive Principle 2020 (2022)

2-4 Key Initiatives to Achieve Carbon Neutrality

The AR6 WG3 report presents four scenarios as illustrative mitigation pathways (IMP) that keep global warming below 1.5°C: Extensive use of Renewables (Ren), Low Demand (LD), Shifting Pathways (SP), and Net Negative Emissions (Neg) (Table 3).

Table 3 Illustrative mitigation pathways that keep global warming below 1.5°C presented in the AR6 WG3 report

Scenario	Feature	Category
Ren	Focused on renewable energy	C1
LD	Focused on low energy demands	C1
SP	Focused on sustainable development pathways	C1
Neg	Focused on negative emissions	C2

Source: Prepared by NEDO's Technology Strategy Center based on the IPCC AR6 WG3 report (2022)

Every mitigation pathway has the same characteristic that GHG emissions will decline rapidly and drastically, but has significantly different strategies for doing so. Figure 10 compares the primary energy supply and CO_2 reduction by negative emission technologies (NETs) under the four illustrative mitigation pathways that keep global warming below 1.5°C. Comparison of these characteristic scenarios suggests the importance of *decarbonization of energy use*, *reduction of final energy consumption*, and *introduction of negative emission technologies* as initiatives to achieve carbon neutrality.

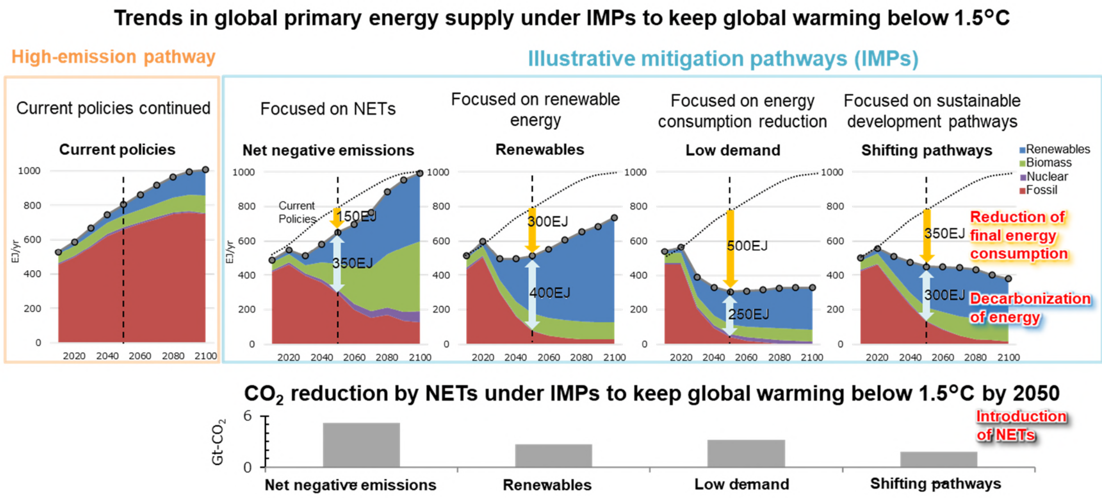

Figure 10 Global primary energy supply and CO_2 reduction by negative emission technologies under the illustrative mitigation pathways that keep the global warming below 1.5°C

Source: Prepared by NEDO's Technology Strategy Center based on the IPCC AR6 WG3 report (2022)

Decarbonization of energy use means a transition to renewable energy and other energy sources not accompanied by carbon emissions and is a fundamental initiative for achieving carbon neutrality. The Ren, LD, and SP scenarios assume that in 2050, the outputs of photovoltaic power generation and wind power generation will be 60 to 169 EJ and 76 to 96 EJ, respectively. The use of renewable energy will thus be expanding in the field of power supply. Also expected to accelerate electrification dramatically is the large-scale introduction of variable renewable energies via significantly expanded use of batteries. As electrification progresses, there will be a growing need to transition to hydrogen, ammonia, synthetic methane, and synthetic fuels, so developing technologies to produce and utilize them without GHG emissions is important.

Reduction of final energy consumption is expected to be effective for lowering the introduction goal for CO_2 reduction technologies necessary to reduce GHG emissions, and at saving resources and costs as well as at mitigating the impact of fluctuations in energy prices. The assumption is that in the LD, SP, and Ren scenarios, the global final energy consumption will decrease from the current level, or 430 EJ, to 245 to 370 EJ in 2050. Many energy saving technologies have a relative low CO_2 abatement cost and already been put to practical use, and the active introduction of these technologies would allow carbon emissions to reach the peak early. Also, promoting the circular economy (CE) is effective in reducing the final energy consumption. It is anticipated that promoting CE will reduce energy consumption as material production falls.

Introduction of negative emission technologies offsets GHG emissions that cannot be reduced by 2050 even if various measures are taken. This is emphasized especially in the Neg scenario, and many other scenarios assume the utilization of negative emission technologies as well. However, these scenarios assume only the negative emission technologies whose feasibility is relatively apparent in terms of technical maturity and cost, such as Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS) and Agriculture, Forestry, and Other Land Use (AFOLU), including afforestation. Therefore, to achieve carbon neutrality, it is important to develop other negative emission technologies as well and accelerate efforts to implement them in society. Also, the technologies for storing CO_2 in nature are expected to enable the immobilization of low-concentration CO_2 at low cost and bring co-benefits from CO_2 storage. However, quantitative understanding of their environmental impacts and CO_2 removal effects is currently insufficient, so scientific evaluation is required for future social implementation. Furthermore, negative emission technologies will make it possible to achieve net negative emissions by separating and storing GHG emissions that exceed the actual amounts emitted after carbon neutrality is achieved. This would make it possible to reduce the GHG concentration in the atmosphere, thereby further mitigating climate change.

The IPCC AR6 report suggests the need to change the raw materials of cement and chemicals in the non-energy fields and reduce methane and N_2O emissions in the agricultural industry. Therefore, in addition to the three initiatives mentioned above, *non-energy related GHG emissions reduction* can also be considered as a key initiative.

Chapter 3 Trends and Prospects for the 3 Essential Social Systems for Sustainable Society and the Digital Transformation Fundamental to them

- Focusing on the key initiatives identified in Chapter 2, namely decarbonization of energy use, reduction of final energy consumption, introduction of negative emission technologies, and non-energy related GHG emissions reductions, this chapter provides an overview of technologies related the three social systems and digital transformation, and presents significant technologies based on the latest social and technical trends.
- It has been made clear that achieving a sustainable society requires continuously implementation of the key initiatives, so promoting the three social systems and digital transformation in an integrated manner is essential.

3-1 Circular Economy

As efforts toward energy transition and decarbonization for carbon neutrality are accelerating, it is considered important to reduce virgin material production by the circular economy (CE) as an effort that will lead to *reduction of final energy consumption*. SITRA's (Finnish innovation fund) report provides an estimate that, CO_2 emissions can be reduced by 56% in the realm of key material production by combining material recycling with the production efficiency of products and effects of sharing and other business models (Figure 11). IEA's NZE scenario, which requires a drastic improvement in the recycling rate, suggests that in the ironmaking industry, the usage rate of raw-material scrap will increase from 32% to 46% by 2050, and the recycling rate of plastic will increase from 17% to 54%.

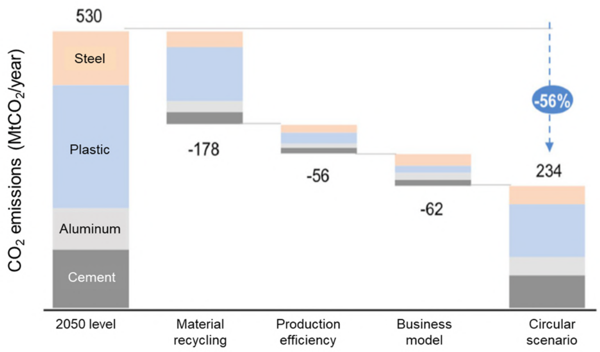

Figure 11 CO_2 reduction potential by CE

Source: Prepared by NEDO's Technology Strategy Center based on The Circular Economy (SITRA, 2018)[15]

Specific ways to reduce virgin material include not only the 3Rs (Reduce, Reuse, and Recycle) but also life extension, repair, remanufacturing, and sharing of product and various other approaches. CE is expected to drive new business and employment based on these approaches, which is consistent with the trend that carbon neutrality is regarded as an opportunity for growth.

In recycling, it is important to maintain the quality of parts and materials collected after recycling. Therefore, it is necessary to utilize information about product design as well as parts and materials, and dismantle and sort those parts and materials appropriately and efficiently in combination with automation using robots, for example. Also important are considerations by arterial industry, such as product design that makes dismantling, crushing or demolition, and sorting, and selecting readily recyclable materials, easy.

Carbon recycling is regarded as resource cycling when considering CO_2 as a resource. Carbon recycling is the process of recovering CO_2 from biomass, industrial exhaust gases, and the atmosphere, and using it as a raw material for such as carbon compounds and concrete. As such, it is considered important as a technology that contributes to *non-energy related GHG emissions reduction*. To transform CO_2 into fuels and basic chemicals, technologies that convert synthesis gases to fuels and chemicals are important as common technologies. At the same time, some of the functional chemicals and cement raw materials that use CO_2 as a raw material do not require hydrogen, and implementation is anticipated to progress quickly.

[15] The Circular Economy (SITRA, 2018) https://www.sitra.fi/app/uploads/2018/06/the-circular-economy-a-powerful-force-for-climate-mitigation.pdf

3-2 Bioeconomy

There is a global movement to accelerate bioeconomy strategies for achieving carbon neutrality. In the EU, contribution of the bioeconomy is anticipated through European Green Deal-related measures, such as Promoting Clean Energy (supplying a sufficient amount of clean and affordable energy) and Striving for Greener Industry (transitioning to cleaner and more recyclable and sustainable industry). In the US, the bioeconomy is clearly defined in The Bioeconomy: A Primer. Also, the Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy was released with a fact sheet stating that bioengineering could account for more than a third of global output of manufacturing industries before the end of the decade—almost $30 trillion in terms of value, showing great expectations for biomanufacturing as a strategic field.

Japan as well has been implementing many measures in recent years. In the Grand Design and Action Plan for a New Form of Capitalism, approved by the Cabinet in June 2022, biomanufacturing is positioned as a key investment destination. Also, in the Strategy for Sustainable Food Systems (Strategy MIDORI), the Ministry of Agriculture, Forestry and Fisheries of Japan set a goal of achieving zero CO_2 emissions by 2050 in the agriculture, forestry, and fisheries industries. In the Cabinet Office's Moonshot Research and Development Program, the development of negative emission technologies, including technologies using biological functions, was added and expanded to help achieve the goal of realizing sustainable resource cycling by 2050 to conserve the global environment. In the Act on Promotion of Resource Circulation for Plastics, the Ministry of the Environment has set a goal of introducing approximately 2 million tonnes of bioplastic by 2030.

As just described, since 2020, with increasing momentum to achieve carbon neutrality, there have been rising expectations for the bioeconomy, including fixing CO_2 through effective utilization of biological natural phenomena; creating economic value by producing useful and functional materials through effective use of biological functions; and promoting resource recycling economy where organic waste materials are reused as resources by taking advantage of biological functions (Figure 12). Especially, biomanufacturing, which applies synthetic biology, food-tech, and agri-tech, are attracting attention.

Biomanufacturing using synthetic biology enables production of a range of materials from various renewable raw materials, and is important for achieving carbon neutrality in the chemical and other industries that have been considered difficult to decarbonize. Especially for green carbon, such as wooden and herbaceous biomass and agricultural waste, and blue carbon, such as seaweed and seagrass, the plant function (photosynthesis) is used to immobilize a low concentration of CO_2 (for example, CO_2 in the atmosphere) with low input energy. Some types of green and blue carbon can be used as biomass, which will help to reduce CO_2 while recycling carbon. Therefore, green and blue carbon are positioned as technologies that could lead to *negative emission technologies, reduction of final energy consumption* and *non-energy related GHG emissions reduction*.

For food-tech and agri-tech, various efforts are drawing attention that take into consideration that the agriculture, forestry, and fisheries industries are both absorption and emission sources. Food-tech and agri-tech should lead to *negative emission technologies*, which are used to store CO_2, for example, in agricultural land and at the same time can be expected to contribute to *reduction of final energy consumption* in the food production industry in ways such as through soil improvement using biochar and the smart food supply chain.

The bioeconomy has a high affinity with nature-based solutions (NbS) and does much to preserve the natural environment and create economic value. However, since many of the technologies in their area are still immature, visualizing their value propositions and converting them to economic value is essential for attracting ongoing investment. To bring the bioeconomy to fruition, there is a need to develop technologies that measure the amount of biologically fixed CO_2, to establish the method of life cycle assessment (LCA) of the technologies related to a bioeconomy and the impact evaluation method for the co-benefits obtained by NbS. By developing and utilizing these technologies, it will become possible to submit scientific evidence to demonstrate the effectiveness of *introduction of negative emission technologies* and *reduction of final energy consumption* in the bioeconomy.

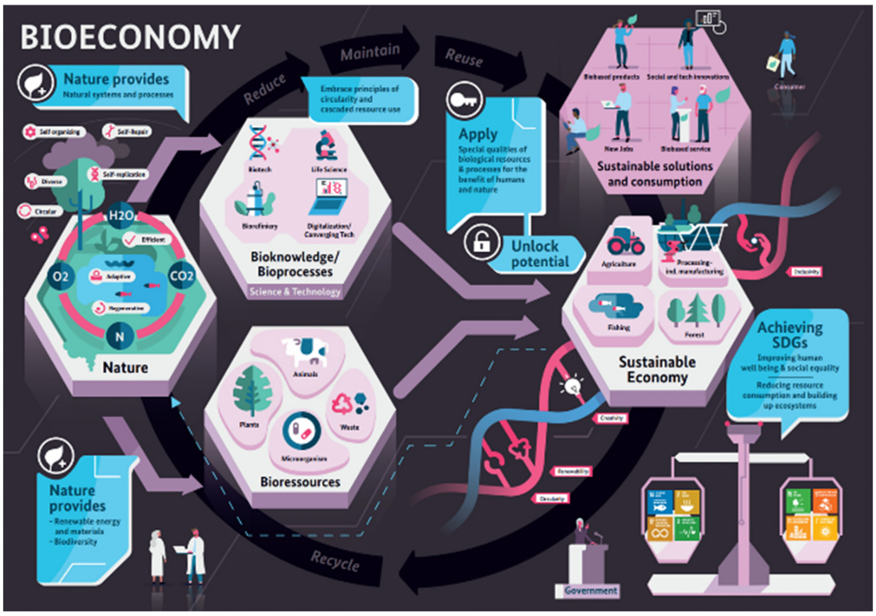

Figure 12 Implementation of bioeconomy

Source: Communiqué of the Global Bioeconomy Summit 2020[16] (Berlin, 2020)

3-3 Sustainable Energy

Total global CO_2 emissions in 2021 were approximately 36.6 billion tonnes. The breakdown of energy supply and consumption is that the global CO_2 emissions were approximately 14.4 billion tonnes in the power supply sector, and in regard to final energy consumption, it was approximately 7.7 billion tonnes in the transportation sector, approximately 9.3 billion tonnes in the industrial sector, and approximately 3 billion tonnes in the consumer sector[17].

In light of these circumstances, *decarbonization of energy use* is a key initiative to achieve carbon neutrality in the power supply sector. A majority of scenarios presented by international organizations and the like, and measures taken by countries, assume the maximum utilization of renewable energy (such as sunlight, wind, geothermal heat, and oceans) as a major premise. Shifting to clean power, which makes the most of renewable energy power generation, in the power supply sector requires reducing the costs of photovoltaic power generation and wind power generation while promoting electrification. IEA's NZE scenario requires an electrification rate of over 50% and a

[16] https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf
[17] IEA WEO 2022 and 2021.

renewable energy rate of 80% or more in the power configuration to be achieved by 2050, when the net CO_2 emissions are expected to be zero (Figure 13).

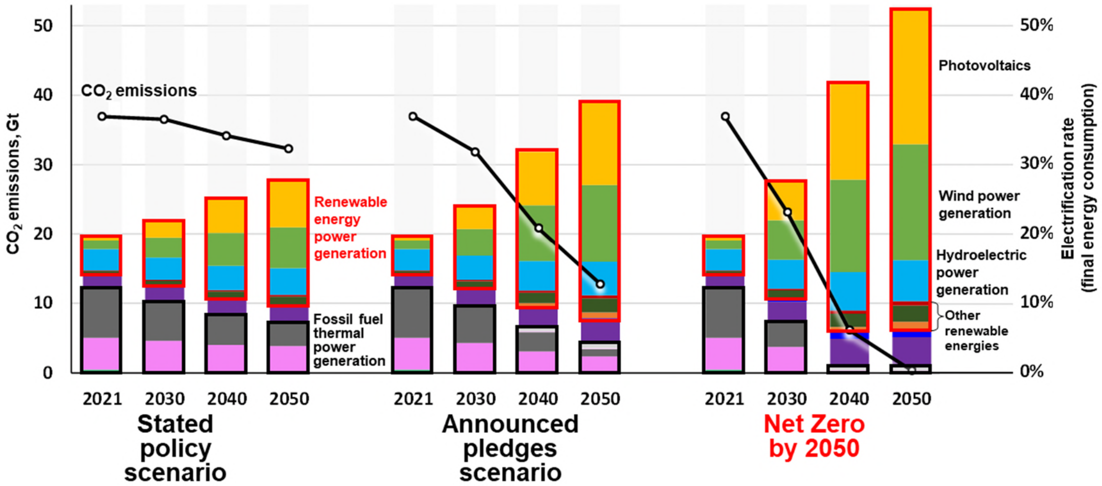

Figure 13 Prediction of CO_2 emissions, electrification rate, and power configuration by IEA WEO 2022 scenario

Source: Prepared by NEDO's Technology Strategy Center based on IEA WEO 2022 (2022)

To ensure maximum and stable use of large amounts of renewable energy introduced as described over long periods of time, there is a need to establish an energy system highly adaptable to fluctuations, dispersion, and uneven distribution of renewable energy. For this to happen, it is important to develop secondary energy technologies (storage, transportation, and conversion), energy management technologies, and energy saving technologies.

For secondary energy technologies (storage, transportation, and conversion), advanced battery technologies are crucial in promoting electrification. In addition, storage, transportation, and conversion are also important in areas other than electric power, so there is demand for technologies that use energy carriers with higher energy. There are expectations for technologies to produce and utilize alternative fuels, such as using biomass and microorganisms, typified by bio-jet fuels. In addition, there is an emphasis on technologies that can produce carbon-free fuels, such as hydrogen and ammonia, with use of renewable energy power.

Regarding energy management technologies, there is the need to eliminate a mismatch between the supply and demand of renewable energy, which fluctuates and is dispersed and unevenly distributed. In addition to power network systems that employ distributed energy resources (DER), it is necessary to introduce demand response, which actively manages the demand side. A new form of social implementation is being explored, including introducing demand response as an aggregation business in collaboration with other industries.

Regarding energy saving technologies, many of them are already at the implementation stage, but promoting steady penetration of these technologies is necessary for them to contribute to *reduction of final energy consumption* over the long term. Also, in order to reduce the consumption and cost of resources necessary for future energy transition, there is the need to develop individual technologies such as power electronics and heat pumps, and streamline energy use throughout society in combination with secondary energy technologies and energy management technologies.

3-4 Importance of an Integrated Approach to the 3 Social Systems

The key initiatives described in Chapter 2 will not be completed in individual social systems.

In some fields of the transportation and industrial sectors, it will be difficult to achieve zero CO_2 emissions, so unavoidable CO_2 emissions will have to be offset by *negative emission technologies*, typified by BECCS and DACCS. With BECCS, as carbon-neutral form of energy use, the CO_2 generated when a biomass-derived fuel is burned is captured and stored to achieve negative emissions. In addition to BECCS, blue and green carbon, which were been described in *Bioeconomy*, are considered to have been born as a result of embodying the concept of carbon recycling, which is a significant technology in the *circular economy*, in combination with the *bioeconomy*. The expectation is that biomass and other waste materials can be burned or converted to chemicals with a low energy input, and they will be valuable carbon resources in carbon recycling. Therefore, they can be expected to contribute to *reduction of final energy consumption* and *non-energy related GHG emissions reduction* through the promotion of material development that takes into account circularity and coupling with post-use resource recycling technologies. DACCS has an advantage of being able to capture CO_2 anywhere, but with conventional technologies, a large amount of energy is required to capture CO_2. In order to put DACCS to practical use, it is necessary to achieve lower energy consumption and *decarbonization of energy use* through innovation, so collaboration with *sustainable energy* is important.

The initiative to achieve *decarbonization of energy use* is also necessary for promoting the *social systems* for carbon neutrality, and energy transition is required as a premise. Replacing existing energy supply facilities with renewable energy ones or installing new renewable energy facilities on a global scale will require enormous amounts of resources, including raw materials, processed materials, and energy, so stable resource procurement is essential. In terms of security risk, which became apparent after Russia invaded Ukraine, stable supply chains are required through diversification and delocalization. Therefore, in addition to innovation with renewable energy technologies, such as reducing resource consumption per unit volume and developing alternative materials and new materials, there is the need for recycling through the *circular economy* to function as a social system in supply chains. Also, since renewable energy facilities will be built across large expanses of land and sea, it is necessary to consider the impact on ecosystems and biodiversity as well as the facilities' coexistence with communities. Furthermore, it is essential to take into account land use for the food supply, which is vital for supporting the population. This is because the global population is expected to continue its rise, especially in developing countries. Therefore, the *bioeconomy* must be considered in the context of development.

As just described, for continuous implementation of the key initiatives, namely *decarbonization of energy use*, *reduction of final energy consumption*, *introduction of negative emission technologies*, and *non-energy related GHG emissions reduction*, promoting the three social systems of the *circular economy*, the *bioeconomy*, and *sustainable energy* in an integrated manner is crucial (Figure 14). Digital transformation is essential as a foundation for doing so, and its roles will be described in the next section.

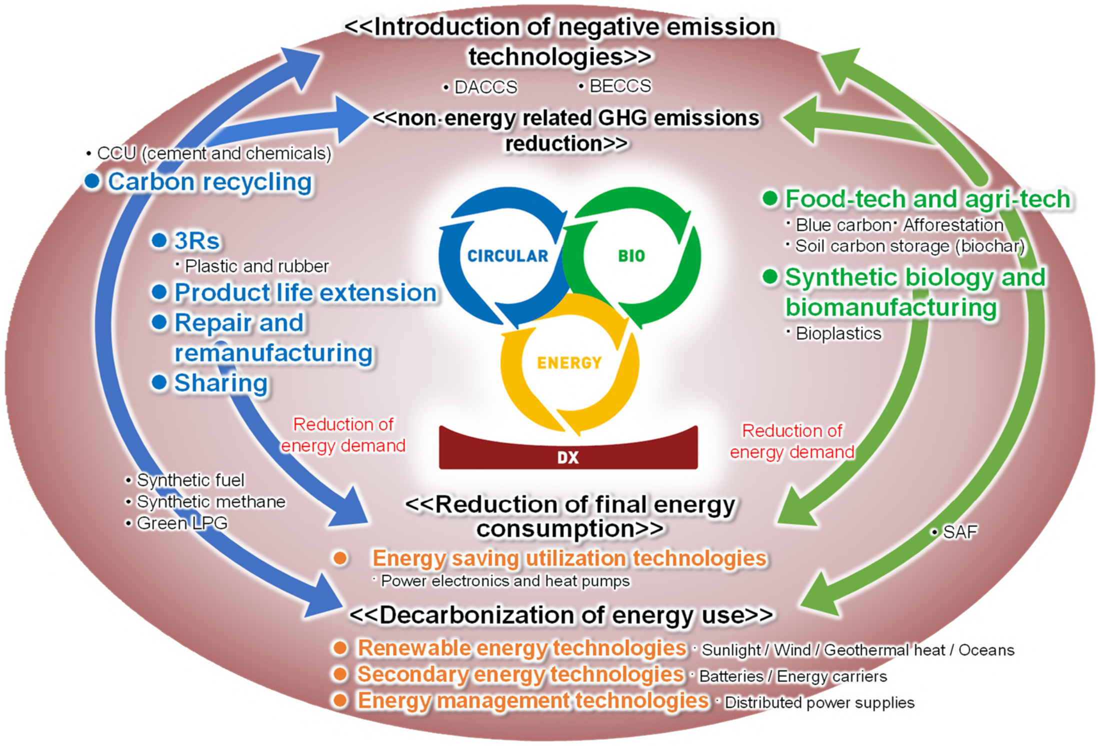

Figure 14 Integrated approach to the *3 Social Systems* for carbon neutrality

3-5 Digital Transformation

Carbon neutrality is a new form of value created as a result of digital transformation. However, digital transformation is not a direct way to achieve carbon neutrality; rather, it is considered as means to support various paths to attaining carbon neutrality. The Green Growth Strategy Through Achieving Carbon Neutrality in 2050 also clearly states that digital transformation is necessary for achieving carbon neutrality.

As a result, *Green by IT*, which uses information technology (IT) to promote carbon neutrality in business activities, has been introduced. This includes *Green by IT* at the level of digitization where the operation status of production equipment, inventory status, and other information are visualized, and *Green by IT* at the level of digitalization where manufacturing processes are streamlined and inventory is optimized based on the visualized data. However, these types of *Green by IT* have been introduced only within individual companies or factories. Many industries are built on supply chains where multiple companies are organically connected, so achieving carbon neutrality right across society requires implementing *Green by IT* throughout the entire supply chain, or at the level of digital transformation. In the *circular economy*, there is an expectation that information about products to be recycled will be visualized, shared between arterial industry and venous industry, and used to upgrade design and recycling processes to minimize GHG emissions and ensure traceability of resource recycling. In *sustainable energy*, digital transformation would be implemented to optimize the balance between energy demand and supply through data linkage to power network systems. In the *bioeconomy*, digital transformation would be implemented for LCA and production streamlining through data linkage among companies involved in food supply chains. Also, visualizing and accurately assessing information obtained through digital transformation is essential to support technical implementation for green transformation, as well as for the incentives for green transformation to work properly.

The Japan Electronics and Information Technology Industries Association presents how to develop *Green by IT* in entire supply chains through digital transformation[18]. With IoT devices installed in production equipment and at warehouses, and other facilities, the power consumption, production volume, GHG emissions, and other information are measured and aggregated in real time into a centralized management server. The aggregated data is used to adjust the electric power or distribute it to other facilities, or plan and adjust production based on demand forecasts.

In line with the progress of *Green by IT*, efforts toward *Green of IT* are underway, the aim of which is to reduce the power consumption of IT equipment itself. According to the IEA's report[19], Internet traffic increased 16-fold in the ten years between 2010 and 2020, and data center processing capacity increased six-fold, but data center power consumption increased by about 6% only. The report says that this is because power efficiency has improved as a result of replacing conventional data centers with hyper-scale data centers. However, the IEA says that over 20 billion IoT devices and 6 billion smartphones are expected to be connected constantly in the 2020s, and it will continue to pay attention to future trends.

As described so far, both Green by IT and Green of IT are necessary for attaining carbon neutrality in true sense, and it is important to promote digital transformation for managing both of them in an integrated manner. Being able to do so at relevant factories

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[18] Homepage of Japan Electronics and Information Technology Industries Association (JEITA). Green x Digital Consortium https://www.jeita.or.jp/japanese/pickup/category/2022/green-digital.html

[19] Data Centres and Data Transmission Networks (IEA, 2022) https://www.iea.org/reports/data-centres-and-data-transmission-networks

or factories of the same type in a supply chain will require the following three approaches (Figure 15)[20].

1. Make the most of local-production-for-local-consumption renewable energy, such as sunlight and wind, to operate IT devices.
2. Share measurement data from individual factories or products and promote life cycle assessment, power demand forecasting, and energy distribution optimization in entire supply chains.
3. Set up a data center in the same area, where renewable energy should be used as well.

These approaches constitute Green of IT itself, which promotes collaboration among the three social systems.

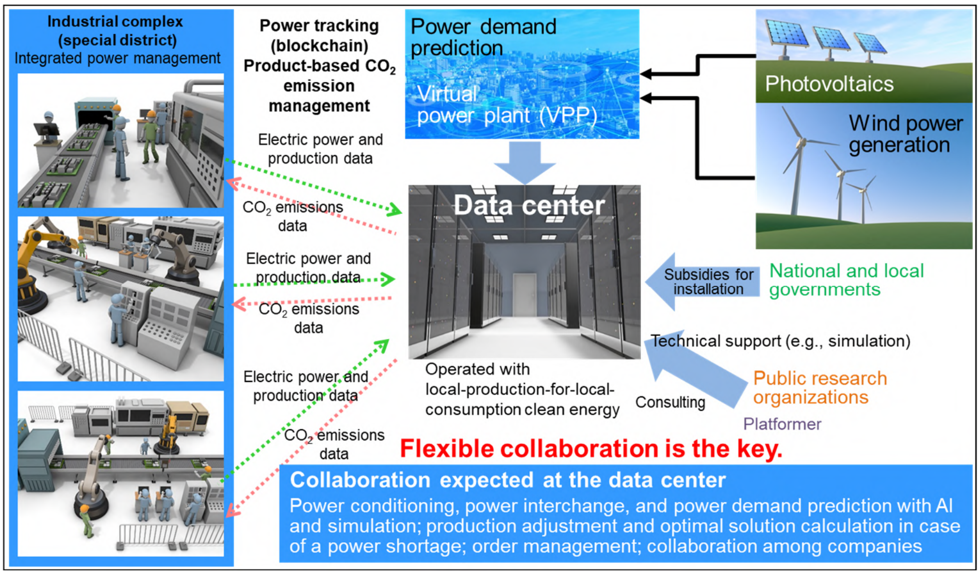

Figure 15 Example of community-based digital transformation infrastructure

[20] TSC Foresight Brief Report: Digital Transformation in Manufacturing (NEDO, 2022) https://www.nedo.go.jp/library/ZZNA_100071.html

Chapter 4 Evaluation of Significant Technologies

- As an approach to objectively evaluating technologies across different fields, *CO_2 reduction potential* and *CO_2 abatement cost* are key factors.
- Focusing on the technologies that contribute to reducing CO_2 emissions presented in Chapter 3, this chapter estimates their *CO_2 reduction potential* and *CO_2 abatement cost*.
- These estimates may increase or decrease due to environmental changes, including introduction policies and social receptivity, as well as technical factors. Therefore, continuous verification is required together with knowledge from those involved.
- Regarding technologies in the energy and environment fields, it takes nearly 20 years until economic effects appear after technology development begins. Therefore, technology development must be initiated as soon as possible to promote innovation.

4-1 Concept of Significant Technologies

In order to identify significant technologies that must be developed to achieve carbon neutrality, there is a need to quantitatively assess the *CO_2 reduction potential* and *CO_2 abatement cost*. Focusing on the significant technologies presented in Chapter 3 by forming an overview of the three social systems and digital transformation from the perspectives of the *key initiatives to achieve carbon neutrality*, this chapter selects significant technologies about which NEDO is able to confirm the details of research and development and estimate the effectiveness for, and estimates the *CO_2 reduction potential* and *CO_2 abatement cost* for these technologies. Table 4 shows the significant technologies selected for estimating the *CO_2 reduction potential* and *CO_2 abatement cost*. Regarding technologies in the energy supply sector, the CO_2 reduction potential has been assessed for power generation technologies only, and other energy technologies have been classified as technologies that contribute to reducing CO_2 emissions in the final consumption stage.

Table 4 Significant technologies selected for estimation

Key initiative	Technology	Significant technology	Key initiative	Technology	Significant technology
Decarbonization of energy use	Renewable energy utilization technologies	Next generation photovoltaics	Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Ship - Ammonia
Decarbonization of energy use	Renewable energy utilization technologies	Next generation wind power	Reduction of final energy consumption	Energy saving technologies	Next generation power electronics
Decarbonization of energy use	Renewable energy utilization technologies	Next generation geothermal power	Reduction of final energy consumption	Energy saving technologies	Superconductivity
Decarbonization of energy use	Renewable energy utilization technologies	Marine power generation	Reduction of final energy consumption	Energy saving technologies	Energy-efficient air conditioning
Decarbonization of energy use	Energy saving technologies	High efficiency fossil power	Reduction of final energy consumption Negative emission technologies	Carbon recycling	CCUS/overall carbon recycling
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Hydrogen power generation	Reduction of final energy consumption	Carbon recycling	Carbon recycling - Basic chemicals
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Ammonia power generation	Reduction of final energy consumption	Carbon recycling	Carbon recycling - Functional chemicals
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Heat (industry) - Hydrogen/ammonia	Reduction of final energy consumption	Carbon recycling	Carbon recycling - Carbonate
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Hydrogen reduction ironmaking (blast furnaces)	Reduction of final energy consumption	Recycling	Tire recycling
Decarbonization of energy use	Use of alternative fuels	Heat (industry) - Synthetic methane	Reduction of final energy consumption	Recycling	Aluminum recycling
Decarbonization of energy use	Renewable energy utilization technologies and energy saving technologies	Heat (industry) - Renewable heat	Reduction of final energy consumption	Recycling	Plastic recycling
Decarbonization of energy use	Use of alternative fuels	Heat (residential/commercial) - Synthetic methane	Reduction of final energy consumption	Synthetic biology and biomanufacturing	Biobased chemical
Decarbonization of energy use	Use of alternative fuels	Heat (residential/commercial) - Green LPG	Reduction of final energy consumption Negative emission technologies	Synthetic biology and biomanufacturing	Cellulose nanofiber
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Stationary fuel cell	Reduction of final energy consumption Negative emission technologies	Synthetic biology and biomanufacturing	Bioplastic
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Automotive - Fuel cell vehicle	Negative emission technologies	Food-tech and agri-tech	Blue carbon
Decarbonization of energy use	Battery technologies	Automotive - Next generation EV	Negative emission technologies	Food-tech and agri-tech	Biochar
Decarbonization of energy use	Use of alternative fuels	Automotive - Synthetic fuel	Negative emission technologies	Food-tech and agri-tech	Afforestation/reforestation
Decarbonization of energy use	Battery technologies	Aircraft - Next generation electric aviation	GHG reduction from non-energy sources	Food-tech and agri-tech	Methane (CH4) emissions from livestock and agricultural practices
Decarbonization of energy use	Use of alternative fuels	Aircraft - Bio-jet fuel	GHG reduction from non-energy sources	Food-tech and agri-tech	Nitrous oxide (N_2O) emissions from agricultural land
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Aircraft - Hydrogen	Reduction of final energy consumption	Green of IT	AI chips
Decarbonization of energy use	Hydrogen and ammonia utilization technologies	Ship - Hydrogen			

Color-coding of technical areas: Circular economy, Bioeconomy, Sustainable energy, Digital transformation

4-2 Approach to Estimating the CO_2 Reduction Potential and CO_2 Abatement Cost

Some of the technologies discussed in Comprehensive Principle 2023 have different levels of maturity and different social backgrounds. With these different backgrounds in mind, the CO_2 reduction potential has been estimated for these technologies based on the following four approaches:

A) The estimate is made based on the technology's assumed penetration rate.

B) Estimates by specialized institutions are used.

C) The estimate is made based on the government's or industry's goals or predictions.

D) The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

The estimates may rise or fall due to technical factors, including the speed of technology advancement and innovation, as well as changes in social environments, including introduction policies and social receptivity. When such uncertainty can be taken into consideration, the CO_2 reduction potential for 2050 is estimated by using multiple scenarios (e.g., penetration rate) for each technology and Equation 1 below.

The CO_2 reduction potentials estimated for the technologies studied in Comprehensive Principle 2020 and Comprehensive Principle 2023 and the basis for them are listed as an appendix to this document.

In estimating the CO_2 reduction potential in the Comprehensive Principles, different technologies have different levels of maturity or overlap with one another, so care is required when summing up their values. As previously mentioned, the estimate is made for the technologies for which NEDO is able to confirm the details of technology development and estimate the effectiveness, so not all the technologies that contribute to CO_2 reduction are included.

However, the total CO_2 reduction potential for the technologies included this time is as high as several hundred millions of tonnes to several billion tonnes, and is expected to contribute significantly to reducing CO_2 emissions.

CO_2 abatement cost refers to how much it will cost to reduce additional one tonne of CO_2 emissions, and is represented in ¥/tCO_2. In the Comprehensive Principles, the CO_2 abatement cost for the social implementation of new CO_2 reduction technologies to be developed in the future (new technologies) is estimated by using Equation 2 below.

If it is possible to reduce the cost for the new technologies through technology development, their social implementation will accelerate, enabling a significant reduction of CO_2 emissions.

The technologies included in this estimate, like those included in the CO_2 reduction potential estimate, have different levels of maturity and different social backgrounds. This time, the CO_2 abatement cost is estimated based on the following approaches:

A) The estimate was made based on existing data, such as learning curves.
B) Estimates by specialized institutions were used.
C) The estimate was made based on the government's or industry's goals or predictions.
D) Other cases

Equation 1

CO_2 reduction potential [tCO_2]

= Introduction amount [Specific unit*] × (Emission intensity of conventional technology

– Emission intensity of new technology) [tCO_2/Specific unit*]

* Specific unit: Wh, J, t, etc.

Equation 2

$$\text{CO}_2 \text{ abatement cost } [\yen/\text{tCO}_2] = \frac{(\text{Unit cost of new technology} - \text{Unit cost of conventional technology})\ [\yen/\text{Specific unit*}]}{(\text{CO}_2 \text{ emission intensity of conventional technology} - \text{CO}_2 \text{ emission intensity of new technology})\ [\text{tCO}_2/\text{Specific unit*}]}$$

* Specific unit: Wh, J, t, etc.

4-3 Examples of CO_2 Reduction Potential Estimation

(1) Next generation photovoltaics

According to IEA WEO 2022, in the NZE scenario, the annual total power generated by photovoltaics (PV) is expected to be 27,006 TWh in 2050. The difference from the STEPS scenario, which assumes the penetration of existing technologies and continuation of current policies, is 14,888 TWh, which would probably come from next-generation photovoltaics technologies. It is equivalent to a CO_2 reduction potential of approximately 9.1 $GtCO_2$ if estimated assuming that fossil fuel thermal power generation is replaced by photovoltaics.

Realizing next-generation PV modules with ultra-high efficiency, ultra-light weight, high flexibility, and advanced design, as well as improving technologies to install and operate them, will make it possible to significantly expand the introduction of PV to various locations and applications where the introduction of PV is considered difficult with conventional technologies. If the power generation is calculated and converted to a CO_2 reduction potential based on the assumption that these modules are installed on building walls (1.68 TW), vehicles (0.56 TW), agricultural land (5 TW), and inland waters (2.3 TW), considering availability at each location, the total CO_2 reduction potential is estimated to be 6.3 $GtCO_2$. Achieving carbon neutrality will require further increasing the CO_2 reduction potential, possibly by utilizing these modules for new applications such as roads and other urban infrastructure, oceans, and electric aircraft.

(2) Hydrogen power generation

It is expected that CO_2 emissions will be reduced by replacing the fossil fuels used in thermal power generation with hydrogen or co-firing them with hydrogen.

The assumption is that hydrogen will replace or be co-fired with the fuels used in natural-gas thermal power generation. In IEA WEO 2022's STEPS scenario, the annual natural-gas thermal power generation is expected to be 6,658 TWh/year in 2050. Assuming that 5 to 15% of the natural-gas thermal power generation is replaced by hydrogen power generation, the CO_2 reduction potential is estimated to be 0.107 to 0.320 $GtCO_2$. This can be converted, based on the thermal efficiency and heating value in combustion, to hydrogen introduction of 13.70 million to 41.11 million tonnes.

However, this value is an estimate in the utilization phase, and the CO_2 emissions arising from hydrogen production, transportation, storage, and supply are not included in this estimate.

(3) Hydrogen reduction ironmaking (blast furnaces)

It is expected that the CO_2 emissions will be reduced by replacing conventional ironmaking using blast furnaces with hydrogen reduction ironmaking.

According to IEA Net Zero by 2050[4], global steel production is expected to increase by approximately 10% by 2050 from 1.787 billion t/year[21] in 2020, 29% of which is expected to be replaced by hydrogen reduction ironmaking, equivalent to hydrogen reduction ironmaking introduction of 570 Mt-Fe/year.

Based on the production emission intensity of the blast furnace-basic oxygen furnace method, which is the best available technology, the CO_2 emission intensity of the conventional technology is estimated to 2.0 tCO_2/t-Fe[22]. Thus, the following examines hydrogen reduction ironmaking (blast furnace) as a new technology in COURSE50. With COURSE50, the CO_2 emissions are expected to decrease by 30% compared to using conventional technology. COURSE50 is aimed at

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21 World Steel in Figures 2021 (World Steel Association, 2021) https://worldsteel.org/world-steel-in-figures-2021/

22 Net-Zero Steel Sector Transition Strategy (Mission Possible Partnership, 2021) https://www.energy-transitions.org/wp-content/uploads/2021/10/MP-Steel-Transition-StrategyFinal-1.pdf

establishing technologies by around 2030 and putting them to practical use and having them penetrated through the industry by 2050. The equivalent emission intensity is 1.4 tCO_2/t-Fe[23]. The maximum potential of the new technology assumes that conventional hydrogen reduction ironmaking will be completely replaced by COURSE50 blast furnace technology.

Based on the above, the CO_2 reduction potential with hydrogen reduction ironmaking (blast furnace) is estimated to be 0.34 $GtCO_2$.

(4) Carbon recycling/basic chemicals

It is expected that CO_2 emissions will be reduced by replacing conventional chemical production using fossil fuels, such as crude oil, with raw materials from basic chemical production using Carbon Capture and Utilization (CCU). The basic chemicals used in this estimate are C_2 olefin (ethylene) and C_3 olefin (propylene).

In the Clean Technology Scenario (CTS) of IEA's The Future of Petrochemicals[24], the total global demand for ethylene and propylene is expected to be 370 Mt-olefin/year in 2050. Considering the maximum utilization potential, all the global demand is assumed to be replaced with production by CCU.

With the new technology, CO_2 is immobilized as a raw material, which is considered to be carbon-neutral. Therefore, the olefin emission intensity of the new technology is assumed to be zero. This estimate does not include the CO_2 emissions from transportation and storage.

Based on the composition ratios of ethylene and propylene in production from naphtha[25] and the LCI database[26], the emission intensity of the conventional technology is assumed to be 1.5 tCO_2/t-olefin.

Based on the above, the CO_2 reduction potential of basic chemical (C_2 olefin and C_3 olefin) production by CCU is estimated to be 0.56 $GtCO_2$/year.

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23 COURSE50, The Japan Iron and Steel Federation https://www.course50.com/

24 The Future of Petrochemicals (IEA, 2018) https://www.iea.org/reports/the-future-of-petrochemicals

25 TSC Foresight: Toward the Formulation of Technology Strategies in the Field of Raw Material Diversification of Basic Chemicals (Rubber Materials C4 and C5) (NEDO, 2022) https://www.nedo.go.jp/content/100952690.pdf

26 LCI Database IDEA ver3.2.0 (April 15, 2022), IDEA Laboratory, Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology

(5) Plastic recycling

Plastic, when incinerated after use, emits as much CO_2 as in the processes from raw material mining to product production, so a large CO_2 reduction effect can be expected by recycling. Currently, plastic is recycled, but not many recycling processes are very effective in terms of CO_2 reduction. In the future, it is expected that innovation will take place in the processes of material sorting, material recycling, chemical recycling, and energy recovery, which will help to promote the reduction of CO_2 emissions.

According to IEA's The Future of Petrochemicals[24], plastic production (PE, PP, PET, and PS) is expected to be 400 million tonnes/year by 2050. Assuming that 10 to 30% of it is replaced by innovative recycling technologies, the amount introduced is estimated to be 40 to 120 million tonnes, which can be converted to a CO_2 reduction potential of 0.11 to 0.32 $GtCO_2$/year.

(6) Blue carbon

Blue carbon is the generic term for carbon captured and storage by the world's ocean and coastal ecosystems. In the capture and storage of carbon as blue carbon, CO_2 in the atmosphere is captured by photosynthesis into blue carbon ecosystems that are present mainly in shallow coastal areas, and then it drifts or is buried in the bottom of the ocean. Because the carbon capture and storage mechanisms are complicated[27], it is difficult to estimate the mitigation potential quantitatively (defined in the same way as CO_2 reduction potential), so uncertainty still remains.

The following is an excerpt from the report released by ICEF in 2022[28], given as one of the latest research results. In this report, even for the same blue carbon ecosystems, *mitigation potential is classified into the mitigation potential by stopping the loss and degradation of these ecosystems (conservation)* and *mitigation potential by rehabilitation and restoration (restoration)*, and the mitigation potentials of conservation and restoration activities are estimated individually. As the mitigation potential by 2050, the sum of the mitigation potential by the conservation and rehabilitation of mangroves, salt marsh and tidelands, and seaweed beds, and the mitigation potential through the increase of macroalgae production by aquaculture

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[27] Website of the Ministry of Land, Infrastructure, Transport and Tourism. What is Blue Carbon? "3. Mechanism of Blue Carbon" https://www.mlit.go.jp/kowan/kowan_tk6_000069.html

[28] Blue Carbon Roadmap (ICEF, 2023) https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Blue_Carbon.pdf

is estimated to be 0.5 to 1.38 $GtCO_2eq$/year. The effects of conserving and rehabilitating natural macroalgae have not been calculated because there is insufficient scientific information, but its scale is large in blue carbon ecosystems, so a high mitigation potential is expected.

(7) Biochar

The global amount of carbon stored in soil is estimated to be approximately 1,700 GtC[29] (equivalent to approximately 6,200 $GtCO_2$), which is the largest amount of carbon stored in land areas[30,31]. It is also said that 133 GtC (equivalent to approximately 490 $GtCO_2$) of soil carbon has been lost due to human activities in the past 12,000 years[32]. Therefore, the potential of soil carbon storage is considered extremely high. To enhance soil carbon stock, there is a need to prevent organic matter put in soil from decomposing and emitting CO_2 into the atmosphere. Among various approaches to achieving this, application of biochar is expected as an advanced technology.

Biochar is the generic term for carbides obtained by the pyrolysis or gasification of biomass raw materials. Biochar prevents CO_2 from being released into the atmosphere by remaining as persistent carbon in soil for centuries. It is difficult to determine the amount of biochar that can be introduced because it depends on soil properties, land use, environmental impact, and other conditions. Therefore, the estimated CO_2 reduction potential differs greatly from one organization to another. With biochar application, the global potential of CO_2 reduction was estimated to be approximately 2.6 $GtCO_2$/year (0.3 to 75 $GtCO_2$/year) by the working group of the Sixth Green Innovation Strategy Promotion Council. Also, the IPPC Special Report on Climate Change and Land (approved at the 50th session of the IPCC, 2019)[33] gives an estimate of 0.03 to 6.6 $GtCO_2$/year.

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29 Between 1850 and 2019, the global cumulative CO_2 emissions are estimated to be approximately 2,400 $GtCO_2$ (IPPC AR6 WG3).

30 Global Carbon Budget 2021 (Global Carbon Project, 2022) https://essd.copernicus.org/articles/14/1917/2022/essd-14-1917-2022.pdf

31 Chapter5: Global Carbon and other Biogeochemical Cycles and Feedbacks, in: IPCC AR6 WG1 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter05.pdf

32 Negative Emissions Technologies and Reliable Sequestration (National Academies, Sciences, Engineering, and Medicine, 2019) https://nap.nationalacademies.org/read/25259/chapter/1 (accessed in August 2022)

33 Official name: Climate Change and Land: IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

(8) Methane (CH_4) emissions from livestock and agricultural practices

Methane emissions from the agriculture, forestry, and fisheries industries are attributable mainly to the activity of microbes in the environment and digestive tracts of livestock. Methane emissions could be reduced through good control of the activity of microbes. In particular, methane emissions from rice cultivation, enteric fermentation, livestock manure management, and waste-water treatment relate mainly to fermentative organisms. It is expected that methane generation will be reduced by new technologies that use functional materials such as microbial inoculants.

According to the National Greenhouse Gas Inventory Report of Japan (2022)[34], approximately 80% of methane emissions in Japan (0.0286 $GtCO_2eq$/year) come from agriculture. Of these, methane emissions from enteric fermentation, livestock manure management, and rice cultivation (0.022 $GtCO_2eq$/year) could be reduced by new technologies. Assuming a reduction effect of 50% based on reports of reducing methane emissions using functional materials in Japan and other countries, and a technology adoption rate of 20%, the domestic reduction potential would be 2.2 $MtCO_2eq$/year.

It is assumed that global methane emissions from agriculture vary depending on the environment where the microbes exist. Assuming that the differences in the fermentation environment are small for methane derived from enteric fermentation, and based on the fact that global amount of methane derived from enteric fermentation is 2.85 $GtCO_2eq$/year[35], the global reduction potential is estimated to be approximately 0.29 $GtCO_2eq$/year. This value is estimated applying the same reduction effect (50%) and technology adoption rate (20%) as the domestic potential.

(9) Nitrous oxide (N_2O) emissions from agricultural land

According to the IPCC Fifth Assessment Report, 59% of human-induced N_2O emissions are said to come from agriculture[36]. Also, according to the Inventory Data

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[34] National Greenhouse Gas Inventory Report of JAPAN (National Institute for Environmental Studies, 2022) https://www.nies.go.jp/gio/archive/nir/jqjm10000017uzyw-att/NIR-JPN-2022-v3.0_J_GIOweb.pdf

[35] FAO inventory (FAOSTAT) http://www.fao.org/faostat/en/#data

[36] Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) https://www.ipcc.ch/report/ar5/wg1/

(2017) by the Food and Agriculture Organization of the United Nations (FAO), global N_2O emissions from agriculture total 7.3 Mt/year (approximately 2.26 $GtCO_2eq$/year[37]), 31.2% of them come from chemical fertilizers, and 9.9% from crop residue[35]. Since the conventional technologies for reducing N_2O emissions from agriculture are only applied to a limited range of crops, the current penetration rate (1% or less) is expected to improve little by 2050; therefore the potential for reducing N_2O emissions can be considered almost zero. However, it is expected that N_2O emissions from chemical (nitrogen) fertilizers and crop residue will be reduced dramatically, without affecting food production, by introducing new technologies such as combining special rhizobia that have N_2O reduction effects with common nitrification inhibitors.

According to the FAO, approximately 20% of the global N_2O emissions from agriculture come from Low-Income Food Deficit Countries (LIFDC). In considering the N_2O emission reduction potential, if it is difficult to make new technologies penetrate in these countries in light of differences in the income or food situation, the maximum rate of emission reduction will be 80%. In addition to crop residue (0.22 $GtCO_2eq$/year) and chemical fertilizers (0.7 $GtCO_2eq$/year) (based on the data released by the FAO (2017)[38]), the CO_2 generated when chemical fertilizers are synthesized (0.45 $GtCO_2$)[39] is assumed as an N_2O source, and the maximum reduction potential is estimated to be 0.88 $GtCO_2eq$/year with a reduction effect of 80%.

If limited to N_2O emissions directly from microbial reactions in soil (e.g., nitrification, denitrification), it is thought that 0.156 $GtCO_2eq$/year of N_2O emissions from crop residue and 0.458 $GtCO_2eq$/year[36,40] of N_2O emissions from chemical fertilizers are targets for consideration. It is expected that N_2O will be reduced by directly controlling microbial reactions, and the reduction potential will be 0.39 $GtCO_2$/year with a reduction effect of 80%.

37 According to FAOSTAT (accessed in 2021), the value based on IPCC Second Assessment Report (SAR) (310) is used as a global warming potential (GWP) for N_2O.

38 According to FAOSTAT (accessed in 2021), the value based on IPCC Second Assessment Report (SAR) (310) is used as a GWP for N_2O.

39 Industrial Ammonia Production Emits more CO_2 than any other Chemical-Making Reaction. C&EN. v.97 Iss.24 (2019) https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24

40 According to FAOSTAT (accessed in November 2022), the value based on the IPCC Fifth Assessment Report (AR5) (265) is used as a GWP for N_2O.

4-4 Examples of CO_2 Abatement Cost Estimation

(1) Next generation photovoltaics (vehicle-integrated PV)

The global average levelized cost of electricity (LCOE) of PV (approximately ¥5.3/kWh)[41] has already fallen below that of fossil fuel thermal power generation, and the CO_2 abatement cost has already fallen below zero (red line in Figure 16). In Japan as well, the cost is decreasing steadily, and has reached the ¥9 level per kWh for commercial PV[42]. In the future, improving the production efficiency and generating efficiency of PV products will enable further cost reduction. However, eliminating the restriction of installation location is a key challenge to overcome to dramatically expand the introduction of PV, and next-generation PV is required that has added value that will contribute to expanded installation locations and applications, such as ultra-high efficiency, ultra-light weight, and high flexibility. The following gives examples of estimates for vehicle-integrated PV.

According to the IEA Energy Technology Perspectives 2016, the cumulative introduction amount of electric vehicles is estimated to be 1.4 million in 2030 and 9 million in 2050. The cumulative introduction amount of vehicle-integrated PV can be calculated by accumulating the introduction amount over this period while interpolating it based on the assumed PV installation rate (1% in 2030 and 10 to 30% in 2050). Then, the unit cost of the new technology at the start of penetration is estimated based mainly on the industry's cost target (in 2030, ¥400,000/kw[43]). After that, the manufacturing cost is assumed to decrease at a constant learning rate (80%) based on the cumulative introduction amount. As for the specifications of vehicle-integrated PV, based on the results of studies made by NEDO, the capacity and availability are assumed to be 1 kW and 10%[44], respectively. In this estimate, in addition to the above, the average period of use of vehicle-integrated PV is assumed to be 12 years to calculate the power generation cost. The conventional technology to be replaced by in-vehicle PV is the grid power used to charge electric vehicles.

41 Renewable Power Generation Cost in 2021 (IRENA, 2022) https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

42 82nd Procurement Price Calculation Committee Meeting Material 1 (Agency for Natural Resources and Energy, 2022) https://www.meti.go.jp/shingikai/santeii/082.html

43 e.g. Analysis for Potential of High-Efficiency and Low-cost Vehicle Integrated Photovoltaics (Yamaguchi et al., 2022, lecture at WCPEC-8)

44 PV-Powered Vehicle Strategy Committee Interim Report (NEDO, 2018) https://www.nedo.go.jp/content/100873452.pdf

As shown in Figure 16, in this estimate example, the power generation cost will decrease to the current PV level in 10 to 20 years after introduction.

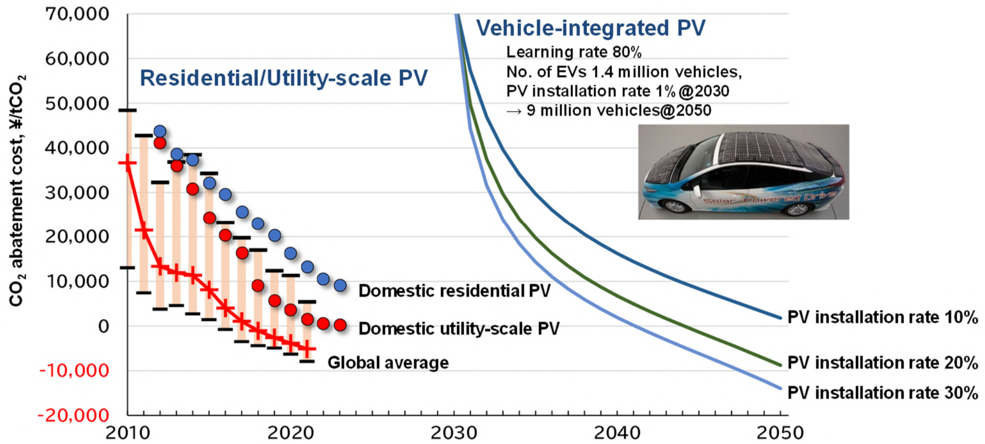

Figure 16 Trends in CO_2 abatement cost of photovoltaics (results and estimation examples)

Source: Prepared by NEDO's Technology Strategy Center based on Renewable Power Generation Cost in 2021 (IRENA, 2022), 82nd Procurement Price Calculation Committee Meeting Material 1 (Agency for Natural Resources and Energy, 2022), Energy Technology Perspectives 2016[45] (IEA, 2016), etc. (2023)

(2) Hydrogen power generation

Regarding hydrogen, the Green Growth Strategy (formulated by the Ministry of Economy, Trade and Industry in June 2021) is aimed at reducing the supply cost to ¥30/Nm^3 by 2030, and ¥20/Nm^3 by 2050. Based on the report issued by the Power Generation Cost Verification Working Group (Ministry of Economy, Trade and Industry, September 2021), these hydrogen costs can be converted to generation costs of ¥17.2/kWh and ¥12.1/kWh, respectively. Based on this policy goal, the CO_2 abatement cost of hydrogen power generation in Japan is summarized in Table 5. The CO_2 abatement cost is projected to be approximately ¥257,000/tCO_2 in 2030. If a hydrogen cost of ¥20/Nm^3 can be achieved by 2050, the CO_2 abatement cost will be ¥98,000/tCO_2[46].

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[45] Energy Technology Perspective (IEA, 2016) https://www.iea.org/reports/energy-technology-perspectives-2016 (2023)

[46] In 2022, the European Union Emissions Trading System (EU-ETS) price hovers around ¥9,500/tCO_2 to ¥13,000/tCO_2.

To achieve this cost reduction, it is important to develop hydrogen power generation technologies (burners and further efficiency enhancement) and hydrogen procurement (e.g., production, transportation, storage) technologies. However, note that if hydrogen is produced by water electrolysis using electricity derived from renewable energy, the renewable energy electricity cost has a great influence on the hydrogen cost.

Table 5 Examples of CO_2 abatement cost estimation for hydrogen power generation

Type	Hydrogen power generation		LNG thermal power generation (conventional technology)
	¥30/Nm^3 *1	¥20/Nm^3 *1	
Power generation cost (¥/kWh)	17.2*2,3	12.1*2,3	9*6
CO_2 emissions (g/kWh)	0*4	0*4	318*5
CO_2 abatement cost (¥/tCO_2)	257,000	98,000	-

The details of the estimate are given as an appendix to this report.

(3) Hydrogen reduction ironmaking

To assess the CO_2 abatement cost by Equation 2 (Section 4-2), the unit costs and CO_2 emission intensities of both the conventional and new technologies need to be known. However, as for hydrogen reduction ironmaking (blast furnace), which is here considered a new technology, these values contain high degrees of uncertainty, so it is difficult to accurately assess the CO_2 abatement cost for it. Therefore, the CO_2 abatement cost of the new technology is assessed as a function having the cost increase arising from the new technology (compared to the conventional technology) and CO_2 emission intensity as variables. The cost increase arising from the new technology corresponds to the numerator on the right-hand side of Equation 2. Regarding the emission intensity of the conventional technology, the emission intensity of the blast furnace-basic oxygen furnace method, which is the best available technology, or 2.0 tCO_2/t-Fe[22], is known. Therefore, when the cost increase arising from the introduction of hydrogen reduction ironmaking is c[¥/t-product] and the CO_2 emission intensity is p[tCO_2/t-product], the CO_2 abatement cost can be expressed as below:

c/(2.0-p) [¥/tCO_2]

From the above, the CO_2 abatement cost of hydrogen reduction ironmaking (blast furnace) can be represented as the function of the cost increase and CO_2 emission intensity, as shown in Figure 17. In this estimate, the CO_2 emission intensity of hydrogen reduction ironmaking is assumed to be 50% or more and less than 100% of that of the conventional technology. Once the emission intensity of the new technology and the cost increase, which depends mainly on capital investment and ironmaking process cost, are determined, the CO_2 abatement cost, as a development goal, can be quantified. The decision whether to introduce a new technology would be made mainly depending on the financial support system, which differs from one country to another, and the conventional technology to be replaced by the new technology.

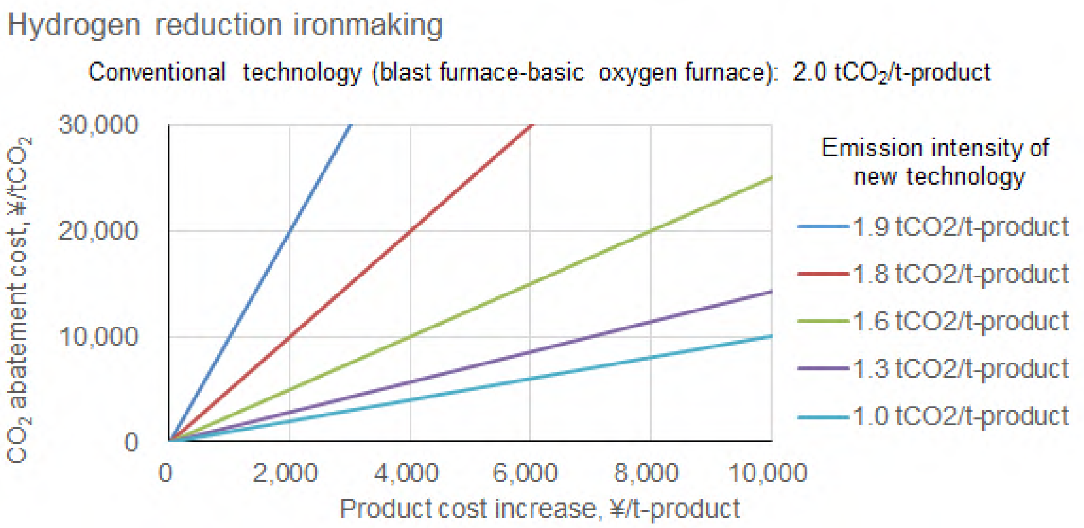

Figure 17 CO_2 abatement cost of hydrogen reduction ironmaking

Source: Prepared by NEDO's Technology Strategy Center (2022)

(4) Carbon recycling/basic chemicals

Assuming that as a new technology, C_2 olefin (ethylene) and C_3 olefin (propylene), which are typical basic chemicals, are produced by CCU, the CO_2 abatement cost is assessed as the function of the CO_2 emission intensity [tCO_2/t-product] and product cost increase [¥/t-product]. The CO_2 emission intensity of production by CCU is obtained by subtracting the amount of CO_2 absorbed into the product (unit quantity) from the CO_2 emissions from the product production process (unit quantity). The CO_2 emissions from the production process are assumed to be p[tCO_2/t-product] as a variable. The amount of CO_2 absorbed into the unit product is estimated to be 3.14 tCO_2/t-olefin based on the ratio of the molecular weights of ethylene and propylene and the molecular weight of CO_2 that can be absorbed and utilized. However, assuming that the energy required to separate and capture CO_2 is 1.0 GJ/tCO_2[47] and covered by natural gas (50 kgCO_2/GJ[48]), the emission intensity of CO_2 separation and capture is 0.05 tCO_2 (emission)/tCO_2 (capture). This means that 95% of the CO_2 absorbed into the product contributes to the reduction. From the above, the CO_2 emission intensity of basic chemical production by CCU is $p - 3.14 \times 95\%$ [tCO_2/t-olefin]. Based on the composition ratios of ethylene and propylene in production from naphtha[25] and the LCI database[26], the emission intensity of the conventional technology is assumed to be 1.5 tCO_2/t-olefin. When the product cost increase is c[¥/t-product], from Equation 2 (Section 4-2), the CO_2 abatement cost of C_2 olefin (ethylene) and C_3 olefin (propylene) production by CCU is as follows:

$$\frac{c}{1.5-(p-3.14\times 95\%)} = \frac{c}{4.48-p} \text{ [¥/tCO}_2\text{]}$$

Based on the above, Figure 18 shows the relationship between the CO_2 abatement cost and product cost increase of C_2 olefin (ethylene) and C_3 olefin (propylene), which are basic chemicals. The lower and upper limits of the CO_2 emission intensity of the production process by CCU are the emission intensity of the conventional technology, and the sum of the emission intensity of the conventional technology and the amount of CO_2 absorbed into the product, respectively. If this upper limit is exceeded, there is no reduction in emitted CO_2. Once the emission intensity of the new technology and the product cost increase, which depends mainly on capital investment, the reaction temperature and catalyst cost are determined, the CO_2 abatement cost, as a development goal, can be quantified. The decision whether to introduce a new technology would be made mainly depending on the financial support system, which differs from one country to another, and the conventional technology to be replaced by the new technology.

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[47] Roadmap for Carbon Recycling Technologies (Ministry of Economy, Trade and Industry, 2019) https://www.meti.go.jp/press/2019/06/20190607002/20190607002-1.pdf

[48] List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment, 2020) https://ghg-santeikohyo.env.go.jp/files/calc/itiran_2020_rev.pdf

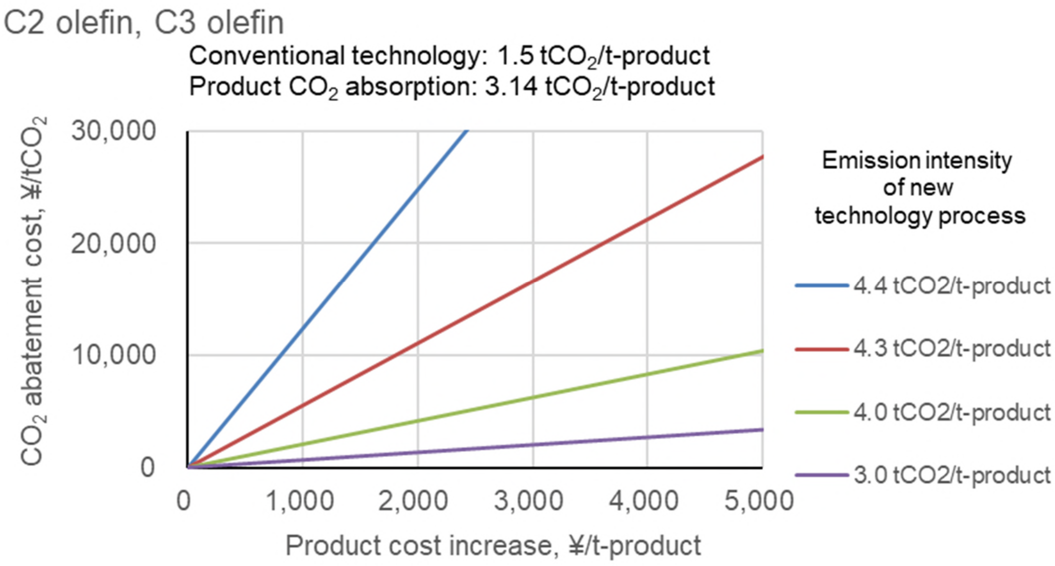

Figure 18 CO_2 abatement cost of carbon recycling/basic chemicals

Source: Prepared by NEDO's Technology Strategy Center (2022)

(5) Plastic recycling

According to the EU's estimates[15], the cost of reducing CO_2 through various plastic recycling measures is relatively low, at -¥10,000 to 5,700/tCO_2 (assuming one US dollar equals 100 yen). In particular, the cost of CO_2 reduction by the reuse of wrapping in the agricultural field, which is reused without any modification, is the lowest and is estimated to be -¥10,000/tCO_2, and the costs of CO_2 reduction by chemical recycling and reuse of packaging and containers are estimated to ¥5,500/tCO_2 and ¥5,700/tCO_2, respectively. As for the case where collected plastic products are reused without any modification, no chemical synthesis or forming processes are necessary, so its cost is lower than that of the products produced from virgin plastics (conventional technology). Therefore, based on the definitional equation, the abatement cost is a negative value. This means that plastic recycling is economically rational and is effective at reducing CO_2.

4-5 Promoting Strategic Development of Innovative Technology

Table 6 lists the CO_2 reduction potentials estimated in Comprehensive Principle 2020 and Comprehensive Principle 2023, including those for the technologies listed in the Appendix. The total CO_2 reduction potential is 43.1 to 88.8 $GtCO_2$eq/year, which means that the technologies cited here are expected to contribute greatly toward achieving carbon neutrality. However, as mentioned in Section 4-2, different technologies have different levels of maturity and certainty, and some competing technologies overlap with one another. Therefore, care is required when summing up their values. In terms of maturity and certainty, negative emission technologies, when evaluated, were found to have a high total CO_2 reduction potential exceeding 10 $GtCO_2$. This reconfirms the importance of such technologies. However, there is a high degree of uncertainty surrounding negative emission technologies, such as a lack of clarity about their carbon storage mechanisms and life cycle assessment. In terms of overlapping, battery, synthetic fuel, hydrogen, and ammonia technologies are competing technologies used in the same applications, such as thermal demand, automobiles, aircraft, and ships, and there is some overlap in the assumed degree to which they will be introduced. In order to ensure that carbon neutrality is achieved in the future, it is important to identify a wider range of significant technologies for all the key initiatives and challenges, and work toward innovation and social implementation.

Table 6 Estimation results of CO_2 reduction potential

Key initiative	Significant technology	$GtCO_2$/year	Pattern
Decarbonization of energy use	Next generation photovoltaics	6.3–9.1	B
Decarbonization of energy use	Next generation wind power	7.8	B
Decarbonization of energy use	Next generation geothermal power	0.25–0.27	B
Decarbonization of energy use	Marine power generation	0.02	B
Decarbonization of energy use	High efficiency fossil power	0.09–0.28	A
Decarbonization of energy use	Hydrogen power generation	0.107–0.32	A
Decarbonization of energy use	Ammonia power generation	0.296–0.889	A
Decarbonization of energy use	Heat (industry) - Hydrogen/ammonia	2.61	A
Decarbonization of energy use	Hydrogen reduction ironmaking (blast furnaces)	0.34	D
Decarbonization of energy use	Heat (industry) - Synthetic methane	1.31	A
Decarbonization of energy use	Heat (industry) - Renewable heat	0.9	B
Decarbonization of energy use	Heat (residential/commercial) - Synthetic methane	0.53	A
Decarbonization of energy use	Heat (residential/commercial) - Green LPG	0.53	A
Decarbonization of energy use	Stationary fuel cell	1.99	A
Decarbonization of energy use	Automotive - Fuel cell vehicle	0.55–0.98	A
Decarbonization of energy use	Automotive - Next generation EV	0.043–0.370	A
Decarbonization of energy use	Automotive - Synthetic fuel	0.46–0.69	A
Decarbonization of energy use	Aircraft - Next generation electric aviation	0.12–0.281	A
Decarbonization of energy use	Aircraft - Bio-jet fuel	0.32–0.75	A
Decarbonization of energy use	Aircraft - Hydrogen	0.59–1.37	A
Decarbonization of energy use	Ship - Hydrogen	0.156	A, B
Decarbonization of energy use	Ship - Ammonia	0.423	A, B
Reduction of final energy consumption	Next generation power electronics	1.03–1.10	A
Reduction of final energy consumption	Superconductivity	0.0	A
Reduction of final energy consumption	Energy-efficient air conditioning	0.53	A
Reduction of final energy consumption Negative emission technologies	CCUS/overall carbon recycling	7.6	B
Reduction of final energy consumption	Carbon recycling - Basic chemicals	0.56	D
Reduction of final energy consumption	Carbon recycling - Functional chemicals	0.05	D
Reduction of final energy consumption	Carbon recycling - Carbonate	0.317	D
Reduction of final energy consumption	Tire recycling	0.015	D
Reduction of final energy consumption	Aluminum recycling	0.07–0.1	A
Reduction of final energy consumption	Plastic recycling	0.11–0.32	A
Reduction of final energy consumption	Biobased chemical	0.123	A
Reduction of final energy consumption Negative emission technologies	Cellulose nanofiber	0.22–0.27	A
Reduction of final energy consumption Negative emission technologies	Bioplastic	0.45–0.67	A
Negative emission technologies	Blue carbon	0.5–1.38	B
Negative emission technologies	Biochar	2.6	B
Negative emission technologies	Afforestation/reforestation	2.3	B
GHG reduction from non-energy sources	Methane (CH_4) emissions from livestock and agricultural practices	0.29	D
GHG reduction from non-energy sources	Nitrous oxide (N_2O) emissions from agricultural land	0.39–0.88	A, B
Reduction of final energy consumption	AI chips	0.209–37.8	A, B

As described in Chapter 2, the cost required to reduce one tonne of CO_2 is estimated to exceed ¥50,000 once carbon neutrality is achieved, so significantly reducing CO_2

abatement cost is an urgent issue. Figure 19 schematically shows the relationship between the CO_2 abatement cost of a new technology (red line) and the CO_2 marginal abatement cost of the conventional technology (blue line). As indicated by the red line (1) in the figure, if the CO_2 abatement cost of a new technology through technology development can be reduced, the penetration of the new technology accelerates once the CO_2 abatement cost of the new technology falls below the marginal abatement cost of the conventional technology. This makes it possible to reduce the marginal abatement cost as indicated by the blue dashed line (2) in the figure. Figure 19 merely gives an example of a new technology. To achieve carbon neutrality by 2050, however, innovation is required for every new technology.

Future technology development needs to include comprehensive judgments from the perspectives of CO_2 reduction potential, CO_2 abatement cost, timing of practical application, effectiveness of technology development as well as performance enhancement, cost reduction, and reliability and safety enhancement. All these factors constitute a fundamental part of industrial competitiveness, and need to function in a more focused and strategic manner. Especially with regard to the timing of practical application, as a result of following up NEDO's projects[49], it is found that in the fields of energy and the environment, it takes nearly 20 years for economic effects to appear after the start of a technology's development. Therefore, it is important to start development as soon as possible when considering how long it will take for innovations to produce economic benefits.

At the same time, there are some existing technologies, such as energy saving technologies, that have not been introduced or have not spread, even though they are technologically mature, because the initial cost is too high and it would take too long to recover the investment[50]. Therefore, to accelerate the transition to carbon neutrality, it is important to further reduce the initial costs of these existing technologies, improve and enhance the durability, efficiency, and usability of equipment, and apply every available technology.

However, carbon neutrality cannot be achieved exclusively by Japan. For new technologies that have already entered practical use, it is important to proceed swiftly

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[49] Examination of the Outcomes of Medium-and Long-term Research and Development Projects: Analysis Based on NEDO's Follow-up Data (NEDO, 2018) https://dspace.jaist.ac.jp/dspace/handle/10119/15606

[50] Application of Low-grade Heat Power Generation Systems to Oil Plants (H. Nagata, 2nd Shonan Workshop, Thermal Engineering Division, The Japan Society of Mechanical Engineers, 2009) https://www.jsme.or.jp/ted/WS2/nagata.pdf

with social implementation in Japan and have these technologies penetrate around the world where they are needed. After all, there is the expectation that Japan will contribute to realizing a sustainable society around the world through developing suitable technologies.

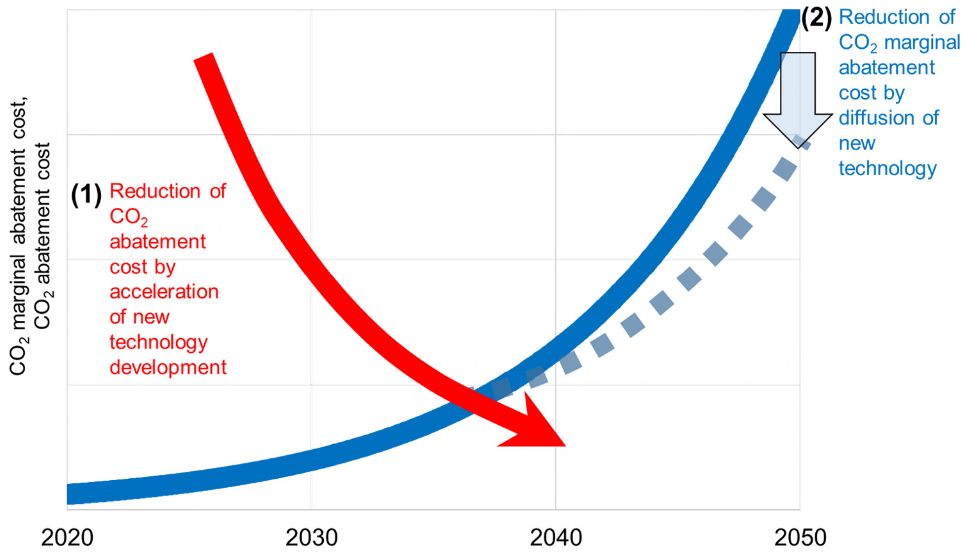

Figure 19 Relationship with cost reduction through technology development

Source: Prepared by NEDO's Technology Strategy Center (2023)

Chapter 5 Expectations for Creating a Framework to Stimulate Innovation

- Significantly reducing CO_2 emissions to achieve carbon neutrality by 2050 is an extremely high technical and economic hurdle, so building a comprehensive framework for stimulating innovation through the social implementation of research and development results is essential.
- Around the world, bold policy mechanisms have been announced to support the transition from research and development to social implementation. Likewise in Japan as well, NEDO has been promoting the Green Innovation Fund Project since FY2021, and the Basic Policy for the Realization of GX has been approved by the Cabinet in order to fulfill international commitments, such as carbon neutrality, and simultaneously achieve economic growth and enhanced industrial competitiveness.

As discussed so far, attaining carbon neutrality by 2050 means significantly reducing CO_2 emissions, but this is an extremely high technical and economic hurdle to overcome. In addition to ensuring that existing technologies, including many energy-saving ones, are introduced and fall in price through research and development, it is essential to stimulate innovations that hold the potential to transform society, drive research and development results toward innovation, and ensure that these results are implemented. To achieve this, it is necessary to identify promising technologies that could help to solve the problem of climate change through comprehensive and objective evaluation and promote research and development with an eye to social implementation. At the same time, there is a need to both enhance institutional support measures for socially implementing research and development results and establish a comprehensive framework where innovation takes place.

Among other countries, the developed countries that have set the goal of achieving carbon neutrality by 2050 have announced bold policy measures to support the transition from research and development to social implementation. These efforts are aimed at not only attaining carbon neutrality but also spurring new industries and employment opportunities, developing new energy sources (such as hydrogen) and industrial infrastructure, and securing resources through resource recycling. The success or failure of these efforts will directly affect the competitiveness of companies and countries.

In Europe, through Horizon Europe, a financial assistance package to the value of 95.5 billion euros has been provided for basic research, demonstration, and implementation. More than 35% of it has been spent on climate change measures. Also, through the EU Innovation Fund, 10 billion euros will be invested over 10 years on demonstrating GHG reduction technologies in energy-consuming industries, such as oil refineries, and in the fields of energy storage and CCUS using renewable energy and hydrogen. The US has decided to invest heavily in supporting the demonstration and introduction of technologies through mechanisms such as the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act. The IRA involves spending 369 billion USD on ensuring energy security and achieving decarbonization, while the Infrastructure Investment and Jobs Act includes investing a total of 88 billion USD on measures such as research and development of CCUS and DAC, demonstration of clean energy, and establishment of tough and smart power infrastructure.

As for Japan, it announced the 2050 Carbon Neutrality Declaration in October 2020, aiming to achieve net-zero GHG emissions by 2050. This goal, which requires that the government sharply accelerate its existing policies, cannot be achieved without extraordinary effort. Making a structural shift in the energy and industrial sectors and accelerating current efforts is imperative through bold investments in innovation and the like. For this to happen, in 2021, the two-trillion-yen Green Innovation Fund was established in NEDO. Through this fund, ambitious and specific goals are shared between the public and private sectors, and continuous support is provided over a maximum of ten years for companies and other organizations that are working on these goals as their business challenges in the stages of research and development, demonstration, and social implementation. In February 2023, the Basic Policy for the Realization of GX was approved by the Cabinet to, fulfill international commitments such as carbon neutrality and achieve economic growth and enhanced industrial competitiveness at the same time on the premise of a stable energy supply. This policy is aimed at realizing and implementing the Growth-oriented Carbon Pricing Concept, which includes the government's bold up-front investment support, amounting to 20 trillion yen, using the GX Economy Transition Bonds, in order for the public and private sectors to make relevant investments of more than 150 trillion yen over the next decade to carry out green transformation.

The expectation is that, as a foundation for these efforts, the government and relevant organizations will continuously work to develop an attractive research environment where wisdom gathers from the industrial and academic sectors. As this will require research and development personnel who have high degrees of expertise in fields such as energy, biotechnology, and the circular economy, and can apply information technology to gain a bird's-eye of areas that transcend their expertise. Also necessary is to implement research results and new technologies and have them penetrate not only within Japan but also all over the world. To achieve this, companies, as players, must take the initiative to run new businesses with an eye on the global market. For this to happen, Japan needs to secure personnel who are actively involved in developing new business models, making investments, and designing new schemes, including rules that take domestic and overseas policy trends into account, and people who are able to demonstrate leadership in leading collaboration across technical fields, industries, and countries. To overcome these challenges, it is important to ensure that the industrial, academic, and public sectors fulfill their respective roles.

As a part of these efforts in Japan, NEDO is working to present the direction of medium-and long-term technology development to find the seeds of innovation and implement them in society. The Comprehensive Principle 2023 is based on the latest scientific knowledge and indicates the direction of medium-and long-term technological development to achieve sustainable development. NEDO is striving to be the first organization in the world to identify these and nurture them to industry-academic-government projects by, for example, formulating technology strategies that take advantage of Japan's strengths and advantages and providing evidence for developing policy. From there, NEDO will strengthen its role as an *innovation accelerator* to promote social implementation of research and development results, thereby contributing further to solving social challenges.

Chapter 6 Conclusion

The purpose of the Comprehensive Principle is to help evaluate technologies that must be developed and demonstrated so that carbon neutrality can be achieved. To do so, the Comprehensive Principle provides an overview of technologies related to the *3 Essential Social Systems for Sustainable Society and the Digital Transformation for Fundamental to them*, and highlights the importance of assessing their CO_2 reduction effects comprehensively and objectively. It also presents significant technologies based on the latest trends, and provides the basis and results of estimating their *CO_2 reduction potential* and *CO_2 abatement cost*.

Climate change is a global issue that must be solved in order to realize a sustainable society. As the world accelerates efforts toward carbon neutrality, new social challenges have appeared, such as assistance for developing countries and security risks in supply chains. Recognizing again that efforts to decarbonize society as a fundamental way to solve these social challenges and climate change issues, Japan must take the initiative to promote technology development for innovation.

Developing a sustainable society requires integrated promotion of the *3 Essential Social Systems for Sustainable Society and the Digital Transformation Fundamental to them*. As key initiatives to achieve carbon neutrality, NEDO must advocate for the *decarbonization of energy use*, *reduction of final energy consumption*, *introduction of negative emission technologies*, and *non-energy related GHG emissions reductions*.

Analysis of the latest data reveals that the marginal abatement cost for achieving carbon neutrality is declining, continuous efforts are necessary to generate innovation with every available technology. Development of technologies in the energy and environmental fields must start without delay because it takes about 20 years for their effects to appear. At the same time, existing technologies such as those for saving energy need to improve and their up-front costs need to decrease for the transition to speed up. Also, it is important to accelerate discussions on technology development for Net Negative with an eye to the future once carbon neutrality has been attained.

Furthermore, a comprehensive approach is required to implement research and development results and spur innovations to attain carbon neutrality.

NEDO will continue to evaluate the latest domestic and overseas trends to identify technologies that should be developed and demonstrated, and will improve evaluation methods and ensure their objectivity through collaboration with external organizations. Also, NEDO will, as part of its technology strategy and the like, quantitatively evaluate the obtained results and methods so they can be used for various evaluations in a range of fields. At the same time, NEDO will strive to ensure that the Comprehensive Principle will be used in its various research and development support programs.

NEDO will strengthen its role as an *innovation accelerator* to identify and nurture the seeds of innovation and implement the results in society, and aim to *solve the issue of global climate change* and *contribute to realizing a sustainable society*, thereby contributing further to solving social challenges.

Index to the Appendix

Appendix 1 Examples of CO_2 Reduction Potential Estimation

Table Examples of CO_2 reduction potentials and underlying logic

(*) Estimation patterns
- A: The estimate is made based on the assumed penetration rate of the technology.
- B: Estimates by other specialized institutions are used.
- C: The estimate is made based on the government's or industry's goals or predictions.
- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Next generation photovoltaics	6.3–9.1	A, B	614 gCO_2/kWh × 9,720 TWh/year + 188 gCO_2/kWh × 1,840 TWh/year = 6.3 $GtCO_2$/year 614 gCO_2/kWh × 14,888 TWh/year = 9.1 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/kWh (This assumes the power generation stage only.) b) Emission intensity of conventional technology: 614 gCO_2/kW (average CO_2 emission intensity of thermal power generation)*1, 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)*2 c) Amount introduced, amount replaced (amount of power generated): up to 14,888 TWh/year d) Description: • 9.1 $GtCO_2$/year: The estimate is made by replacing thermal power generation with next generation photovoltaics. This is based on the assumption that the difference in the amount of power generated by photovoltaics between the NetZero Emission by 2050 (NZE) scenario (2050) of the IEA's World Energy Outlook (WEO) 2022 (27,006 TWh) and the Stated Policy Scenario (STEPS) scenario of the same report (12,118 TWh) is the potential of next generation photovoltaics (14,888 TWh). With regard to the difference between the STEPS and NZE scenarios, for example, the report mentions efforts based on the Green Growth Strategy in Japan. Technologies to eliminate the restriction of installation locations can expand the introduction of PVs into applications like water surfaces, agricultural lands, walls, and vehicles, as described below. • 6.3 $GtCO_2$/year: Assuming the introduction of next generation photovoltaic modules, the amount of power generated is expected to be 2.3 TW on 1% of inland waters around the world; 5 TW on 0.1% of agricultural lands; 1.68 TW on building walls; and 0.56 TW in vehicles. Also, the equipment utilization rate is assumed to be 15.2% (on waters and agricultural lands), 9.6% (on walls), and 8.7% (in vehicles). It is assumed that on inland waters and agricultural lands, next generation photovoltaics will replace thermal power generation directly; however, on walls and in vehicles it will be used to reduce grid power consumption. (On waters) 2.3 TW × 24 hours × 365 days × 15.2% = 3,062.5 TWh (On agricultural lands) 5 TW × 24 hours x 365 days × 15.2% = 6,657.6 TWh (On waters + On agricultural lands: Replacement of thermal power generation) 9,720 TWh (On walls) 1.68 TW × 24 hours × 365 days × 9.6% = 1,412.8 TWh (In vehicles) 0.56 TW × 24 hours × 365 days × 8.7% = 426.8 TWh (On walls + In vehicles: Reduction of grid power consumption) 1,840 TWh *1 Average CO_2 emission intensity of thermal power generation: Calculated based on the global CO_2 emissions (7,891 $MtCO_2$) and amount of power generated (12,869 TWh) in the IEA's WEO 2022 STEPS scenario (2050). *2 CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050).

Table Examples of CO_2 reduction potentials and underlying logic

(*) Estimation patterns
- A: The estimate is made based on the assumed penetration rate of the technology.
- B: Estimates by other specialized institutions are used.
- C: The estimate is made based on the government's or industry's goals or predictions.
- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Next generation wind power	7.8	B	614 gCO_2/kWh × 12,776.9 TWh/year = 7.8 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/kWh b) Emission intensity of conventional technology: 614 gCO_2/kWh (average CO_2 emission intensity of thermal power generation)*1 c) Amount introduced, amount replaced (amount of power generated): 12,776.9 TWh/year d) Description: The estimate is made by replacing thermal power generation with wind power generation of the next generation. This is based on the assumption that the difference in the annual amount of power generated by wind turbines between the IEA's WEO 2022 NZE scenario (2050) (23,486.3 TWh) and the STEPS scenario of the same report (10,691.4 TWh) is the potential of next generation wind power generation (12,776.9 TWh). With regard to the difference between the STEPS and NZE scenarios, for example, the report mentions efforts based on the Green Growth Strategy in Japan. Technologies for next generation wind power include new technologies such as floating wind power generation and cost-reducing technologies for bottom-fixed wind power generation. *1 Average CO_2 emission intensity of thermal power generation: Calculated based on the global CO_2 emissions (7,891 $MtCO_2$) and amount of power generated (12,869 TWh) in the IEA's WEO 2022 STEPS scenario (2050).
Next generation geothermal power	0.25–0.27	B	614 gCO_2/kWh × 399–434 TWh/year = 0.25–0.27 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/kWh b) Emission intensity of conventional technology: 614 gCO_2/kWh (average CO_2 emission intensity of thermal power generation)*1 c) Amount introduced, amount replaced (amount of power generated): 399–434 TWh/year d) Description: • 0.25 $GtCO_2$/year: The estimate is made by replacing thermal power generation with next generation geothermal power generation. This is based on the assumption that the difference in the amount of power generated by geothermal facilities between the IEA's WEO 2022 NZE scenario (2050) (857 TWh) and the STEPS scenario of the same report (458 TWh) is the potential of next generation geothermal power generation, including supercritical geothermal power generation and enhanced geothermal systems (EGS). • 0.27 $GtCO_2$/year: This estimate assumes that, in addition to Deep EGS (322 TWh), which is discussed in GeoVision 2019 (https://www.energy.gov/sites/prod/files/2019/06/f63/GeoVision-full-report-opt.pdf), about 50 300,000 kW-class power plants, including supercritical geothermal power plants and EGS (112 TWh, Availability: 85%) are introduced mainly in Japan and European countries. *1 Average CO_2 emission intensity of thermal power generation: Calculated based on the global CO_2 emissions (7,891 $MtCO_2$) and amount of power generated (12,869 TWh) in the IEA's WEO 2022 STEPS scenario (2050).

Table Examples of CO_2 reduction potentials and underlying logic

(*) Estimation patterns
A: The estimate is made based on the assumed penetration rate of the technology.
B: Estimates by other specialized institutions are used.
C: The estimate is made based on the government's or industry's goals or predictions.
D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Marine power generation	0.02	B	614 gCO_2/kWh × 36.91 TWh/year = 0.02 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/kWh b) Emission intensity of conventional technology: 614 gCO_2/kWh (average CO_2 emission intensity of thermal power generation)*1 c) Amount introduced, amount replaced (amount of power generated): 28.44 TWh/year d) Description: The estimate is made by replacing thermal power generation with next generation marine power generation. This is based on the assumption that the difference in the amount of power generated by marine power plants between the IEA's WEO 2022 NZE scenario (2050) (124.58 TWh) and the STEPS scenario of the same report (96.14 TWh) is the potential of next generation marine power generation technology. In the IEA's WEO 2022, there is no clear description of next generation technologies for marine power generation, but it is assumed that a competitive power generation cost will be achieved by enhancing technical maturity with various power generation methods, including ocean-current power generation, wave energy converter, and tidal-current power generation*2. *1 Average CO_2 emission intensity of thermal power generation: Calculated based on the global CO_2 emissions (7,891 $MtCO_2$) and amount of power generated (12,862 TWh) in the IEA's WEO 2022 STEPS scenario (2050). *2 TSC Foresight Vol. 28, Toward the Formulation of Technology Strategies in the Field of Ocean Energy (NEDO, 2018) https://www.nedo.go.jp/content/100880816.pdf
High efficiency fossil power	0.09–0.28	A	(362 - 295) gCO_2/kWh × 333–999 TWh/year + (890 - 650) gCO_2/kWh × 295–884 TWh/year = 0.09–0.28 $GtCO_2$/year a) Emission intensity of new technology: 295 gCO_2/kWh (natural gas), 650 gCO_2/kWh (coal) b) Emission intensity of conventional technology: 362 gCO_2/kWh (natural gas), 890 gCO_2/kWh (coal) c) Amount introduced, amount replaced (amount of power generated): 333–999 TWh/year (natural gas), 295–884 TWh/year (coal) d) Description: Since a large amount of renewable energy has been introduced, not only high efficiency but also enhanced characteristics, including ability to start and stop power generation frequently, partial load, and minimum availability, are required for future thermal power generation. Therefore, new technology development is necessary. For the emission intensity of the new technology, in the Technology Roadmap for Next Generation Thermal Power Generation, the average value of GTCC and GTFC (efficiency: about 60%) is adopted for natural-gas thermal power generation, and the average value of IGCC and IGFC (efficiency: about 50%) for coal thermal power generation. The emission intensity of the conventional technology is estimated based on the amounts of power generated and CO_2 emissions of natural-gas thermal power generation and coal thermal power generation in the IEA's WEO 2022 STEPS scenario. The amount introduced is estimated based on the assumption that 5 to 15% of natural-gas thermal power generation (6,658 TWh) and coal thermal power generation (5,892 TWh) will be replaced by the new technologies as assumed in the IEA's WEO 2022 STEPS scenario. As for enhanced characteristics such as ability to start and stop power generation frequently, partial load, and minimum availability, these can eventually result in a rise in the amount of variable renewable energy, such as photovoltaics, introduced, but their effects are not included in this estimate.

Table Examples of CO_2 reduction potentials and underlying logic

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- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Hydrogen power generation	0.107–0.320	A	362 gCO_2/kWh × 294.6–883.8 TWh/year = 0.107–0.320 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/kWh (This assumes the utilization phase only.) b) Emission intensity of conventional technology: 362 gCO_2/kWh c) Amount introduced, amount replaced (amount of power generated): 294.6–883.8 TWh/year d) Description: In the IEA's WEO 2022 STEPS scenario (2050), the amount of power generated by natural-gas thermal power sources is estimated to be 6,658 TWh/year, and it is assumed that 5 to 15% of it (294.6 to 883.8 TWh/year) will be replaced by hydrogen power generation. • CO_2 emission intensity of natural-gas thermal power generation: Calculated based on the global CO_2 emissions and amount of power generated by natural-gas thermal power facilities in the IEA's WEO 2022 STEPS scenario (2050). • c) Amount introduced [Reference value: Hydrogen introduced amount-equivalent]: Calculated with the high heating value of hydrogen, or 142 MJ/kg, based on the assumption that the thermal efficiency of natural-gas thermal power generation stated in the Ministry of Economy, Trade and Industry's 2021 Power Generation Cost Verification Working Group report (54.5%) can be applied to hydrogen power generation as well. 294.6–883.8 TWh/year / 54.5% / 142 MJ/kg = 13.70–41.11 MtH_2/year However, the CO_2 emissions from hydrogen production, transportation, and storage are not included in this estimate.
Ammonia power generation	0.296–0.889	A	890 gCO_2/kWh × 332.9–998.7 TWh/year = 0.296–0.889 $GtCO_2$/year a) Emission intensity of new technology: 0 $kgCO_2$/kWh (This assumes the utilization phase only.) b) Emission intensity of conventional technology: 890 gCO_2/kWh c) Amount introduced, amount replaced (amount of power generated): 332.9–998.7 TWh/year d) Description: In the IEA's WEO 2022 STEPS scenario (2050), the amount of power generated by coal thermal power facilities (without CO_2 recovery) is estimated to be 5,892 TWh/year, and it is assumed that 5 to 15% of it (332.9 to 998.7 TWh/year) will be replaced by ammonia power generation. • CO_2 emission intensity of coal thermal power generation: Calculated based on the global CO_2 emissions and amount of power generated by coal thermal power generation facilities in the IEA's WEO 2022 STEPS scenario (2050). • c) Amount introduced [Reference value: Ammonia consumption-equivalent]: Calculated with the high heating value of ammonia, or 22.5 MJ/kg, based on the assumption that the thermal efficiency of natural-gas thermal power generation stated in the Ministry of Economy, Trade and Industry's 2021 Power Generation Cost Verification Working Group report (54.5%) can be applied to ammonia power generation as well. 332.9–998.7 TWh/year / 54.5% / 22.5 MJ/kg = 97.73–293.2 MtH_3/year However, the CO_2 emissions from ammonia production, transportation, and storage are not included in this estimate.

Table Examples of CO_2 reduction potentials and underlying logic

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D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Heat (industry) - Hydrogen/ammonia	2.61	A	5.22 $GtCO_2$/year × 1/2 = 2.61 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/MJ (This assumes the utilization phase only.) b) Emission intensity of conventional technology: N/A (No data is available since various forms of utilization are expected.) c) Amount introduced, amount replaced: It is assumed that 1/2 of the fossil fuel consumption in this field will be replaced by the new technology. d) Description: Of the global industrial CO_2 emissions in the Sustainable Development Scenario 2019–2070 (IEA, last updated on October 26, 2022), the CO_2 emissions from thermal demand, except *Process Emissions* (emissions not from energy but from raw materials) in each industry and *Steel* (it is assumed that the majority of coal is consumed to generate heat or meet process requirements, and the former is discussed in *Hydrogen reduction ironmaking*), are estimated to be 4.31 $GtCO_2$. A chart in this report shows that from the 2019 level, the entire *Direct Emissions*, including *Process Emissions*, are expected to increase about 1.21 times in the 2050 STEPS scenario (9.02 $GtCO_2$ → 10.92 $GtCO_2$). Thus, assuming that the emissions from all emission sources will increase 1.21 times, the maximum CO_2 reduction potential is estimated to be the product of 4.31 $GtCO_2$ and 1.21, or 5.22 $GtCO_2$. There are various options for decarbonization, including electrification, hydrogen, ammonia, and synthetic methane. Assuming that the maximum contribution of hydrogen and ammonia combustion is about 1/2, the reduction potential is estimated to be 2.61 $GtCO_2$ (5.22 $GtCO_2$ × (1/2)). • c) Amount introduced [Reference value: Hydrogen/ammonia consumption-equivalent]: After the reduction potential is estimated (3.48 $GtCO_2$), the required amount of hydrogen is estimated assuming that all the emissions are covered by natural gas. Because the emission factor of natural gas, 0.0135 tC/GJ (Ministry of the Environment) is adopted, and as the per-unit heating value of hydrogen, 120 MJ/KgH_2 (lower heating value) is adopted. 3.48 $GtCO_2$ × (12/44) / 0.0135 / 120 MJ/kgH_2 = 585 MtH_2/year

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Hydrogen reduction ironmaking (blast furnaces)	0.34	D	570 Mt/year × (2.0 tCO_2/t - 1.4 tCO_2/t) = 342 $MtCO_2$/year ＝ 0.34 $GtCO_2$/year a) Emission intensity of new technology: 1.4 tCO_2/t-Fe b) Emission intensity of conventional technology: 2.0 tCO_2/t-Fe c) Amount introduced, amount replaced (steel production): 570 Mt-Fe/year d) Description: In CO_2 reduction potential [tCO_2/year] = Amount introduced [t/year] × (Emission intensity of conventional technology - Emission intensity of new technology) [tCO_2/t]: • Amount introduced (c): Estimated based on the increase in steel production by 2050 from the 2020 level (approximately 10%) (Figure 3.15); the expected percentage of hydrogen reduction ironmaking in 2050 (29%) (Table 3.3); and the global iron production in 2020 (1,787 Mt/year)[*2] in the IEA's Net Zero by 2050[*1]. Amount introduced = 1,787 Mt-Fe/year × 1.1 × 29% = 570 Mt-Fe/year • Emission intensity of conventional technology (b): Assumed to be 2.0 tCO_2/t-Fe based on the production emission intensity of the blast furnace - basic oxygen furnace method, which is the best available technology[*3]. • Emission intensity of new technology (a): Assumed to be 1.4 tCO_2/t-Fe, which is equivalent to a reduction of 30% from the conventional blast furnace technology, based on the target value of hydrogen reduction ironmaking (blast furnaces) in COURSE50[*4]. • As for the penetration rate, it is assumed that conventional hydrogen reduction ironmaking will be completely replaced by COURSE50 blast furnace technology. *1: Net Zero by 2050 (IEA, 2021) https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf *2: World Steel Association, World Steel in Figures 2021 https://worldsteel.org/world-steel-in-figures-2021/ *3: Net-Zero Steel Sector Transition Strategy (Mission Possible Partnership, 2021) https://www.energy-transitions.org/wp-content/uploads/2021/10/MP-Steel-Transition-StrategyFinal-1.pdf *4: The Japan Iron and Steel Federation, COURSE50: https://www.course50.com/technology/

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Heat (industry) - Synthetic methane	1.31	A	5.22 $GtCO_2$/year × 1/4 = 1.31 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/MJ (This assumes emissions from biomass.) b) Emission intensity of conventional technology: N/A (No data is available since various forms of utilization are expected.) c) Amount introduced, amount replaced: It is assumed that 1/4 of the fossil fuel consumption in this field will be replaced by the new technology. d) Description: Of the global industrial CO_2 emissions in the Sustainable Development Scenario 2019–2070 (IEA, last updated on October 26, 2022), the CO_2 emissions from thermal energy demand in 2019, except *Process Emissions* (emissions not from energy but from raw materials) in each industry and *Steel* (it is assumed that the majority of coal is consumed to generate heat or meet process requirements, and the former will be discussed in *Hydrogen-reduction ironmaking*), are estimated to be 4.31 $GtCO_2$. A chart in this report shows that from the 2019 level, the entire *Direct Emissions*, including *Process Emissions*, are expected to increase about 1.21 times in the 2050 STEPS scenario (9.02 $GtCO_2$ → 10.92 $GtCO_2$). Thus, assuming that the emissions from all emission sources will increase 1.21 times uniformly, the maximum CO_2 reduction potential can be estimated to be the product of 4.31 $GtCO_2$ and 1.21, or 5.22 $GtCO_2$. For synthetic methane in this technical field, CO_2 is assumed to be derived from biomass or renewable energy-derived H_2. Thus, assuming that synthetic methane is carbon-neutral* in this estimate, the emission intensity is assumed to be 0 gCO_2/MJ. The CO_2 emissions from synthetic methane production, transportation, and storage are not included in this estimate. In addition to synthetic methane, there are various other options for decarbonization, including electrification, hydrogen, and ammonia. Assuming that the maximum contribution of biomass-derived synthetic methane is about 1/4, the reduction potential is estimated to be 1.31 $GtCO_2$ (4.31 $GtCO_2$ × (1/4)). • c) Amount introduced [Reference value: Synthetic methane introduced amount-equivalent]: After the reduction potential is estimated (1.74 $GtCO_2$), the required amount of biomass energy is estimated assuming that all the emissions are covered by natural gas. As the emission factor of natural gas, 0.0135 tC/GJ (Ministry of the Environment) is used. 3.48 $GtCO_2$/year × (12/44) / 0.0135 = 35 EJ/year This value is within the range of global biomass potential (200 to 500 EJ/year) that assumes the sustainable resource utilization presented in the NEDO Renewable Energy White Paper. Based on the lower heating value of methane, or 49.67 MJ/kg, the amount of methane introduced can be calculated to be 0.7 Gt-CH_4/year. * FY2018 Accomplishment Report, Strategy Formulation Survey Project: Survey on low-environmental-impact automotive fuels using renewable energy-derived hydrogen etc. (NEDO, 2020)

Table Examples of CO_2 reduction potentials and underlying logic

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D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Heat (industry) - Renewable heat	0.9	B	(53.9 - 0) $MtCO_2$/EJ × (9.5 + 2.05) EJ/year + (53.9 - 20.5) $MtCO_2$/EJ × (2.05 + 6.9) EJ/year = 0.9 $GtCO_2$/year a) Emission intensity of new technology: 0 $MtCO_2$/EJ (biomass/solar heat), 20.5 $MtCO_2$/EJ (ground source heat/district heating and cooling) (Both estimates assume that the technology is in the utilization phase.) b) Emission intensity of conventional technology: 53.9 $MtCO_2$/EJ c) Amount introduced, amount replaced (replaced amount of fossil fuel consumed in this field): 9.5 EJ (biomass), 2.05 EJ (solar heat), 2.05 EJ (geothermal heat/ground source heat), 6.9 EJ (renewable energy heat in district heating and cooling) d) Description: • a) Emission intensity of new technology: Ground source heat/district heating and cooling: Estimated to be 20.5 $MtCO_2$/EJ (= 61.6 $MtCO_2$/EJ / 3) based on the emission intensity of power consumption (61.6 $MtCO_2$/EJ) estimated from the IEA's WEO 2022 STEPS scenario, assuming that COP = 3 as a rough estimate for both of them as well as assuming the use of heat pumps. • b) CO_2 emission intensity of conventional technology: In the IEA's WEO 2022 STEPS scenario (2050), approximately 30 EJ of natural gas and approximately 9 EJ of crude oil are expected to be consumed by the building sector. Assuming that they are replaced by the new technology, the emission intensity is estimated by the weighted average of the CO_2 emissions per calorie in fuel consumption (Mains-supply gas: 49.8 $MtCO_2$/EJ, Kerosene: 67.8 $MtCO_2$/EJ, Ministry of the Environment[*1]) (equivalent to the assumption that the heat utilization efficiency of the conventional technology is 100%). (49.8 $MtCO_2$/EJ × 30 EJ + 67.8 $MtCO_2$/EJ × 9 EJ) / (30 EJ + 9 EJ) = 53.9 $MtCO_2$/EJ • c) Amount of heat from renewable energy: The amount introduced is estimated based on the World Energy Transitions Outlook 2022's (IRENA) 1.5°C scenario. However, the Business-As-Usual (BAU) scenario, which is based on the conventional technology, is not mentioned in the report. In this estimate, therefore, the new technologies introduced between 2019 and 2050 under the 1.5°C scenario are assumed as new technologies. • Solar heat: 2.05 EJ (difference between 3.1 EJ@2050 and 1.05 EJ@2019[*2]) • Biomass: 9.5 EJ (In the 1.5°C scenario, the amount introduced in 2050 is estimated based on the assumption that traditional biomass utilization before 2019 will be completely replaced by modern biomass utilization.) • Geothermal heat/Ground source heat: 2.05 EJ (difference between 3.1 EJ@2050 and 1.05 EJ@2019[*2]) • Utilization of heat from renewable energy by district heating and cooling: 6.9 EJ (difference between 7.3 EJ@2050 and 0.4 EJ@2019) *1: List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment) *2: In the World Energy Transition Outlook 2022 (IRENA), only the total amount introduced of solar heat and geothermal heat/ground source heat is mentioned, and their proportions are unclear. In this estimate, their proportions are assumed to be 50/50.

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Heat (residential/commercial) - Synthetic methane	0.53	A	{(0.0498 $kgCO_2$/MJ × 30 EJ/year) + (0.0678 $kgCO_2$/MJ × 9 EJ/year)} × 1/4 = 0.53 $GtCO_2$/year a) Emission intensity of new technology: 0 $kgCO_2$/MJ (This assumes emissions from biomass.) b) Emission intensity of conventional technology: 49.8 gCO_2/kWh (mains-supply gas), 67.8 gCO_2/kWh (kerosene) c) Amount introduced, amount replaced: It is assumed that 1/4 of the fossil fuel consumption in this field will be replaced by the new technology. d) Description: In the STEPS scenario, by 2050, 30 EJ of mains-supply gas and 9 EJ of crude oil are expected to be used by the building sector. This is assumed to be thermal demand in the residential and commercial sectors accompanying CO_2 emissions. In the calculation of CO_2 emissions from mains-supply gas and crude oil, the CO_2 reduction potential is estimated, as in the equation above, by setting the mains-supply gas and kerosene in Japan as emission factors*1 and assuming that approximately 1/4 of the total emissions will be replaced by synthetic methane (the rest of them will be replaced by hydrogen, green LP gas, and electricity, including heat pump). For synthetic methane in this technical field, CO_2 is assumed to be derived from biomass or renewable energy-derived H_2. Thus, assuming that synthetic methane is carbon-neutral*2 in this estimate, the emission intensity is assumed to be 0 $kgCO_2$/MJ. The CO_2 emissions from synthetic methane production, transportation, and storage are not included in this estimate. 9.8 EJ (= (30 EJ + 9 EJ) × 1/4), which is assumed to be replaced by synthetic methane, is within the range of global biomass potential (200 to 500 EJ/year) that assumes the sustainable resource utilization presented in the NEDO Renewable Energy White Paper. • c) Amount introduced [Reference value: Synthetic methane introduced amount-equivalent]: Regarding the per-unit heating value of synthetic methane, the heating value of natural gas, or 54.6 MJ/kg, is adopted (source: Ministry of the Environment). {30 EJ (mains-supply gas) + 9 EJ (kerosene)} × 25% / 54.6 MJ/kg = 0.71 Gt/year *1 List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment) *2 FY2018 Accomplishment Report, Strategy Formulation Survey Project: Survey on low-environmental-impact automotive fuels using renewable energy-based hydrogen etc. (NEDO, 2020)

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Heat (residential/commercial) - Green LPG	0.53	A	(49.8 gCO_2/MJ × 30 EJ/year + 67.8 gCO_2/MJ × 9 EJ/year) × 1/4 = 0.53 $GtCO_2$/year a) Emission intensity of new technology: 0 $kgCO_2$/MJ (This assumes emissions from biomass.) b) Emission intensity of conventional technology: 49.8 gCO_2/kWh (mains-supply gas), 67.8 gCO_2/kWh (kerosene) c) Amount introduced, amount replaced: It is assumed that 1/4 of the fossil fuel consumption in this field will be replaced by the new technology. d) Description: In the STEPS scenario, by 2050, 30 EJ of mains-supply gas and 9 EJ of crude oil are expected to be used in the building sector. It is assumed that they are thermal demands in the residential and commercial sectors accompanying CO_2 emissions. In the calculation of CO_2 emissions from mains-supply gas and crude oil, the CO_2 reduction potential is estimated, as in the equation above, by setting the mains-supply gas and kerosene in Japan as emission factors[*1] and assuming that 1/4 of the total emissions will be replaced by green LPG (the rest of them will be replaced by hydrogen, synthetic methane, and electricity, including heat pump). For green LPG in this technical field, CO_2 is assumed to be derived from biomass or renewable energy-derived H_2. Thus, assuming that green LPG is carbon-neutral[*2] in this estimate, the emission intensity is assumed to be 0 $kgCO_2$/MJ. The CO_2 emissions from green LPG production, transportation, and storage are not included in this estimate. 9.8 EJ (= (30 EJ + 9 EJ) × 1/4), which is assumed to be replaced by green LPG, is within the range of global biomass potential (200 to 500 EJ/year) that assumes the sustainable resource utilization presented in the NEDO Renewable Energy White Paper. • c) Amount introduced [Reference value: Green LPG introduced amount-equivalent]: Regarding the per-unit heating value of green LP gas, the heating value of commonly used LPG, or 50.8 MJ/kg, is adopted (source: Ministry of the Environment). {30 EJ (mains-supply gas) + 9 EJ (kerosene)} × 25% / 50.8 MJ/kg = 0.77 Gt/year *1 List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment) *2 FY2018 Accomplishment Report, Strategy Formulation Survey Project: Survey on low-environmental-impact automotive fuels using renewable energy-based hydrogen etc. (NEDO, 2020)

Table Examples of CO_2 reduction potentials and underlying logic

(*) Estimation patterns
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D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Stationary fuel cell	1.99	A	1.99 $GtCO_2$/year (= (1)1.06 + (2) 0.47 + (3) 0.46 $GtCO_2$/year) In this estimate, the CO_2 reduction effect is estimated focusing on heat supply by stationary fuel cells using hydrogen as a fuel. Regarding the emission intensity of stationary fuel cells, which are considered as new technology, in consideration of CO_2 emissions during the production stage, the CO_2 emission intensity is calculated on the life-cycle basis. (1) Residential sector: (51.9 - 5.5) $kgCO_2$/GJ × 22.9 EJ/year = 1.06 $GtCO_2$/year a-(1)) Emission intensity of new technology: 5.5 $kgCO_2$/GJ b-(1)) Emission intensity of conventional technology: 51.9 $kgCO_2$/GJ c-(1)) Amount introduced, amount replaced: 22.9 EJ d-(1)) Description: According to the 2007 Survey on Life-Cycle Assessment of Stationary Fuel Cell Systems and Fuel Cell Vehicles, the CO_2 emissions from the production of stationary fuel cells with a thermal output of 1.4 kW are 1,105 $kgCO_2$, and the operation time is 40,000 hours; accordingly, the total thermal output is 56,000 kWh (= 200 GJ). Based on these values, the emission intensity of the new technology is estimated to be 5.5 $kgCO_2$/GJ. As the conventional technology, residential gas water heaters are adopted. Regarding the emission intensity, the value for natural gas combustion stated in the IEA's WEO 2022 STEPS scenario is adopted. For global energy consumption in the residential sector, the residential final energy consumption (106 EJ) is cited from the WEO 2022's STEPS scenario. Also, according to the actual energy demand in FY2020 reported by the Agency for Natural Resources and Energy, 27.4% of the residential energy consumption in Japan is for water heating, and 26.5% is for space heating. These proportions are applied for global residential energy consumption. In this estimate, considering EcoCute and heat pumps as competing technologies in the residential sector, the introduction ratio is assumed as below. In Japan, heat pumps are expected to spread further but the proportion of cold areas in the world is larger than that in Japan. Thus, the introduction ratio is set as follows: (Space heating) Ene-Farm : Heat pumps = 30:70 (Water heating) Ene-Farm : EcoCute = 50:50 Accordingly, the total amount introduced of stationary fuel cells (Ene-Farm) for space heating and water heating is estimated to be 22.9 EJ. (2) Commercial sector: (56.4 - 5.5) $kgCO_2$/GJ × 9.2 EJ = 0.47 $GtCO_2$/GJ a-(2)) Emission intensity of new technology: 5.5 $kgCO_2$/GJ b-(2)) Emission intensity of conventional technology: 56.4 $kgCO_2$/GJ c-(2)) Amount introduced, amount replaced: 9.2 EJ d-(2)) Description: The emission intensity of stationary fuel cells is as described in *(1) Residential sector.* Regarding the conventional technology, the fuels used for space heating and water heating (coal, crude oil, gas, and electricity) are adopted. As for the emission intensity, the values given in the WEO 2022's STEPS scenario are adopted. The proportions of energy sources for space heating and water heating were cited from the Introduction to Reading Energy and Economic Data (The Institute of Energy Economics, Japan, 2017), and the product of the emission intensity of each energy source is used as the emission intensity of conventional technology.

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- C: The estimate is made based on the government's or industry's goals or predictions.
- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Stationary fuel cell (continued)	1.99	A	• Emission intensity of each fuel ($kgCO_2$/GJ) Coal: 88.9, Crude oil: 56.3, Natural gas: 51.9, Power consumption: 61.6 • Proportions of energy sources for space heating (%) Coal: 1.6, Crude oil: 58.4, Gas/heat: 29.7, Electric power: 10.3 • Proportions of energy sources for water heating (%) Coal: 7.7, Crude oil: 31.1, Gas/heat: 55.0, Electric power: 6.2 According to the EDMC Handbook of Japan's & World Energy & Economic Statistics (The Institute of Energy Economics, Japan, 2022), the energy consumptions for space heating and water heating in Japan are 48.7 Pcal and 49.1 Pcal, respectively. In this estimate, considering heat pumps as competing technology to be introduced in the commercial sector, the introduction ratio is assumed as below. (Space heating) Stationary fuel cell : Heat pumps = 50:50 (Water heating) Stationary fuel cell : Heat pumps = 80:20 Thus, the total amount introduced of stationary fuel cells for space heating and water heating is estimated to be 266 PJ. Since the proportion of Japan's final energy consumption (consumer, agriculture, etc.) to the global final energy consumption is 2.9%, the global energy consumption for space heating and water heating is roughly estimated to be 9.2 EJ. (3) Industrial sector: (51.9 - 5.5) $kgCO_2$ × 10.0 EJ = 0.46 $GtCO_2$/GJ a-(3)) Emission intensity of new technology: 5.5 $kgCO_2$/GJ b-(3)) Emission intensity of conventional technology: 51.9 $kgCO_2$/GJ c-(3)) Amount introduced, amount replaced: 10.0 EJ d-(3)) Description: The emission intensity of stationary fuel cells is as described in *(1) Residential sector*. As the conventional technology, boilers are adopted. As for the emission intensity, the value for natural gas combustion given in the WEO 2022's STEPS scenario is adopted. According to that scenario, the total industrial energy consumption in 2050 will be 209 EJ, and according to IEA Insight Series 2017 Renewable Energy for Industry–From green energy to green materials and fuels, the proportion of heat utilization to the final energy consumption in the industrial sector will be 24%. Thus, the energy consumption by heat utilization in the industrial sector is estimated to be 50.2 EJ. In addition, assuming that the industrial heat demand at a temperature range of 400°C or less can be replaced by fuel cells, the proportion of that industrial heat demand to the total industrial demand is 25%, and accordingly, the amount of heat energy that can be replaced by stationary fuel cells is 12.5 EJ. Considering heat pumps as competing technology to be introduced in the industrial sector, the introduction ratio is assumed as below. Stationary fuel cells : High-temperature heat pump = 80:20 Accordingly, in this estimate, the amount introduced is 10.0 EJ.

Table Examples of CO_2 reduction potentials and underlying logic

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- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Automotive - Fuel cell vehicle	0.55–0.98	A	0.55–0.98 $GtCO_2$/year (= (1) 0.1–0.3 + (2) 0.45–0.68 $GtCO_2$/year) (1) LDVs (Light Duty Vehicles) (38.7 - 2–4) gCO_2/km × 2.75–8.25 trillion km/year = 0.1–0.3 $GtCO_2$/year a-(1)) Emission intensity of new technology: 2–4 gCO_2/km b-(1)) Emission intensity of conventional technology: 38.7 gCO_2/km c-(1)) Amount introduced, amount replaced (total mileage of fuel cell vehicles (LDVs): 2.75–8.25 trillion km/year d-(1)) Description: Among fuel cell vehicles, the estimate is made for passenger vehicles (LDVs). As for the emission intensity of fuel cell vehicles, 2–4 gCO_2/km is cited from The MIRAI LCA Report (Toyota Motor Corporation, 2015). The emission intensity of the conventional technology is calculated based on the CO_2 emissions in the WEO 2022's STEPS scenario (2.47 Gt/year) and the annual mileage of LDV in 2050 estimated in the Energy Technology Perspective (ETP) 2017's Reference Technology Scenario (RTS). The annual mileage is calculated assuming that one person is transported by an LDV and the cargo weight of an LDV is 1 tonne. Thus, the total annual mileage of LDVs in FY2050 is estimated to be 63.9 trillion km/year, based on which the emission intensity is calculated. According to the EPT 2017's RTS, the breakdown of stocks of LDVs (2.5 billion vehicles) is that the proportions of internal combustion engine vehicles (including hybrid vehicles (HVs)) and electric vehicles (pure EVs, plug-in hybrid EVs (PHEVs), and fuel cell EVs (FCEVs)) are 86% and 14%, respectively. This estimate assumes that internal combustion engine vehicles will be replaced by fuel cell vehicles. Accordingly, the total annual mileage of internal combustion engine vehicles, which are assumed to be replaced by fuel cell vehicles, is 55 trillion km/year. Then, the total mileage of fuel cell vehicles (LDVs) is estimated assuming that the penetration rate of fuel cell vehicles is 5 to 15% of internal combustion engine vehicles. Total mileage of fuel cell vehicles = Total annual mileage of internal combustion engine vehicles × Penetration rate of fuel cell vehicles = 55.0 trillion km × 5–15% = 2.75–8.25 trillion km/year (2) HDVs (Heavy Duty Vehicles) (287 - 2–4) gCO_2/km × 1.6–2.4 trillion km/year = 0.45–0.68 $GtCO_2$/year a-(2)) Emission intensity of new technology: 2–4 gCO_2/km b-(2)) Emission intensity of conventional technology: 287 gCO_2/km c-(2)) Amount introduced, amount replaced (total mileage of fuel cell vehicles (HDVs): 17.8–26.6 trillion km/year d-(2)) Description: Among fuel cell vehicles, the estimate is made for buses and trucks (HDVs: heavy duty vehicles). As for the emission intensity of fuel cell vehicles, 2–4 gCO_2/km is cited from The MIRAI LCA Report (Toyota Motor Corporation, 2015). The emission intensity of the conventional technology is calculated based on the CO_2 emissions in the of the WEO 2022's STEPS scenario (2.44 Gt/year) and the annual mileage of HDVs in 2050 estimated in the ETP 2017's RTS. The annual mileage is calculated assuming that 50 people are transported by an HDV bus and the cargo weight of an HDV truck is 10 tonnes.

Table Examples of CO_2 reduction potentials and underlying logic

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D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Automotive - Fuel cell vehicle (continued)	0.55–0.98	A	Thus, the total annual mileage of HDVs in FY2050 is estimated to be 8.5 trillion km/year, based on which the emission intensity is calculated. According to the EPT 2017's RTS, the breakdown of stocks of HDVs (0.24 billion vehicles) is that the proportions of internal combustion engine vehicles (including hybrid vehicles (HVs)) and electric vehicles (pure EVs, plug-in hybrid EVs (PHEVs), and fuel cell EVs (FCEVs)) are 95% and 5%, respectively. This estimate assumes that internal combustion engine vehicles will be replaced by fuel cell vehicles. Accordingly, the total annual mileage of internal combustion engine vehicles, which are assumed to be replaced by fuel cell vehicles, is 8.1 trillion km/year. Then, the total mileage of fuel cell vehicles (HDVs) is estimated assuming that the penetration rate of fuel cell vehicles is 20 to 30% of internal combustion engine vehicles. Total mileage of fuel cell vehicles = Total annual mileage of internal combustion engine vehicles × Penetration rate of fuel cell vehicles = 8.1 trillion km × 20–30% = 1.6–2.4 trillion km/year
Automotive - Next generation EV	0.043–0.37	A	(46.9 - 36–45) gCO_2/km × 22.5–33.7 trillion km/year = 0.043–0.37 $GtCO_2$/year a) Emission intensity of new technology: 36–45 gCO_2/km b) Emission intensity of conventional technology: 46.9 gCO_2/km c) Amount introduced, amount replaced (total mileage of EVs equipped with next generation batteries: 22.5–33.7 trillion km/year d) Description: In the Environment Innovation Strategy, the amount of CO_2 to be reduced by taking various measures for CO_2 emissions from automobiles, including electrification and fuel decarbonization, is estimated to be 6 Gt. In this estimate, the CO_2 reduction potential of next generation batteries for EVs (passenger vehicles) that are assumed to be charged at home is estimated. • The emission intensity of EVs is calculated based on the power consumption of EVs per unit mileage as of 2018, or 0.19 to 0.24 kWh/km (including a charge loss of 5%; IEA Global EV Outlook 2019), and the emission intensity of electricity, or 0.188 $kgCO_2$/kWh (WEO 2022 STEPS). Emission intensity of EVs = Power consumption of EVs per unit mileage × Emission intensity of electricity • The emission intensity of the conventional technology is calculated based on the CO_2 emissions from LDVs in 2021 in the WEO 2022 (3 Gt/year) and the annual mileage in the ETP 2017. The annual mileage is calculated assuming that one person is transported by an LDV and the cargo weight of an LDV is 1 tonne. Thus, the total annual mileage of HDVs in FY2050 is estimated to be 63.9 trillion km/year, based on which the emission intensity is calculated. The breakdown of stocks of LDVs (2.4 billion vehicles) is that the proportions of internal combustion engine vehicles (including HVs) and electric vehicles (pure EVs, plug-in hybrid EVs (PHEVs), and fuel cell EVs (FCEVs)) are 88% and 12%, respectively. This estimate assumes that internal combustion engine vehicles will be replaced by EVs equipped with next generation batteries. Accordingly, the total annual mileage of internal combustion engine vehicles, which are assumed to be replaced by EVs equipped with next generation batteries, is 56.2 trillion km/year. Then, the total mileage of EVs equipped with next generation batteries is estimated assuming that the penetration rate of EVs equipped with next generation batteries is 40 to 60% of internal combustion engine vehicles. (Total mileage of EVs equipped with next generation batteries) = (Total annual mileage of internal combustion engine vehicles) × (Penetration rate of EVs equipped with next generation batteries) = 56.2 trillion km/year × 40–60% = 22.5–33.7 trillion km/year

Table Examples of CO_2 reduction potentials and underlying logic

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- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Automotive - Synthetic fuel	0.46–0.69	A	(287 - 0) gCO_2/km × 1.6–2.4 trillion km/year = 0.46–0.69 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/km (This assumes emissions from biomass.) b) Emission intensity of conventional technology: 287 gCO_2/km c) Amount introduced, amount replaced (total mileage of freight trucks using synthetic fuel): 1.6–2.4 trillion km/year d) Description: In the Environment Innovation Strategy, the amount of CO_2 to be reduced by taking various measures against CO_2 emissions from automobiles, including electrification and fuel decarbonization, is estimated to be 6 Gt. In this estimate, the CO_2 reduction potential of buses, freight trucks, and other heavy duty vehicles (HDVs) using synthetic fuel produced by using biomass-based CO_2 as a raw material is estimated. The emission intensity of HDVs using synthetic fuel is assumed to be 0 gCO_2/km because synthetic fuel is derived from biomass and is considered carbon-neutral*. The CO_2 emissions from synthetic fuel production, transportation, and storage are not included in this estimate. The emission intensity of the conventional technology is calculated based on the CO_2 emissions in the WEO 2022's STEPS scenario (2.44 Gt/year) and the annual mileage in 2050 estimated in the ETP 2017's RTS. The annual mileage is calculated assuming that 50 people are transported by an HDV bus and the cargo weight of an HDV truck is 10 tonnes. Thus, the total annual mileage of HDVs in FY2050 is estimated to be 8.5 trillion km/year, based on which the emission intensity is calculated. According to the EPT 2017's RTS, the breakdown of stocks of HDVs (0.24 billion vehicles) is that the proportions of internal combustion engine vehicles (including HVs) and electric vehicles (pure EVs, plug-in hybrid EVs (PHEVs), and fuel cell EVs (FCEVs)) are 95% and 5%, respectively. This estimate assumes that internal combustion engine vehicles will be replaced by HDVs using synthetic fuel. Accordingly, the total annual mileage of internal combustion engine vehicles, which are assumed to be replaced by HDVs using synthetic fuel, is 8.1 trillion km/year. Then, the total mileage of HDVs using synthetic fuel is estimated assuming that the penetration rate of HDVs using synthetic fuel is 20 to 30% of internal combustion engine vehicles. Total mileage of HDVs using synthetic fuel = Total annual mileage of internal combustion engine vehicles × Penetration rate of HDVs using synthetic fuel = 8.1 trillion km × 20–30% = 1.6–2.4 trillion km/year In the WEO 2022's STEPS scenario, the energy consumption of HDVs is 39 EJ/year. This value is within the range of global biomass potential (200 to 500 EJ/year) that assumes the sustainable resource utilization presented in the NEDO Renewable Energy White Paper. * FY2018 Accomplishment Report, Strategy Formulation Survey Project: Survey on low-environmental-impact automotive fuels using renewable energy-based hydrogen etc. (NEDO, 2020)

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Aircraft - Next generation electric aviation	0.120–0.281	A	0.195–0.455 $GtCO_2$/year × (1 - (231 gCO_2/kWh / 603 gCO_2/kWh)) = 0.120–0.281 $GtCO_2$/year a) Emission intensity of new technology: 231 gCO_2/kWh b) Emission intensity of conventional technology: 603 gCO_2/kWh c) Amount introduced, amount replaced (CO_2 emissions of jet fuel to be replaced): 0.195–0.455 $GtCO_2$/year d) Description: In the Environment Innovation Strategy, the CO_2 reduction potential is estimated to be 2.0 Gt assuming that, in the aviation industry, measures are taken based on the long-term targets set by International Air Transport Association (IATA), such as electrification and fuel decarbonization (Ministry of Economy, Trade and Industry). This estimate examines the contribution of electric aircraft. Considering electric aircraft for domestic flights using next generation batteries as the new technology, the estimate is made based on the assumption that they can fly 1,000 km or so only with a next generation battery charged from the grid power. In this estimate, the energy consumption for the stages up to actual flight operations is taken into consideration, and conventional aircraft and electric aircraft are assumed to require the same energy consumption for their flights. The emission intensity of electric aircraft is calculated based on the assumption that the emission intensity of electricity is 188 gCO_2/kWh (WEO 2022) and the energy efficiency of electric aircraft is 81% (estimated with a motor efficiency of 95%, energy conversion efficiency of 95%, and battery charge/discharge efficiency of 90%). (Emission intensity of electric aircraft) = (Emission intensity of electricity) / (Efficiency of electric aircraft) The emission intensity of the conventional technology is assumed to be 0.0671 tCO_2/GJ based on the carbon emission intensity of jet fuel (0.0183 tC/GJ) (Ministry of the Environment, https://www.env.go.jp/council/16pol-ear/y164-04/mat04.pdf). Then, the estimate is made by using a conversion factor of 0.278 Wh/kJ assuming that the jet engine efficiency of aircraft is 40%. Emission intensity of conventional technology = Emission intensity of jet fuel / Efficiency of jet engine / 0.278 Wh/kJ The CO_2 emissions of jet fuel in 2050 is estimated based on the predicted rate of CO_2 increase approved by the International Civil Aviation Organization (ICAO), which is cited as an official opinion in the European Parliament held in September 2019 (European Parliament's opinion: https://www.europarl.europa.eu/RegData/etudes/ATAG/2019/640169/EPRS_ATA(2019)640169_EN.pdf) (2016) (the CO_2 emissions are expected to increase by 300 to 700% compared to the 2005 level) and the CO_2 emissions of jet fuel in 2005 given in the IATA's report, or 0.65 Gt (IATA Airline Industry Economic Performance, https://www.iata.org/publications/economics/Reports/Industry-Econ-Performance/Central-forecast-midyear-2018-tables-v1.0.pdf, 2018).The CO_2 emissions of jet fuel in 2050 are estimated to be 1.95 $GtCO_2$/year, with a rate of increase of 300% from the 2005 level, and 4.55 $GtCO_2$/year with a rate of increase of 700%. The proportion of energy consumption is set to 10% based on the assumption that half of the aircraft for domestic flights will be replaced by electric aircraft and the penetration rate of electric aircraft is 1/4 of those for domestic flights. The percentage of energy consumption for domestic flights is set to 40% of the total energy consumption (IATA, Air Passenger Market Analysis, (October, 2020)). CO_2 emissions of jet fuel to be replaced = CO_2 emissions of jet fuel in 2050 × Penetration rate of electric aircraft = 0.65 $GtCO_2$/year × 300–700% × 10% = 0.195–0.455 $GtCO_2$/year

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Aircraft - Bio-jet fuel	0.32–0.75	A	(0.0671 - 0.03 tCO_2/GJ) × 8.75–20.35 EJ/year = 0.32–0.75 $GtCO_2$/year a) Emission intensity of new technology: 0.03 tCO_2/GJ b) Emission intensity of conventional technology: 0.0671 tCO_2/GJ c) Amount introduced, amount replaced (jet fuel to be replaced): 8.75–20.35 EJ/year d) Description: In the Environment Innovation Strategy, the CO_2 reduction potential is estimated to be 2.0 Gt assuming that, in the aviation industry, measures are taken based on IATA's long-term targets, such as electrification and fuel decarbonization (Ministry of Economy, Trade and Industry). In this estimate, the contribution of bio-jet fuel is estimated. Bio-jet fuel and hydrogen are expected to be used in the same field, and the ratio of bio-jet fuel and hydrogen is assumed to be 50:50. It is assumed that bio-jet fuel and hydrogen will be widespread in 2050 and that half of the energy consumption for international flights (60%: IATA (2017) https://www.iata.org/contentassets/9faa9f69011d46c484d93e6dd97a7f52/passenger-analysis-jul-2017.pdf) will be covered by bio-jet fuel. The CO_2 emission intensity of bio-jet fuel varies depending on the raw material and production method. In this estimate, it is assumed to be 0.03 tCO_2/GJ based on the recent evaluation results*. The emission intensity of conventional jet fuel is assumed to be 0.0671 tCO_2/GJ based on the carbon emission intensity of jet fuel (0.0183 tC/GJ) (Ministry of the Environment, https://www.env.go.jp/council/16pol-ear/y164-04/mat04.pdf). The jet fuel consumption in 2050 is estimated based on the CO_2 emissions prediction. Specifically, an increase rate of 300 to 700% is adopted based on the CO_2 increase rate prediction approved by the ICAO, which is cited as an official opinion in the European Parliament held in September 2019 (European Parliament's opinion: https://www.europarl.europa.eu/RegData/etudes/ATAG/2019/640169/EPRS_ATA(2019)640169_EN.pdf) (2016) (the CO_2 emissions are expected to increase by 300 to 700% compared to the 2005 level). Incidentally, the CO_2 emissions from jet fuel in 2005 are estimated to 0.65 $GtCO_2$/year (https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industryeconomic-performance---2018-mid-year---table/). Thus, the CO_2 emissions from jet fuel for international flights in 2050 is estimated to be 1.17 $GtCO_2$/year with an increase rate of 300% from the 2005 level, and 2.73 $GtCO_2$/year with an increase rate of 700%. Based on a CO_2 emission intensity of 0.0671 tCO_2/GJ, the energy consumption is estimated to be 17.5 to 40.7 EJ/year. Half of it is 8.75 to 20.35 EJ/year. * Example: FY2019 Survey on Measures for Stable Fuel Supply (Ministry of Economy, Trade and Industry, 2020) https://www.meti.go.jp/meti_lib/report/2019FY/000447.pdf

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Aircraft - Hydrogen	0.59–1.37	A	(0.0671 - 0.0 tCO_2/GJ) × 8.75–20.35 EJ/year = 0.59–1.37 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/GJ (This assumes the utilization phase only.) b) Emission intensity of conventional technology: 0.0671 tCO_2/GJ c) Amount introduced, amount replaced (jet fuel to be replaced): 8.75–20.35 EJ/year d) Description: In the Environment Innovation Strategy, the CO_2 reduction potential is estimated to be 2.0 Gt assuming that, in the aviation industry, measures are taken based on IATA's long-term targets, such as electrification and fuel decarbonization (Ministry of Economy, Trade and Industry). In this estimate, the contribution of hydrogen is estimated. Bio-jet fuel and hydrogen fuel are expected to be used in the same field, and the ratio of bio-jet fuel and hydrogen is assumed to be 50:50. It is assumed that bio-jet fuel and hydrogen will be widespread in 2050 and that half of the energy consumption for international flights (60%: IATA (2017) https://www.iata.org/contentassets/9faa9f69011d46c484d93e6dd97a7f52/passenger-analysis-jul-2017.pdf) will be covered by hydrogen. The CO_2 emission intensity of hydrogen is zero. The emission intensity of conventional jet fuel is assumed to be 0.0671 tCO_2/GJ based on the carbon emission intensity of jet fuel (0.0183 tC/GJ) (Ministry of the Environment, https://www.env.go.jp/council/16pol-ear/y164-04/mat04.pdf). The jet fuel consumption in 2050 is estimated based on the CO_2 emissions prediction. Specifically, an increase rate of 300 to 700% is adopted based on the CO_2 increase rate prediction approved by the ICAO, which is cited as an official opinion in the European Parliament held in September 2019 (European Parliament's opinion: https://www.europarl.europa.eu/RegData/etudes/ATAG/2019/640169/EPRS_ATA(2019)640169_EN.pdf) (2016) (the CO_2 emissions are expected to increase by 300 to 700% compared to the 2005 level). Incidentally, the CO_2 emissions from jet fuel in 2050 are estimated to 0.65 tCO_2/year (https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industryeconomic-performance---2018-mid-year---table/). Thus, the CO_2 emissions from jet fuel for international flights in 2050 is estimated to be 1.17 $GtCO_2$/year with an increase rate of 300% from the 2005 level, and 2.73 $GtCO_2$/year with an increase rate of 700%. Based on a CO_2 emission intensity of 0.0671 tCO_2/GJ, the energy consumption is estimated to be 17.5 to 40.7 EJ/year. Half of it is 8.75 to 20.35 EJ/year.

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Ship - Hydrogen	0.156	A, B	(0.92 - 0.0) $GtCO_2$/year × 17% = 0.156 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/MJ (This assumes the utilization phase only.) b) Emission intensity of conventional technology: N/A c) Amount introduced, amount replaced: (energy consumption of the shipping industry): 17% d) Description: Drawing from the vessel-based approach (Option 1) in the Fourth IMO Greenhouse Gas Study (International Maritime Organization (IMO), 2020, https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx), the emissions in 2018 are estimated to be 0.92 Gt. In addition, the 80th session of the Marine Environment Protection Committee (MEPC) has adopted a strategy to achieve net-zero GHG emissions by 2050, so the emissions from the new technology are assumed to be zero. Meanwhile, according to the NZE scenario in Net Zero by 2050 (IEA, 2021), the energy consumption of hydrogen in the transportation sector (ships) is 17%. The CO_2 reduction potential can be estimated, as in the equation above, by multiplying the maximum possible reduction of the above-mentioned CO_2 emissions by this percentage. • c) Amount introduced [Reference value: Hydrogen introduced amount-equivalent]: After the reduction potential is estimated (0.156 $GtCO_2$), the amount of hydrogen required is estimated assuming that all the emissions are covered by natural gas. Because the emission factor of natural gas, 0.0135 t-C/GJ (Ministry of the Environment) is used, and as the per-unit heating value of hydrogen, 120 MJ/kg-H_2 (lower heating value) is used. 0.156 $GtCO_2$ × (12/44) / 0.0135 / 120 MJ/kg-H_2 = 26.30 Mt-H_2/year
Ship - Ammonia	0.423	A, B	(0.92 - 0.0) $GtCO_2$/year × 46% = 0.423 $GtCO_2$/year a) Emission intensity of new technology: 0 gCO_2/MJ (This assumes the utilization phase only.) b) Emission intensity of conventional technology: N/A c) Amount introduced, amount replaced: (energy consumption of the shipping industry): 46% d) Description: Drawing from the vessel-based approach (Option 1) in the IMO's Fourth IMO Greenhouse Gas Study (2020, https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx), the emissions in 2018 are estimated to be 0.92 Gt. In addition, the 80th session of the Marine Environment Protection Committee (MEPC) adopted a strategy to achieve net-zero GHG emissions by 2050, so the emissions from the new technology are assumed to be zero. Meanwhile, according to the NZE scenario in Net Zero by 2050 (IEA, 2021), the energy consumption of ammonia in the transportation sector (ships) is 46%. The CO_2 reduction potential can be estimated, as in the equation above, by multiplying the maximum possible reduction of the above-mentioned CO_2 emissions by this percentage. • c) Amount introduced [Reference value: Ammonia introduced amount-equivalent]: After the reduction potential is estimated (0.423 $GtCO_2$), the amount of ammonia required is estimated assuming that all the emissions are covered by natural gas. Because the emission factor of natural gas, 0.0135 t-C/GJ (Ministry of the Environment) is used, and as the per-unit heating value of ammonia, 18.6 MJ/kg- NH_3 (lower heating value) is used. 0.423 $GtCO_2$ × (12/44) / 0.0135 / 18.6 MJ/kg-NH_3 = 0.459 Gt-NH_3/year

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- C: The estimate is made based on the government's or industry's goals or predictions.
- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Next generation power electronics	1.03–1.10	A	188 gCO_2/kWh × 5,462–5,843 TWh/year = 1.03–1.10 Gt/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)[*1] c) Amount introduced, amount replaced (power consumption savings): 5,462–5,843 TWh/year (= (1) 1,010 + (2) 428–809 + (3) 4,024 TWh/year) d) Description: (1) Distributed power supply inverters (Global: 1,010 TWh/year) Based on the IEA WEO 2022's NZE scenario, global photovoltaic power generation and wind power generation in 2050 are estimated to be 27,006 TWh and 23,486 TWh, respectively. Then, assuming that efficiency is improved by 2%[*2,3] through replacement of Si by SiC and the SiC replacement rate is 100% in 2050, the power consumption savings are estimated. (27,006 + 23,486) TWh/year × 2% = 1,010 TWh/year (2) Electric vehicles (Global: 492–930 TWh/year) According to the IEA's ETP 2017, the breakdown of stocks of LDVs (2.4 billion vehicles) is that the proportions of internal combustion engine vehicles (including HVs) and electric vehicles (pure EVs, plug-in hybrid EVs (PHEVs), and fuel cell EVs (FCEVs)) are 88% and 12%, respectively. It is assumed that 40 to 60% of them will be replaced by EVs equipped with next generation power electronics. Also, according to the ETP 2017, the total annual mileage of LDVs is 63.9 trillion km/year. Then, the annual mileage of EVs equipped with next generation power electronics can be calculated as follows: (Total mileage of EVs equipped with next generation batteries) = (Total annual mileage of LDVs) × (Percentage of internal combustion engine vehicles) × (Penetration rate of EVs equipped with next generation power electronics) = 63.9 trillion km/year × 88% × 40–60% = 22.5–33.7 trillion km/year The power consumption savings are estimated assuming that the power consumption of electric vehicles (EVs) per unit mileage is 0.19 to 0.24 kWh/km (including a charge loss of 5%, IEA Global EV Outlook 2019); the efficiency is improved by 10%[*4] through replacement of Si by SiC; and the SiC replacement rate in 2050 is 100%. (Power consumption savings from EVs) = (Power consumption of EVs per unit mileage) × (Total mileage of EVs equipped with next generation batteries) × (Efficiency improvement by power electronics) = 0.19–0.24 kWh/km × 22.5–33.7 trillion km/year × 10% = 428–809 TWh/year (3) Others: Items based on domestic estimates (Global: 4,024 TWh/year) The global power consumption savings cannot be estimated for the following items. For these items, the global power consumption savings are estimated by estimating the Japan's power consumption reduction rate (power consumption savings / amount of power generated) and then multiplying the resulting value by the global amount of power generated. The amounts of power generated globally and by Japan are calculated by obtaining the amounts of power generated globally and by Japan in 2050 based on the 1.5°C scenarios (C1 and C2) in the IPPC AR6 and averaging them. Power consumption savings (global) = Power consumption savings (Japan) / (amount of power generated by Japan) × (amount of power generated globally) = 82 TWh/year / 1,219 TWh/year × 59,821 TWh/year = 4,024 TWh/year In the estimate below, the rate of replacement from Si to SiC in 2050 is assumed to be 100%.

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Next generation power electronics (continued)	1.03–1.10	A	(3)-1 Home electric appliances (air conditioners and refrigerators) (Japan) The respective annual power consumption of one air conditioner and one refrigerator are assumed to be 950 kWh and 520 kWh. Also, their stock quantities are assumed to be 100 million units and 60 million units, respectively. In addition, the efficiency is assumed to be improved by 6%[*2] through replacement of Si by SiC. (950 kWh × 100 million units + 520 kWh × 60 million units) × 6% = 7.6 TWh (3)-2 Computers (Japan) Assuming that the production is 21.5 million units and the life cycle is three years, the stock quantity is assumed to be 65 million units. Also, the power consumption and annual operating time are assumed to be 150 W and 2,000 hours, respectively. In addition, the efficiency is assumed to be improved by 5%[*5] through replacement of Si by SiC. 0.15 kW × 2,000 h × 65 million units × 5% × 100% = 1 TWh (3)-3 Uninterruptible power systems (Japan) Assuming that the power consumption of uninterruptible power systems is 300 W; the annual operating time is 8,760 hours; the annual production is approximately 0.2 million units (Current Production Statistics by the Ministry of Economy, Trade and Industry); and the useful life is five years, the stock quantity is estimated to be 1 million units. In addition, the efficiency is assumed to be improved by 5%[*5] through replacement of Si by SiC. 0.3 kW × 8,760 h × 1 million units × 5% × 100% = 0.1 TWh (3)-4 Adoption of inverters for industrial equipment (Japan) The industrial power demand and commercial power demand are estimated to be approximately 350 billion kWh and 200 billion kW, respectively (FY2010 Electricity Demand by The Federation of Electric Power Companies of Japan, April 2012) while their motor power consumption rates are estimated to approximately 70% and 60%, respectively[*6]. Accordingly, motor power consumption is estimated to be 365 billion kWh. The rate of adoption of inverters for general-purpose three-phase motors and the efficiency improvement through replacement of Si by SiC are assumed to be approximately 37%[*7] and 2%[*2,3], respectively. 365 billion kWh × 37% × 2% = 2.7 TWh (3)-5 Increased adoption of inverters (Japan) As mentioned in the estimation for *Adoption of inverters for industrial equipment* ((3)-4), motor power consumption is expected to be 365 billion kWh. Thanks to downsizing by replacement of Si by SiC, the adoption of inverters is expected to be expanded to small pumps and other industrial equipment. It is assumed that the current adoption rate of inverters, or 37%[*7], increases to 80%, and the energy saving effect of inverters is 45%[*7]. 365 billion kWh × (80 - 37)% × 45% = 70.6 TWh *1 CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2 Mitsubishi Heavy Industries Technical Review Vol. 90, No.5, P.7–10, (2016) *3 Mitsubishi Heavy Industries Technical Review Vol. 92, No.7, P.46–49, (2018) *4 Estimated mainly based on the announcement made by Toyota Motor Corporation on May 20, 2014 (https://global.toyota/jp/detail/2657262). *5 Estimated mainly based on the announcement made by Hitachi Industrial Products, Ltd. (https://www.hitachi-ip.co.jp/products/ups/products/uniparamini/index.html). *6 Survey on Current and Near-Future Trends of Power Consumption of Electrical Equipment (Research and Development Association for Future Electron Devices, 2009) *7 Inverters Will Contribute to Sustainable Society 2021–2022 (The Japan Electrical Manufacturers' Association)

Table Examples of CO_2 reduction potentials and underlying logic

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D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Superconductivity (high-voltage cable)	0.00051	A	188 gCO_2/kWh × 2.73 TWh/year ≈ 0.00051 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)[*1] c) Amount introduced, amount replaced (power consumption savings): 2.73 TWh/year d) Description: [Amount of energy saved per kilometer (MWh/(year·km))] • Amount of energy saved = (Current cable system loss) - (Superconductive cable loss) - (Cooling-system power). This estimate assumes the renewable of two types of cables: 275-kV(POF) cable and 66-kV(POF) cable. According to Reference[*2], the amount of energy saved is assessed as below: • When a three-line 275- kV/1-kA cable with a transmission capacity of 1,440 MVA is renewed by replacing it with a three-line 66-kV/4.0-kA superconductive cable with a transmission capacity of 1,440 MVA when it has aged, 359,784 MWh/(30 years·20 km)[*2] ≈ 600 MWh/(year·km) • When a 66-kV cable is renewed by replacing it with a 66-kV superconductive cable when it has aged, it is tentatively assumed that the effect is 1/4 of that obtained when a three-line 275-kV/1-kA cable with a transmission capacity of 1,440 MVA is renewed by replacing it with a two-line 275-kV/1.5-kV superconductive cable with a transmission capacity of 1,440 MVA in Reference[*2]. Thus, when a three-line 66-kV/1-kA cable with a transmission capacity of 360 MVA is renewed by replacing it with a two-line 66-kV/1.5-kA cable with a transmission capacity of 360 MVA, 1/4 of 51,496 MWh/(30 years·20 km)[*2] ≈ 21.5 MWh/(year·km) [Amount of energy saved (TWh/year)] The maximum introduction potential is calculated as follows: • Maximum introduction potential (Japan): Approximately 15,000 km (275-kV class: Approximately 1,800 km, 66-kV class: Approximately 13,200 km) (Underground cable length for 77 kV or higher: 1,770 km, Underground cable length for 66 kV or lower: 13,200 km)[*3] • 599.6 MWh/(year·km) × 1,800 km + 21.5 MWh/(year·km) × 13,200 km ≈ 1,360 GWh/year Assuming that the penetration rate is 50%, • Maximum introduction potential (Japan) = 1,360 GWh/year × 0.5 = 0.68 TWh/year • Maximum introduction potential (global): According to Reference[*4], Japan's maximum introduction potential is multiplied by 4 as follows: 680 GWh/year × 4 ≈ 2.73 TWh/year *1 CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2 FY2012 Accomplishment Report, Case Study of Expanded Application and Standardization of High-Temperature Superconductive Electrical Equipment (NEDO) *3 Handbook of Electric Power Industry (FY2014) *4 According to the FY2014 Survey Report on the Formulation of Technical Strategies for Market Formation of Superconductive Equipment (NEDO), the overseas market for underground transmission cables is about three times the domestic market, so the overseas amount of underground transmission cables introduced is three times the domestic amount introduced. Thus, the global amount introduced is assumed to be four times the domestic amount.

Table Examples of CO_2 reduction potentials and underlying logic

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- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Superconductivity (railway DC feeder)	0.0028	A	188 gCO_2/kWh × 14.9 TWh/year ≈ 0.0028 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)[*1] c) Amount introduced, amount replaced (power consumption savings): 14.9 TWh/year d) Description: [Amount of energy saved per kilometer (GWh/(year·km))] • Amount of energy saved: = (Current cable system loss) - (Superconductive cable loss) - (Cooling system power) This estimate assumes that DC feeders with a voltage of 1,500 V and a current of 12 kA or less are renewed when they have aged. If they are replaced by superconductive cables, 69,589 MWh / (30 years × 3 km) (a) ≈ 773 MWh/(year·km) [Japan's amount of energy saved (TWh/year)] Maximum introduction potential: 773 MWh/(year·km) × (6,354.5 + 5,452.0) km × (Proportion of densely-inhabited districts 66%) (b) ≈ 6,020 GWh/year Assuming that the penetration rate is 50%, • Maximum introduction potential (Japan) = 6,020 GWh × 0.5 ≈ 3.0 TWh/year [Global amount of energy saved (TWh/year)] Maximum introduction potential: Japan's amount of energy saved (3,010 GWh/year) × (Global total railway track length 1,370,000 km/Japan's total railway track length 27,672 km) × (Proportion in densely-inhabited districts 10%) (c) = (3,010 GWh/year) × 49.5 × 0.1 ≈ 14,900 GWh/year • Maximum introduction potential (global) = 14,900 GWh/year = 14.9 TWh/year <Basis for calculation> (a) The amount of energy saved (kWh) is calculated assuming that the amount of CO_2 to be reduced is 26,096 t-CO_2/3 km and the CO_2 emission intensity is 0.375 kg-CO_2/kWh according to Reference[*2]. (b) Japan's DC electric railway track length: Japan Railway Companies → 6,354.5 km Other private railway companies → 5,452.0 km. It is assumed that the new technology will be introduced in densely-populated districts. The lengths in densely-populated districts are assumed to be 66% of the total length[*3]. (c) Estimated by the proportional division of the global total railway track length. This estimate assumes that the new technology will be introduced in urban districts. It is assumed that 10% of the total railway track length is located in densely-populated district[*3]. *1 CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2 FY2012 Accomplishment Report, Case Study of Expanded Application and Standardization of High-Temperature Superconductive Electrical Equipment (NEDO) *3 FY2014 Survey Report on the Formulation of Technical Strategies for Market Formation of Superconductive Equipment (NEDO)

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Superconductivity (MRI)	0.00001	A	188 gCO_2/kWh × 0.055 TWh/year ≈ 0.00001 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)*1 c) Amount introduced, amount replaced (power consumption savings): 0.067 TWh/year d) Description: [Japan's amount of energy saved (TWh/year)] If low-temperature superconductive magnetic resonance imagers (MRIs) are renewed by replacing them with high-temperature superconductive MRIs when they have aged, annual power consumption for cooling low-temperature MRIs (kWh/(unit·year)) × $1/1{,}000^3$ (converted to TWh) × (Number of MRIs possessed: 6,996 units) × (1 - (High-temperature superconductivity cooling temperature (°C) / Liquid helium temperature at cooling (°C)) = 78,840 (kWh/(unit·year)) × $1/1{,}000^3$ × 6,996 units × (1 - 263°C/269°C) (a) ≈ 0.012 TWh/year [Global amount of energy saved (TWh/year)] (0.012 TWh/year)/ 0.222 (b) ≈ 0.055 TWh/year <Basis for calculation> (a) The annual power consumed to cool conventional MRIs is based on the industry information. The number of MRIs possessed in Japan is assumed to be 6,996*2. (b) Proportion of annual sales of MRIs in Japan to the global annual sales of MRIs: 22.2%*3. *1: CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2: Based on the data for 2020 in OECD Health Statistics 2021 (https://www.oecd.org/els/health-systems/health-data.htm) *3: FY2018 Information on International Competitiveness of Products, Services, and Software of Japanese Companies (NEDO)

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Superconductivity (electromagnetic induction heating)	0.0013	A	188 gCO_2/kWh × 7.03 TWh/year ≈ 0.0013 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)*1 c) Amount introduced, amount replaced (power consumption savings): 7.03 TWh/year d) Description: [Japan's amount of energy saved (TWh/year)] If electromagnetic induction heaters are renewed by replacing them with those with superconductive coils when they have aged, [(Amount of energy saved through application of superconductivity to electromagnetic induction heaters) (a) - (Loss of chillers for keeping the HTS coils at around 20 to 30 K)] (b) × 1,000 units (c) = [(5 MW × 8,760 h/year × 0.2 × 0.25) - (0.00724 MW × 1 × 8,760 h/year)] × 1,000 ≈ (2,190 - 63) MWh/year × 1,000 = 2,130 GWh/year [Global amount of energy saved (TWh/year)] 2,130 GWh/year × 2.3 + 2,130 GWh/year (d) = 7.03 TWh <Basis for calculation> (a) • Equipment capacity 5 MW (intermediate value between 1 and 10 MW) • Availability 20% • Energy saving rate 25% (power consumption of the coils: 20 to 30%) (b) • Chiller loss (kW) = 7.2 + 0.04 = 7.24 (Chiller availability 100%) However, this does not take into account the power consumed by the power supplies for exciting the HTS coils. (c) • The number of electromagnetic induction heaters to be introduced is assumed to be 1,000*2. (d) • The overseas amount of energy saved is assumed to be 2.3 times that in Japan*2. <Notes> • Chiller: SRP-082B2S-F70H (Sumitomo Heavy Industries, Ltd. Cooling capacity: available with a thermal load of 40 W at 77 K) • Power consumption: 7.2 kW (50 Hz) • Rated current: 300–450 A • Chiller loss = Power consumption for cooling × Current lead loss. The power consumption of the chiller assumes a heat input of 300 K → 77 K. Current lead loss: around 36–40 W. • The heat generated at the coil connections and the heat input into the cryostat are ignored because they are much smaller than the heat input into the current lead. *1: CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2: FY2014 Survey Report on the Formulation of Technical Strategies for Market Formation of Superconductive Equipment (NEDO)

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Superconductivity (industrial motor)	0.013	A	188 gCO_2/kWh × 68 TWh/year ≈ 0.013 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)*1 c) Amount introduced, amount replaced (power consumption savings): 68 TWh/year d) Description: [Japan's amount of energy saved (TWh/year)] If industrial motors are renewed by replacing them with superconductive motors when they have aged, annual power consumption of conventional industrial motors (MWh/year) (a) × Increase in efficiency through adoption of superconductive industrial motors (b) × 1/1,000 (converted to GWh) - (Loss of chillers for keeping the HTS coils at around 20 to 30 K) = [(0.7 MW × 0.65 × 8,760 h/year × 25,500 units) × 0.025 + (2.5 MW × 0.65 × 8,760 h/year × 10,400 units) × 0.035] × 1/1,000 - (0.00724 MW × 1 × 8,760 h/year × 35,900 units) × 1/1,000 ≈ 5.44 TWh/year [Global amount of energy saved (TWh/year)] 5.44 TWh/year / 0.08 (c) ≈ 68 TWh/year <Basis for calculation> (a) • It is assumed that 25,500 0.7-MW industrial motors and 10,400 2.5-MW industrial motors will be introduced*2. • Annual availability: 65% (b) • Per-unit increase in efficiency through adoption of superconductive industrial motors - 0.7-MW industrial motors 2.5%/unit - 2.5-MW industrial motors 3.5%/unit (c) • Japan's amount of energy saved by motors is assumed to be 8% of the global amount of energy saved by motors*2. *1: CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2: FY2014 Survey Report on the Formulation of Technical Strategies for Market Formation of Superconductive Equipment (NEDO)

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Superconductivity (power generator)	0.012	A	188 gCO_2/kWh × 65 TWh/year ≈ 0.012 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)[*1] c) Amount introduced, amount replaced (power consumption savings): 65 TWh/year d) Description: It is assumed that the proportion of the amount of power generated by turbine generators, including thermal power generators, hydroelectric power generators, and nuclear power generators, to global total power generation (49,845 TWh)[*2] is 65% and the generating efficiency will be increased by 1% through the application of superconductive power generators[*3]. • Maximum introduction potential: 49,845 TWh/year × 0.65 × 0.01 ≈ 324 TWh/year Assuming that the penetration rate is 20%, • Maximum introduction potential (global) = 324 TWh/year × 0.2 = 65 TWh/year *1: CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2: IEA's WEO 2022 STEPS scenario (2050) *3: H. Takesue, Superconducting Technology for Electric Power System: Superconductive Generators, The Journal of the Institute of Electrical Engineers of Japan Vol. 124 No. 7, 2004.
Energy-efficient air conditioning	0.53	A	188 gCO_2/kWh × 2,800 TWh/year ≈ 0.53 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption)[*1] c) Amount introduced, amount replaced (power consumption savings): 2,800 TWh/year d) According to Reference[*2], it is assumed that the global power demand for air conditioning can be reduced by 2,800 TWh through the introduction of energy-efficient air conditioning. The expected increase in efficiency of air conditioning equipment in 2050 is equivalent to a SEER (Seasonal Energy Efficiency Ratio) improvement of 5.5 to 8.5. *1: CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2: The Future of Cooling (IEA, 2018)

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
CCUS	7.6	B	d) Description: The potential of reduction by CCUS in the 2050 NZE scenario presented in the IEA's Net Zero by 2050 is estimated to be 7.6 $GtCO_2$.
Carbon recycling - Basic chemicals	0.56	D	370 Mt/year × 1.5 tCO_2/t = 555 $MtCO_2$/year = 0.56 $GtCO_2$/year a) Emission intensity of new technology: 0 tCO_2/t-olefin b) Emission intensity of conventional technology: 1.5 tCO_2/t-olefin c) Amount introduced, amount replaced: 370 Mt-olefin/year (global demand prediction for 2050) d) Description: As the conventional technology, the production of basic chemicals using crude oil as a raw material is used, and as the new technology, the production of basic chemicals by CCU (Carbon Capture and Utilization) to estimate CO_2 reduction. As the basic chemicals, C_2 olefin (ethylene) and C_3 olefin (propylene) are used. This estimate assumes the maximum utilization of them in the world. CO_2 reduction potential [tCO_2] = Amount introduced [t] × (Emission intensity of conventional technology - Emission intensity of new technology) [tCO_2/t]: • c) Amount introduced: As the maximum utilization potential, the ethylene and propylene components of the global demand prediction for 2050 based on the Clean Technology Scenario (CTS) in the IEA's The Future of Petrochemicals are added[*1]. Assuming that the entire global demand is replaced by production through CCU, the amount introduced is estimated to be 370 Mt-olefin (= ethylene 220 Mt/year + propylene 150 Mt/year). • Emission intensity of new technology (a): With the new technology, CO_2 is immobilized as a raw material and is considered carbon-neutral. Therefore, the emission intensity of olefin from of the new technology is assumed to be zero. This estimate does not include the CO_2 emissions from transportation and storage. • Emission intensity of conventional technology (b): Based on the composition ratios of ethylene and propylene in production from naphtha[*2] and the LCI database[*3], the emission intensity of the conventional technology is assumed to be 1.5 tCO_2/t-olefin. *1: The Future of Petrochemicals(IEA, 2018) https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf *2: TSC Foresight Vol. 109, Toward the Formulation of Technology Strategies in the Field of Raw Material Diversification of Basic Chemicals (Rubber Materials C4 and C5) (NEDO, 2022) https://www.nedo.go.jp/content/100952690.pdf *3: LCI Database IDEA ver3.2.0 (April 15, 2022), IDEA Laboratory, Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology

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- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Carbon recycling - Functional chemicals	0.05	D	● Polycarbonate (DPC) 19 Mt/year × 0.20 tCO_2/t = 3.7 $MtCO_2$/year = 0.004 $GtCO_2$/year a) Emission intensity of new technology: 7.49 tCO_2/t-DPC b) Emission intensity of conventional technology: 7.69 tCO_2eq/t (polycarbonate CFP) c) Amount introduced, amount replaced: 19 Mt/year (global demand prediction for 2050) d) Description: Amount of CO_2 absorbed into product: 0.21 tCO_2/t-DPC ● Polyurethane (MDI) 76 Mt/year × 0.33 tCO_2/t = 25.3 $MtCO_2$/year = 0.025 $GtCO_2$/year a) Emission intensity of new technology: 4.30 tCO_2/t-MDI b) Emission intensity of conventional technology: 4.63 tCO_2eq/t (polyurethane (soft) CFP) c) Amount introduced, amount replaced: 76 Mt/year (global demand prediction for 2050) d) Description: Amount of CO_2 absorbed into product: 0.35 tCO_2/t-MDI ● Superabsorbent polymer (acrylic acid) 28 Mt/year × 0.58 tCO_2/t = 16.2 $MtCO_2$/year = 0.016 $GtCO_2$/year a) Emission intensity of new technology: 1.64 tCO_2/t-acrylic acid b) Emission intensity of conventional technology: 2.22 tCO_2eq/t (acrylic acid CFP) c) Amount introduced: 28 Mt/year (global demand prediction for 2050) d) Description: Amount of CO_2 absorbed into product: 0.61 tCO_2/t-acrylic acid For polycarbonate, polyurethane, and superabsorbent polymer (SAP), which are representative CCU functional chemicals that do not require the procurement of CO_2-free hydrogen and are expected to be implemented in society in the near future, the estimate is made based on the following assumptions. CO_2 reduction potential [tCO_2] = Amount introduced [t] × (Emission intensity of conventional technology - Emission intensity of new technology) [tCO_2/t]: • Amount introduced (c): The global demand prediction for 2050 is calculated[*1]. Considering the maximum utilization potential, all the global demand is assumed to be used in the form of CCU. • Emission intensity of conventional technology (b): Carbon footprints (CFPs) of representative compounds[*2]. Carbon footprints of polycarbonate, polycarbonate (soft), and acrylic acid (SAP material). • Emission intensity of new technology (a): Emission intensity of new technology = Emission intensity of CO_2 separation and capture + Emission intensity of energy input of new technology - Intensity of CO_2 absorbed into product This assumes that the emission intensity of energy input of the new technology is equal to the emission intensity of the conventional technology. Accordingly, (Emission intensity of conventional technology - Emission intensity of new technology) = (Intensity of CO_2 absorbed into product - Emission intensity of CO_2 separation and capture) • The intensity of CO_2 absorbed into the product is calculated based on the proportion of the molecular weight of the CO_2 absorbed to the molecular weight of each of the representative raw compounds. The representative compound used for each product is as follows: - Polycarbonate: Diphenyl carbonate (DPC): Mw = 214.2 - Polyurethane: Diphenylmethane diisocyanate (MDI): Mw = 250.25

Table Examples of CO_2 reduction potentials and underlying logic

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<table>
<tr><th>Technology</th><th>CO_2 reduction potential $GtCO_2$/year</th><th>Estimation pattern (*)</th><th>Basis for the estimated CO_2 reduction potential
a) Emission intensity of new technology
b) Emission intensity of conventional technology (tCO_2/specific unit)
c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc.
d) Description</th></tr>
<tr><td>Carbon recycling - Functional chemicals (continued)</td><td>0.05</td><td>D</td><td>
- SAP: Acrylic acid: Mw = 72.06
One molecule of CO_2 is absorbed into one molecule of DPC, two molecules of MDI, and one molecule of acrylic acid, respectively. The intensities of CO_2 absorbed into these products are 0.21 tCO_2/t-DPC, 0.35 tCO_2/t-MDI, and 0.61 tCO_2/t-acrylic acid, respectively.
• The energy required to separate and capture CO_2 is assumed to be 1.0 GJ/tCO_2[*3]. In this estimate, for energy, the emission intensity of natural gas utilization[*4], or 50 $kgCO_2$/GJ is used, and the emission intensity of separation and capture is assumed to be 0.05 tCO_2(emissions)/tCO_2(capture).
<table>
<tr><th rowspan="2"></th><th rowspan="2">Percentages of CO_2-derived components Wt% Representative compounds</th><th colspan="2">Global demand in 2018[*1]</th><th rowspan="2">Demand prediction for 2050 Mt</th><th rowspan="2">CO_2 reduction potential $MtCO_2$/year</th><th rowspan="2">Mw</th></tr>
<tr><th>Mt</th><th>Growth rate %</th></tr>
<tr><td>Polycarbonate</td><td>20.5</td><td>4.6</td><td>4.5</td><td>19</td><td>(1) 3.7</td><td>CO_2: 44.01
DPC: 214.2</td></tr>
<tr><td>Polyurethane material (polyol and isocyanate)</td><td>22.4</td><td>21.6</td><td>4</td><td>76</td><td>(2) 25.3</td><td>2 CO_2: 88.02
MDI: 250.25</td></tr>
<tr><td>SAP material (acrylic acid)</td><td>61.2</td><td>6.8</td><td>4.5</td><td>28</td><td>(3) 16.2</td><td>CO_2: 44.01
Acrylic acid: 72.06</td></tr>
</table>
*1: 2015 Engineering Plastic Market Prospects and Global Strategies, Development and Market of Carbon Fiber-Reinforced Plastics (CFRP) 2020, CMC Research; The Japan Plastics Industry Federation, Sales of Plastic Materials; 2019 Global Market of Polyurethane Material and Product (Fuji Keizai Group); The Chemical Daily Co., Ltd., Chemical Industrial Economy, March 2018 Vol. 65 No. 4 (White Paper on the Global Chemical Industry); Nippon Shokubai Co., Ltd., Reborn Nippon Shokubai 2020 NEXT

*1: 2015 Engineering Plastic Market Prospects and Global Strategies, Development and Market of Carbon Fiber-Reinforced Plastics (CFRP) 2020, CMC Research; The Japan Plastics Industry Federation, Sales of Plastic Materials; 2019 Global Market of Polyurethane Material and Product (Fuji Keizai Group); The Chemical Daily Co., Ltd., Chemical Industrial Economy, March 2018 Vol. 65 No. 4 (White Paper on the Global Chemical Industry); Nippon Shokubai Co., Ltd., Reborn Nippon Shokubai 2020 NEXT
*2: CFP Program, CFP Database (accessed in July 2020) https://www.cfp-japan.jp/calculate/verify/database2012-2.html
*3: Based on Roadmap for Carbon Recycling Technologies (Ministry of Economy, Trade and Industry, 2019) https://www.meti.go.jp/press/2019/06/20190607002/20190607002-1.pdf
*4: List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment) https://ghg-santeikohyo.env.go.jp/files/calc/itiran_2020_rev.pdf
</td></tr>
</table>

Table Examples of CO_2 reduction potentials and underlying logic

(*) Estimation patterns
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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Carbon recycling - Carbonate	0.317	D	1.03 Gt-limestone/year × (0.44 - 0.132) tCO_2/t-limestone = 0.317 $GtCO_2$/year a) Emission intensity of new technology: 0.132 tCO_2/t-carbonate alternative to limestone b) Emission intensity of conventional technology: 0.44 tCO_2/t-limestone c) Amount introduced, amount replaced: 1.03 Gt/year d) In cement production, CO_2 is generated when limestone ($CaCO_3$, $MgCO_3$) is burned. As an alternative to natural limestone, CO_2 is absorbed into waste-derived Ca and Mg to carbonate them, which is assumed as the new technology. CO_2 reduction potential [tCO_2/year] = Amount introduced [t/year] × (Emission intensity of conventional technology - Emission intensity of new technology) [tCO_2/t]: • Emission intensity of conventional technology (b): The adopted emission intensity of CO_2 is that derived from the process of desorption which takes place when limestone is heated. As for the chemical composition of limestone, the weight ratio of $CaCO_3$: $MgCO_3$ is assumed to be 99:1. Then, the emission intensity is calculated to be 0.44 tCO_2/t-limestone by weighted average[*1]. • Emission intensity of new technology (a): 0.44 tCO_2stored/t-limestone × 0.30 tCO_2emi./tCO_2stored = 0.132 tCO_2/t-carbonate alternative to limestone. When 1 tonne of carbonate is produced from waste-derived CaO and MgO, as an alternative to limestone, stoichiometrically, 0.44 tonnes of CO_2 is absorbed. This is equal to the amount of CO_2 absorbed when limestone is heated, which means that the emission intensity is zero. However, CO_2 emissions are unavoidable unless the electricity and heat in the reaction process of the new technology is carbon-free. Therefore the emission intensity is calculated assuming that the CO_2 absorption loss in the CO_2 separation and capture and carbonatization reactions is 30%, or 0.3 tCO_2 emissions/tCO_2 immobilization. • Amount introduced (c): 4.7 (Gt-cement/year) × 1.1 t-limestone/t-cement × 0.2 (penetration rate) = 1.03 Gt/year According to the IEA's cement roadmap, the global cement production in 2050 will be approximately 4.7 Gt/year[*2], and the amount of limestone consumed per tonne of cement is calculated to be 1.1 t. Also, the penetration rate in 2050 is estimated to be 20%, assuming that the penetration rate increases annually by 1% from 2030. *1: Ministry of the Environment, https://www.env.go.jp/earth/ondanka/santeiho/kento/h2303/1.pdf *2: Technology Roadmap. Low-Carbon Transition in the Cement Industry (International Energy Agency (IEA) & Cement Sustainability Initiative (CSI), 2018)

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Tire recycling	0.015	D	9.3 Mt/year × (6.54 tCO_2/t - 4.98 tCO_2/year = 15 $MtCO_2$/year a) Emission intensity of new technology: 4.98 tCO_2/t-tire (chemical recycling of rubber components in production) b) Emission intensity of conventional technology: 6.54 tCO_2/t-tire (production + incineration) c) Amount introduced, amount replaced: 9.3 Mt/year (amount of waste tires incinerated) d) It is assumed that all the rubber components of waste tires incinerated around the world are recycled as tires via chemical recycling. CO_2 reduction potential [tCO_2/year] = Amount introduced [t/year] × (Emission intensity of conventional technology - Emission intensity of new technology) [tCO_2/t]: • Amount introduced (c): Global amount of waste tires disposed of 30.90 Mt × Incineration rate 15%[*1] × Two-fold increase in transportation by 2050 = 9.3 Mt/year • The emission intensity is estimated based on the Tire $LCCO_2$ Calculation Guidelines Ver. 2.0[*2] and CFP Database[*3]. • Emission intensity of conventional technology (b): CO_2 emissions from tire production and tire incineration. The natural rubber component is not considered carbon-neutral, and is included in the estimate. • Emission intensity of new technology (a): It is assumed that even in the chemical recycling of tires, carbon black and components other than rubber components are not recycled and are incinerated. In chemical recycling, the rubber components in the tires (natural rubber + synthetic rubber) are used as alternatives to the raw material, but this technology has not been established yet. Therefore, it is assumed that the CO_2 emissions from synthetic rubber raw material production by chemical recycling is equal to those of the conventional technology, which uses crude oil as a raw material. Therefore, the difference in emission intensity between the conventional technology and new technology is assumed to come from CO_2 emissions from the incineration of tires made of the rubber components used as alternatives to the raw material. *1: World Business Council for Sustainable Tire Industry Project, "Global ELT Management–A global state of knowledge on regulation, management systems, impacts of recovery and technologies", 2019 *2: Tire $LCCO_2$ Calculation Guidelines Ver. 2.0 (The Japan Automobile Tyre Manufacturers Association, 2012) https://www.jatma.or.jp/environment/pdf/lcco2guideline.pdf *3: CFP Program, CFP Database (accessed in July 2020) https://www.cfp-japan.jp/calculate/verify/database2012-2.html

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Aluminum recycling	0.07–0.1	A	(7.2 - 0.3 tCO_2/t-aluminum) × (0.0106–0.0147 Gt/year) = 0.07–0.10 $GtCO_2$/year a) Emission intensity of new technology: 0.3 tCO_2/t-aluminum b) Emission intensity of conventional technology: 7.2 tCO_2/t-aluminum c) Amount introduced, amount replaced: 0.0106–0.0147 Gt/year d) The emission intensity is a value after power distribution, and the emission intensity of the conventional technology takes into account efficiency gains and the impact of electricity decarbonization (Current: 12 tCO_2/t → 2050: 7.2 tCO_2/t. Source (emission intensity): SITRA, The Circular Economy 2018. The aluminum demand in 2050 is assumed to be 0.211 Gt by using a growth rate of 2.41%, which is obtained from the actual demand in 2017 and expected demand in 2040. The amount introduced assumes that the rate of increase in secondary material use is 5 to 7%.
Plastic recycling	0.11–0.32	A	(4.48 - 1.85 tCO_2/t-plastic) × (0.4–1.2 Gt/year) = 0.11–0.32 $GtCO_2$/year a) Emission intensity of new technology: 1.85 tCO_2/t-plastic b) Emission intensity of conventional technology: 4.48 tCO_2/t-plastic c) Amount introduced, amount replaced: 0.04–0.12 Gt/year d) It is assumed that 25% of recovered plastic will be processed through material recycling, 25% via chemical recycling, and the other 50% using energy recovery. The emission intensity of the new technology (1.27, 0.48, and 2.83 tCO_2/) is estimated by weighted averaging with the above-mentioned proportions of each technology, and the emission intensity of the conventional technology (3,72, 3.28, and 5.46 tCO_2/t) is estimated in the same way (the emission intensity of each technology is estimated by NEDO/TSC). The introduction potential is set to a range of 0.04 to 0.12 Gt (10 to 30%), while the plastic production in 2050 (PE, PP, PET, and PS) is estimated to be 0.4 Gt/year (IEA, The Future of Petrochemicals, 2018).

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Biobased chemicals	0.123	A	Among chemical products, acrylic acid and phenol are selected because they are produced in relatively large volumes, and a large CO_2 reduction effect can be anticipated by replacing the crude oil-based raw materials with bio-based raw materials. ● Acrylic acid (8.77 - 1.25 tCO_2/-acrylic acid) × (0.007 Gt/year) = 0.052 $GtCO_2$/year a) Emission intensity of new technology: 1.25 tCO_2/t-acrylic acid b) Emission intensity of conventional technology: 8.77 tCO_2t-acrylic acid c) Amount introduced, amount replaced: 0.007 Gt/year d) Description • Emission intensity of new technology (a): GHG emissions from acrylic acid production from biomass with a production transition rate of 50%, which is a neutral assumption [*1]. • Emission intensity of conventional technology (b): GHG emissions from acrylic acid produced from fossil resources[*1]. • Amount introduced (c): Based on the global acrylic acid demand in 2018 (6.80 Mt[*2]) and the market growth rate (4.5%)[*3], the global demand for acrylic acid in 2050 is forecast to be 28 Mt/year based on the assumption that 25% will be produced using new technologies (replacement rate of biomass-based products suggested by the Japan Chemical Industry Association[*4]). ● Phenol (6.69 - 2.21 tCO_2/t-phenol) × (0.016 Gt/year) = 0.071 $GtCO_2$/year a) Emission intensity of new technology: 2.21 tCO_2/t-phenol b) Emission intensity of conventional technology: 6.69 tCO_2/t-phenol c) Amount introduced, amount replaced: 0.016 Gt/year d) Description • Emission intensity of new technology (a): GHG emissions from phenol production from biomass with a production transition rate of 50%, which is a neutral assumption[*1]. • Emission intensity of conventional technology (b): GHG emissions from phenol production from fossil resources[*1]. • Amount introduced (c): Based on the phenol production capacity in 2020 (13.63 Mt[*5]) and a market growth rate between 2022 through 2027 of 5.37%[*6], based on the assumption that 25% of the global phenol demand in 2050 (65.46 Mt/year) will be produced using new technologies (replacement rate of biomass-based products suggested by the Japan Chemical Industry Association[*4]).

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Biobased chemicals (continued)	0.123	A	*1: ACS Sustainable Chem. Eng. 2021, 9, 43, 14480-14487 *2: Nippon Shokubai Co., Ltd., Reborn Nippon Shokubai 2020 NEXT *3: The Chemical Daily Co., Ltd., Chemical Industrial Economy, March 2018 Vol. 65, No. 4. (White Paper on the Global Chemical Industry) *4: Japan Chemical Industry Association, Chemical Industry's Stance Toward Carbon Neutrality https://www.nikkakyo.org/system/files/20210518CN.pdf *5: The Heavy & Chemical Industries News Agency, Handbook of Chemicals 2021 *6: IMARC Services Private Limited, Phenol Market Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2022–2027
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) Description: 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 lightweight 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.
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) Amount introduced, amount replaced (proportion of plastic to be replaced): 20 to 30% d) Description: 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.

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Blue carbon	0.5–1.38	B	d) Description: Blue carbon is the generic term for carbon captured and stored by the world's ocean and coastal ecosystem*1. Capture and storage of carbon as blue carbon generally begins with absorption of atmospheric CO_2 via photosynthesis into blue carbon ecosystems existing in shallow coastal areas. However, the carbon capture and storage mechanism is complicated; it is difficult to estimate the mitigation potential quantitatively, so uncertainty still remains. The mechanism of separating and storing carbon as blue carbon is complicated; currently, quantitative assessment of the mitigation potential is accompanied by high uncertainty. This uncertainty includes, for example, the effects of accumulation and burial of blighted blue carbon ecosystems on the sea bed and the effects obtained when the strands of seaweed growing on reefs are run into the open sea due to tidal currents and remain in deep sea (e.g., mesopelagic) for a long time while being decomposed*2. In this estimate, as one of the latest research results, the estimate presented in ICEF's Blue Carbon Roadmap–Carbon Captured by the World's Coastal and Ocean Ecosystems (November 18, 2022, https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Blue_Carbon.pdf) is excerpted. Blue carbon does not serve as an alternative to a specific conventional technology that emits CO_2, but instead works to lower the CO_2 concentration in the atmosphere. In many documents, including this reference, the quantitative effect of blue carbon is referred to as the *mitigation potential*. Mitigation potential in 2050 (Total: 0.5–1.38 $GtCO_2$eq/year) ● Potential for mitigation through preventing the loss and degradation of ecosystems (Scenario 1: Conservation) Mangroves: 0.02–0.04 $GtCO_2$eq/year Salt marsh and tidelands: 0.04–0.07 $GtCO_2$eq/year Seaweed beds: 0.19–0.65 $GtCO_2$eq/year ● Potential for mitigation through the rehabilitation and restoration of ecosystems and organisms (Scenario 2: Rehabilitation) Mangroves: 0.16–0.25 $GtCO_2$eq/year Salt marsh and tidelands: 0.01–0.03 $GtCO_2$eq/year Seaweed beds: 0.03–0.05 $GtCO_2$eq/year ● Increase in macroalgae production by aquaculture: 0.05–0.29 $GtCO_2$eq/year Based on the above, the total potential of blue carbon was estimated to be 0.5 to 1.38 $GtCO_2$eq/year. The effects of conserving and rehabilitating macroalgae have not been calculated because there is insufficient scientific information, but its scale is large in blue-carbon ecosystems, and a high mitigation potential is expected. According to the Special Report on the Ocean and Cryosphere in a Changing Climate, released by the IPCC in 2019, the global total mitigation potential of blue carbon is equivalent to about 0.5% of the global total annual GHG emissions. According to the Special Report on the Ocean and Cryosphere in a Changing Climate, released by the IPCC in 2019, the global total mitigation potential of blue carbon is equivalent to about 0.5% of the global total annual GHG emissions. *1: Report by the United Nations Environment Programme (UNEP) (2009) *2: Homepage of the Ministry of Land, Infrastructure, Transport and Tourism. What is Blue Carbon? "3. Mechanism of Blue Carbon" https://www.mlit.go.jp/kowan/kowan_tk6_000069.html

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<tr><th>Technology</th><th>CO_2 reduction potential $GtCO_2$/year</th><th>Estimation pattern (*)</th><th>Basis for the estimated CO_2 reduction potential
a) Emission intensity of new technology
b) Emission intensity of conventional technology (tCO_2/specific unit)
c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc.
d) Description</th></tr>
<tr><td>Biochar</td><td>2.6</td><td>B</td><td>
d) Description:
The estimate based on the recent report presented at the working group of the Sixth Green Innovation Strategy Promotion Council (https://www.meti.go.jp/shingikai/energy_environment/green_innovation/006.html) is quoted.

This working group estimated the CO_2 reduction potential to be approximately 0.014 $GtCO_2$/year by summing up the amounts of biomass resources available in Japan. Also, based on the recent report, the global CO_2 reduction potential is estimated to be approximately 2.6 $GtCO_2$/year (0.3 to 75 $GtCO_2$/year).

Potential of CO_2 reduction through applying biochar to agricultural land in Japan
<table>
<tr><th></th><th>Amount of biomass available (10,000 t)</th><th>Carbonization yield (%)</th><th>Carbon content of biochar</th><th>100-year carbon residual rate of biochar</th><th>Amount of CO_2 absorption (10,000 t)*1</th></tr>
<tr><td>Wood (e.g., forest residue)</td><td>750</td><td>40</td><td>0.77</td><td>0.89</td><td>763</td></tr>
<tr><td>Bamboo</td><td>256</td><td>27</td><td colspan="2">0.439*2</td><td>113</td></tr>
<tr><td>Rice straw</td><td>751</td><td>50</td><td>0.49</td><td>0.65</td><td>439</td></tr>
<tr><td>Rice husk</td><td>200</td><td>50</td><td>0.49</td><td>0.65</td><td>117</td></tr>
<tr><td colspan="5">Total</td><td>1,432</td></tr>
</table>
*1 Amount of CO_2 absorption (10,000 t) = Amount of biomass available × Carbonization yield × Carbon content of biochar × 100-year residual rate of biochar × 44/12 (CO_2-equivalent)
*2 Value that includes the carbon content and carbon residual rate.

Also, in the IPPC's Special Report on Climate Change and Land (2019), the global potential of CO_2 reduction through application of biochar to soil is estimated to be almost the same, namely 0.03 to 6.6 $GtCO_2$/year.
</td></tr>
<tr><td>Afforestation/ reforestation</td><td>2.3</td><td>B</td><td>d) Description:
The estimate based on the recent report presented at the working group of the Sixth Green Innovation Strategy Promotion Council (https://www.meti.go.jp/shingikai/energy_environment/green_innovation/pdf/006_03_01.pdf) is quoted.</td></tr>
</table>

Table Examples of CO_2 reduction potentials and underlying logic

(*) Estimation patterns
- A: The estimate is made based on the assumed penetration rate of the technology.
- B: Estimates by other specialized institutions are used.
- C: The estimate is made based on the government's or industry's goals or predictions.
- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Methane (CH_4) emissions from livestock and agricultural practices	0.29	D	Approximately 0.29 $GtCO_2$/year a) Emission intensity of new technology: The effect of reduction by the new technology is assumed to be 50%. c) Amount introduced, amount replaced: The penetration rate of the new technology is assumed to be 20%. d) Description: The domestic potential is estimated based on the total amount of methane that is expected to be reduced through utilizing biological materials and other functional materials in the domestic agricultural industry, approximately 0.022 $GtCO_2$eq/year (methane emissions from enteric fermentation: 7.63 $MtCO_2$eq/year; farm livestock manure management: 2.39 $MtCO_2$eq/year; rice cultivation: 12.00 $MtCO_2$eq/year). 0.022 $GtCO_2$eq/year × 50% × 20% = 0.0022 $GtCO_2$eq/year Methane emission sources in agriculture differ between Japan and other countries. However, regarding methane emissions from enteric fermentation of farm animals, it is assumed that the estimate can be made on the same premise. The global potential is estimated based on the assumption that global methane generation from enteric fermentation is 2.85 $GtCO_2$eq/year, the methane reduction effect is 50%, and the technology adoption rate is 20%. 2.85 $GtCO_2$eq/year × 50% × 20% = 0.285 $GtCO_2$eq/year The reduction effect (50%) is based mainly on the following case studies. • Addition of seaweed to livestock feed (1%) cuts methane emissions by about 60%. (University of California, Davis) https://animalscience.ucdavis.edu/news/research-led-ermias-kebreab-tests-if-seaweed-cuts-methane-emissions-dairy-farms • Addition of vegetable oil extracted from cashew nuts to livestock feed cuts methane emissions by about 90%. (Idemitsu Kosan Co., Ltd., National Agriculture and Food Research Organization, Hokkaido University) https://agriknowledge.affrc.go.jp/RN/2030873698.pdf • Addition of amino acid to livestock feed cuts methane emissions by 12.5–50%. (Evonik (Germany), Sumitomo Chemical Co., Ltd.) https://www.nikkakyo.org/sites/default/files/ICCA_GasReduction_Guidelines_200dpi_300316.pdf • Addition of cable bacteria increases sulfate concentration in rice-vegetated soils by 5-fold and reduces methane emissions by 93%. (Aarhus University, Denmark) https://www.nature.COm/articles/s41467-020-15812-w/ • Addition of rice straw biochar to rice paddy soil reduces methane emissions by 39.5%. (National Natural Science Foundation of China, Zhejiang Provincial Natural Science Foundation) https://europepmc.org/article/pmc/4835783 • Development of Greenhouse Gas Reduction Technologies in Agriculture Through International Cooperation: A goal of reducing GHG by 30% or more has been achieved in field tests conducted in four countries by using water-saving cultivation technology in irrigated rice paddies called AWD (Alternate Wetting and Drying). (Ministry of Agriculture, Forestry and Fisheries of Japan) https://www.affrc.maff.go.jp/docs/project/seika/2018/attach/pdf/seika2018-41.pdf

Table Examples of CO_2 reduction potentials and underlying logic

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- D: The estimate is made based on the maximum penetration of the technology or maximum installation of the equipment.

Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
Nitrous oxide (N_2O) emissions from agricultural land	0.39–0.88	A, B	d) The estimate is made assuming the technology to reduce the global N_2O generation from agricultural lands by 80%. ● Maximum reduction potential that can be estimated The estimation results used are those acquired with cooperation from the National Agriculture and Food Research Organization as a specialized institution. The sources of N_2O generation to be reduced are assumed to be crop residue (0.22 $GtCO_2$eq/year) and chemical fertilizer (0.7 $GtCO_2$eq/year) (based on the data released by the Food and Agriculture Organization of the United Nations (FAO) (2017)[*1]. Also, the CO_2 generated in the process of synthesis of chemical fertilizer[*2] (0.45 $GtCO_2$/year) is included as a reduction target. The potential is estimated to be 0.88 $GtCO_2$/year, assuming that this technology can be penetrated into countries other than low-income food deficit countries (LIFDC) (equivalent to 20% of the global N_2O emissions), taking into account differences in income and food situations from country to country. ● Potential of reduction through direct control of microbial reactions (e.g., nitrification, denitrification) in crop residue and chemical fertilizer The source of N_2O to be reduced is N_2O emitted directly due to microbial reactions in crop residue and chemical fertilizer. • Crop residue (0.156 $GtCO_2$eq/year), chemical fertilizer (0.458 $GtCO_2$eq/year) (based on the data released by the FAO (2017)[*3] The potential is estimated to be 0.39 $GtCO_2$/year, assuming that this technology can be penetrated into countries other than LIFDCs (where 0.125 $GtCO_2$eq/year of N_2O is emitted, which is equivalent to 20% of the global N_2O emissions), taking into account differences in income and food situations from country to country. *1 As the global warming potential (GWP) of N_2O, the value based on the IPCC's Second Assessment Report (310) is used. (FAOSTAT, accessed in 2021) *2 https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-productionemits-CO2/97/i24 *3 As the GWP for N_2O, the value based on the IPCC's Fifth Assessment Report (265) is used. (FAOSTAT, accessed in November 2022)

Table Examples of CO_2 reduction potentials and underlying logic

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Technology	CO_2 reduction potential $GtCO_2$/year	Estimation pattern (*)	Basis for the estimated CO_2 reduction potential a) Emission intensity of new technology b) Emission intensity of conventional technology (tCO_2/specific unit) c) Amount introduced, amount replaced (specific units) Specific units: kWh, GJ, kg, t, etc. d) Description
AI chips	0.209–37.8	A, B	188 gCO_2/kWh × 1,113.6 TWh/year = 0.209 $GtCO_2$/year 188 gCO_2/kWh × 200,800 TWh/year = 37.8 $GtCO_2$/year b) Emission intensity of conventional technology: 188 gCO_2/kWh (CO_2 emission intensity of grid power consumption*1) c) Amount introduced, amount replaced (power consumption savings): 1,113.6 TWh (assumed for 2030)–200,800 TWh (assumed for 2050) d) Description: Penetration of chips designed for specific use, including AI chips, which are superior in processing efficiency in specific use to chips used in with general-purpose processors, such as CPU and GPU, is expected to contribute to reducing CO_2 through lower power consumption. • c) Amount replaced (global power consumption savings) The power consumption of AI servers operating in data centers, especially their processors, is expected to increase to 1,320 TWh/year by 2030 and 251,000 TWh by 2050*2. Assuming that general GPUs (power efficiency: 2 TOPS/W*3) are currently used as general-purpose processors and all of them will be replaced by the latest AI chips currently under development (power efficiency: 10 TOPS/W)*4, the power consumption savings are estimated as below: In 2030 1,320 TWh × (1 - 2/10) = 1,113.6 TWh In 2050 251,000 TWh × (1 - 2/10) = 200,800 TWh The predictions for the numbers of data centers and AI servers operating in data centers contain high uncertainty, as they depend greatly on the progress of digital transformation. In this estimate, the potential is calculated based on the predictions for 2030 and 2050, but these predictions need to be regularly verified. In the STEPS and other BAU scenarios based on conventional technologies and policies, such a drastic increase in energy consumption by data centers cannot be taken into consideration, so it is inappropriate to compare this estimation result with other estimation results. *1: CO_2 emission intensity of grid power consumption: Calculated based on the global power consumption (151 EJ = 41,962 TWh) and CO_2 emissions from the entire power generation sector (7,899 $MtCO_2$) in the IEA's WEO 2022 STEPS scenario (2050). *2: Impact of Progress of Information Society on Energy Consumption Vol. 2 (Center for Low Carbon Society Strategy, Japan Science and Technology Agency (JST), 2020) https://www.jst.go.jp/lcs/pdf/fy2020-pp-03.pdf *3: TOPS/W: OPS (operations per second) is an indicator that represents the number of commands executed per second and processor performance, and OPS per unit of power consumption (OPS/W) is used as an indicator that represents power efficiency. 1 [TOPS/W] = 10^{12} [OPS/W]. *4: NEDO news release: Artificial Intelligence (AI) Chip Has Been Developed That Has Power Efficiency up to 10 Times Higher Than Conventional Technology https://www.nedo.go.jp/news/press/AA5_101596.html

Appendix 2 Examples of CO_2 Abatement Cost Estimation

Table Examples of CO_2 abatement cost and underlying logic

(*) Estimation patterns
A: The estimate is made based on existing data, such as learning curves.
B: Estimates by other specialized institutions are used.
C: The estimate is made based on the government's or industry's goals or predictions.
D: Others

Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Next generation photovoltaics (vehicle-integrated PV)	-13,900–1,810	A	(6.99–9.96 - 9.62) ¥/kWh / (188 - 0) gCO_2/kWh = ¥-13,900–1,810/tCO_2 a) ¥6.99–9.96/kWh b) ¥9.62/kWh c) 0 gCO_2/kWh (This assumes that PV is in the utilization phase only.) d) 188 gCO_2/kWh e) Grid power consumption for charging is considered as the conventional technology. The way the cost decreases with time through increased penetration of vehicle-integrated PV (VIPV) is estimated. The above value is for 2050. • a) Unit cost of new technology According to the IEA's ETP 2016, the cumulative number of electric vehicles introduced is expected to be 1.4 million vehicles in 2030 and 9 million vehicles in 2050. Assuming that the PV installation rate is 1% in 2030 and 10 to 30% in 2050, the cumulative number of VIPV modules introduced is calculated by integrating the number of VIPV modules over this period while interpolating it linearly. Then, it is assumed that the unit cost of the new technology will be ¥40,000/kW in 2030, when the penetration of the new technology is expected to begin, based on the industry's cost target*1. After that, the manufacturing cost will decrease at a certain learning rate (80%) in line with the cumulative amount of introduced capacity. Based on the studies made in the past by NEDO*2, the unit cost is calculated as the levelized cost of electricity (LCOE), assuming that the VIPV capacity is 1 kW, the availability is 10%, and the average period of use is 12 years. In this case, the annual power generation is 876 kWh. For example, electric vehicles achieving an electricity consumption of 12.5 km/kWh is equivalent to an average daily mileage of 30 km. • b) Unit cost of conventional technology Roughly estimated by weighted averaging based on the power generation amount and cost around the world in the IEA's WEO 2022 STEPS scenario. • d) Emission intensity of grid power Calculated based on the grid power consumption and emissions in the power generation sector in the IEA's WEO 2022 STEPS scenario. *1 E.g., Analysis of the Potential of High-Efficiency and Low-cost Vehicle Integrated Photovoltaics (Yamaguchi et al., 2022, lecture at WCPEC-8) *2 PV-Powered Vehicle Strategy Committee Interim Report (NEDO, 2018)

Table Examples of CO_2 abatement cost and underlying logic

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C: The estimate is made based on the government's or industry's goals or predictions.
D: Others

Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Hydrogen power generation	9,800 –25,700	C	(17.2–12.1 - 9) ¥/kWh / (318 - 0) gCO_2/kWh = ¥9,800–25,700/tCO_2 a) ¥12.1–17.2/kWh b) ¥9/kWh (LNG thermal power) c) 0 gCO_2/kWh (This assumes the utilization phase only.) d) 318 gCO_2/kWh (LNG thermal power) e) • a) Unit cost of new technology Calculated based on the information given in the section titled *LNG thermal power generation* in the Power Generation Cost Verification Working Group report (Ministry of Economy, Trade and Industry, 2021). However, the fuel cost is calculated based on the target costs suggested in the Green Growth Strategy, ¥30/Nm^3 (2030) and ¥20/Nm^3 (2050) (Ministry of Economy, Trade and Industry, 2021). The generating efficiency of hydrogen power generation is assumed to be 57.0% (HHV), which is the same as the target generating efficiency of LNG thermal power generation (2030), with an auxiliary power ratio of 2.3%. The cost of hydrogen power generation is assumed to be the same as that of LNG thermal power generation, except the fuel cost including miscellaneous expenses (e.g., petroleum and coal tax, import charges, unloading charges, gasification cost). The cost of hydrogen power generation does not include infrastructure and land, such as ports, and technology development. • b) Unit cost of conventional technology Calculated based on the information given in the section titled *LNG thermal power generation* in the Power Generation Cost Verification Working Group report (Ministry of Economy, Trade and Industry, 2021). However, it is assumed that the fuel cost will be constant over the operating period ($10/MMBtu, $1 = ¥110). • d) Emission intensity of conventional technology Based on the Standard Calorific Values and Carbon Emission Factors (Comprehensive Energy Statistics) (Ministry of Economy, Trade and Industry, 2020) and the Power Generation Cost Verification Working Group report (Ministry of Economy, Trade and Industry, 2021).

Table Examples of CO_2 abatement cost and underlying logic

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<table>
<tr>
<th>Technology</th>
<th>CO_2 abatement cost ¥/tCO_2</th>
<th>Estimation pattern (*)</th>
<th>Basis for the estimated CO_2 abatement cost
a) Unit cost of new technology
b) Unit cost of conventional technology (¥/specific unit)
c) Emission intensity of new technology
d) Emission intensity of conventional technology (tCO_2/specific unit)
e) Description</th>
</tr>
<tr>
<td>Automotive – Next generation EV</td>
<td>The CO_2 abatement cost is estimated as the relationship with the difference in vehicle price between ICEVs and EVs.</td>
<td>D</td>
<td>

e) Considering internal combustion vehicles (ICEVs) as conventional vehicles, it is assumed that they will be replaced by electric vehicles equipped with next generation batteries (next generation EVs). The CO_2 abatement cost of next generation EVs is defined as the value obtained by dividing the additional cost incurred to replace ICEVs by next generation EVs by the CO_2 emission reduction amount. As for the additional cost, the differences in the vehicle price and the cost of energy consumed to run the vehicle over its entire life cycle should be considered at the same time. As for the CO_2 emissions, emissions from both vehicle use and production should be considered. Then, the CO_2 abatement cost of next generation EVs is calculated as in the equation below:

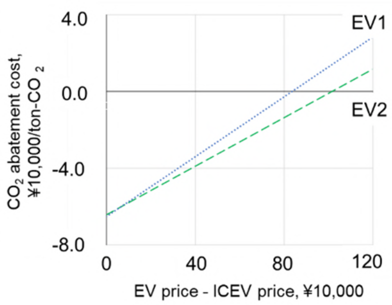
• CO_2 abatement cost (¥/tCO_2)
= Additional costs over the life cycle (¥)
/ CO_2 emission reduction amount (tCO_2)

• Additional costs over the life cycle (¥)
= Total mileage × {(Electricity consumption × Electricity price)
- (Fuel consumption × Fuel price)} + Difference in vehicle price

• CO_2 emission reduction amount in the life cycle
= Total mileage
× {(Fuel consumption × CO_2 emission intensity of fuel)
- (Electricity consumption × CO_2 emission intensity of electricity)}
+ Difference in CO_2 emissions from vehicle production

Assuming that the fuel consumption of ICEVs is 19.6 km/l (GEVO (Global EV Outlook) 2019); the electricity consumption by electric vehicles is 5.3 km/kWh (with an assumed charge rate of 95%, GEVO2019); the fuel price is ¥160/l (based on the market price in 2022, Japan); the electricity price is ¥24/kWh (median value of the electricity prices of 10 major countries, Central Research Institute of Electric Power Industry (2018)); the total mileage over the entire life cycle is 23,000 km*1; and the difference in CO_2 emissions from vehicle production is 7.54 t/vehicle (EV1, compact car)*2, the CO_2 abatement cost can be represented as the function of the difference in vehicle price between next generation EVs and ICEVs, as shown in the figure below. This figure includes the case for EV2, a larger vehicle class, which is calculated on the same assumption.

These two cases (EV1 and EV2) show that since the electricity cost, which is the operating cost of electric vehicles, is lower than the liquid-fuel cost, the CO_2 abatement cost is negative even if the electric vehicle purchase price is higher than that of the internal combustion engine vehicle by ¥800,000 to 1,000,000. In other words, it is desirable to actively introduce electric vehicles even if there is a price difference of ¥800,000 to 1,000,000. However, if the price difference is ¥1,200,000, the CO_2 abatement cost is ¥10,000 to 30,000/tonne-CO_2.



*1 J. Buberger et al., Renewable and Sustainable Energy Reviews 159 (2022) 112158
*2 GEVO2019: Global EV Outlook 2019

</td>
</tr>
</table>

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Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Carbon recycling - Basic chemicals	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	Considering the production of C_2 olefin (ethylene) and C_3 olefin (propylene), which are basic chemicals, through the new technology of CCU, the CO_2 abatement cost is estimated relative to the product cost increase (¥/t-product), with emission intensities of the new technology varying within an appropriate range. c) Emission intensity of new technology: {[Emission intensity of CO_2 separation and capture (tCO_2/t-product)] + [Emission intensity of new technology process (tCO_2/t-product)]} Here, the emission intensity of the new technology process is defined as the value obtained by subtracting the amount of CO_2 absorbed by the product as a raw material from the amount of CO_2 emitted as an energy input. That is, [Emission intensity of new technology] = [Emission intensity of CO_2 separation and capture] + [Emission intensity of new technology process] - [Intensity of CO_2 absorbed by product] d) Emission intensity of conventional technology: 1.5 tCO_2/t-olefin. Calculated based on the composition ratio of ethylene and propylene in production from naphtha[*1] and the LCI database[*2]. e) Description: • As for the emission intensity of CO_2 separation and capture, 0.05 tCO_2(emitted)/tCO_2(captured) is used, which is obtained from CO_2 emissions (50 $kgCO_2$/GJ[*4] based on the assumption that the energy required for CO_2 separation and capture is 1.0 GJ/tCO[*3], and this 1 GJ is supplied by natural gas. This means that 95% of the CO_2 absorbed by the product contributes to the reduction. • The intensity of CO_2 absorbed by the product is calculated based on the ratios of the molecular weights of ethylene and propylene and the molecular weight of CO_2 that can be absorbed and utilized. For both ethylene and propylene, the CO_2 intensity is 3.14 tCO_2/t-olefin. • From the above, when the product cost increase is c (¥/t-product) and the emission intensity of the new technology process is p (tCO_2/t-product), the CO_2 abatement cost [¥/t-CO_2] is as follows: C_2 olefin, C_3 olefin: $\frac{c}{1.5-(p-3.14\times 95\%)} = \frac{c}{4.48-p}$ ¥/tCO_2 • The lower and upper limits of the emission intensity of the new technology process are assumed to be the emission intensity of the conventional technology, and the sum of the emission intensity of the conventional technology and the amount of CO_2 absorbed by the product, respectively. If this upper limit is exceeded, there is no reduction in the amount of CO_2. • Based on the above, the relationship between the CO_2 abatement cost and product cost increase of C_2 olefin (ethylene) and C_3 olefin (propylene), which are basic chemicals, is shown in the figure below. Once the emission intensity of the new technology and the product cost increase are determined, which depends mainly on capital investment, reaction temperature, and catalyst costs, the CO_2 abatement cost, as a development goal, can be quantified. The decision whether to introduce the new technology can be made mainly depending on the financial support system, which differs from one country to another, and the conventional technology to be replaced by the new technology. However, quantifying environmental value in this way offers a useful indicator to the developers.

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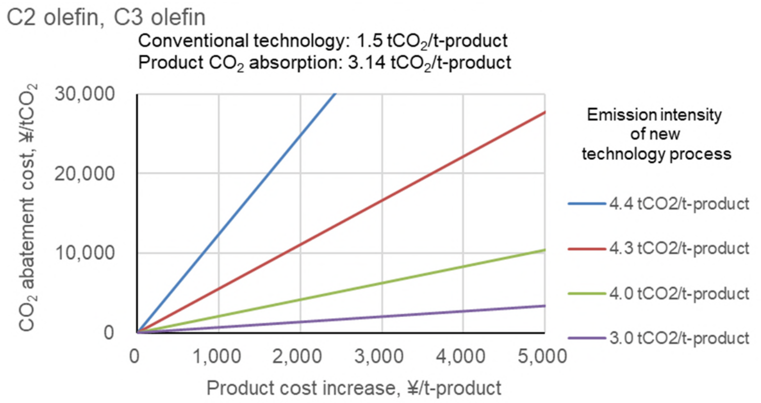
Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Carbon recycling - Basic chemicals (continued)	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	 Figure CO_2 abatement cost of carbon recycling - basic chemicals *1: TSC Foresight Vol. 109, Toward the Formulation of Technology Strategies in the Field of Raw-Material Diversification of Basic Chemicals (Rubber Materials C4 and C5) (NEDO, 2022) https://www.nedo.go.jp/content/100952690.pdf *2: LCI Database IDEA ver3.2.0 (April 15, 2022), IDEA Laboratory, Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology *3: Roadmap for Carbon-Recycling Technologies (Ministry of Economy, Trade and Industry, 2019) https://www.meti.go.jp/press/2019/06/20190607002/20190607002-1.pdf * 4 List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment, 2020) https://ghg-santeikohyo.env.go.jp/files/calc/itiran_2020_rev.pdf

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Carbon recycling - Functional chemicals	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	Considering the production of polycarbonate, polyurethane, and superabsorbent polymer (SAP) as functional chemicals via CCU as a new technology, the CO_2 abatement cost is estimated relative to the product cost increase (¥/t-product), with emission intensities of the new technology varying within an appropriate range. c) Emission intensity of new technology (tCO_2/t-product): {[Emission intensity of CO_2 separation and capture (tCO_2/t-product)] + [Emission intensity of new technology process (tCO_2/t-product)]} Here, the emission intensity of the new technology process is defined as the value obtained by subtracting the amount of CO_2 absorbed by the product as a raw material from the amount of CO_2 emitted as an energy input. That is, [Emission intensity of new technology] = [Emission intensity of CO_2 separation and capture] + [Emission intensity of new technology process] - [Intensity of CO_2 absorbed by product] d) Emission intensity of conventional technology (tCO_2/t-product): Carbon footprints of polycarbonate, polyurethane (soft), and acrylic acid as a SAP material[*1] e) Description: • [Emission intensity of CO_2 separation and capture]: 0.05 tCO_2(emitted)/tCO_2(captured) is used, which is obtained from CO_2 emissions (50 $kgCO_2$/GJ[*3]) based on the assumption that the energy required for CO_2 separation and capture is 1.0 GJ/tCO[*2]. This 1 GJ is supplied by natural gas. • [CO_2 intensity absorbed by product]: Calculated based on the proportion of the ratio of the molecular weight of diphenyl carbonate (DPC), which is a prime integral of polycarbonate, diphenylmethane diisocyanate (MDI) for polyurethane, or acrylic acid for SAP and the amount of CO_2 that can be absorbed and utilized. The intensities of CO_2 absorbed by these products are 0.21 tCO_2/t-DPC, 0.35 tCO_2/t-MDI, and 0.61 tCO_2/t-acrylic acid, respectively. • In [CO_2 abatement cost (¥/tCO_2) = [Product cost increase (¥/t-product) / {[Emission intensity of conventional technology (tCO_2/t-product)] - [Emission intensity of new technology (tCO_2/t-product)]}, when the product cost increase is c (¥/t-product) and the emission intensity of the new technology process is p (tCO_2/t-product), the CO_2 abatement cost (¥/tCO_2) is as follows: Polycarbonate: $\frac{c}{7.69-(p-0.21\times 95\%)} = \frac{c}{7.89-p}$ ¥/tCO_2 Polyurethane: $\frac{c}{4.63-(p-0.35\times 95\%)} = \frac{c}{4.96-p}$ ¥/tCO_2 Acrylic acid: $\frac{c}{2.22-(p-0.61\times 95\%)} = \frac{c}{2.80-p}$ ¥/tCO_2 • The lower and upper limits of the emission intensity of the new technology process are assumed to be the emission intensity of the conventional technology, and the sum of the emission intensity of the conventional technology and the amount of CO_2 absorbed by the product, respectively. If this upper limit is exceeded, there is no reduction in the amount of CO_2. • The figure below shows the relationship between the CO_2 abatement cost and product cost increase for each compound. As shown in the figure, once the emission intensity of the new technology and the product cost increase are determined, which depends mainly on capital investment, reaction temperature, and catalyst costs, the CO_2 abatement cost, as a development goal, can be quantified. The decision whether to introduce the new technology can be made mainly depending on the financial support system, which differs from one country to another, and the conventional technology to be replaced by the new technology. However, quantifying environmental value in this way offers a useful indicator to the developers.

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D: Others

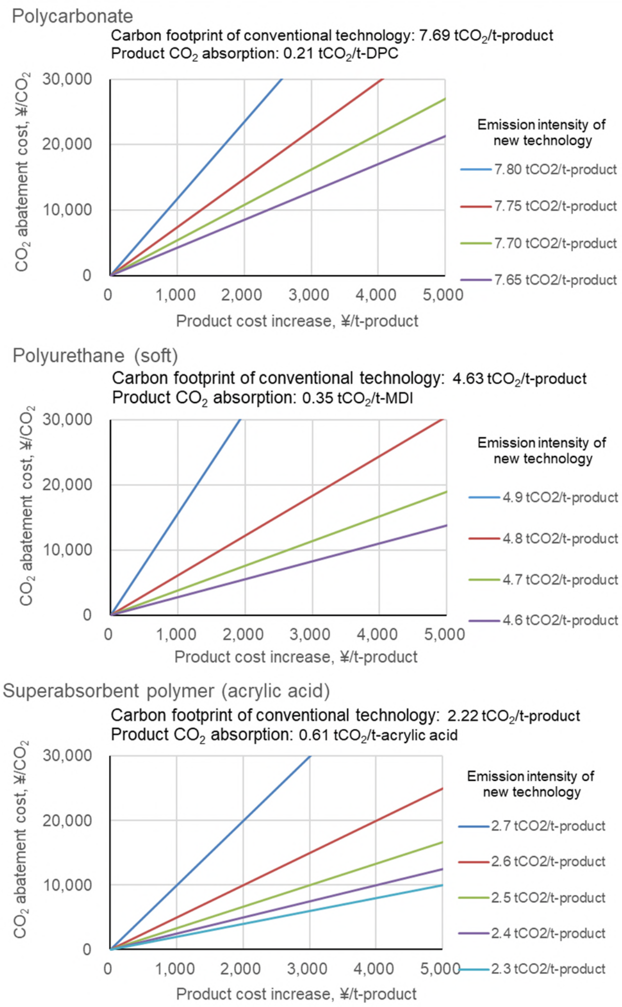
Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Carbon recycling - Functional chemicals (continued)	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	 Figure CO_2 abatement cost of carbon recycling - functional chemicals *1: CFP Program, CFP Database (accessed in July 2020) https://www.cfp-japan.jp/calculate/verify/database2012-2.html *2: Roadmap for Carbon Recycling Technologies (Ministry of Economy, Trade and Industry, 2019) https://www.meti.go.jp/press/2019/06/20190607002/20190607002-1.pdf *3: List of Calculation Methods and Emission Factors for Greenhouse Gas Emissions Calculation, Reporting and Publication System (Ministry of the Environment, 2020) https://ghg-santeikohyo.env.go.jp/files/calc/itiran_2020_rev.pdf

Table Examples of CO_2 abatement cost and underlying logic

(*) Estimation patterns
- A: The estimate is made based on existing data, such as learning curves.
- B: Estimates by other specialized institutions are used.
- C: The estimate is made based on the government's or industry's goals or predictions.
- D: Others

Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Carbon recycling - Carbonate	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	In cement production, CO_2 is generated when limestone ($CaCO_3$, $MgCO_3$) is burned. As an alternative to natural limestone, CO_2 is absorbed into waste-derived Ca and Mg to carbonate them. This is assumed to be a new technology. Based on equation (1) below, which represents the relationship between the emission intensity of this new technology, or carbonate, and the acceptable rise in the market price of limestone from the current level (¥/t-limestone), the CO_2 abatement cost is roughly estimated as shown in the figure below. Equation (1): [CO_2 abatement cost (¥/tCO_2)] = [Acceptable rise in market price (¥/t-carbonate as an alternative to limestone) / {[Emission intensity of conventional technology (tCO_2/t-limestone)] - [Emission intensity of new technology (tCO_2/t-carbonate as an alternative to limestone)]} a) Cost of new technology: The application of the new technology is reflected in the market price, and the cost of the new technology is assumed to be one to eight times the cost of the conventional technology so as to cover a CO_2 abatement cost of approximately ¥30,000/tCO_2. b) Cost of conventional technology (¥/t-limestone): Market price of limestone. The market price is set to ¥1,000/t-product ($1 = ¥100), assuming that the global production (2019) is 6.9 Gt/year and the global total revenue (2019) is $73,015 million based on the market survey report[*1]. d) Emission intensity of conventional technology (tCO_2): The emission intensity of CO_2 derived from the process of desorption that takes place when limestone is heated is adopted. Assuming that the chemical composition of limestone is $CaCO_3$: $MgCO_3$ = 99:1 by weight, the emission intensity of the conventional technology is calculated to be 0.44 tCO_2/t-limestone by weighted averaging (using the equation below)[*2]. Molecular weight of CO_2 / Molecular weight of $CaCO_3$ × $CaCO_3$ content + Molecular weight of CO_2 / Molecular weight of $MgCO_3$ × $MgCO_3$ content = (44.0 / 100.1) × 0.99 + (44.0 / 84.3) × 0.01) c) Emission intensity of new technology (tCO_2/t-carbonate as an alternative to limestone): Assuming that the emission intensity of the conventional technology is 0.44 tCO_2/t-limestone and an emission reduction of 70 to 10% is achieved, the emission intensity of the new technology is assumed to be 0.04 to 0.31 tCO_2/t-carbonate as an alternative to limestone. e) Description: In this estimate, it is assumed that process-derived CO_2 is emitted when limestone (carbonate) is burned but can be absorbed into waste-derived calcium and other materials and carbonated, and utilized as a raw material. Basically, this makes it possible to avoid emitting CO_2 into the atmosphere due to not using natural limestone. In this case, stoichiometrically, when 1 tonne of carbonate is produced as an alternative to limestone, 0.44 tonne of CO_2 is absorbed, which means that the emission intensity is essentially zero. However, CO_2 emissions are unavoidable unless the electricity and heat in the reaction process of the new technology is carbon-free. Therefore, the emission intensity of the new technology is assumed to be 70 to 10% of the conventional technology.

Table Examples of CO_2 abatement cost and underlying logic

(*) Estimation patterns
- A: The estimate is made based on existing data, such as learning curves.
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- C: The estimate is made based on the government's or industry's goals or predictions.
- D: Others

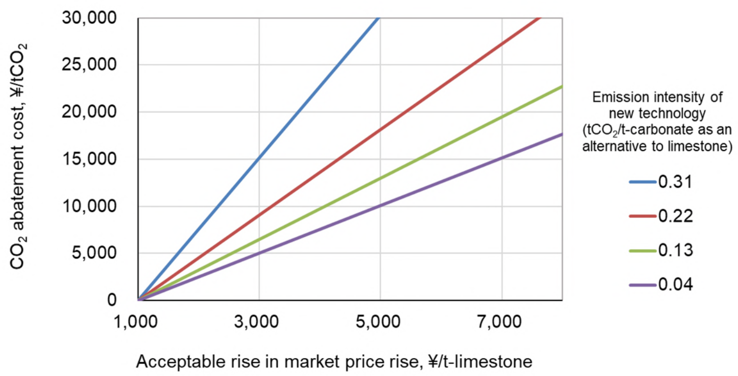
<table>
<tr>
<th>Technology</th>
<th>COCO_2 abatement cost ¥/tCO_2</th>
<th>Estimation pattern (*)</th>
<th>Basis for the estimated CO_2 abatement cost
a) Unit cost of new technology
b) Unit cost of conventional technology (¥/specific unit)
c) Emission intensity of new technology
d) Emission intensity of conventional technology (tCO_2/specific unit)
e) Description</th>
</tr>
<tr>
<td>Carbon recycling - Carbonate (continued)</td>
<td>The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.</td>
<td>D</td>
<td>


Figure CO_2 abatement cost of cement production using carbonate derived from waste and other materials
Source: Prepared by NEDO's Technology Strategy Center (2021)

This figure shows that when the CO_2 abatement cost is arbitrary, a technology with a greater CO_2-reducing effect is more acceptable even if the market price rises significantly. If society is able to accept a CO_2 abatement cost of ¥20,000, as indicated by the blue line in the figure, an eight- to nine-fold rise in the market price (¥8,000 to 9,000) can be accepted as long as the emission intensity is lowered to 0.04 tCO_2/t-product.

*1: Limestone Market Analysis (Grand View Research, Inc. 2020)
https://www.gii.co.jp/report/grvi963076-limestone-market-size-share-trends-analysis-report.html
Based on global production in 2019 (6,924.8 Mt/year) and global profit in 2019 ($73,015.3 million), the market price is assumed to be approximately ¥1,000. This assumes that $1 equals ¥100.
*2: FY2010 Committee for Greenhouse Gas Emissions Estimation Methods, Breakout Group on Energy and Industrial Processes (Ministry of the Environment, 2011)
https://www.env.go.jp/earth/ondanka/santeiho/kento/h2303/1.pdf
</td>
</tr>
</table>

Table Examples of CO_2 abatement cost and underlying logic

(*) Estimation patterns
A: The estimate is made based on existing data, such as learning curves.
B: Estimates by other specialized institutions are used.
C: The estimate is made based on the government's or industry's goals or predictions.
D: Others

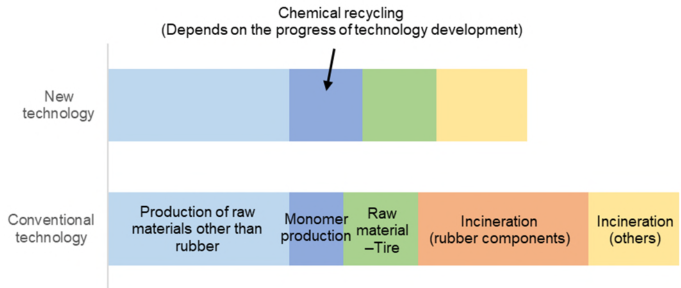
Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Tire recycling	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	The CO_2 abatement cost is estimated relative to the product cost increase (¥/t-product) caused by replacing the incineration of tire rubber with chemical recycling that uses the new technology, with emission intensities due to the new technology varying within an appropriate range. This estimate is made for the process of producing synthetic rubber monomer such as butadiene through chemical recycling waste tires. Considering the difference between the conventional technology and new technology, the new technology can eliminate the CO_2 emissions from monomer production and rubber incineration that arise when using conventional technology, so only the increase in CO_2 emissions from monomer production by chemical recycling should be considered.  Figure CO_2 reduction effects due to chemical recycling Source: Prepared by NEDO's Technology Strategy Center (2021) d) Emission intensity of conventional technology (tCO_2/t-product): 1.92 tCO_2/t-butadiene of CO_2 is emitted in the processes from raw-material mining to butadiene production[*1]. c) Emission intensity of new technology (tCO_2/t-product): The CO_2 emission intensity of chemical recycling is used as a parameter. The value obtained by adding the amount of CO_2 emitted in synthetic rubber production from butadiene, which corresponds to the amount of CO_2 emitted by chemical recycling reactions, to the amount of CO_2 derived from tire components other than rubber when incinerated, is set as the lower limit. The CO_2 emissions of the conventional technology is set as the upper limit. If this upper limit is exceeded, there is no reduction in the amount of CO_2. e) Description: • In [CO_2 abatement cost (¥/tCO_2)] = [Product cost increase (¥/t-product)] / {[Emission intensity of conventional technology (tCO_2/t-product)] - [Emission intensity of new technology (tCO_2/t-product)]}, the difference between the emission intensities of the conventional technology and the new technology in the denominator equals the value obtained by subtracting the emission intensity of chemical recycling, or the new technology, from the sum of the emission technology for monomer production and the emission intensity of rubber incineration using the conventional technology. When the emission intensity of chemical recycling is e (tCO_2/t-tire) and the product cost increase is c (¥/t-tire), $$\frac{c}{1.92 \times 35\% + 1.56 - e} = \frac{c}{2.23 - e} ¥/tCO_2$$ In this calculation, it is assumed that the synthetic rubber content of a tire is 35% and the amount of CO_2 derived from rubber incineration is 1.56 tCO_2/t-tire. Also, it is assumed that the lower limit of the CO_2 emission intensity of chemical recycling, which is set as a parameter, is 1.1 tCO_2 /t-tire, which is 1/2 of the sum of the emission intensities of monomer production and rubber incineration, or 2.23 tCO_2t-tire, and the upper limit equals the sum of the emission intensities of monomer production and rubber incineration, or 2.2 tCO_2t-tire.

Table Examples of CO_2 abatement cost and underlying logic

(*) Estimation patterns
- A: The estimate is made based on existing data, such as learning curves.
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- D: Others

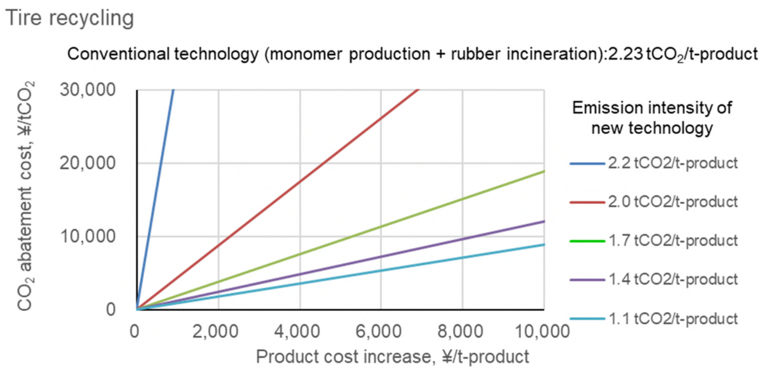
Technology	CO_2 abatement cost ¥/tCO_2	Estimation pattern (*)	Basis for the estimated CO_2 abatement cost a) Unit cost of new technology b) Unit cost of conventional technology (¥/specific unit) c) Emission intensity of new technology d) Emission intensity of conventional technology (tCO_2/specific unit) e) Description
Tire recycling (continued)	The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.	D	• The figure below shows the relationship between the CO_2 abatement cost and product cost increase. Once the emission intensity of the new technology and the product cost increase are determined, which depends mainly on capital investment, reaction temperature, and catalyst costs, the CO_2 abatement cost, as a development goal, can be quantified. The decision whether to introduce the new technology can be made mainly depending on the financial support system, which differs from one country to another, and the conventional technology to be replaced by the new technology. However, quantifying environmental value in this way offers a useful indicator to the developers.  Figure CO_2 abatement cost by chemical recycling of tire rubber Source: Prepared by NEDO's Technology Strategy Center (2021) *1: CFP Program, CFP Database (accessed in July 2020) https://www.cfp-japan.jp/calculate/verify/data.html

Table Examples of CO_2 abatement cost and underlying logic

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<table>
<tr>
<th>Technology</th>
<th>CO_2 abatement cost ¥/tCO_2</th>
<th>Estimation pattern (*)</th>
<th>Basis for the estimated CO_2 abatement cost
a) Unit cost of new technology
b) Unit cost of conventional technology (¥/specific unit)
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d) Emission intensity of conventional technology (tCO_2/specific unit)
e) Description</th>
</tr>
<tr>
<td>Hydrogen reduction ironmaking (blast furnaces)</td>
<td>The CO_2 abatement cost is estimated as the relationship between the product cost increase due to the new technology and emission intensity.</td>
<td>D</td>
<td>

Regarding blast-furnace ironmaking, considering hydrogen reduction ironmaking (blast furnaces) as a new technology, the CO_2 abatement cost is estimated relative to the product cost increase, with emission intensities of the new technology varying within an appropriate range.

c) Emission intensity of new technology: Half of the emission intensity of the conventional technology is set as the lower limit, and the emission intensity of the conventional technology is set as the upper limit. If this upper limit is exceeded, there is no reduction in the amount of CO_2.

d) Emission intensity of conventional technology: Assumed to be 2.0 tCO_2/t-Fe based on the production emission intensity of the blast furnace-basic oxygen furnace method, which is the best available technology[*1].

e) Description:

- When the product cost increase is c (¥/t-product) and the emission intensity of the new technology is p (tCO_2/t-product), the CO_2 abatement cost is as follows:

$$CO_2 \text{ abatement cost of hydrogen reduction ironmaking} = \frac{c}{2.0-p} \text{ ¥/}tCO_2$$

- The figure below shows the relationship between the CO_2 abatement cost and product cost increase for hydrogen reduction ironmaking (blast furnaces). Once the emission intensity of the new technology and the product cost increase are determined, which depends mainly on capital investment and ironmaking process costs, the CO_2 abatement cost, as a development goal, can be quantified. The decision whether to introduce the new technology can be made mainly depending on the financial support system, which differs from one country to another, and the conventional technology to be replaced by the new technology. However, quantifying environmental value in this way offers a useful indicator to the developers.

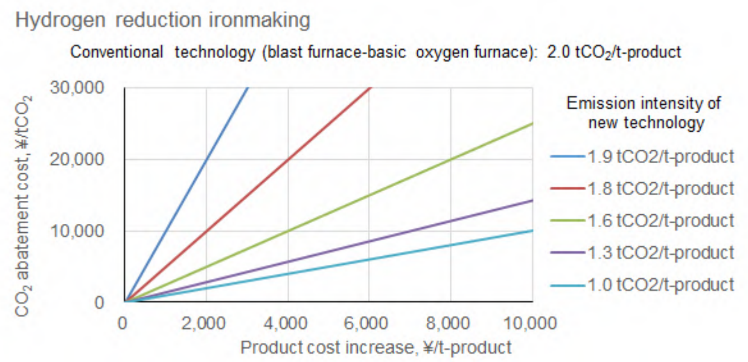

Figure CO_2 abatement cost of hydrogen reduction ironmaking

*1: Net-Zero Steel - Sector Transition Strategy -, Box1 (Mission Possible Partnership, 2021) https://www.energy-transitions.org/wp-content/uploads/2021/10/MP-Steel-Transition-StrategyFinal-1.pdf

</td>
</tr>
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Table Examples of CO_2 abatement cost and underlying logic

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<tr><th>Technology</th><th>CO_2 abatement cost ¥/tCO_2</th><th>Estimation pattern (*)</th><th>Basis for the estimated CO_2 abatement cost
a) Unit cost of new technology
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c) Emission intensity of new technology
d) Emission intensity of conventional technology (tCO_2/specific unit)
e) Description</th></tr>
<tr><td>Plastic recycling</td><td>-10,000
–5,700</td><td>A</td><td>e) Description:
• According to the EU's estimates[*1], the cost of CO_2 reduction via various plastic recycling measures is relatively low: between -¥10,000 to 5,700/tCO_2 ($1 = ¥100). In particular, the cost of CO_2 reduction by reusing wrapping in the agricultural industry, which is reused without any modification, is the lowest and is estimated to be -¥10,000/tCO_2. Meanwhile, the costs of CO_2 reduction through chemical recycling and reuse of packaging and containers are estimated to ¥5,500/tCO_2 and ¥5,700/tCO_2, respectively. As for the case where collected plastic products are reused without any modification, no chemical synthesis or forming processes are necessary, so its cost is lower than that of the products produced from virgin plastics (conventional technology). Accordingly, based on the definitional equation, the abatement cost is a negative value. This means that plastic recycling is economically rational and is effective for reducing CO_2.

*1: The Circular Economy, A Powerful Force for Climate Mitigation (SITRA, 2018) https://www.sitra.fi/app/uploads/2018/06/the-circular-economy-a-powerful-force-for-climate-mitigation.pdf</td></tr>
<tr><td>CCS</td><td>7,050
–12,400</td><td>B</td><td>e) Description:
• This figure is an excerpt from a report by the Global CCS Institute[*1] that provides detailed analysis of CCS's CO_2 abatement cost. Except for ammonia production and accompanying gases that have an extremely high CO_2 concentration, the CO_2 abatement cost in 2017 is between ¥7,050 to 12,400/tCO_2 ($1 = ¥100)[*2], and a cost reduction of 20 to 30% is anticipated through future technology development.

Table CO_2 abatement cost by CO_2 emission source[*3] ($/t$CO_2$)
<table>
<tr><th></th><th colspan="4">Power generation type</th><th colspan="3">Manufacturing industry</th><th rowspan="2">Associated gas</th></tr>
<tr><th></th><th>Pulverized coal /supercritical</th><th>Oxygen combustion /supercritical</th><th>IGCC</th><th>NGCC</th><th>Steel</th><th>Cement</th><th>Ammonia</th></tr>
<tr><td>Conventional technology</td><td>78.5</td><td>70.5</td><td>97.0</td><td>89.0</td><td>77.0</td><td>124.0</td><td>25.4</td><td>21.5</td></tr>
<tr><td>Future</td><td>55.0</td><td>52.0</td><td>46.0</td><td>43.0</td><td>65.0</td><td>103.0</td><td>23.8</td><td>20.4</td></tr>
</table>
Source: Prepared by NEDO's Technology Strategy Center based on the Global Costs of Carbon Capture and Storage 2017 (2020)

*1: Global Costs of Carbon Capture and Storage (Global CCS Institute, 2017) https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf
*2: In the Roadmap for Carbon Recycling Technologies, the target CO_2 abatement cost by 2050 is ¥1,000/tCO_2 or less with CO_2 separation and capture only.
*3: This assumes pipeline transportation and CCS in the US.</td></tr>
</table>

Technology Strategy Center Report

TSC Foresight

Comprehensive R&D Principle for
Sustainable Society 2023

Published on August 22, 2023

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