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Energy Security Enhancement and Energy Policy Movements toward Decarbonization

Modeling Potential Installation of Solar and Wind Energy Considering Cannibalization Effect

Decarbonization of the Aviation Sector: Current Status, Challenges, and Future Outlook

Design of Emissions Trading System in Japan (Based on lessons learnt from the European Union Emissions Trading System (EU ETS))

The Institute of Energy Economics, Japan

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Energy Security Enhancement and Energy Policy Movements toward Decarbonization

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Fossil Fuel Market Trends and Outlook
<Summary > ◆

Tetsuo Morikawa[*] Hiroshi Hashimoto[**] Atsuo Sagawa[***]

Key Points of the Report

1. While oil market demand will recover to 100 million barrels per day (mb/d) in the fourth quarter of 2022, supply will exceed demand due to the release of oil stockpiling and production growth mainly in the United States and Saudi Arabia in the second half of 2022. We forecast the average Brent price in the second half of 2022 at $105 per barrel. Crude oil prices will remain unstable due to concern about recession, the potential tightening of Western sanctions on Russia and supply disruption risks. In particular, Russia's potential retaliatory embargoes may represent a great risk of upward pressure on oil prices.
2. As LNG from the United States shift towards Europe with the European Union's efforts to phase out dependence on Russian gas supply, the difficult time for Japan's electric power and gas companies continues for their procurement of LNG. Under the great shift the global LNG market is expected to expand by 5% in 2022. The imminent challenge is securing mid- and long-term LNG supply, as well as underpinning investment.
3. While coal market demand surpassed supply from the second half of 2021, coal prices spiked twice due to Russia's invasion of Ukraine and a Russian coal embargo by the European Union and Japan. After turning down in June, steam coal prices have risen beyond $400 per ton again. Coking coal prices have fallen to around $250/t. In the second half of 2022, we forecast steam coal prices to decline on coal-producing countries' recovery of supply before leveling off on a winter demand rise. Coking coal prices are predicted to level off. The average price in the second half of 2022 is projected at around $360/t for steam coal and around $250/t for coking coal.

Oil market

4. Oil market will remain oversupplied demand due to production growth in Saudi Arabia and the United States in the second half of 2022, despite a demand recovery and a production decrease in Russia. We forecast the average Brent price in the period at $105/bbl.
5. The OPEC-plus is expected to increase production in the second half of 2022 by 2 mb/d year on year, while many member countries of the group remain unable to reach their respective production target. Saudi Arabia and the United Arab Emirates will account for most of the production increase. The OPEC-plus's production surplus is very low, indicating their vulnerability to respond to supply disruptions.
6. In the second half of 2022, oil market will focus on risks of a recession amid interest increase in the U.S. and tighter sanctions on Russia. Depending on these risks, oil prices could fluctuate wildly. Particularly, Russia could resort to oil export embargos in retaliation for the Western sanctions, leading to a great upside risk for oil prices.

LNG market

7. Japan's average LNG import price in 2022 is expected to rise to USD 16.5 per million Btu, from USD 10.13 in 2021. The assessed spot LNG prices in Northeast Asia are expected to stay at a high level of around USD 35 on average in 2022. The term contract prices are expected to average around USD 12.4, driven up by the high levels of crude oil prices.

◆ Created based on the published research in the 441tst Forum on Research Works with the information available as of July 2022.

[*] Senior Economist, Manager, Oil Group, Fossil Energies & International Cooperation Unit, IEEJ

[**] Senior Analyst, Manager, Gas Group, Fossil Energies & International Cooperation Unit, IEEJ

[***] Senior Research Fellow, Coal Group, Fossil Energies & International Cooperation Unit, IEEJ

8. Global LNG trade is expected to increase by 5% to 390 million tonnes in 2022 from 372 million tonnes in 2021. Although global natural gas consumption rebounded by 4.5% in 2021 from a 2% decrease in 2020, the global gas demand in 2022 is expected to stay at almost the same level as in 2021, or even slightly decline. The future growth potential of global gas demand entails uncertainty due to the war in Ukraine, the pandemic, and expensive gas prices, with forecast numbers for 2023 and thereafter are smaller than the previous forecast.
9. Gas prices in Europe and Asia have been in the highest levels in history and more expensive than crude oil since July 2021. In 2022, the gas and LNG markets embrace more uncertain factors due to developments in the global arena.
10. The global LNG market has observed increasing sale and purchase deals to procure mid- to long-term LNG supply. Expectations are high that more investment in new LNG production and more supporting policy measures should be realized.

Coal market

11. Among the four biggest coal importers, China reduced coal imports in the January-May period year on year due to domestic production expansion and a consumption fall amid the COVID-19 spread. India cut steam coal imports in January and February before increasing them on a rise in coal demand for power generation from March, posting a year-on-year steam coal import increase for the five months. Its coking coal imports in the period remained almost unchanged from a year earlier. Japan expanded steam coal imports in the January-May period by 2.75 million tons year on year. South Korea's steam coal imports in the first half of this year grew by 5 million tons. Coking coal imports decreased by 0.8 million tons in Japan and by 0.95 million tons in South Korea.
12. Coal supply plunged due to a ban on coal exports in Indonesia in the first half of January and bad weather (torrential rainfall) in Australia in 2022.
13. Under such a situation, spot prices spiked (to $400/t for steam coal and more than $600/t for coking coal) in the wake of Russia's invasion of Ukraine. They spiked again due to a Russian coal embargo by the European Union and Japan, surpassing $400/ton for steam coal and $500/t for coking coal. Both steam and coking coal prices turned down in June. In July, however, steam coal prices rose again on torrential rainfall in New South Wales, Australia. In contrast, coking coal prices rapidly fell to around $250/t on a supply increase in July.
14. As steam coal supply is expected to increase on the strength of price hikes, steam coal prices are projected to weaken in the third quarter of 2022 before leveling off on procurement for the winter demand season in the fourth quarter. Coking coal prices will level off from the third quarter on stable supply and demand.

European and U.S. Energy Security Enhancement Based on Ukraine Crisis <Summary> ◆

Kei Shimogori[*]

European trends

1. The European Union's European Green Deal was positioned as the core of the green recovery plan following the COVID-19 pandemic and has still been a top priority even since Russia's invasion of Ukraine. While the 2050 carbon neutrality goal is still maintained despite the invasion, energy security (to phase out dependence on Russian fossil fuels) has grown even more important. The EU is ready to tolerate a temporary increase in CO_2 emissions to promote energy security.
2. The REPowerEU Plan for phasing out dependence on Russian energy sources features the Fit for 55 Package to cut greenhouse gas emissions by at least 55% from 1990 by 2030, seeking to reduce natural gas consumption by 155 billion cubic meters (equivalent to natural gas imports from Russia in 2021) by 2030 through the energy saving, the diversification of energy supply and the acceleration of renewable energy.
3. Major short-term measures include the diversification of liquefied natural gas and pipeline gas imports, the postponement of plans to phase out coal power generation and the extension of existing nuclear reactors' lifetime. The EU's additional LNG procurement has potential to tighten the supply-demand balance in the international LNG market.
4. Particularly, Europe is expected to increase LNG procurement from the United States and Qatar. Rapid European moves to secure LNG supply have potential to bring about negative impacts including a fiercer race to procure LNG and subsequent price hikes in Japan and the Asian market.
5. Over the medium to long term, Europe is destined to link energy security to decarbonization and accelerate decarbonization initiatives including the acceleration of renewable energy, the improvement of energy efficiency and electrification. In France, the United Kingdom and Eastern Europe, the utilization or introduction of nuclear energy will become a leading option in addition to renewable energy.

U.S. trends

6. No change has been seen in the U.S. Biden administration's key strategic goal of enhancing climate change countermeasures. On the other hand, responses to energy price spikes have become an urgent challenge, prompting the Biden administration to release strategic oil reserves, launch summer sales of gasoline with an ethanol content of 15% and resume oil and gas development on federal lands.
7. The United States has shared a long-term decarbonization policy with the EU and indicated its readiness to help the EU procure additional LNG to phase out dependence on Russia. The United States and Europe have set up EU-US Task Force on Energy Security in pursuit of LNG supply diversification and natural gas demand reduction to meet climate change goals. The United States has offered efforts to secure additional LNG supply to the EU market.
8. While the United States is expected to take leadership in expanding global LNG production, long-term guaranteed demand is required for investment decisions leading to LNG production expansion. How far will LNG production be increased in the United States and the rest of the world even under carbon neutrality and other long-term decarbonization goals and concern about stranded assets resulting from gas sector investment? With respect to this question, we may have to pay attention to moves for securing long-term LNG procurement contracts and initiatives for decarbonizing fossil fuels. (As of July 22)

◆ Created based on the published research in the 441tst Forum on Research Works with the information available as of July 2022.

[*] Senior Researcher, Global Energy Group 1, Strategy Research Unit, IEEJ

Carbon Pricing – Current Status and Issues regarding Institutional Designs in Japan and Other Countries

<Summary > ◆

Junko Ogawa*

1. Trends regarding carbon pricing systems in Japan and other countries

(1) Under the global trend of setting carbon neutral goals, carbon pricing policy as one of the measures for decarbonizing has been actively discussed in Japan.

(2) The Japanese government has vowed to utilize a carbon pricing system that would contribute to economic growth. In addition, as the financial sector, consumers and other various climate change stakeholders increasingly urge companies to implement decarbonization initiatives, the industry sector (Japan Business Federation) has become more positive than earlier about a cap-and-trade emissions trading system as one of the promising policy options.

(3) The Ministry of Economy, Trade and Industry is preparing for launching a Green Transformation League in FY2023 to encourage companies to implement ambitious decarbonizing targets. This scheme is also planning to introduce a voluntary emissions trading system that would support the companies' actions and investments. A total of 440 companies have endorsed the GX League initiative, covering about 38% of total carbon emissions in industrial, commercial and energy conversion sectors.

2. Issues to note for considering a carbon pricing system

(4) The government should address the following issues in designing a “growth-oriented carbon pricing system” to simultaneously achieve energy security, economic growth and carbon neutrality:

(5) Japanese energy prices: Energy prices in Japan are higher than in other major developed countries and far higher than in other Asia-Pacific countries which account for about 80% of Japan’s trading partners.

(6) Carbon leakage: Higher price may cause an adverse effect on international competitiveness. For example, Japan's heavy industries will face the risk of industrial hollowing out due to high energy prices. Furthermore, if Japan's energy-efficient industries leak to less energy-efficient regions, global greenhouse gas emissions will increase. Given that a carbon pricing system influences the industrial structure, the government is required to clarify which industry should be protected as a Japanese industrial strategy.

(7) Regressivity: Energy is indispensable goods of our life and industrial activities. Thus, energy price hikes exert a greater burden on low-income and aged households, small and medium sized companies and energy-intensive heavy industries.

(8) Emission reduction effects: Among consumption goods, energy features the lowest price elasticity, indicating that any emission reduction effect of price hikes will be limited particularly in a short term. In addition, if no alternative fuels exist, consumers’ burden may increase while failing to contribute to emission abatement. Moreover, how much energy price hikes can be passed on to wholesale prices may vary depending on the supply chain structure.

(9) Implicit carbon pricing: Japan has already implemented various actions on several stages of energy use, such as the Act on the Rational Use of Energy, the Act on the Promotion of Use of Non-fossil Energy Sources and Effective Use of Fossil Energy Materials by Energy Suppliers, energy taxes and other measures. These overlapping policies are one of the causes of rising energy prices. Therefore, the review of these existing measures and the identification of their interactions with a carbon pricing system is indispensable for designing an efficient carbon pricing system.

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[*] Senior Researcher, Climate Change Group, Climate Change and Energy Efficiency Unit, IEEJ

(10) International initiatives: How to secure compatibility with other international initiatives such as EU carbon border adjustment is essential for the strategic designing of a Japanese domestic carbon pricing system.

3. Realities of forerunning foreign carbon pricing systems

(11) Emissions trading systems have already been implemented in European Union, South Korea, and other countries. These prior schemes, however, have demonstrated difficulty to ensure fairness in determining emission targets or free allocation to the covered companies. In addition, emissions allowance prices have been fairly affected and fluctuated by not only demand fundamentals but also speculations, nature climate, and other factors. These problems have led to government-controlled markets where regulatory authorities conduct ex-post facto control on quotas. These frequent rule changes have affected the predictability of the systems and impeded incentives for early emission cuts and investment.

(12) Carbon taxes have been introduced in European and other countries. In some countries, carbon pricing schemes have been combined with policy measures for reducing tax burdens or subsidizing alternative technologies. However, it turned out that it was difficult for taxation or price effects alone to secure efficient emission cuts. Furthermore, carbon taxes may lead to energy cost hikes and are less acceptable to citizens. Therefore, generally, carbon taxes have been imposed where cost hikes are avoided in sectors suitable for such taxes.

4. Towards a growth-oriented carbon pricing system

(13) Experience to date on institutional designs and operations of forerunning carbon pricing systems has indicated the following challenges. First, massive institutional and administrative costs accompany institutional designing and operations. Second, administrative capabilities are closely linked to the stability of a carbon pricing system. Third, actual system operations deviate from neoclassical economic theories. Given these issues, considerable determination is required to introduce any carbon pricing systems in Japan. Based on such determination, the following three perspectives are important for designing a “growth-oriented carbon pricing system” for Japan.

(14) The first perspective is to maximize emission cuts at minimum cost. As optimum policy approaches differ depending on emission reduction options, target sectors, and timings, priority targets and industries to be supported must be clarified. Then, costs and benefits of existing multi-layered existing policies must be verified for the potential consolidation and integration of specific measures.

(15) The second perspective is to design a carbon pricing system that would lead Japanese companies in expanding their markets or business operations worldwide. Given that contributions to overseas’ reduction where there is a large amount of cheaper emission reduction potential will enable them to lessen cost of mitigation. Simultaneously, a mechanism to quickly obtain cheap but high quality emission credits must be incorporated into the system. In this respect, cooperation with other Asia-Pacific countries becomes even more critical.

(16) The third perspective is to secure a fair transition. Ensuring alternative measures is indispensable for a cost-effective and steady transition. Given that energy prices in Japan are much higher than in other Asia-Pacific countries, measures to reduce costs must be implemented. Any carbon pricing system would impose additional burdens on citizens over the short term. Therefore, it is indispensable to have a transparent dialogue with the public in order to promote citizens’ understanding and to increase the social acceptability of any carbon pricing system.

Challenges to Increase Renewable Energy under Resources Price Spikes <Summary>◆

Yasushi Ninomiya*

Under the resources price spikes, renewables maintain the advantage over fossil power generation despite cost hikes

1. Manufacturing and transportation costs for renewable power generation facilities have risen due to resources price spikes since 2021. Solar PV and wind power generation costs entered into an uptrend for the first time after continuing to decline over more than 10 years. As the Ukraine crisis has added fuel to cost hikes, power generation facility installation costs in 2022 are projected to increase by around 15 % for solar PV and by around 20% for onshore wind.
2. At the same time, resources price spikes associated with the Ukraine crisis have led fossil power generation costs to increase substantially. Solar PV and wind power generation cost hikes have been less than those for fossil power generation, maintaining a cost advantage over fossil power generation.

Global renewable power generation capacity to post record growth in 2022

3. Growth in global renewable energy power generation capacity increased from 270 GW (including 130 GW in solar PV and 110 GW in wind) in 2020 to a new high of 280 GW (including 150 GW in solar PV and 95 GW in wind) in 2021. As renewable power generation capacity continues to expand even amid resources price spikes and the Ukraine crisis, capacity growth is likely to surpass 300 GW (including 180 GW in solar PV and 90 GW in wind power generation). From 2022 and on, the annual growth of 300 GW in renewable energy power generation capacity is likely to become a baseline.

Solar PV to continuously cover 60% of global renewable capacity growth

4. Solar PV accounts for a dominant share of annual growth in renewable energy power generation capacity. Solar PV's advantages, including cost competitiveness, high versatility and easy maintenance, will remain unchanged even under resources price spikes. Therefore, solar PV will continue to account for some 60% of growth in renewable energy power generation capacity in 2022 and 2023. As well as solar PV capacity, offshore wind power generation capacity is posting a year-on-year increase of more than 20%.
5. China rapidly increased its offshore wind power generation capacity in 2021 to 26 GW, the highest national level in the world. Europe as a whole was the largest offshore wind power generation market in 2021, commanding 28 GW, including 13 GW for the United Kingdom, 8 GW for Germany, 2 GW for the Netherlands and 2 GW for Denmark. From 2022 and on, China will thus drive global market growth for offshore wind power generation, as well as solar PV and onshore wind.
6. Renewable energy's share of global power generation has expanded at an annual pace of 1 percentage point and is expected to reach around 29% in 2022, including 15 % for hydro, 4 % for solar PV and 7 % for wind.

Japan's renewable generation capacity growth decelerates while ensuring power grid flexibility becomes an urgent challenge

7. In Japan, growth in renewable power generation capacity has been decelerating remarkably since 2021 due to a gradual transition of public support scheme from the Feed-in Tariff to the Feed-in-Premium, a decline of tariff rates for the existing feed-in tariff, a decrease in suitable lands for large scale solar PV and local residents' opposition to

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[*] Senior Researcher, Manager, Renewable Energy Group, Electric Power Industry & New and Renewable Energy Unit, IEEJ

renewable energy development. Therefore, the government needs to enhance policy measures to achieve the renewable target for 2030.

8. While renewable power generation capacity grows in Japan, ensuring power grid flexibility to accommodate a massive volume of variable renewable energy (VRE) has become an urgent challenge. A range of measures from short- to long-term are required to apply. Immediate short-term measures are almost limited to demand side energy management (DSM) through demand response (DR) and virtual power plant (VPP). Among medium-term measures are securement of dispatchable power plants, deployment of storage batteries and improvement of grid operations. Long-term measures can be enhancement/reinforcement of grid capacity and grid connection, possibly including innovative technologies such as P2G to produce hydrogen from surplus renewable electricity. These various measures represent additional costs accompanying VRE expansion.

Need for diversifying renewables supply chains and securing stable rare mineral supply

9. The Ukraine crisis has demonstrated the national security risk of depending heavily on certain countries for energy supply. Regarding renewable energy, concern has grown about China's dominance of the global solar PV supply chain. Diversification of the solar PV supply chains is globally viewed as indispensable for energy security. Interest is also growing in reusing and recycling massive used solar PV modules and other waste equipment for renewables in the future.
10. Solar PV and wind power generation equipment depend more on rare mineral resources than fossil power generation. Initiatives to reduce such dependence will be required along with global cooperation arrangements for a stable supply of rare minerals.

Latest Nuclear Energy Situations in Japan and Other Countries <Summary> ◆

Kenji Kimura*

Nuclear energy situation

1. As of January 1, 2022, global nuclear power generation capacity totaled about 407 gigawatts, slightly less than a year earlier. A capacity decline in Europe and the United States outdid an increase in China and other countries.
2. As countries have set ambitious greenhouse gas emission reduction goals in recent years, nuclear energy has attracted attention as a zero-emission baseload electricity source. Since 2021, global fossil fuel price spikes have led countries in the world to give priority to stable energy supply.
3. Furthermore, Russia's invasion into Ukraine in February 2022 prompted countries in the world to recognize the significance of energy self-sufficiency anew and take a new look at the importance of nuclear energy utilization.

European and U.S situations

4. The U.S. Biden administration has indicated its attitude of giving priority to nuclear energy. In April 2022, the federal government began to receive applications for the Civilian Nuclear Credit Program to support existing nuclear reactors on the brink of being shut down for economic reasons. The government has proactively supported the development of new nuclear reactors including small modular reactors.
5. In response to the Ukraine crisis, the United Kingdom has announced a new energy strategy including a plan to build up to eight new nuclear reactors by 2030. Under a new nuclear power generation support system, its government has indicated a plan to apply the Regulatory Asset Base model to a project to construct a Sizewell C reactor. In advanced reactor development, it plans to focus on a high temperature gas-cooled reactor. At the same time, a consortium including Rolls-Royce is developing a light-water small modular reactor.
6. In France, President Emmanuel Macron in February announced an energy policy to reach carbon neutrality by 2050. He vowed to prolong the service life of existing nuclear reactors, construct six (with an option for another eight) new version of European pressurized water reactors by 2050 and build small modular reactors.
7. The Czech Republic and Romania are planning to expand nuclear energy utilization. Poland is trying to introduce nuclear power generation.
8. The European Union is discussing a plan to include nuclear energy and natural gas into the taxonomy system to certify sustainable economic activities. In July 2022, the European Parliament approved the plan.
9. In Canada, provincial governments and electric power utilities have indicated their high interest in small modular reactors. In December 2021, Ontario Power Generation named GE Hitachi Nuclear Energy as its technology partner for small modular reactor construction in Darlington.

Japanese situation

10. In Japan, a warning about a tighter electricity supply-demand balance was issued on March 22 for the first time ever. The balance tightened in late June as well. An even tighter balance is predicted for the coming winter. Prime Minister Fumio Kishida indicated that up to nine nuclear reactors would be in operation.
11. Latest government policy statements pointed out the importance of nuclear energy anew and emphasized priority given to the early restart of existing reactors and the development of new reactors. Government and industry sector initiatives regarding nuclear energy after July's House of Councillors election will attract attention.

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[*] Senior Researcher, Nuclear Group, Strategy Research Unit, IEEJ

Chinese and Russian Situations

12. China and Russia account for a large share of nuclear reactors under construction and planning, indicating their dominance in the current nuclear reactor market. Particularly, Russia boasts a low unit construction cost for nuclear reactors. Its state-run Rosatom provides integrated nuclear plant services covering construction, operation and fuel supply.
13. China and Russia are proactively developing fourth generation and small nuclear reactors and introducing some of such new reactors. China is constructing two CFR-600 demonstration fast reactors. In December 2021, it connected the HTR-PM demonstration high temperature gas-cooled reactor to the grid. China is also building the ACP100, also known as the Linglong One, demonstration light-water small modular reactor.
14. Russia is operating two fast reactors (BN-600 and BN-800) and is planning a larger fast reactor named BN-1200. In May 2020, a floating nuclear power plant named Akademik Lomonosov started commercial operation in Pevek, the Far East. It is also planning to construct the RITM-200N ground-installed small modular reactor.

Russia's invasion into Ukraine and reactions from other countries

15. In response to Russia's invasion into Ukraine from February 2022, some countries have been moving to break away from their dependence on Russia in the nuclear energy field. Ukraine has agreed with Westinghouse of the United States to construct a total of nine AP1000 reactors.
16. On the other hand, Russian nuclear reactor construction has continued in China, Turkey, Bangladesh, Hungary and so on. We must closely watch how moves to break away from dependence on Russia in the nuclear energy field will develop.

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Modeling Potential Installation of Solar and Wind Energy Considering Cannibalization Effect◆

Hideaki Obane* Seiya Endo* Yuji Matsuo** Toru Genkai*** Yoshiteru Nagao***

Abstract

Increasing variable renewable energies with zero marginal cost cause the decline of wholesale electricity prices and undermine their own value by “cannibalization effect”. While capital costs of renewable energies are expected to decline, their income is also to decrease because of declined wholesale electricity prices. This study integrated GIS (geographic information system) model that assesses business feasibility into an optimal power generation mix model that assess wholesale electricity prices. By developing an integrated model, it is possible to assess potential installation capacity of solar and wind energy by considering both economic rationality and land use restrictions. In the case of Japan, this study revealed that increasing solar and wind energies cause the significant decline of wholesale electricity prices in specific electric network area such as Hokkaido. Even if capital costs of these energies decrease through learning effect, economic potential of installed renewable capacities is significantly limited if business feasibility is considered. Thus, the decline of electricity prices by cannibalization effect can seriously stagnate installation of both solar and wind energies. This study implies that further cost reduction faster than previous trend is needed to realize “subsidy-free” energy sources.

Key words: Renewable energy, Solar energy, Wind energy, Energy model, Cannibalization effect

1. Introduction

Photovoltaic systems (PV systems) and wind energy systems are expected to a large-scale reduction of greenhouse gases. When examining future measures for the utilization of PV and wind energy systems, it is important to assess the installation potential of each system after considering such factors as economic rationality and land use restrictions.

Up to now, the Feed-in Tariff (FIT) has been introduced in Japan in July 2012. From April 2022, it will shift to Feed-in Premium (FIP), which adds a certain premium to wholesale electricity prices. Accordingly, the business potential of PV and wind energy systems in the future will be influenced by wholesale electricity prices that fluctuate depending on time and power generation mix.

On the other hand, previous studies[1)-4)] have shown that when large-scale PV and wind energy systems are installed occurs the “cannibalism effect”, that the more power is generated by these systems, the lower the wholesale electricity price is during the time zone and the value of its own kWh. In the initial stage of the introduction of PV systems, it contributes a certain amount to reduce power demand peak and has the effect of reducing fuel costs such as gas-fired power generation with high fuel cost. However, as PV systems significantly increase, it replaces coal-fired power generation where fuel costs are low; thus, the effect of reducing fuel costs becomes smaller. Therefore, in order to assess the installation potential of PV and wind energy systems considering economic rationality over the long term toward 2050, it is important to consider the impacts of this “cannibalism effect.”

Previously, there have been a number of studies that assess the economic potential of PV and wind energy systems considering economic rationality[5)-8)]. As an example, in a study in the United States[5)], the economic potential at each point is assessed from the difference between the levelized cost of electricity (LCOE) of each power supply and the levelized avoided cost of electricity (LACE) by using geographic information (GIS) system. In addition, the research of MacDougall et al.[9)] assesses the internal rate of return (IRR) according to the level of policy support by using GIS.

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* The Energy Data and Modelling Center, The Institute of Energy Economics, Japan
** College of Asia Pacific Studies, Ritsumeikan Asia Pacific University
*** JERA

In Japan, several studies have assessed the economic rationality of renewable energy under the scenario of a certain selling price for a specific year[10)-12)]. For example, a report by the Japanese Ministry of the Environment[10)] assessed the economic potential of renewable energy using the premise that generated electricity is sold at a fixed price by FIT. Additionally, study assessing the potential of PV systems considering the distance from transmission line affecting the initial investment[13)] and study on the economic assessment of the installation of PV systems for residential use under the FIT have also been carried out[14)].

Like this, studies on the assessment of installation potential considering the economic rationality of PV and wind energy systems have been abundantly carried out. However, detailed research considering the influence of the cannibalism effect has not been conducted. In Japan, since the current FIT will shift to sales based on wholesale electricity prices, it is more important to consider the effects of cannibalism in chronological order in assessing the potential installation capacity of each power supply.

Following this fact, in order to solve such problems, this study aims to examine the potential assessment model of PV and wind energy systems considering the cannibalism effect by integrating the power generation mix model and the GIS model that spatially assess the economic rationality of each location. By using this model, it is possible to reflect the impacts of the wholesale electricity price decrease in the mass introduction of each power supply, and to assess the installation potential of PV and wind energy systems by considering economic rationality more clearly.

2. Potential Assessment Model

2-1. Overview

The potential assessment model proposed in this study is a model that integrates a power generation mix model, which outputs wholesale electricity prices every 8,760 hours using input values such as the amount of introduction of each power supply and the installed capacity, and a GIS model, which spatially assesses the IRR for each 100-500 m grid mesh using the wholesale electricity price and the capital cost of each power supply as input values (Fig. 1).

In this model, when the installed capacity of PV and wind energy systems in a specific year is given as an initial value, the wholesale electricity price for every 8,760 hours is output first by the power generation mix model. Then, the GIS assessment model outputs the installed capacity that satisfies the specified IRR using wholesale electricity prices as input values. The installed capacity obtained by considering a constant introduction rate in this installed capacity is again the input value of the power generation mix model. In this model, by performing the loop calculation every year, it is possible to assess the transition of wholesale electricity prices over the medium to long term and the transition of the installed capacity of PV and wind energy systems that satisfy economic rationality.

As the introduction of PV and wind energy systems progresses, the value of kWh during the time zone when each power supply is generating power decreases due to the cannibalism effect, but when electricity is sold through the wholesale electricity market, the IRR by the power generation business of each power supply contributes toward the decrease. On the other hand, if the capital cost decreases due to the learning effect of the power generation facility, it will contribute to the increase of IRR. In this model, considering these mutual effects, it is possible to assess the effect of the large-scale introduction of each power supply more clearly.

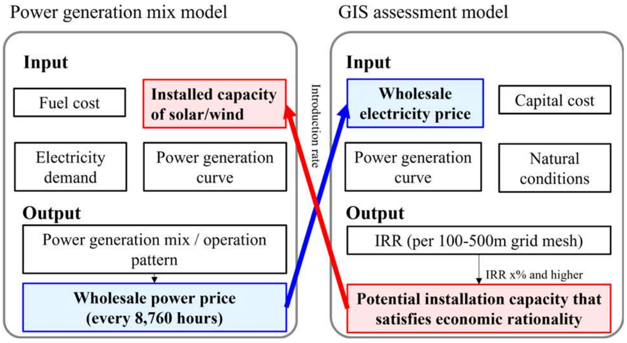


Fig. 1 Overview of Potential Assessment Model

2-2. Power Generation Mix Model

The power generation mix model used in this study was originally developed by the FUJII-KOMIYAMA Laboratory[15] and improved by Komiyama et al. (2014)[16], Komiyama et al. (2017)[17], Matsuo et al. (2018)[18], Nagatomi et al.[19], and Matsuo et al. (2020)[20]. This model outputs wholesale electricity prices and operation patterns of each power supply every 8,760 hours when the sum of capital cost and variable cost of the entire power system is minimized using the input value such as the installed capacity and fuel cost of each power generation facility. The objective function is obtained by equation (1).

$$min.TC = \sum_{i} \left(g_i \cdot pf_i \cdot K_i + \sum_{d,t} pv_i \cdot X_{i,d,t} \right) + \sum_{j} CS_j \tag{1}$$

$$\begin{aligned} CS_j = gs1_j \cdot pfs1_j \cdot KS1_j + gs2_j \cdot pfs2_j \cdot KS2_j \\ + pfs3_j \frac{TCha_j}{cycle_j} \end{aligned} \tag{2}$$

$$TCha_j = \sum_{d,t} Cha_{j,d,t} \tag{3}$$

Where, g_i: annual fixed cost factor of generator *i*, initial investment cost of generator i pf_i, K_i: generator *i* rated output [GW], generator *i* variable cost pv_i, $X_{i,d,t}$: generator *i* day *d*, output in time *t* [GW], $gs1_j$: fixed cost factor per output of storage battery *j*, $pfs1_j$: initial investment cost per output of storage battery *j* [JPY/GWh], $Ks1_j$: Rated output of storage [GW], *gs2*: fixed cost coefficient per storage capacity of storage battery *j*, $pfs2_j$: initial investment cost per storage capacity of storage battery *j* [JPY/GWh], $Ks2_j$: Rated storage capacity [GWh], $pfs3_j$: external cost associated with deterioration of storage battery [JPY], *cycle*: maximum number of charging and discharging of storage batteries, *Cha*: power charged to storage batteries [GW].

As constraints, power supply and demand constraints at each time, spare power constraints, and balance constraints of energy storage facilities are given. This study describe a linear planning problem by pyomo, a library of Python, and obtained a solution by operating Xpress, which is a solver.

The target areas of the power generation mix model were the 10 areas of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa, which are under the authority of general transmission and distribution business operators. Each area is connected by interconnection lines, and it is assumed that the interconnection lines are enhanced based on "power supply uneven distribution scenario (30 GW) of the Organization for Cross-regional Coordination of Transmission Operators (OCCTO)[21]. In addition, the wholesale electricity price in each area was treated as a shadow price of the supply-demand balance constraint type of each area obtained as the optimal solution of the dual problem. Although there is no wholesale electricity market in the Okinawa area, it was treated as electricity sales based on the potential price.

The power generation amount of PV and wind energy systems was calculated in advance using a normalized power generation pattern based on the data of the regional meteorological observation system (AMeDAS) in each area and a value of 8,760 hours based on the installed capacity for each area. In practice, while the power generation pattern of each power supply changes gradually by the installation of power generation facilities in various places, the power generation pattern is constant in this model for simplicity.

2-3 GIS Assessment Model

The GIS assessment model outputs the IRR for each mesh by inputting capital cost of power generation facilities and wholesale electricity price based on mesh information related to land use and sea area use. By applying a certain lower limit to this IRR, the installed capacity of the power generation facility which satisfies economic rationality is obtained. In this model, as in previous studies24)-26), the territory of Japan was divided into 100 m mesh and the territorial waters of Japan were divided into 500 m grid mesh using ArcGIS, and various data related to land and sea area use were stored in each mesh. Based on this developed data, this study extracted the places where PV and wind energy systems can be physically installed in advance, and calculated the IRR at each point from data such as sunlight and wind speed.

IRR is given by r in equation (4) and is determined by the initial investment amount CI [JPY] and annual cash flow CF_t [JPY]. The initial investment is mainly equivalent to the capital cost of the power generation facility in the year installed. In addition, the cash flow is determined by the sales revenue dependent on the power generation amount E_i [kWh] and the wholesale electricity price W_i [JPY /kWh], the premium FIT price which is the difference between FIP_{base} [JPY/kWh] and the FIP reference price FIP_{ref} [JPY/kWh], and the annual maintenance cost OM [JPY/kWh], and is shown in equation (5).

$$\sum_{t=1}^{30} \frac{CF_t}{(1+r)^t} - CI = 0 \qquad (4)$$

$$CF_t = \sum_{i=1}^{8760} \left(E_i \cdot W_i + E_i \left(FIP_{base} - FIP_{ref} \right) \right) - OM \qquad (5)$$

3. Assumptions

3-1. Target years and Power Sources

The forecast of cumulative introduction of PV and wind energy systems by 2030 was indicated at the Basic Policy Subcommittee (April 13, 2020)22), based on the lead time of construction and the implementation status of environmental assessments. Therefore, in this study, 2030 was the starting point of the assessment, and the target period of this assessment spanned until 2050.

In this study, the three types of power supplies were ground-based PV systems, onshore wind energy systems, and offshore wind energy systems. Since it is considered that the introduction incentives for building-based PV systems are considered to affect the introduction incentives such as self-consumption and mandatory installation of PV systems, this study excludes their assessment.

Referencing the installation capacity forecast indicated by the Basic Policy Subcommittee22), the initial value of the installation capacity of each power supply in 2030 was 41.6 GW for ground-based solar power, 15.3 GW for onshore wind power, 3.7 GW of fixed-type offshore wind power, 0.02 GW for floating offshore wind power, 19.3 for building-based solar power (detached houses) and 26.7 GW for building-based solar power (non-detached houses). The amount of introduction by grid area in 2030 was estimated by estimating the installed capacity certified by FIT as of June 2021 and the equipment capacity of the project in which the environmental assessment consideration and method documents were submitted by grid area and prorated from the total introduction volume forecast for all areas in 2030 (Fig. 2).

For building-based PV systems, the installation capacity is assumed to be advanced by self-consumption and mandatory installation of PV systems, and the installation capacity was given exogenically in the model. In this study, referencing the "social acceptability-oriented scenario" of the Central Research Institute of Electric Power Industry23), the cumulative installation capacity in 2050 reached 45 GW of PV systems installed in detached houses and 62 GW of PV systems installed in non-detached houses.

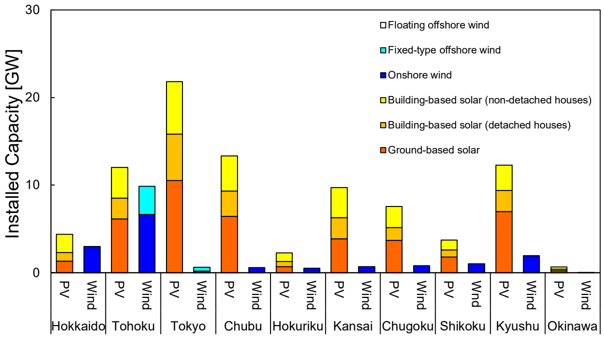


Fig. 2 Assumption of installed capacity by grid Area in 2030 [GW]

3-2. Correlation between Natural Conditions and Installed Capacity

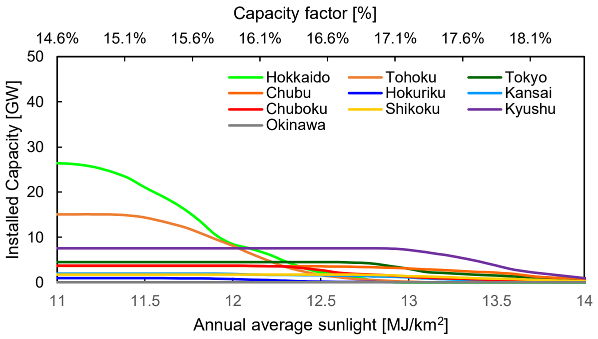
Referencing bane et al.[24), 25)], the site of ground-based PV systems and onshore wind energy systems were installed in places excluding natural parks, natural environmental conservation areas, and bird and animal sanctuaries (normal and special protection) among the four types of land categories: grassland, shinochi (bamboo grove), bare land, and difficult-to-regenerate degraded farmland, taking into account the land use competition and natural environment effects of each power source. Based on this approach, the Japanese contiguous land was divided into 100 m grid meshes, and the available area was estimated to be 3,321 km^2 when the in available area was extracted using the latest GIS data obtained as of April 2021. In addition, since it is assumed that land use competition will occur between ground-based PV systems and onshore wind power system when large-scale introduction of PV and wind energy systems is assumed, ground-based PV systems will be installed at a place with an average wind speed of less than 5.0 m/s per year (980 km^2) and onshore wind power at a location with an average wind speed of 5.0 m/s or more (2,341 km^2). In these places, up to 65.7 GW of ground-based PV systems and 23.4 GW of onshore wind power were assumed able to be installed.

Referencing the Moderate conflict scenario of Obane et al.[26)] considering legal restrictions and social acceptability, the site of offshore wind power was assumed to be 5.0 - 22.2 km (in territorial waters), among sea areas that meet the designated requirements of "promotion zone" stipulated by the Act of Promoting Utilization of Sea Areas in Development of Power Generation Facilities Using Maritime Renewable Energy Resources where the traffic volume of ships equipped with automatic ship identification system is less than 21 ships/month, and sea areas that satisfy all the sea areas where fishery rights are not set. Following the study, when the sea area was extracted using the latest GIS data as of April 2021, the area was estimated to be 28,865 km^2. Of these, if fixed-type offshore wind power is installed in sea areas (5,137 km^2) with a depth of less than 60 m and floating offshore wind power in sea areas from 60 m to less than 200 m (23,728 km^2), the maximum installed capacity of fixed-type offshore wind power would be 30.8 GW and floating offshore wind force 142.3 GW.

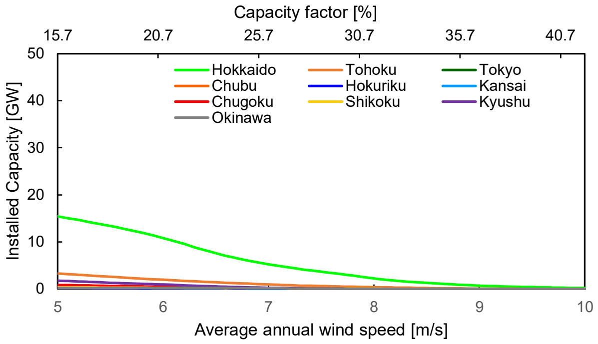
Fig. 3 shows the relationship between natural conditions and equipment capacity in each power area based on the above assumptions. The facility utilization rate is simply converted from the average annual wind speed and the average annual sunlight, as in each study[24)-26)], and it is assumed that overloading is performed for ground-based PV systems.

From Fig. 3(A) and (B), the available of ground-based PV systems and onshore wind power is mainly concentrated in the Hokkaido area. Since the wind conditions in the Hokkaido area are also better than the other areas, onshore wind power will be introduced preferentially with the decrease in capital costs of power generation facilities. On the other hand, since the irradiance in the Hokkaido area is lower than the other areas, ground-based PV systems will be introduced later when compared with other areas.

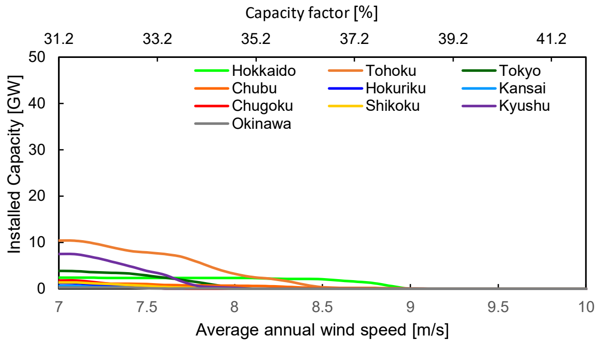
For fixed-type offshore wind and floating offshore wind power shown in Figures 3(C) and (D), there are many installation sites in Tohoku and Kyushu area. In particular, since the wind conditions are better in Tohoku, offshore wind power will be introduced preferentially.



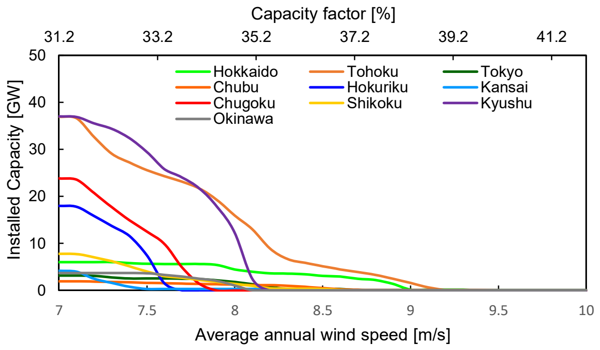
(A) Ground-based PV systems



(B) Onshore wind power



(C) Fixed-type offshore wind power



(D) Floating offshore wind power

Fig. 3 Correlation between Natural Conditions and Installed Capacity

3-3. Assumptions on Capital Costs and Required IRR

Assumptions such as capital costs and necessary IRRs in this study were based on actual or assumed values shown by the Procurement Price Calculation Committee[27)]. Table 1 shows the preconditions related to these assumptions and the transition of capital expenses assumed in Figure 4 until 2050.

The capital cost is the sum of equipment cost, connection cost, and operation maintenance cost (O&M cost), and the equipment cost is assumed to decrease the cost based on the learning curve. In addition, the learning rate applied the value corresponding to the middle of the estimated value range shown in each literature[28)], and the installation capacity used in the estimation of the learning curve was the assumed installation capacity of the entire world until 2050 in the Stated Energy Policies Scenario (STEPS) of IEA WEO 2020[29)].

The actual value of equipment cost in FY2019 is the average value of the equipment for PV systems of 250-500 kW (204,000 JPY/kW) shown by the Procurement Price Calculation Committee, the estimated value of the equipment cost of onshore wind power in the FIT purchase price calculation (269,000 JPY/kW), and the estimated cost of offshore wind energy systems equipment (512,000 JPY/kW) in the “promotion area.” Referencing Stehly et al.[30)] for floating offshore wind power, it was assumed that the capital cost was 1.3 times larger than fixed-type offshore wind power, and the learning rate was the same as the fixed-type offshore wind power. In this study, all prices were treated as real prices in 2019.

The IRR required for each power supply to obtain economic rationality was 5% for ground-based PV systems, 7% for onshore wind power, 10% for fixed-type offshore wind power, and 10% for floating offshore wind power, referring to the Procurement Price Calculation Committee[27)].

Table 1 Assumptions on Capital Cost and Required IRR

	Ground-based solar	Onshore wind	Offshore wind (fixed)	Offshore wind (floating)
Equipment cost (2019) [JPY/kW]	204,000	269,000	512,000	665,600
Connection cost [JPY/kW]	9,100	13,000		
O&M cost [JPY/kW]	4,900	9,300	18,400	18,400
Learning rate (equipment cost)	15%	7%	10%	10%
Required IRR	5%	7%	10%	10%

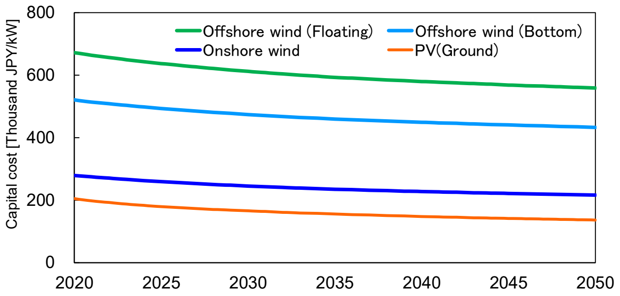


Fig. 4 Assumptions on Capital Cost [Thousand JPY/kW]

3-4. Assumptions on Thermal Power, Nuclear Power and Electricity Demand

The installed capacity of coal-fired power generation and gas-fired power generation in the power generation mix model is based on the capacity of existing equipment remaining in 2050 when operating for 40 years, and the lower limit was coal-fired power at 13.7 GW and gas-fired power generation at 24.7 GW. For nuclear power generation, 30.6 GW is set as a fixed value referring to the technical progress scenario of IEEJ Outlook 2021[31)].

The coal and LNG prices used in thermal power generation referenced STEPS (2040) of IEA WEO 2020[29)], making coal: 77 USD2019/t and LNG: 9 USD2019/MMBtu. CO_2 emissions were considered at carbon prices, and 52 USD2019/t-CO_2 of STEPS (2040) was used.

The annual electricity demand in the power generation mix model was 1,027 TWh, which deducted the loss factor of plant-home use of 3.5% from the amount of power generated in 2030 in the long-term energy supply and demand outlook. Although fuel prices, carbon prices, and electricity demand fluctuate year by year, in this study, these were constant regardless of time, in order to clearly assess the decrease in capital costs of solar and wind energy systems and the decrease in electricity sales revenue due to the decrease in wholesale electricity prices.

3-5. Assumptions on FIP

In Japan, FIP will be introduced to be used to sell electricity generated by renewable energy by increasing the power price by adding a certain premium to the wholesale electricity price. Therefore, in this study, four types of cases were assumed for the FIP premium price determined by the difference between the FIP standard price and the FIP reference price (Table 2).

First, referencing the difference between current FIT purchase price and avoidable cost (assumed to be 8 JPY / kWh) as of 2021, the FIP premium price was 3 JPY /kWh for ground-based PV systems/ kWh, 9 JPY /kWh for onshore wind power, landing type offshore wind force 24 JPY/kWh for fixed-type offshore wind power, and 28 JPY / kWh for floating offshore wind power. This was set as the “(1) current FIT level case.”

Second, these premium prices were set to 2/3 as “(2) 2/3 level case,” and the same price was set to 1/2 in the “(3) 1/2 level case.” In addition, assuming that each power supply will become a “subsidy-free power supply” that does not depend on the subsidy system in the future, the premium price of each power supply was set as 0 JPY / kWh in “(4) case without FIP.”

It should be noted that in Japan, since offshore wind power is in the initial introduction stage, the assumed premium price of offshore wind power is significantly higher than PV systems and onshore wind power.

Table 2 Assumption of FIP Premium Prices (JPY/kWh)

	Ground-based PV	Onshore wind	Fixed-type offshore wind	Floating offshore wind
Current FIT Level	3	9	24	28
2/3 level	2	6	16	18
1/2 level	1.5	4.5	12	14
Without FIP	0	0	0	0

4. Results and discussion

4-1. Single Year Assessment Targeting 2030

Fig. 5 shows the evaluated wholesale electricity price of each power area by the power generation mix model for 2030, the first year of the assessment. Since PV and wind energy systems are variable power sources, weights are given to wholesale electricity prices that fluctuate at each time by the amount of power generated at each hour, and the weighted average wholesale electricity price for one year is calculated.

As the result, it was shown that the weighted average wholesale electricity price tended to be comparatively lower in the Hokkaido area and Kyushu area out of 10 electric grid areas. One of the factors contributing to this is that the ratio of power generation by PV and wind energy systems is high compared to the electricity demand in these power areas. In particular, in the Kyushu area, 13 GW of PV systems will be introduced as of 2030. Hence, the wholesale electricity price in the daytime time zone, when PV systems are generated, will be particularly low.

Then, by inputting the wholesale electricity price of each power area and using the GIS assessment model, the potential installation capacity (hereinafter referred to as the installed capacity that satisfies economic rationality) of the power generation facility that satisfies the specified IRR was assessed for 2030 (Fig. 6). In the figure, the far right bar graph (gray) shows the technical potential determined only by the land use restrictions assumed in Section 3.2, and does not take economic rationality into account. In addition, the bar graph on far left (gray dashed line) shows the installation capacity as of 2030 assumed in Section 3.1. Since the installation capacity as of 2030 includes much equipment introduced under the high FIT price at the beginning of FIT introduction, the installation capacity is more than in the case where the subsidy by FIP is assumed to be the current level.

For ground-based PV systems, if the premium price of FIP is maintained at the current subsidy level of 3 JPY/kWh, the potential installation capacity that satisfies economic rationality will be 6.5 GW. Until now, under the FIT purchase price of 11 JPY/kWh (equivalent to the subsidy level of 3 JPY/kWh), certain PV systems have been certified by FIT auction. However, if the wholesale electricity price decreases in the future, economic rationality will not be obtained in many places except in those where sunlight conditions are enough.

For offshore wind power, on the other hand, when the premium price of FIP is maintained at 24 JPY/kWh (Bottom-fixed) and 28 JPY /kWh (floating), which corresponds to the current subsidy level, the installed capacity that satisfies economic rationality is equal to the maximum installation capacity determined by land use restrictions. However, this is because the supplementary level of FIT in 2020 is set high, and there is no guarantee that the same level will be maintained even after 2030. When the FIP premium price is 12 JPY/kWh (Bottom-fixed) and 14 JPY/kWh (floating), which is half of the current subsidy level, there are few facilities that satisfy economic rationality. Therefore, in order to install offshore wind power without subsidy in Japan, it is necessary to significantly reduce the cost.

In addition, when there is no subsidy in all power supplies, the potential installation capacity that satisfies economic rationality is almost zero under the assumed various conditions. Therefore, this indicates that it is difficult to achieve "subsidy-free" when cost reduction advances based on the learning rate estimated from the previous trends.

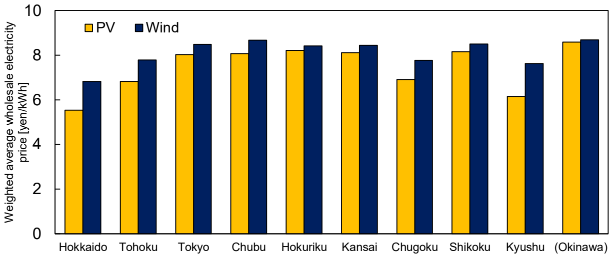


Fig. 5 Weighted Average Wholesale Electricity Price in 2030 (Shadow price for Okinawa area) [JPY/kWh]

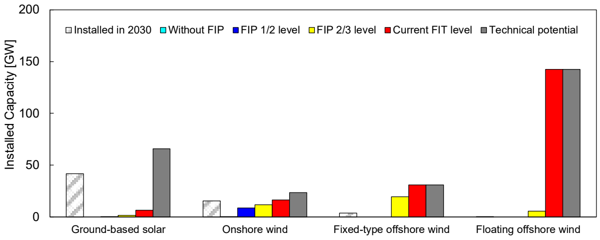


Fig. 6 Potential Installation Capacity that Satisfy Economic Rationality based on FIP Premium Price in 2030 [GW]

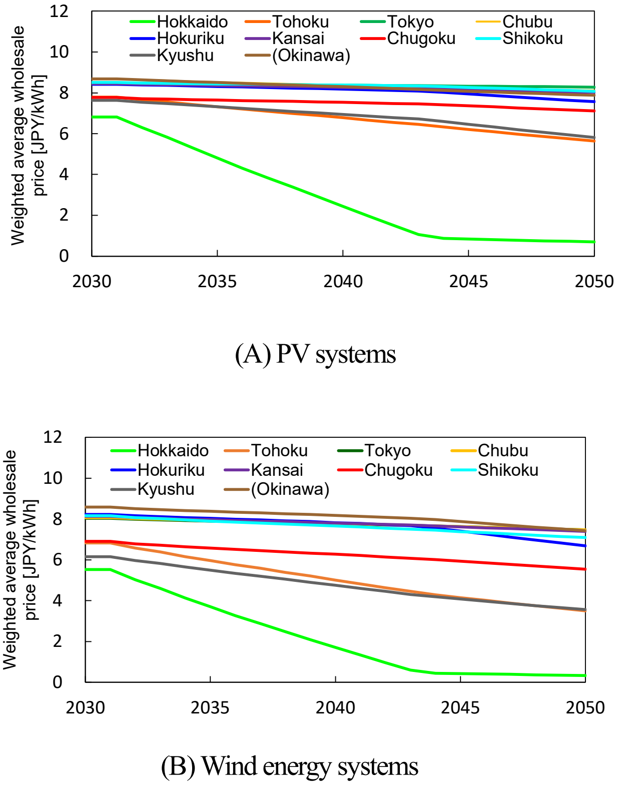
4-2. Time-series Assessment to 2050

The assessment for 2030 showed that it was difficult to introduce PV or wind energy systems without subsidies such as FIP. Therefore, assuming that support by FIP will continue after 2030 for the expansion of PV and wind energy systems, under the assumption that the FIP premium price corresponding to 2/3 of the current subsidy level is set, the transition of the potential installation capacity that satisfies economic rationality by 2050 was assessed. The premium unit price of FIP assumed here is 2 JPY/kWh for ground-based PV systems, 6 JPY/kWh for onshore wind power, 16 JPY/kWh for fixed-type offshore wind power, and 18 JPY/kWh for floating offshore wind power. In particular, it should be noted that a significantly high FIP premium unit price is set here for offshore wind power.

When focusing on onshore wind power, wholesale electricity prices in the Hokkaido area where electricity demand is low gradually decrease because onshore wind power is introduced mainly from the Hokkaido area (Fig. 7 [A]). As a result, the installed capacity of onshore wind and fixed-type offshore wind that satisfies economic rationality also decreases because electricity sales revenue also decreases (Fig. 8 [A]). In other words, under the conditions assumed in this study, economic rationality cannot be obtained after a specific year because the influence of the decrease in electricity sales revenue caused by the decrease in wholesale electricity prices exceeds the decrease in capital costs of onshore wind energy systems. Here, focusing on the relationship between potential installation capacity and cumulative installed capacity in the Hokkaido area (Fig. 9), it has been shown that the introduction of onshore wind power will stagnate after 2035, since the cumulative installation capacity reaches the installed capacity that satisfies economic rationality in 2035.

From the potential installation capacity (Fig. 8 [B]) which satisfies economic rationality nationwide, the capacity of the onshore wind power decreases with the passage of time. As shown earlier, this is mainly due to the decrease in wholesale electricity prices in the Hokkaido area.

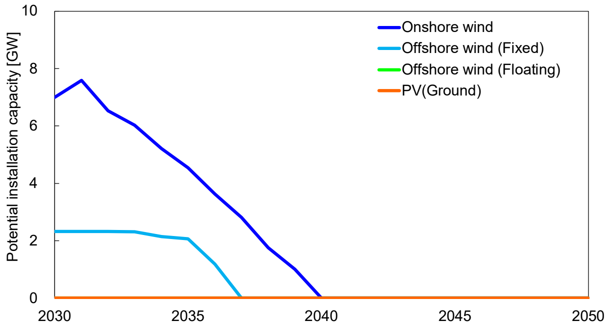
On the other hand, for ground-based PV systems and floating offshore wind power, the installed capacity that satisfies economic rationality tended to increase because the influence of the decrease in capital costs was greater than the decrease in electricity sales revenue due to the decrease in wholesale electricity prices. However, although potential installation capacity will increase due to the decrease in capital costs, the growth of the increase will plateau around 2040. Although The technical potential of ground-based PV systems considering only land use restrictions was 65.7 GW, the potential installation capacity that satisfies economic rationality remains at 14.6 GW in 2050. This is due to the fact that many of the places to be installed ground-based PV systems are in the Hokkaido area where irradiance is poor and wholesale electricity prices are decreasing. Hence, almost all PV systems do not satisfy economic rationality.



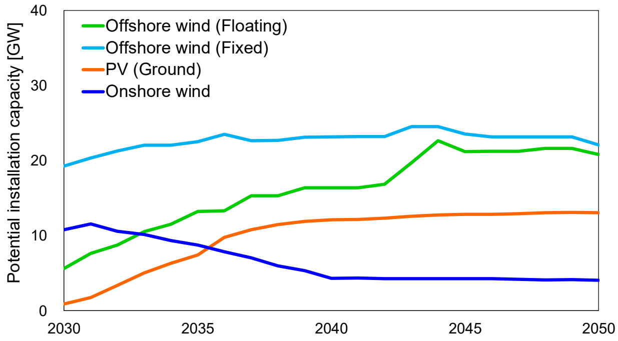
(A) PV systems

(B) Wind energy systems

Fig. 7 Weighted Average Wholesale Electricity Price up to 2050 [GW]
(FIP premium price: 2/3 current level case)



(A) Hokkaido area



(B) Nationwide

Fig. 8 Installed Capacity that Satisfies Economic Rationality [GW] (FIP premium price: 2/3 current subsidy level case)

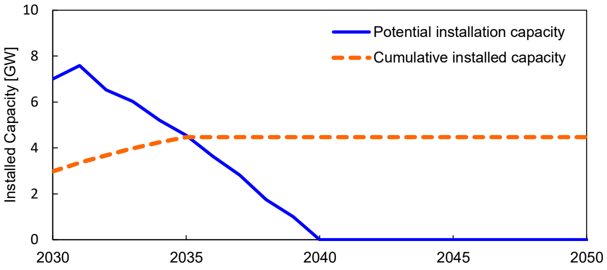


Fig. 9 Correlation of Potential installation capacity and Cumulative Installed capacity of Onshore Wind Power in the Hokkaido Area [GW]

4-3. Single Year Assessment for 2050

Focusing on 2050, the last year of the assessment period, this study assessed potential installation capacity that satisfies economic rationality according to the FIP premium price as in Section 4.1 (Fig. 10).

Focusing on the potential installation capacity of ground-based PV and onshore wind power, the result showed that the potential installation capacity of the case where the same level was raised to 2/3 was slightly lower than the case where the FIP premium price was set to 1/2 of the current level. This is because in the current level of 2/3 cases, the wholesale electricity price decreases due to the priority introduction of offshore wind power, and the electricity sales revenue of ground-based PV systems and onshore wind energy systems decreases. Following this, when a specific power plant is intensively introduced, it may have a large influence on the economic rationality of other power sources.

Focusing on the case without any subsidies for each power supply, even if the capital cost decreases toward 2050, the potential installation capacity that satisfies economic rationality was limited. Here, even if the FIP premium price was raised to 2/3 of the subsidy level of the current FIT, the potential installation capacity did not increase significantly compared with 2030 because the influence of the decrease in electricity sales revenue due to the decrease in wholesale electricity prices is large. Following this, in order to promote the expansion of PV and wind energy systems by 2050, it is necessary to reduce costs at a pace that greatly exceeds the previous learning effect.

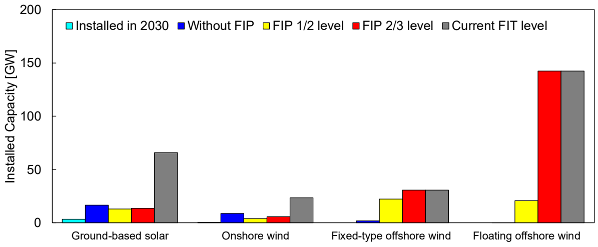


Fig. 10 Potential installation capacity that Satisfy Economic Rationality based on FIP Premium Price in 2050 [GW]

5. Conclusion

This study examined the potential assessment model of PV and wind energy systems considering the cannibalism effect by integrating the power generation mix model and GIS model which spatially assess the economic rationality of each location. As the result, it was shown that the decrease of the wholesale electricity price by the expanded introduction of PV and wind energy systems was assessed in chronological order, and the effect on the economic rationality of each power supply could be quantitatively assessed.

Issues posed by this model include consideration of capital cost of power generation facilities different by geographical factors such as water depth and consideration of the influence of self-consumption. Especially in the case of self-consumption, even during times when wholesale electricity prices are decreasing, the power purchased by retail electricity charges can be offset with power generated by PV or the other systems. Thus, considering the power of this offset, the substantial business income of the power generation business may increase. It is expected that more practical assessments will be carried out on these issues in future improvements.

In the previous model for assessing the economic potential of PV and wind energy systems, the sale of electricity at a fixed price by FIT was assumed. However, when electricity is sold based on wholesale electricity prices in the future, the potential installation capacity that satisfies economic rationality is limited, suggesting the possibility that the introduction may be sluggish. In order for PV and wind energy systems to become subsidy-free power sources, it is necessary to reduce costs at a pace that greatly exceeds the previous learning effects.

The potential assessment model examined in this study is effective for the assessment of the economic rationality of PV and wind energy systems from a medium- to long-term viewpoint, and it is expected to contribute to the examination of the policy making for the expansion of PV and wind energy systems in the future.

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Decarbonization of the Aviation Sector: Current Status, Challenges, and Future Outlook

Masato Yoshida*

Introduction

The aviation sector is known to be one of the "hardest-to-abate" sectors alongside the steel and heavy industries. Governments are taking various actions to decarbonize their industrial sectors in order to achieve their GHG emissions reduction targets. In the international aviation sector, however, efforts have lagged behind due to the complexities of crossing national borders, difficulty of establishing a framework for international collaboration, and the limited options available. In response, efforts to introduce sustainable air fuels have been accelerating worldwide and are receiving much attention. This report summarizes the current situation surrounding sustainable aviation fuels, discusses the challenges for increasing their use, and analyzes the outlook.

1. Current Status of Decarbonization of the Aviation Sector

First, let's consider the current situation of decarbonizing the aviation sector. Fig. 1 below shows the final energy consumption of the world as a whole and the share by sector, and Fig. 2 shows the breakdown of final energy consumption in the transportation sector. The world's final energy consumption was 10 billion tonnes of oil equivalent in 2019, of which the transportation sector accounted for 29%. In this sector, land transport was the largest energy consumer with 74%, while international air transport accounted for 7.1%. In short, **on a global basis, air transport accounts for approximately 2.0% of final energy consumption and thus its impact is relatively small.**

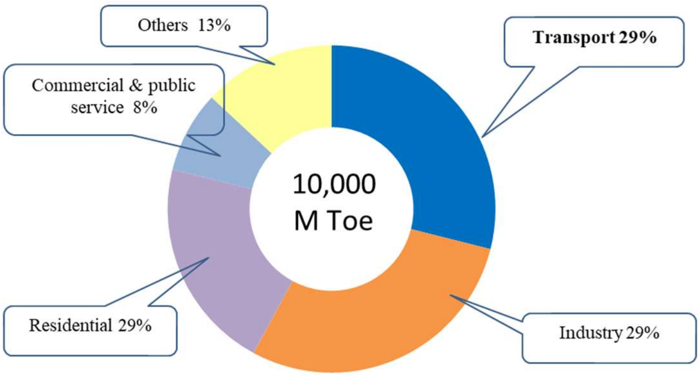

Fig. 1 Final energy consumption by sector (2019)

Source: Prepared by the author based on the IEA World Energy Statistics and Balances (July 2021)

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[*] Senior Researcher, New Energy System Group, Electric Power Industry & New and Renewable Energy Unit, IEEJ

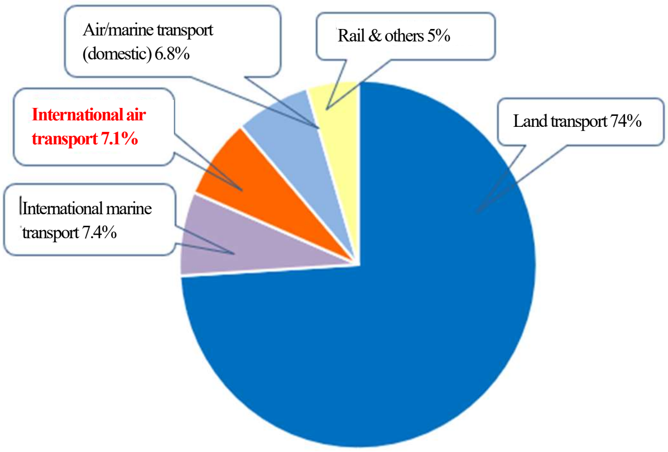

Fig. 2 Breakdown of final energy consumption in the transportation sector (2019)
Source: Prepared by the author based on the IEA World Energy Statistics and Balances (July 2021)

The reason for the increasing attention on decarbonizing the aviation sector, despite its relatively small impact, is the sheer difficulty of reducing its GHG emissions. Fig. 3 below compares the GHG emissions of the European Union (EU) by sector with the EU's target trajectory for GHG emissions reduction (a 95% reduction by 2050). Unlike the significant progress of reducing GHG emissions in the power generation, industry, agriculture, and building sectors, the transportation sector deviates sharply from the ideal path. The chart shows that decarbonizing the transportation sector is difficult even for the EU, which has voluntarily introduced strict guidelines and acted early.

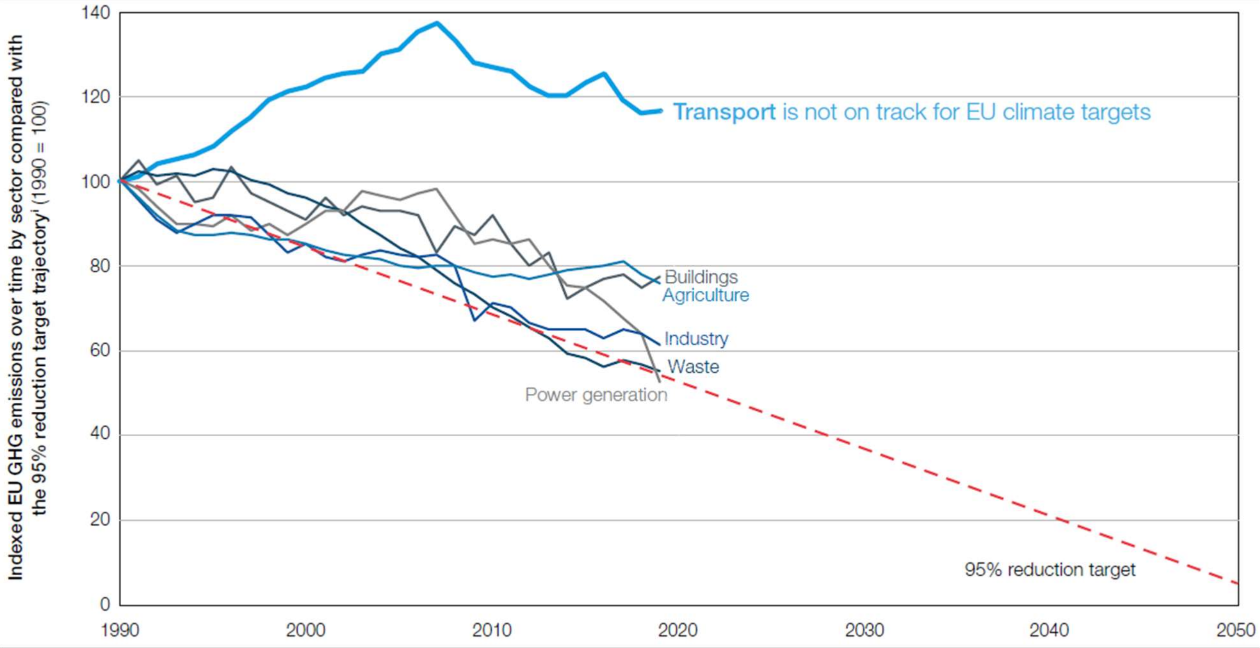

Fig. 3 Changes in the EU's GHG emissions by sector (compared with the 2050 target trajectory; 1990 = 100)
Source: World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation[1] (November 2020)
(Original source: European Federation for Transport and Environment)

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[1] World Economic Forum (in collaboration with McKinsey & Company) (November 2020), *Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation,* World Economic Forum, p.7

As such, European countries are already shifting the focus of their decarbonization efforts to the aviation sector. This has happened mainly because the aviation industry, despite having experienced a temporary pandemic-induced drop in demand, is expected to continue to post high growth in line with global economic growth and thus generate more CO_2 emissions[2] (Fig. 4); the transport sector, including aviation, is considered to be more costly to decarbonize than others[3] despite having a great emissions reduction potential because efforts have been put on the back burner until now (Fig. 5); it is essential to establish an internationally coordinated legislative framework but adjustments will take time; and it will be a long time before innovative technologies to reduce emissions for aircraft, even if developed, are commercialized and start producing effects because passenger aircraft have an extremely long upgrade cycle of around 25 years.

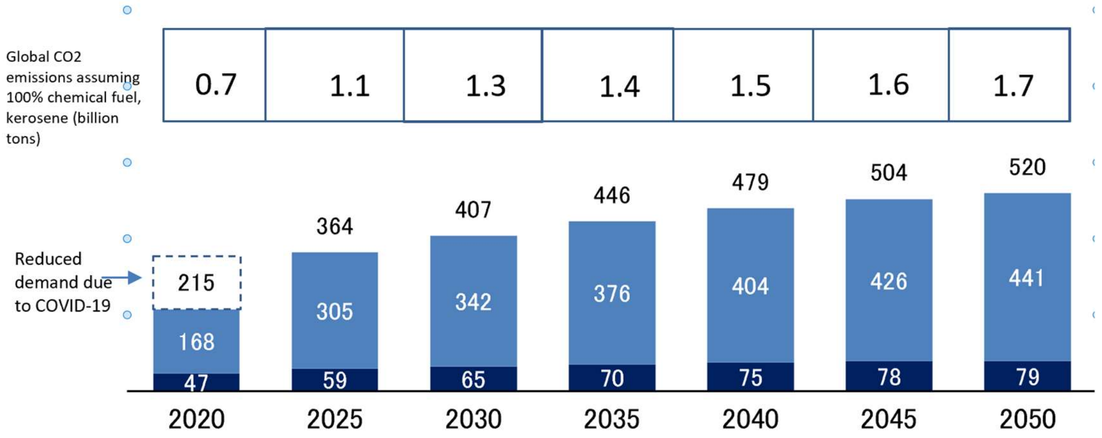

Fig. 4 Outlook for global aviation fuel demand (till 2050; millions of tonnes/year)

Note: Assumed to emit 3.15 ton-CO_2 per tonne of fossil-based kerosene.

Source: Prepared by the author based on World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation[4] (November 2020) (Original source: Energy Insight's Global Energy Perspective, Reference Case A3 October 2020; IATA; ICAO)

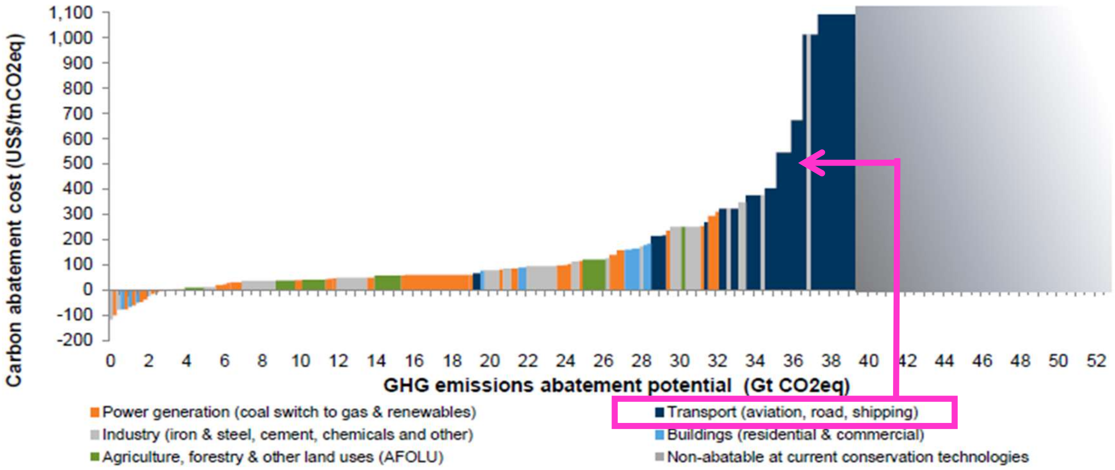

Fig. 5 GHG emissions reduction potential and CO_2 emissions reduction cost (based on currently available technologies)

Source: Goldman Sachs Global Investment Research (December 11, 2019)

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[2] *Ibid*., p.8

[3] The aviation sector has a great emissions reduction potential but is estimated to cost at least five times more to decarbonize than the power generation and agricultural sectors, Goldman Sachs Global Investment Research (December 11, 2019), "Carbonomics: The Future of Energy in the Age of Climate Change," https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-f/report.pdf

[4] World Economic Forum (in collaboration with McKinsey & Company) (November 2020), *Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*, Swiss: World Economic Forum, p.7

The aviation sector is making its own efforts to reduce GHG emissions. While the sector is outside the scope of the Paris Agreement, the member states of the International Civil Aviation Organization (ICAO) have ratified the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and are working toward achieving a path of carbon neutral growth (CNG) in 2020 and beyond (Fig. 6).

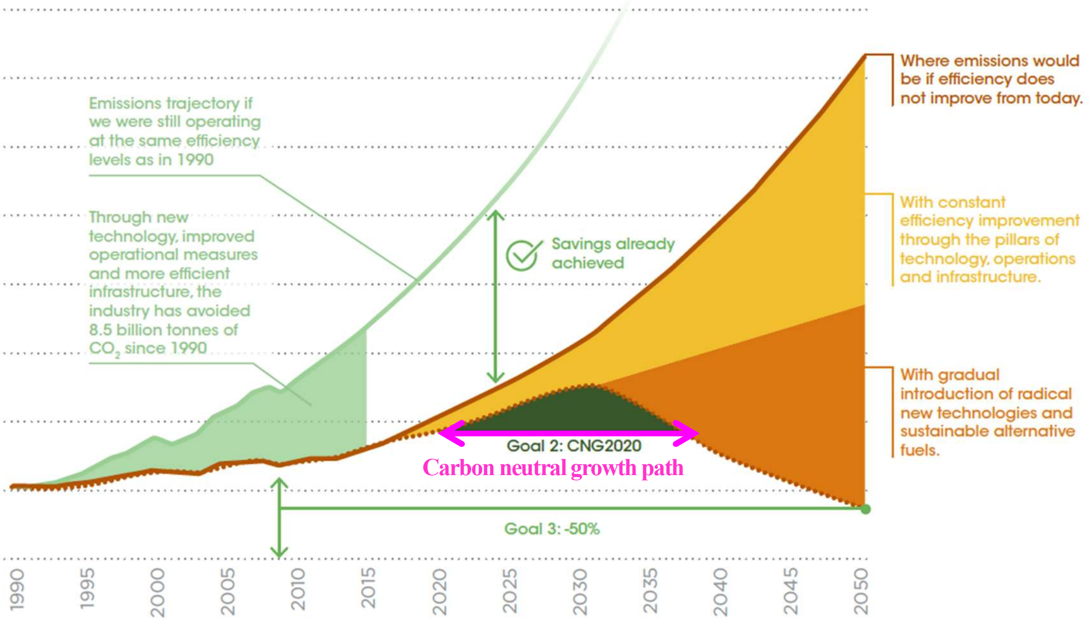

Fig. 6 Roadmap for reducing GHG emissions in the aviation sector

Source: IRENA (July 2021)[5], with information added by the author

Sustainable aviation fuel (SAF) is currently receiving increasing attention as a CORSIA-compliant GHG emissions reduction technology. Fossil fuel-sourced kerosene, or jet fuel which is currently used as aviation fuel, is an excellent fuel in terms of both volumetric energy density and mass energy density (Fig. 7). To decarbonize the aviation sector, it is necessary to replace jet fuel with liquid fuels that have the same properties, or to electrify the power source or adopt fuel cells or hydrogen engines (Fig. 7). However, the latter involves various issues. First, to shift to electricity as the power source, it will be essential to electrify long-haul flights of more than 1,500 km, which account for more than 80% of the GHG emissions of the aviation sector, which will require batteries with an extremely high energy density. However, it is difficult to significantly increase the battery energy density with currently available technologies, and so even if electricity is adopted, it will initially only be used for short- to medium-haul flights (of up to 1,000 km). Hydrogen is considered to be promising for fuel cells and hydrogen direct combustion engines as liquid hydrogen has an extremely high mass energy density of three times that of jet fuel; however, fuel cells that can support flights of over 2,000 km are unlikely to become commercially available until the 2040s. France's Airbus is developing a hydrogen direct combustion engine for aircraft for long-haul flights of over 2,000 km, but its commercial launch is not likely to happen until 2035 at the earliest. Therefore, **for the next 10 to 15 years, SAF is the only realistic option with an energy efficiency equivalent to that of jet fuel (Fig. 8).**

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[5] IRENA (July 2021), *Reaching Zero with Renewables: Biojet Fuels*, Abu Dhabi: International Renewable Energy Agency, p.19

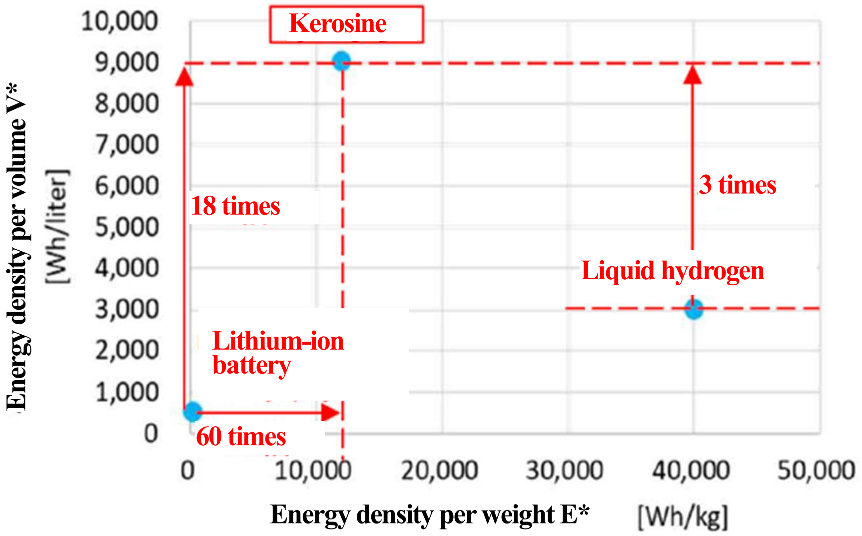
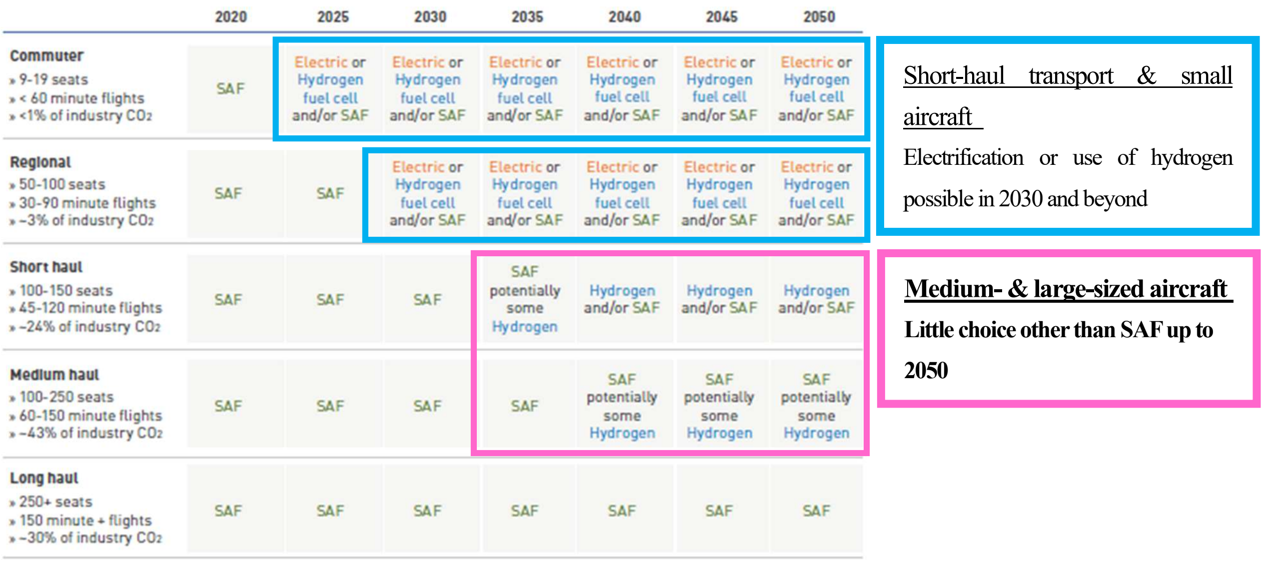


Fig. 7 Comparison of volumetric energy density and mass energy density of aviation fuel

Source: Ministry of Land, Infrastructure and Transport and Tourism (Original source: Electric Flight – Potential and Limitations, Institute of Aerodynamics and Flow Technology, Martin Hepperle, German Aerospace Center)[6]



	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-19 seats » < 60 minute flights » <1% of industry CO_2	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Short-haul transport & small aircraft

Electrification or use of hydrogen possible in 2030 and beyond

Medium- & large-sized aircraft

Little choice other than SAF up to 2050

Fig. 8 Outlook for introducing technologies to decarbonize aircraft

Source: Waypoint 2050 (ATAG, September 2021)[7], with information added by the author

The Air Transport Action Group (ATAG) is considering various scenarios for achieving net-zero emissions in the aviation sector by 2050. As for SAF's contribution to GHG reduction as of 2050, the ATAG estimates that SAF will account for 53% of the reduction under the advanced technology scenario and for 71% under the aggressive SAF deployment scenario (Fig. 9).

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[6] Civil Aviation Bureau, Ministry of Land, Infrastructure, Transport and Tourism (March 22, 2021), First Study Group on Reducing CO_2 in the Aviation Operation Sector

[7] ATAG (September 2021), *Waypoint 2050*, Swiss: Air Transport Action Group, p.54

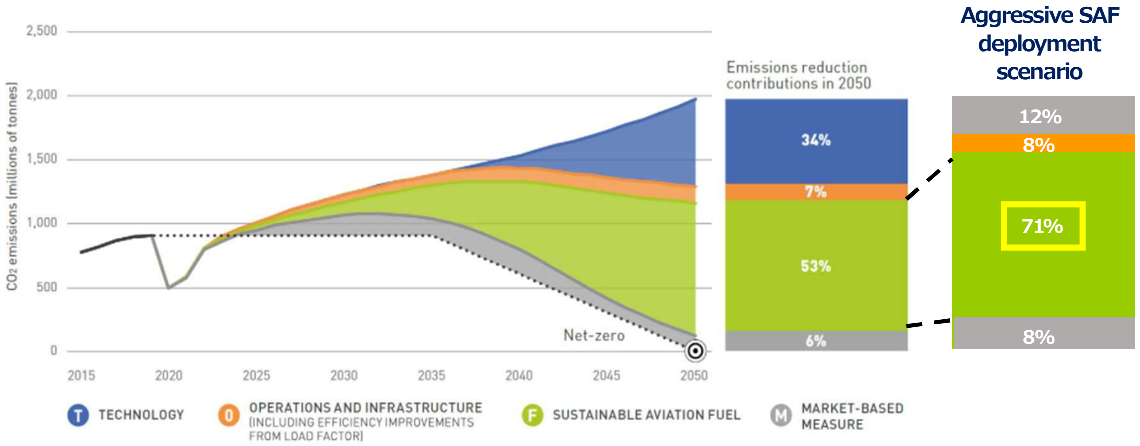
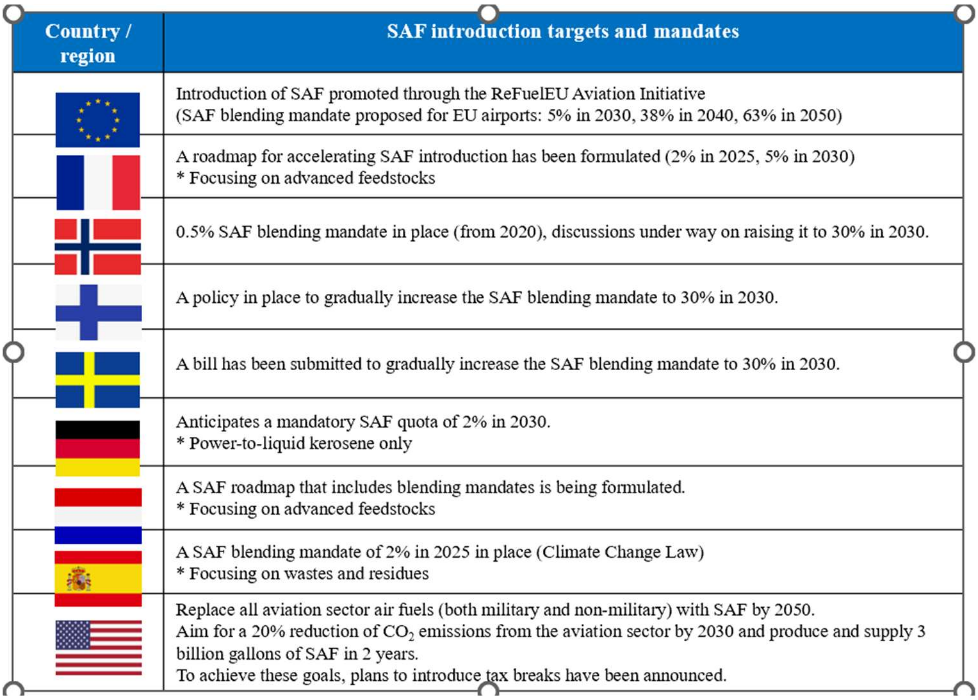


Fig. 9 Roadmap for reducing GHG emissions in the aviation sector

Source: Waypoint 2050 (ATAG), p.26 with information added by the author

European countries and the United States have made a head start and have already set policy goals to accelerate the introduction of SAF (Table 1). Japan is also considering setting a target to supply 10% of aviation fuel demand with SAF by 2030.[8]

Table 1 National and regional government targets for introducing SAF



Country / region	SAF introduction targets and mandates
	Introduction of SAF promoted through the ReFuelEU Aviation Initiative (SAF blending mandate proposed for EU airports: 5% in 2030, 38% in 2040, 63% in 2050)
	A roadmap for accelerating SAF introduction has been formulated (2% in 2025, 5% in 2030) * Focusing on advanced feedstocks
	0.5% SAF blending mandate in place (from 2020), discussions under way on raising it to 30% in 2030.
	A policy in place to gradually increase the SAF blending mandate to 30% in 2030.
	A bill has been submitted to gradually increase the SAF blending mandate to 30% in 2030.
	Anticipates a mandatory SAF quota of 2% in 2030. * Power-to-liquid kerosene only
	A SAF roadmap that includes blending mandates is being formulated. * Focusing on advanced feedstocks
	A SAF blending mandate of 2% in 2025 in place (Climate Change Law) * Focusing on wastes and residues
	Replace all aviation sector air fuels (both military and non-military) with SAF by 2050. Aim for a 20% reduction of CO_2 emissions from the aviation sector by 2030 and produce and supply 3 billion gallons of SAF in 2 years. To achieve these goals, plans to introduce tax breaks have been announced.

Source: Prepared by the author based on the press releases, etc.[9] of various national and regional governments

An overview of decarbonizing the skies has been described so far. The next chapter examines the basic properties, production technologies, and raw materials of SAF, as well as an overview of its current supply and demand and the future outlook.

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[8] The Nikkei (February 15, 2022), "Decarbonize the skies: Government sets target to supply 10% of aviation fuel demand with renewable fuels," https://www.nikkei.com/article/DGXZQOUA089TK0Y2A200C2000000/

[9] Introduction of tax break for the US SAF blending operators: Reuters (April 14, 2022), "Biden renews push for sustainable aviation fuel tax credit," https://www.reuters.com/business/energy/biden-renews-push-sustainable-aviation-fuel-tax-credit-2022-04-12/

2. Sustainable Aviation Fuels (SAF)

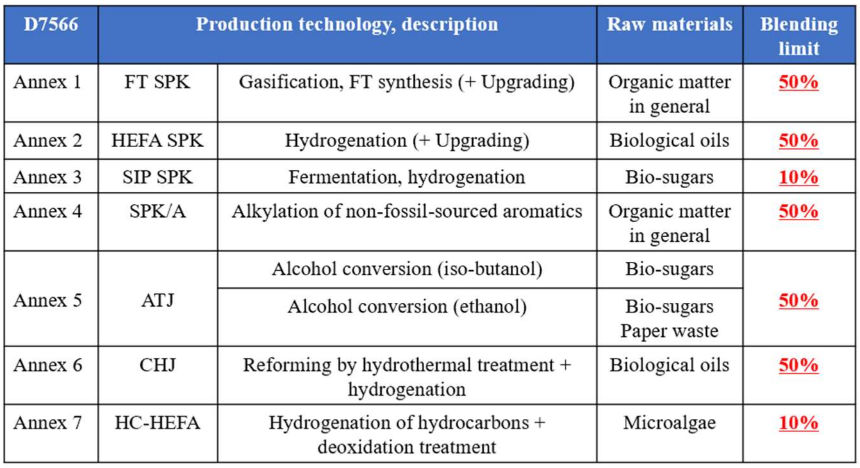
2-1. What is SAF?

SAF is an aviation fuel produced using biomass, wastes such as waste cooking oil and municipal garbage, and carbon, hydrogen, etc. contained in exhaust gases as raw materials. It functions like kerosene but is estimated to emit 60–80% less CO_2 compared to fossil-based fuels. The International Air Transport Association (IATA) defines SAF as "a fuel for aviation with non-fossil sources, an aviation fuel that is sustainable and produced from alternative feedstock to crude oil."[10] The ICAO defines SAF as **"fuels that have a potential to be sustainably produced and to generate lower carbon emissions than conventional kerosene on a life cycle basis."**[11] This report will adopt the ICAO's definition in its analysis.

2-2. International standards for SAF and CORSIA's criteria for sustainability

ASTM International categorizes and certifies the international standards for SAFs based on their production technology and raw materials in Annex 1 to 6 of its ASTM D7566 (Table 2). When a SAF is produced by one of the certified technologies and satisfies the properties specified by ASTM, the blended fuel produced by mixing SAF with jet fuel (maximum blending ratio of 50%) is recognized as satisfying the international jet fuel standards (ASTM D1655), making any additional safety measures or infrastructure modifications unnecessary.

Table 2 International standards for SAF (ASTM D7566 Annex)



D7566	Production technology, description		Raw materials	Blending limit
Annex 1	FT SPK	Gasification, FT synthesis (+ Upgrading)	Organic matter in general	50%
Annex 2	HEFA SPK	Hydrogenation (+ Upgrading)	Biological oils	50%
Annex 3	SIP SPK	Fermentation, hydrogenation	Bio-sugars	10%
Annex 4	SPK/A	Alkylation of non-fossil-sourced aromatics	Organic matter in general	50%
Annex 5	ATJ	Alcohol conversion (iso-butanol)	Bio-sugars	50%
		Alcohol conversion (ethanol)	Bio-sugars Paper waste	
Annex 6	CHJ	Reforming by hydrothermal treatment + hydrogenation	Biological oils	50%
Annex 7	HC-HEFA	Hydrogenation of hydrocarbons + deoxidation treatment	Microalgae	10%

Source: Prepared by the author based on IEA Bioenergy[12] and others

In order for SAF to be used as fuel for international flights, in addition to meeting the ASTM standards, the SAF manufacturer must obtain traceability certification approved by the ICAO's Sustainable Certification Schemes (SCS) as well as certification of compliance with CORSIA's Sustainability Criteria for SAFs (Table 3).

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[10] IATA, "What is SAF?," https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-what-is-saf.pdf

[11] ICAO, "Alternative Fuels: Questions and Answers," https://www.icao.int/environmental-protection/Pages/AltFuel-SustainableAltFuels.aspx#:~:text=WHAT%20ARE%20SUSTAINABLE%20ALTERNATIVE%20JET,on%20a%20life%20cycle%20basis.

[12] IEA Bioenergy (May 2021), *Progress in Commercialization of Biojet/Sustainable Aviation Fuel (SAF): Technologies, potential and challenges*, IEA Bioenergy Task 39, France: International Energy Agency, pp.13-16

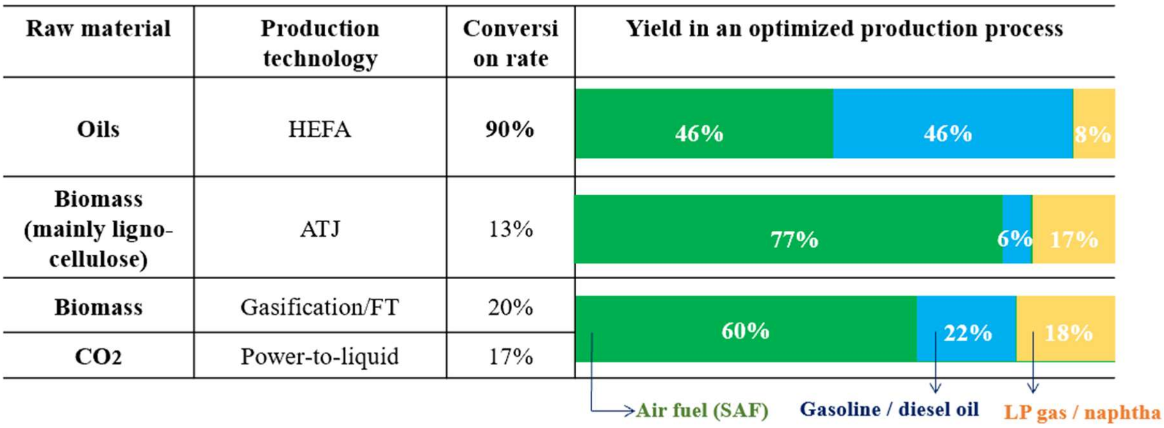
Table 3 CORSIA sustainability criteria for SAFs

GHG gases	**Principle**	CORSIA-eligible fuel shall generate lower carbon emissions on a life cycle basis.
	Criterion	Achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis (including induced land use change).
Carbon stock	**Principle**	CORSIA-eligible fuel shall not be made from biomass obtained from land with high carbon stock.
	Criterion 1	CORSIA-eligible fuel shall not be made from biomass obtained from land converted after January 1, 2018 that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
	Criterion 2	・In the event of land use conversion after January 1, 2018, as defined based on IPCC land categories, direct land use change (DLUC) emissions shall be calculated. ・If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value shall replace the default ILUC value.

Source: Prepared by the author based on CORSIA Sustainability Criteria for CORSIA Eligible Fuels (ICAO)[13]

2-3. Production technologies: technological maturity, raw materials, and yield

As shown in Table 2 above, seven SAF production technologies have obtained ASTM certification to date. Hydrotreated Eaters and Fatty Acids – Synthesized Paraffinic Kerosene (HEFA-SPK) described in Annex 2, a production technology in which biological oils are hydrogenated, is the most technologically mature and has already been launched commercially. By optimizing the production process to maximize the yield of SAF, the technology will be able to produce SAF equivalent to up to 46% of the raw material input (Fig. 10).



Raw material	Production technology	Conversion rate	Yield in an optimized production process
Oils	HEFA	90%	46% / 46% / 8%
Biomass (mainly ligno-cellulose)	ATJ	13%	77% / 6% / 17%
Biomass	Gasification/FT	20%	60% / 22% / 18%
CO2	Power-to-liquid	17%	

Fig. 10 Comparison of yield of SAF products (by technology)

Source: Prepared by the author based on: World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (November 2020) (Original source: McKinsey Global Energy Practice; ICCT; IRENA, etc.)

2-4. Supply and demand: Current situation and future outlook

The global supply of SAF was less than 50,000 tonnes in 2020 and is estimated to account for about 0.03% of the global aviation fuel demand. Nevertheless, a large number of SAF production and capacity expansion projects are under way worldwide on the back of strong demand, and SAF output is expected to rise sharply in the next few years. In particular, Finland's NESTE has one of the world's highest SAF supply capabilities, with plans to launch a SAF production plant (1 million tonnes/year) in Singapore in the first quarter of 2023 (Table 4). Further, the company's Renewable Products segment,

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[13] ICAO (June 2019), *CORSIA Sustainability Criteria for CORSIA Eligible Fuels*, CANADA: International Civil Aviation Organization

which includes renewable diesel, has become a high-added-value business that consistently delivers 300 million euros in operating profit (EBIT) and 7 to 8 million US dollars/tonne in sales margin each quarter (Fig. 11).

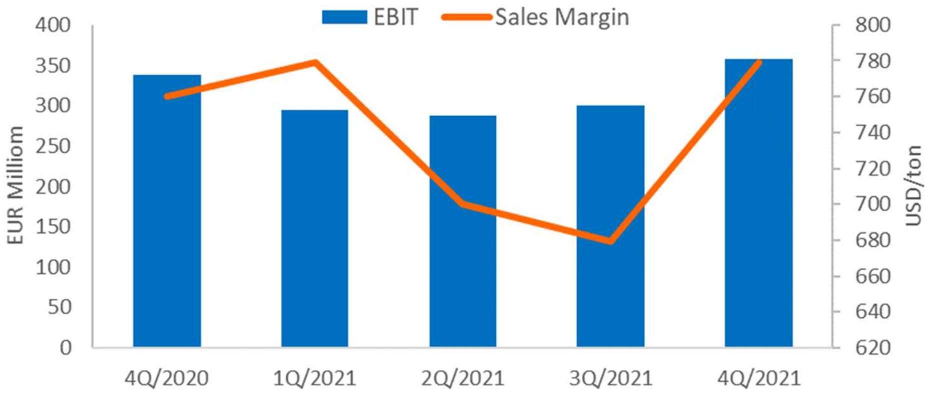

Fig. 11 NESTE's Renewable Products business: Quarterly operating profits (EBIT) and sales margin

Note: NESTE's Renewable Products segment: Produces renewable diesel, SAF, renewable solvents, and bioplastics raw materials based on the company's own patented technology and sells them in domestic and international wholesale markets.
Source: Prepared by the author based on NESTE Annual Report 2021[14] and quarterly report[15]

Table 4 lists SAF manufacturers and their location, production technology, raw materials, and capacity. Some manufacturers' capacities are aggregated with renewable diesel, etc., making accurate analysis difficult, but in order to replace 10% of the world's current jet fuel demand (approximately 167 million tonnes) with SAF, 16 million tonnes of SAF will be required, and thus the current supply capacity is extremely small. HEFA-SPK is effectively the only SAF production technology that is commercially available, and is currently used by most SAF manufacturers for commercial production. Demonstration projects are under way worldwide for SAF production using FT-SPK and ATJ technologies but commercial launch is not expected until a few years later. Thus, to resolve any supply bottlenecks over the next five to ten years, further process optimization and increasing the SAF output from HEFA-SPK through technological breakthroughs will be key, assuming that SAF raw materials can be stably secured. Further, raw materials for SAF are distributed unevenly in different parts of the world, limiting the scale of SAF production at each location. Therefore, to secure a stable SAF supply, it is necessary to develop a system for distributing small quantities. Regarding the production and supply of SAF so far, the market has been driven by independent operators such as World Energy and Finland's NESTE, which took the lead in focusing on the renewable products business. But recently, first- and second-tier oil majors such as France's TotalEnergies, Italy's ENI, and Spain's Repsol have entered the market. Because SAF is blended with jet fuel and is distributed via supply chains, it appears relatively easy for oil companies, which possess oil refining technologies, large plants, and established jet fuel supply chains, to capture market share from existing players.

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[14] https://www.neste.com/sites/neste.com/files/attachments/corporate/investors/corporate_governance/neste_annual_report_2021.pdf
[15] https://www.neste.com/investors/materials

Table 4 Summary of SAF supply

Producer	Location	Technology	Raw materials	Capacity (tonne/yr)
NESTE	Rotterdam (Netherlands)	HEFA	Plant oil, waste cooking oil, tallow	450,000
	Porvoo (Finland)	HEFA	Plant oil, waste cooking oil, tallow	100,000
	Delfzil (Netherlands)	HEFA	Plant oil, waste cooking oil, tallow	100,000
	Singapore (Singapore)	HEFA	Plant oil, waste cooking oil, tallow	1,000,000 (1Q, 2023)
World Energy	Paramount (US)	HEFA	Non-cooking oil, waste	570,000*
Diamond Green Diesel	Norco (Louisiana, US)	HEFA	Plant oil, tallow, waste cooking oil	1,500,000*
	Port Arthur (Texas, US)	HEFA	Plant oil, tallow, waste cooking oil	1,800,000 (2023)*
UPM	Lappeenranta (Finland)	HEFA	Crude tall oil	500,000*
Renewable Energy Group (Chevron)	Geismar (Louisiana, US)	HEFA	Free fatty acid	1,300,000 (2023)*
ST1	Gothenburg (Sweden)	HEFA	Tall oil	70,000
Preem	Gothenburg (Sweden)	HEFA	Tallow, raw tall oil	270,000 (2024)
TotalEnergies	La Mede (France)	HEFA	Waste cooking oil, plant oil	100,000
	Granpuits (France)	HEFA	Waste cooking oil, plant oil	170,000
ENI	Gela (Italy)	Ecofining	Waste cooking oil, fat	150,000 (2024)*
Repsol	Cartagena (Spain)	Co-processing	Plant oil	N.A.
	Purrtollano (Spain)	Co-processing	Plant oil	N.A.

Note 1: (*) Aggregate total with renewable diesel output
Note 2: FT-SPK, ATJ, etc. and other technologies in demonstration stage not included
Source: Prepared by the author based on IRENA (July 2021), Argus Media, and websites and press releases of various companies

The most powerful drivers of SAF demand are airlines, air freight carriers, and oil companies. A large number of SAF trade contracts have been signed in recent years, and a framework for supplying SAF is gradually developing mainly in Europe and the United States (Fig. 12).

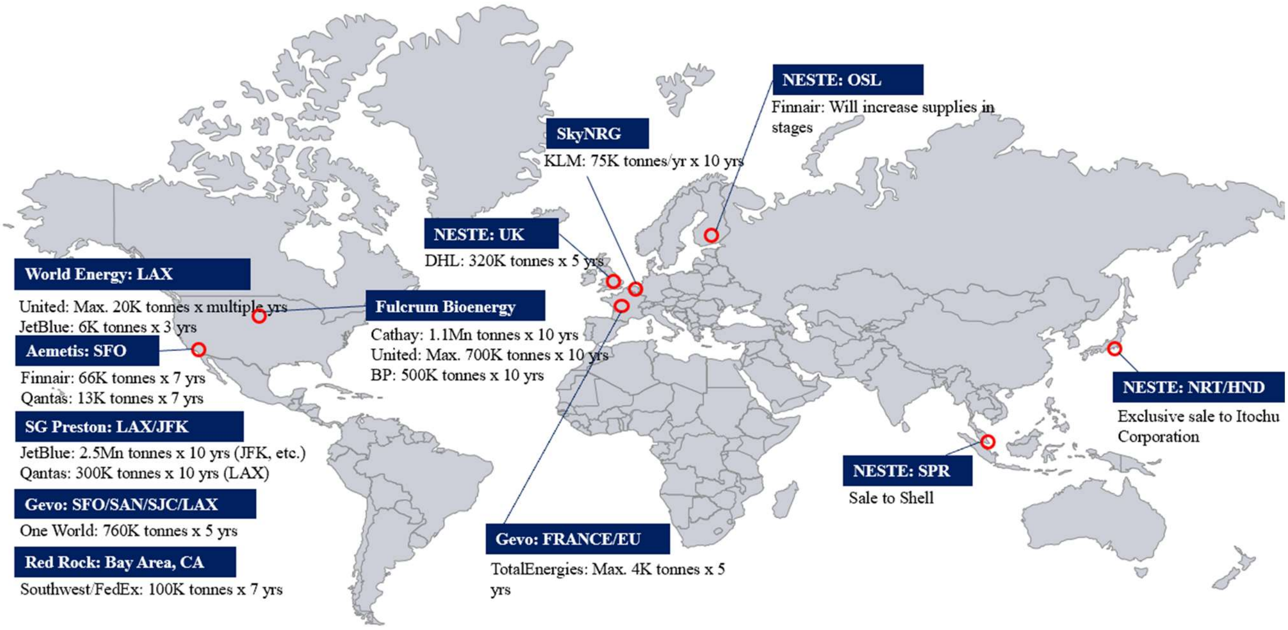

Fig. 12 Map of the world's SAF supply status

Source: Prepared by the author based on the State of Sustainable Aviation Fuel (SAF) (CAAFI), various corporate press releases, etc.

3. Challenges for further expansion and the future outlook

The previous chapter summarized the characteristics, production technologies, and raw materials of SAF as well as the current status of supply and demand and their outlook. SAF is currently attracting attention and raising expectations as the key for decarbonizing the skies, but are there any challenges to overcome for expanding the use of SAF in the future? This chapter looks at the challenges faced by SAF and its future outlook.

The greatest challenge for increasing the use of SAF is to reduce production costs. Fig. 13 below shows the SAF production cost for each technology from 2020 toward 2050, revealing that **SAF is extremely expensive to produce as of 2020, costing roughly 3 to 7 times as much as jet fuel (estimated at $500/tonne).** As for the feasibility of reducing costs going forward, HEFA, the most mature technology that has already been commercialized, is the most cost competitive and is expected to remain so. However, it is estimated that the cost of HEFA can be reduced by only 20% by 2050 due to the difficulty of drastically cutting its raw materials cost, which accounts for around 60% of the production cost (Fig. 14). Meanwhile, Germany is focusing on power-to-liquid (e-fuel), which currently costs far more to produce than other technologies at $3,500/tonne. However, it is expected to be able to reduce that cost by around 67% by 2050 because of the sizeable scope for reducing renewable power generation costs and the medium- to long-term facility investment and operation costs (Fig. 13).

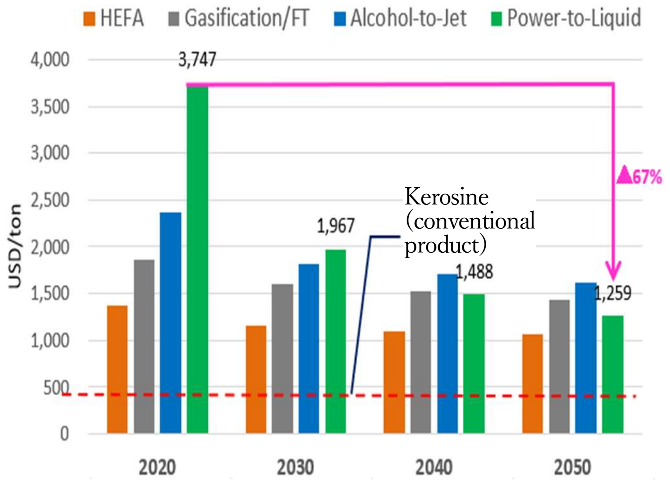

Fig. 13 SAF production cost: current status and outlook

Source: Prepared by the author based on World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (November 2020)

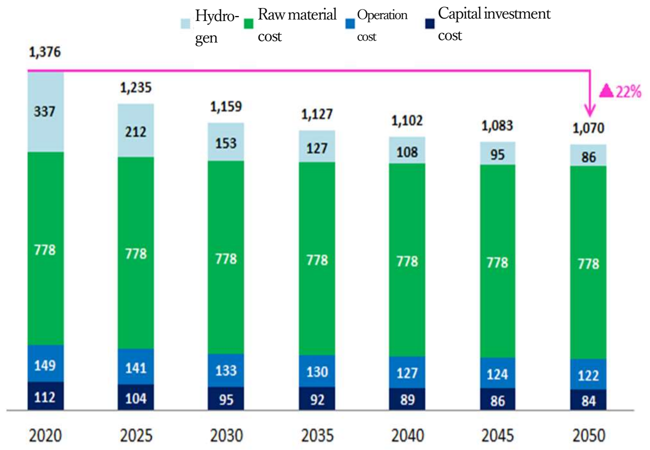

Fig. 14 SAF production cost: Breakdown (for HEFA)

Source: Prepared by the author based on World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (November 2020)

Are there any challenges concerning securing raw materials? The World Economic Forum estimates that approximately 500 million tonnes of SAF can be produced and supplied based on the potential of raw materials such as advanced feedstock and waste that does not compete with food. This is equivalent to 120% of the aviation fuel demand of 400 million tonnes as of 2030[16]. As for the supply volume, SAF raw materials such as biomass, residue, and municipal waste can also be used to produce heat energy by burning directly. They are also used for producing biomass power and waste incineration power and therefore compete as a primary energy source. Thus, the amount of raw materials for SAF production that can be secured may not be as large as the theoretical potential. It is also possible that the prices of raw materials could rise so much in the future that it would become difficult to purchase them. We can assume that projects that are already producing SAF on a commercial scale or are undergoing proof-of-concept can secure raw materials relatively easily. In the future, as the demand for SAF rises, the value of those raw materials may rise, or municipal waste, which is now available for free by bearing the collection cost, may be bought and sold in the future. As a potential increase in raw material costs would be passed directly onto the sales price of SAF, it could hamper the expansion of the fuel.

It is important to produce SAF in Japan also from the standpoint of curbing transportation costs (Table 5 below). As there are no commercial SAF plants in the country as of now, Japan must depend on foreign imports for the time being. A tight supply-demand balance in the international market could not only push up the market price of SAF but also make it difficult to secure sufficient volumes.

Table 5 List of domestic SAF manufacturers

Raw material		Technology	Company	Status
Oil	Waste cooking oil	HEFA-SPK	JGC Holdings, JGC Japan, REVO International, Cosmo Oil	NEDO PoC under way (till 2024)
	Microalgae	HC-HEFA	IHI	NEDO PoC done; supplied to domestic flights
	Euglena	HC-HEFA	Euglena	NEDO PoC under way (till 2024)
Biomass	Wood, pulp	FT-SPK	JERA, Mitsubishi Power Toyo Engineering, Itochu Corporation	NEDO PoC under way (till 2024)
		ATJ	Biomaterial in Tokyo Sanyu Plant Service	NEDO PoC under way (till 2024)
	Ethanol	ATJ	ANA, Mitsui Corporation (utilizing US LanzaJet's technology)	GI fund* being considered
Municipal waste Exhaust gas	Common waste	FT-SPK	JAL, Marubeni, ENEOS, JGC, and others (utilizing US Fulcrum BioEnergy's technology)	PoC under way
	Plastics			
	Exhaust gas	ATJ	N.A.	N.A.
Synthetic fuel	CO_2 + green H_2	CO_2 electrolysis	ANA, Toshiba ES, Toshiba, Idemitsu Kosan, TOYO Engineering, Japan CCS	Feasibility assessment
	CO_2 + H_2O	Co-electrolysis	Seikei University, ENEOS, Nagoya University, Yokohama National University, Idemitsu Kosan, AIST, Japan Petroleum Energy Center	NEDO PoC under way (till 2024)
	CO_2 + green H_2	Direct FT synthesis		

Source: Prepared by the author based on various sources including Japan Airlines[17], NEDO and other corporate press releases

It must be noted that whether SAF supplies can be increased still depends greatly on technological breakthroughs. As described earlier, while the current market is being driven by HEFA, the greatest cost reduction toward 2050 is expected to come from power-to-liquid (e-fuel). Power-to-liquid needs renewable and other clean electricity supplies, but currently, renewable electricity supplies are tightening as the world strives to achieve carbon neutrality. It will be necessary to secure large quantities of inexpensive clean electricity, but the fight for it is expected to intensify for various uses. Japan estimates

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[16] World Economic Forum (in collaboration with McKinsey & Company) (November 2020), *op. cit.*, p.27

[17] Japan Airlines (February 17, 2022), "*The Role Domestic SAF Will Play*", https://www.jttri.or.jp/seminar220217-05.pdf

that 23 million kl (18 million tonnes) of SAF will be introduced in 2050[18], but this deviates from the estimated total SAF production and supply from HEFA, gasification, FT synthesis, and ATJ by as much as 11 million kl (8 million tonnes) as of 2050. The gap is planned to be closed by producing SAF from algae[19]. The production of biofuels from algae dates back as far as the 1970s when Japan experienced two energy crises. Ventures mushroomed mainly in the United States around 2010 when oil prices soared, but most of them withdrew after they failed to achieve mass production. Therefore, technological breakthroughs are still needed to produce large quantities of biofuels from algae. If domestic SAF production does not proceed smoothly, Japan will have to continue to depend on imports and bear high transportation costs. Investing in a broad range of technologies is essential for enhancing energy security as well.

As described earlier, various efforts are currently under way in Japan utilizing mainly government aid, including R&D funds from NEDO, which aims to establish a domestic SAF production system early on and to reduce costs. However, with no SAF production project yet commercialized, it is difficult to reduce production costs significantly in the near term. As such, in addition to government aid, it will be necessary to simultaneously consider a mechanism for society as a whole to absorb any rise in costs resulting from using SAF. As an example, European airlines such as Air France and KLM have a system whereby any SAF-induced increase in fuel cost is added on to the ticket price as a biofuel surcharge[20]. Further, more and more companies are voluntarily paying for the cost of offsetting the GHG emissions arising from their employees' international business air travel[21]. To expand the use of SAF going forward, it will be necessary to consider similar private-sector efforts that promote behavioral changes.

Conclusion

Recently, SAF has attracted steadily increasing attention. SAF production and supply projects led by the private sector are already being implemented in various places, but so far, the global supply of SAF is still small and it costs several times more than jet fuel. Further, as the raw materials used for SAF production must be absolutely sustainable, there is a risk that raw materials costs may rise in the medium to long term and pose a challenge. On the other hand, looking at the situation as a whole, SAF is likely to play an important role in the medium to long term in the international aviation sector, in which valid options for decarbonization are limited. To reduce costs sufficiently for the expansion of SAF going forward, technological breakthroughs by leveraging policy measures as well as a mechanism for sharing the costs by society as a whole are needed.

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[18] Japan Airlines (October 8, 2021, press release), ANA and Japan Airlines Towards 2050 Carbon Neutral Joint Report on SAF, https://press.jal.co.jp/ja/release/202110/006263.html

[19] Japan Transport and Tourism Research Institute (February 17, 2022), "*Challenges and Solutions for the Overall Supply Chain Towards the Expanded Use of SAF in Japan (report)*", https://www.jttri.or.jp/seminar220217-06.pdf

[20] France24 (January 10, 2022), "Air France-KLM adds biofuel surcharge to plane tickets," https://www.france24.com/en/live-news/20220110-air-france-klm-adds-biofuel-surcharge-to-plane-tickets

[21] BCG's Net-Zero Strategy, https://www.bcg.com/about/net-zero

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Design of Emissions Trading System in Japan

(Based on lessons learnt from the European Union Emissions Trading System (EU ETS))

Toshiyuki Sakamoto[*] Tohru Shimizu[**]

Efforts are underway to initiate emissions trading as a voluntary measure in Japan from 2023 as one of the initiatives of the GX League, led by the Ministry of Economy, Trade and Industry (METI)[1]. This initiative was framed as "preparation for a future mechanism to reduce emissions" in the interim report of Clean Energy Strategy[2]. Also, the Japan Business Federation (Keidanren) recently stated that a cap-and-trade emissions trading system (ETS) "could be a strong option."[3] It, therefore, appears that both the public and private sectors are now prepared to introduce an ETS in Japan.

ETS have been introduced in some countries and regions. Among these, the European Union Emissions Trading System (EU ETS) has undergone a number of trial-and-error processes and systemic reforms since the start of the system in 2005; reviewing the practical realities of this system once again will allow Japan to obtain a number of suggestions for its ETS introduction.

This paper will analyze the reforms undertaken in the past and status of the EU ETS, and discuss the issues related to the ETS design.

1. Changes in the EU ETS

The EU ETS began operation in 2005 following the Emission Trading Directive (Directive 2003/87/EC) in 2003[4]. Looking back the late 1990s, the European Commission considered introducing the regional common carbon tax across the EU and presented its proposal to EU member states, with the aim of achieving the targets of the Kyoto Protocol. However, the consensus of all EU member states, which was required for this common tax proposal, could not be obtained. As this vision suffered a setback, the EU instead introduced an ETS, which could be introduced via the qualified majority voting method (in which votes are cast in accordance with the population of each member state), as an alternative.

The EU ETS, which started in 2005, underwent progressive systemic reforms under Phase 1 (trial phase), followed by Phase 2, Phase 3, and Phase 4. In addition, a trial-and-error process comprising reforms of several relevant regulations, both major and minor, have continued throughout the phases and is still ongoing, meaning that the system is still not fully complete as an ETS.

The greenhouse gas (GHG) emissions from facilities covered by the EU ETS Directive in 2020 stood at 1,398Mt-CO_2, covering 38% of the EU's total emissions (including land use, land-use change and forestry (LULUCF) activities and international aviation). Although this represents a 41% reduction from the 2,369Mt-CO_2 emitted at the outset of the EU ETS in 2005, assessing whether this reduction has resulted from the ETS requires careful deliberation.

1-1. Excessive allocation and market intervention by the European Commission

The most principal element of an ETS is the formation of rules for the allocation of emissions allowances for covered facilities; designing such a system in an appropriate manner and building a consensus on this is complicated. The European

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[*] Board Member, Director for Climate Change and Energy Efficiency Unit, IEEJ

[**] Senior Researcher, Climate Change Group, Climate Change and Energy Efficiency Unit, IEEJ

[1] METI (2022a)

[2] METI (2022b)

[3] Japan Business Federation (2022)

[4] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003, establishing a system for greenhouse gas emission allowance trading within the Union, and the amending Council Directive 96/61/EC

Commission is working to improve the sluggish EUA prices that were caused by failures in allocation, by reducing the supply of EUAs to the market through auctioning.

Fig.1 shows the emission cap in the EU ETS since 2005, the volume of allocations for covered facilities, emission volumes, and use of offset credits. During Phase 1 (2005-2007), which was the trial phase of the scheme, the postponement of decisions on National Allocation Plans (NAPs) for free EUA allocation to covered facilities, in addition to the overly loose guidance on allocation given by the European Commission, resulted in excessive allocation. Following this, the excessive allocation issue continued to be unaddressed in Phase 2 (2008-2012), with the emission volume exceeding the allocation volume in 2008 alone, while the allocation plans based on the NAPs continued to be maintained without necessary revisions being made. The issue then began to aggravate with the influx of large volumes of offset credits.

As a result of this excessive allocation, the price of EUAs traded in the market slumped. The EUAs that were allocated and left unused in Phase 2 could be "banked" from one phase to the next; as a result, the oversupply situation has continued.

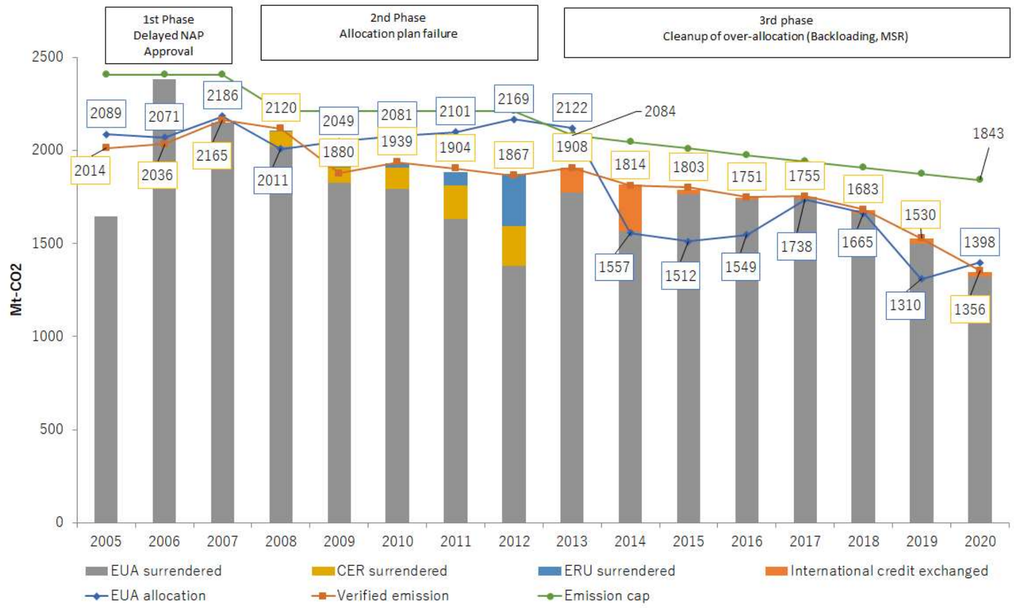

Fig. 1 Allocations, surrenders and emissions under the EU ETS

Source: European Environment Agency, "European Union Emissions Trading System (EU ETS) data from EUTL," and estimated by IEEJ based on materials from the European Commission.

In response to this situation, two countermeasures were proposed by the European Commission during Phase 3 (2013-2020) and were introduced after complicated negotiations between member states and industries.

- Backloading (restriction of the market supply): Over 2014-2016, the European Commission decided to set aside the auction supply of 900Mt-CO_2 EUAs.
- MSR (Market Stability Reserve): the European Commission calculate surplus allowances (Total Number of Allowances in Circulation, TNAC) in the market, then they decide on a number to set aside for the auction supply for the market based on the TNAC if it will be reaching a certain level. Those allowances are transferred to the MSR account from the auction account. This system was introduced in 2019, at the same time, unused New Entrant Reserves and 900Mt-CO_2 allowances (backloading) were transferred to the MSR.

The ETS Directive also includes a system for market intervention by the European Commission, to serve as a safety valve if EUA prices rise to very high levels. In such intervention, the authorities take steps to bring auctions forward if the market price of EUAs exceeds as much as three times the previous two years' average price for six consecutive months; however, so far, such actions have never been carried out.

During Phase 3, the oversupply of allowances was temporarily alleviated through backloading and the MSR; however, EUA prices continued to be low at 3-30 euros/t-CO_2 due to the surpluses that were banked from Phase 2.

1-2. Enormous amount of accumulated surpluses

From Phase 2 onwards, surpluses, which have remained unused for compliance, have accumulated in the operator accounts covered by the Directive. According to the European Commission, these currently exceed 1,579Mt-CO_2 (as of 2020), as shown in Fig. 2. With annual GHG emissions from facilities covered by the EU ETS Directive standing at 1,398Mt-CO_2 as of 2020, this means that a surplus exceeding annual total emission is still held by operators covered by the Directive.

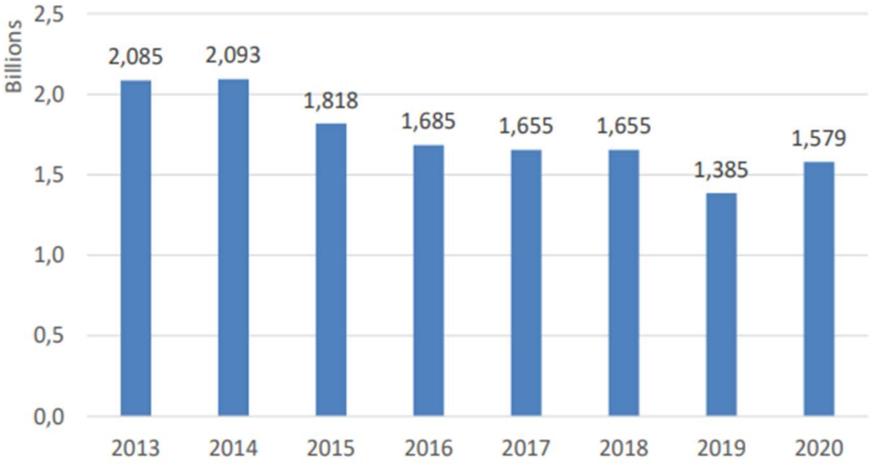

Fig. 2 Surplus of allowances in EU ETS
Source: DG CLIMA (2021)

In the power sector, which has been subject to auctioning from Phase 3 onwards, surpluses carried over from Phase 2 appear to have been exhausted. Free allocation for the power sector in Eastern European countries has been maintained, but such free allocation is now provided on a project basis. The power sector basically procures EUAs from auctions and from the market. This means that industrial sectors other than the power sector hold several years of surpluses. The results of our calculations of the difference between allocation volumes and surrendered volumes for covered facilities for each sector, published by the European Commission, suggest that the iron and steel sector and the cement sector possess enormous surpluses, amounting to seven years and three years of their annual emissions respectively, as of 2020.

Fig. 3 shows the actual compliance costs for each sector. These represent the volume of EUAs purchased in the year multiplied by the average price of EUAs in that year, and then divided by the total emission volume for each sector. As for combustion facilities, most of which have transitioned to auctioning, surpluses have mostly become scarce, and therefore the compliance costs have been approaching the average price of EUAs in recent years. Conversely, in other sectors, surpluses have continued to be ample and free allocation has continued; as a result, EU ETS compliance costs are close to zero, and only minor costs are being observed in aviation, petroleum refining and coke manufacturing.

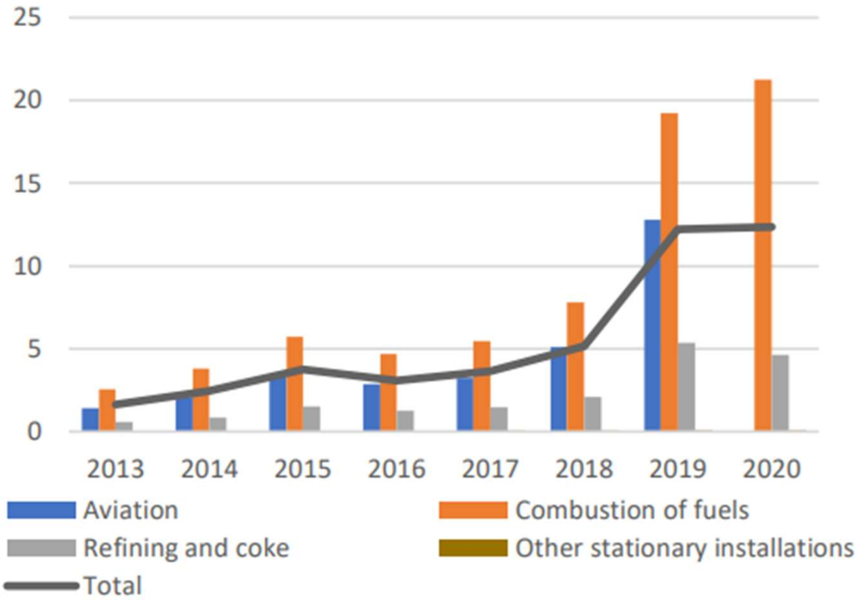

Fig. 3 Cost of compliance by sector (Unit: euros/t-CO_2)
Source: The European Roundtable on Climate Change and Sustainable Transition (2022)

1-3. Which sectors have seen decreases in emissions, and what are the reasons for the decreases?

From around 2012 onwards, emissions from facilities covered by the EU ETS Directive began to decrease, as shown in Fig. 4. This decrease in emissions can be largely attributed to combustion facilities, which contributed relatively more to the overall decrease than other sectors. Most of the emissions from combustion facilities are from thermal power generation facilities, with their emissions intensity improving by around 30% over the 2013-2019 period due to the introduction of renewable energy. However, there have been no major changes in emission intensities in other sectors than combustion facilities.

It therefore could be the case that the emissions reductions are not necessarily due to the EU ETS but due to the renewable energy policies undertaken in various countries, such as Feed-in Tariffs (FITs). The European Roundtable on Climate Change and Sustainable Transition (ERCST) has noted that "…most of the reductions in Phase 3 were achieved in the power sector, and while the EU ETS played a guiding role, it is generally accepted that it was not the driving factor. This decarbonization is largely due to other policies and measures as well as a significant level of subsidies received by the power sector."

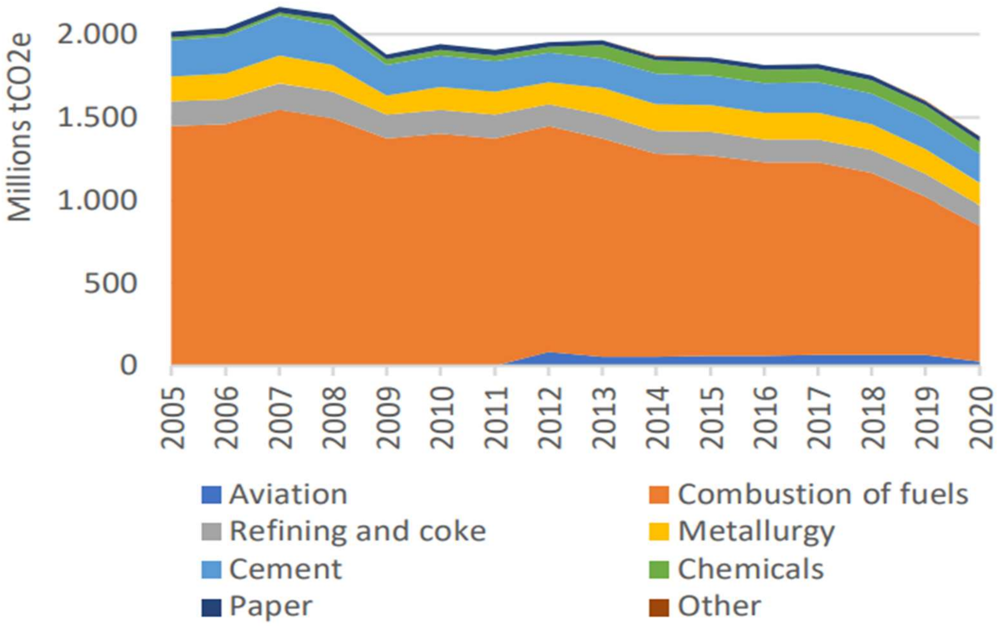

Fig. 4 Trends in emissions for each type of facility covered by regulations under the EU ETS

Source: The European Roundtable on Climate Change and Sustainable Transition (2022)

Fig. 5 shows trends in emissions from power generation facilities covered by the EU ETS, and in the electricity generation mix within the region. Whereas emissions from power generation facilities stood at 987 million t-CO_2 in 2008, this figure had fallen to 462 million t-CO_2 as of 2020. Looking at trends in the electricity generation mix, the share of coal-fired power generation has fallen, while the shares of natural gas-fired power and nuclear power have also declined by around 20% each. Meanwhile, these have been substituted by a sharp increase in wind power and expansion in biomass, leading to reduced emissions.

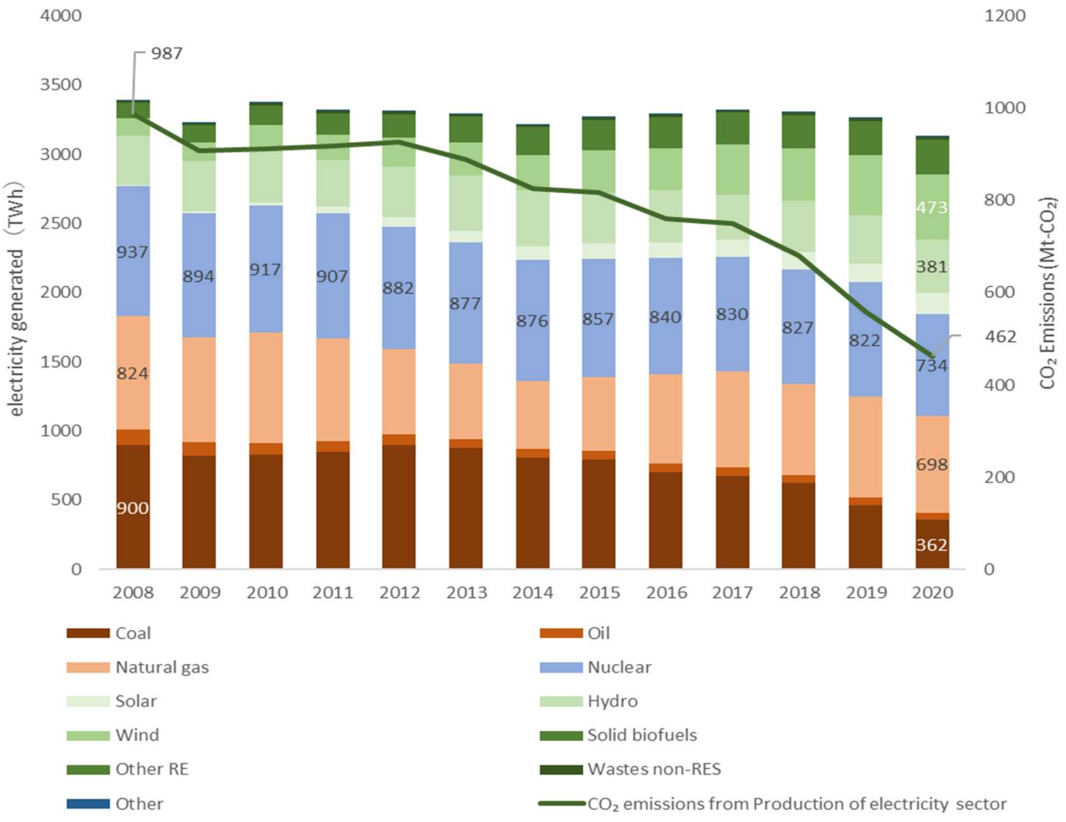

Fig. 5 CO_2 emissions from production of electricity sector covered by the EU ETS and in the electricity generation mix in the EU

Source: the power generation mix from Eurostat, CO_2 emissions from production of electricity sector from the European Union Transaction Log (EUTL) and the European Commission estimation

1-4. Who is trading allowances?

EU ETS allocation is split approximately equally between auctioning and free allocation (benchmarks). According to the auction reports from the European Energy Exchange (EEX)[5], which conducts auctions on behalf of the European Commission, and reports by the European Commission[6], in recent times, around 60% of successful bids have been from operators covered by the EU ETS, with the rest being from financial organizations. Conversely, looking at the participants in the "secondary market" (exchange trading) which follows this, transactions by financial organizations overwhelmingly dominate, as shown in Fig. 6. In the wake of soaring EUA prices, the European Securities and Markets Authority (ESMA) undertook a survey of the EUA trading markets such as ICE and EEX in response to requests from Poland and other member states but concluded that speculation was not taking place. However, it is probably the case that prices are fluctuating much more due to the transactions by financial organizations, given the large share of EUA transactions are made by them in ICE and other markets.

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[5] European Energy Exchange (2022)

[6] DG CLIMA (2022)

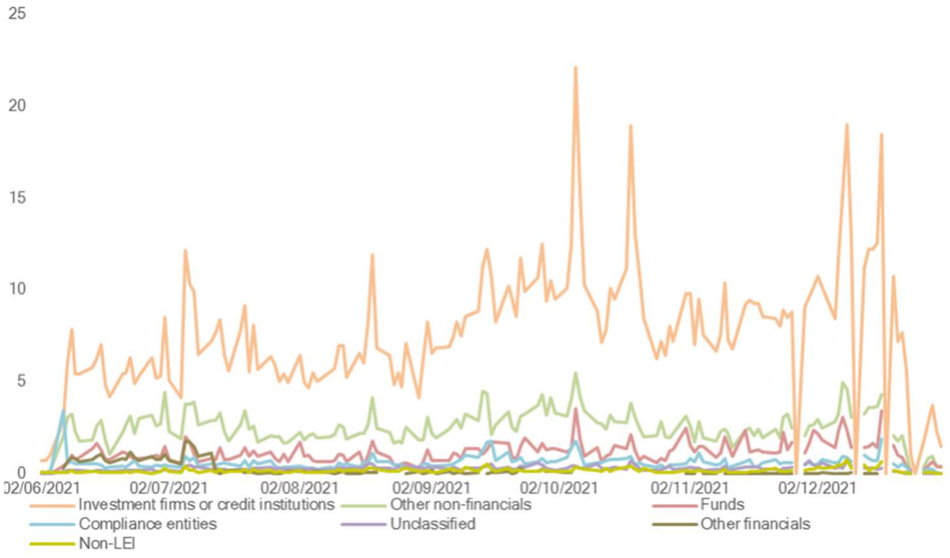

Fig. 6 Number of EUA transactions, by type of market participant

Source: European Securities and Markets Authority (2022)

1-5. Uncertainty of EUA prices

Since the system began in 2005, EUA prices had been within the 3-30 euros/t-CO_2 range, repeating a cyclical movement of sharp rise, crash in prices and continuing slump; then, from 2018 onwards, prices began to rise, and increased even more sharply in 2021. The main factor behind this is believed to be the fact that the EU in December 2020 raised its target for 2030 emission reduction to 55% compared to the 1990 level, making it easier to envisage that the emission cap for sectors covered by the EU ETS would become more stringent. In July 2021, a package of policies aiming to achieve the stricter 2030 target was announced as “Fit for 55”. The impact assessment of the reform of the EU ETS Directive, which was proposed as part of this package, estimated that the EUA price would rise to a level of more than 90 euros/t-CO_2 by 2030. This assessment served to drive a rapid increase in the price. Following this, unpromising weather conditions within the region resulted in a slump in wind power generation, causing the price of natural gas to soar. As a switch away from excessively expensive natural gas to coal-fired power generation was therefore anticipated, this created a chain reaction that pushed up the prices of EUAs as well.

As spot prices of EUAs reached a historic high of 96.9 euros/t-CO_2 in early February this year, Poland and some other countries suggested the possibility of speculation, as discussed previously. EUA prices were expected to rise still further amid skyrocketing natural gas prices because of Russia’s invasion of Ukraine. Contrarily, however, EUA prices fell to 60.9 euros/t-CO_2, before coming to hover around the 80 euros/t-CO_2 mark. With storage of natural gas being prioritized this summer in preparation for the winter, some expect a move towards coal-fired power generation and an increasing demand for EUAs, which would lead EUA prices to exceed 100 euros/t-CO_2. However, with concerns also being expressed about an economic slowdown due to the increasingly tight energy supply, it is not unclear whether the price will move upward or downward.

Other than market trends of this kind, ERCST has noted that EUA prices fluctuate in line with the net positions of financial organizations. As Fig. 7 shows, when EUA prices have fluctuated in the past, substantial changes have occurred in the net positions of financial organizations, suggesting that this is one factor behind price fluctuations.

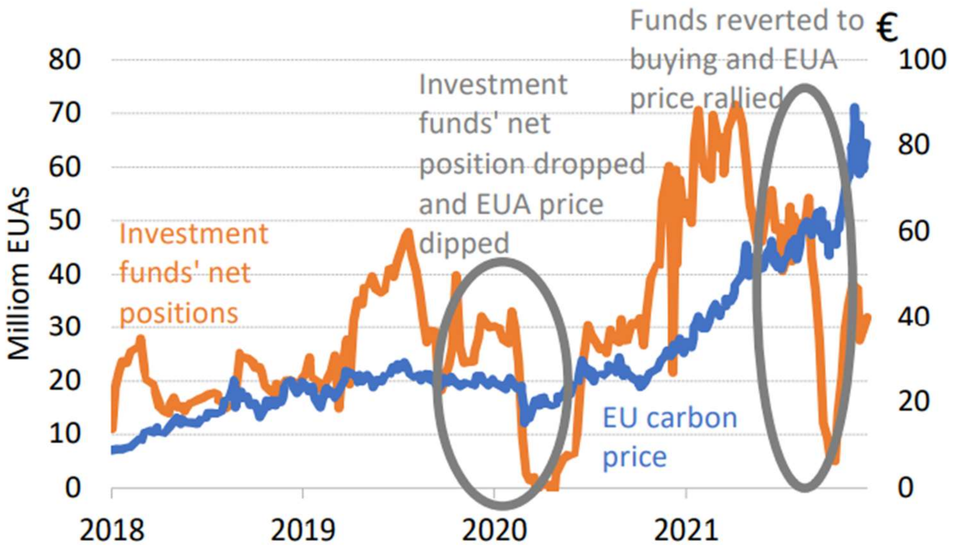

Fig. 7 Trends in investment funds' net positions and the EUA price

Source: European Securities and Markets Authority (2022)

1-6. Further changes to the system during Phase 4 (2021-2030)

Fit for 55 proposes reforms to the EU ETS Directive[7]. Proposed reforms include increasing the 2030 emissions reduction target for facilities covered by the EU ETS Directive from 43% to 61% compared with the 2005 levels and introducing a new ETS which would include fuel suppliers for residential building heating and for land transportation as its targets. Regarding this proposed ETS, as rises in the prices of energy have a tremendous impact on ordinary citizens, steering a path to consensus among the European Commission, European Parliament and European Council will be a difficult task in the wake of soaring energy prices in recent times.

1-7. Concerning the abolition of free allocation through the CBAM and the handling of exports

In June 2022, the European Parliament, and European Council compiled their opinions on the European Commission's proposals concerning the introduction of the Carbon Border Adjustment Mechanism (CBAM) in the EU. The most important issue was how to move forward with the reduction/abolition of free allocation for sectors covered by the CBAM (which the European Commission proposed to be steel, cement, aluminum, and fertilizer). The following variations in opinion were noted; the progress of behind-the-closed-door discussions on the CBAM as well as revisions to the ETS Directive will merit attention going forward.

- European Commission[8]: Phase in the CBAM by carrying out reductions of free allocation in 10% annual increments over 10 years from 2025.
- Relevant industries[9]: Initiate the reduction of free allocation from 2030 after ascertaining the efficacy of the CBAM.
- European Parliament[10]: Abolish free allocation by 2032 (brought forward three years from the date proposed by the European Commission).
- European Council[11]: Abolish free allocation over 10 years, but initially reduce it by 5% increments each year rather

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[7] COM (2021) 551 final

[8] COM (2021) 564 final

[9] CEMBUREAU, EUROFER, EUROMETAUX, EUROPEAN ALUMINIUM and FERTILIZERS EUROPE (2022)

[10] European Parliament P9_TA (2022) 0248

[11] European Council 7226/22

than 10%, and thereafter gradually raise the rate of reduction.

Demands for the rebate of EUAs cost for exports have also been heard from the relevant industries. In response, the European Commission, European Parliament, and European Council's position are that charges will initially be levied on imports, and that the impact of carbon leakage, which may emerge due to competitive disadvantage for exports, will then be assessed going forward.

1-8. Is the EU ETS a model to be imitated, or a negative example?

The above discussions concerning the EU ETS could be summarized as follows.

- The EU ETS is a regulatory system that includes tools for quantitative market intervention by the authorities, and cannot be described as a system that functions solely through market mechanisms. The European Commission may wish to use the EUA price as a price signal, but has been unable to control the range of price fluctuations through it. Conversely, some European industrialists argue that EUA prices can be predicted more readily than a carbon tax, since the tax rate can be changed by politicians' will; a perspective which goes against opinions heard in Japan.
- A certain level of compliance cost is observed in the power sector; however, this has recently stood at around the 20 euros/t-CO_2 level, and some believe that the previous reductions in emissions are the result of other renewable energy policies. In other sectors, the costs of compliance are close to zero due to free allocation, and in addition, enormous surpluses are still held due to excessive free allocation in the past. In particular, with the iron and steel sector holding EUAs equivalent to seven years of annual emissions and the cement sector holding three years, significant inequalities have emerged among different sectors.
- With the announcement of proposed reforms to the ETS Directive being brought forward as part of Fit for 55 in July 2021, EUA prices rose substantially largely due to increasingly active trading by financial organizations, which expected EUA prices to surge. In addition to this, instability in the energy supply within the EU and Russia's invasion of Ukraine led to a situation where EUA prices could reach 100 euros/t-CO_2.
- With the prospect of free allocation being reduced/abolished due to the introduction of the CBAM, the industry has, at last, started to recognize EU ETS as a price signal for cutting emissions. It has taken 17 years since the start of the EU ETS for this to happen; by the time free allocation is actually reduced, more than a quarter of a century will have passed.

2. Suggestions for Japan, and future issues

On the basis of the above consideration of the EU ETS, the major issues of ETS could be set out as follows.

- Roadmap of the cost burden (who will participate, when and how): If auctions are made mandatory among those sectors where alternative technologies are not anticipated, it will result in a fine and nothing else, rather than an incentive to reduce emissions; the original intention of ETS. Based on the experience of the EU ETS where free allocation still remains, it is essential to consider how to draw a line between auction and free allocation, to clarify the timing and terms of the transition towards auction, and alternatively to design a system which will start with auction only and thereafter increase the participating sectors gradually. As such, a roadmap for shouldering the emission reduction costs is necessary, taking into account the sectoral prospects of transition to alternative technologies. On the other hand, Japan cannot enjoy the luxury of spending 20 years to create a system, as the EU did.
- Handling free allocation and ensuring fairness: The experience of the EU ETS attests to the difficulties of free allocation. Free allocation through grandfathering is based on historical emissions, while the benchmark will be based on CO_2 intensity; however, whichever is the case, allocation can only depend on the previous actual values. To avoid the unfairness of enormous surpluses building up in particular sectors, systematic arrangements are essential such as through monitoring the operational status and the volume of production activities of companies

and facilities covered by the ETS. Moreover, while over-allocation has been a problem for the EU ETS, in the case of South Korea's ETS there have been numerous cases of companies suing the government for insufficient allocation. Both ETSs have a problem with free allocation.

- Securing international competitiveness and responding to carbon leakage: In the case of Japan, ensuring a level playing field with the overseas companies that Japanese firms compete with is essential, as overseas markets have greater importance for Japan than for the EU. As there are concerns that the CBAM could obstruct free trade, as well as worries about compatibility with World Trade Organization (WTO) rules and about stirring up north-south confrontations, addressing carbon leakage through the CBAM must be handled with great care.
- Use of external credits: The EU ETS has completely prohibited the use of offset credits outside the region from Phase 4 onward. In the case of Japan, efforts are underway to reduce overseas emissions via the Joint Crediting Mechanism (JCM), and companies will be able to contribute to emission reductions while minimizing their cost burden by using offset credits by this mechanism. In addition, carbon removal technologies, such as direct air carbon capture and storage (DACCS), forests as carbon sinks and blue carbon, will be essential in order to achieve carbon neutrality by 2050. Since locations outside Japan will be superior as sites for these technologies' implementation from a cost perspective, a platform for enabling overseas carbon removal credits to be used, in addition to offset credits, will be essential.
- Stability and liquidity of emission allowance prices: Whether we should accept intervention by the authorities as a price stabilization measure given the nature of a government-regulated market, or whether we should pursue a market mechanism, is a fundamental question related to the ETS design. In considering this question, it should be noted that the participation of financial organizations brings the advantage of increasing the liquidity of the market and the transparency of prices through transactions at exchanges. On the other hand, as is the case in the EU ETS, there is also a possibility that the price could be more uncertain due to transactions with expectations for a tighter supply-demand balance in the future. This is one of the issues to be considered.
- Measurement, reporting, and verification (MRV) preparation period, system design and administrative costs in public-private sectors: In Japan, companies have up to now reported their emissions to the authorities based on the Act on the Rational Use of Energy and the Act on Promotion of Global Warming Countermeasures, but these reported emissions have not been verified by third parties. If monetary value is to be bestowed in the form of emission allowances based on past emissions, reliable verification will surely be necessary to start with. In addition, more than 100 officials across the whole EU are believed to be implementing the EU ETS, including more than 40 officials in charge at the European Commission DG CLIMA (which has jurisdiction over the EU ETS), as well as more at the relevant departments within EU member states' governments for their national implementation. Even greater administrative costs are likely to be required for the design and introduction of the ETS, in addition to implementation.

The following issues surrounding the ETS also need to be addressed.

- Could a carbon tax initiative be suspended by the ETS introduction? How could the ETS be demarcated from a carbon tax?: It is hard to envisage a new carbon tax being raised under the present circumstances when soaring energy prices have become a social issue, but it is also difficult to imagine that the introduction of an ETS will bring about a complete halt to this initiative. Demarcation between the ETS and a carbon tax needs to be elaborated with the European counties' cases as a reference.
- Setting out the relationship with the Act on the Rational Use of Energy and the Act on the Promotion of Use of Non-fossil Energy Sources and Effective Use of Fossil Energy Materials by Energy Suppliers: As a matter specific to Japan, it is of course essential to set out the relationship between the ETS and existing legislation such as the Act on the Rational Use of Energy and the Act on the Promotion of Use of Non-fossil Energy Sources and Effective

Use of Fossil Energy Materials by Energy Suppliers, which have been built, developed and refined over the course of many years. Questions will no doubt arise as to whether officials themselves are ready to take up this task concerning the changes in these existing legislations.

- Burden on the public: When targeting the power sector, it will be essential to take into account the impacts that must be borne by the public, given the highly regressive nature of the burden of energy prices for households.

In any event, public and private sectors must push forward discussions sooner than later with firm resolution.

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Editor: Yoshihiko Omori

Publisher: The Institute of Energy Economics, Japan
Inui Bldg., Kachidoki, 13-1,
Kachidoki 1-chome, Chuo-ku, Tokyo
104-0054, Japan
e-mail: report@tky.ieej.or.jp

Please contact the editor for inquiry
e-mail: yoshihiko.omori@tky.ieej.or.jp

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