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Transition to Renewable Energy Society in Germany and the U.K.
- Historical paths to FIP and CfD Introduction and Implications for Japan -

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Contents

HELE Risks and Opportunities for Japanese Oil Industry◆

Yohei Kato*

Abstract

Japan's domestic oil demand is on a long-term downward trend. In addition, social and economic changes arise from covid-19 have further increased the uncertainty of oil demand, and climate change put stronger management pressure on the oil industry. However, the degree of impact varies from region to region around the world. Although there are many risks, we can find the regions with growing demand and opportunities in new fields such as renewable energy and decarbonization technologies.

This article will identify ways for Japanese oil industry to overcome this difficult situation by analyzing the prospect of different type of energy and the efforts of energy companies around the world.

In the short term, the Japanese oil industry needs to strengthen its domestic revenue base and expand overseas oil business, particularly in Asia, where demand is growing. There are also opportunities in the renewable energy sector, especially in offshore wind power. In the medium to long term, there is great potential for innovative technologies such as carbon recycling, so efforts in this area are also essential. Policy support and business collaboration are important to realize and maximize opportunities.

Key words: Japanese oil industry, renewable, carbon recycling, offshore wind, decarbonization

1. Introduction

The environment surrounding the Japanese oil industry is undergoing substantial changes. These changes include falling domestic demand for oil caused by a declining population, increased fuel efficiency of vehicles, and introduction of EVs, along with the worldwide trends toward combating climate change and decarbonization. Such environmental changes are necessitating major reforms in the Japanese oil industry, which until has been supported by stable, long-term demand.

While uncertainty about the future seems to be rising, this paper will identify the actual risks faced by the industry and analyze where opportunities may be found. Based on this, this paper will review the moves of each fossil fuel company to address these worldwide trends and review sectors where the Japanese oil industry can exploit its strengths. Through the examination of these points, this paper will reveal to which fields and based on what priority the Japanese oil industry should allocate resources and act accordingly.

2. Characteristics of the Oil Company Business and Risks

2-1. Characteristics of Japanese Oil Companies

First, this paper will examine the characteristics of Japanese oil companies. Looking at net sales by the segment of Japan’s two major oil companies (Idemitsu Kosan and ENEOS), 79.7% of Idemitsu Kosan’s net sales originate from petroleum, while the energy segment of ENEOS, which is different from Idemitsu Kosan in terms of the segment classification but is mainly composed of petroleum, accounts for 84.0% of its net sales (see Fig. 1 and 2). As a result, around 80% of the net sales of these oil companies come from petroleum, indicating that petroleum transactions account for an extremely large weighting of their businesses.

◆ This article is a presenting paper at the 37th Conference on Energy, Economy, and Environment that Japan Society of Energy and Resources (JSER) hosted.

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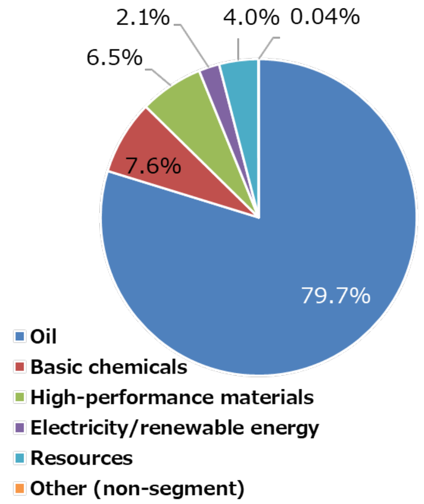

Fig. 1 Segment Sales (2019) of Idemitsu Kosan

Source: Compiled by the author based on securities reports

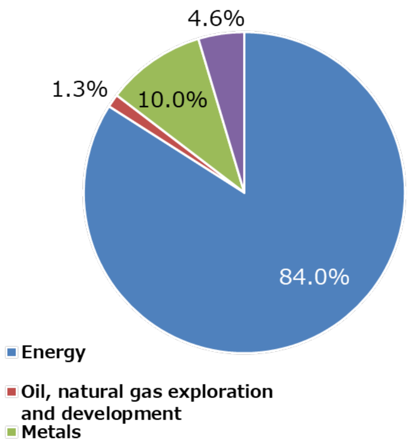

Fig. 2 Segment Sales (2019) of ENEOS

Source: Compiled by the author based on securities reports

Next, looking at net sales by region, Japan accounts for 78.4% of Idemitsu Kosan's net sales and 79% for ENEOS. This illustrates that the net sales of both companies lean greatly toward Japan (see Fig. 3 and 4). This is not a one-off in nature, but rather a similar trend has persisted looking back several years. As such, Japanese oil companies are highly dependent on petroleum sales in Japan.

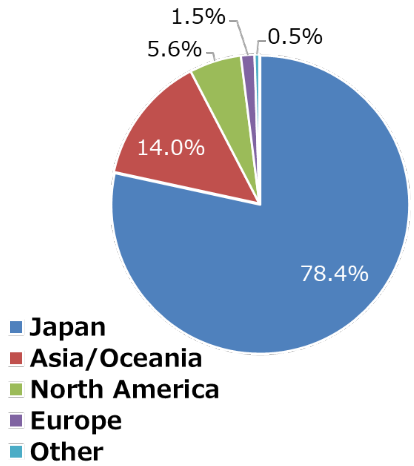

Fig. 3 Sales by Region (2019) of Idemitsu Kosan

Source: Compiled by the author based on securities reports

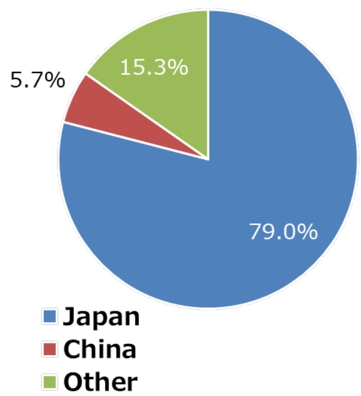

Fig. 4 Sales by Region (2019) of ENEOS

Source: Compiled by the author based on securities reports

2-2. Demand Trends for Oil in Japan

This section will look at demand trends in domestic oil products, which account for a large weighting of Japanese oil companies' business portfolios. Demand for petroleum products in Japan continues to decline driven by changes in the social structure including demographics, fuel conversion in response to the environment, and increasing fuel economy of vehicles. Demand has already peaked for all types of oil products. Demand for fuel oil overall peaked in FY1999 at 245.97 million KL, while demand for gasoline peaked in FY2004 at 61.48 million KL (see Table 1).

Table 1 Timing and Volume of Peak Oil Demand in Japan

Type	All fuel oil	Gasoline	Diesel
Year	1999	2004	1996
Quantity	245.97 million KL	61.48 million KL	46.06 million KL
Type	**Kerosene**	**Heavy Oil A**	**Heavy Oil C**
Year	2002	2002	1973
Quantity	30.62 million KL	30.14 million KL	110.00 million KL

Source: Created by the author based on statistics on resources and energy, Ministry of Economy, Trade and Industry

Demand will continue to decline even in short-term forecasts. The forecast for the demand for oil products released by the Ministry of Economy, Trade and Industry (METI)[1] says that demand for all types of oil products will decline on average by 1.3% per annum until 2023. Diesel will only see a rate of decline of 0.2% until 2023 because of cargo transport volumes, but demand for gasoline is expected to decline by an average of 2.2% per annum until 2023 due to improvements in fuel economy and declining in the number of miles driven by passenger vehicles. The domestic market, which accounts for a majority of Japanese oil companies' net sales, will continue to shrink, and the business environment is expected to become even more severe.

As for the long-term forecast, according to the Institute of Energy Economics, Japan (IEEJ) Outlook 2020[2], the final consumption of oil will gradually decline from 150 Mtoe in 2017 in both the Reference Scenario and the Advanced Technologies Scenario[3] As of 2050, demand will range between 83Mtoe and 95Mtoe, marking a loss of between 40 and 50% over around 30 years. Therefore, there are limitations posed by a business portfolio based on the domestic market alone.

2-3. The Trend of Climate Change Countermeasures

The adoption of the Paris Agreement in 2015 created two common long-term goals for the world. The first is to keep a global temperature rise in this century well below 2 degrees Celsius above pre-industrial level and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius. To that end, second is to undertake rapid reductions of emissions in order to achieve a balance between emissions by sources and removals by sinks (e.g. forest) of greenhouse gases in the second half of the 21st century. This has resulted in the major trend of low carbon or decarbonization, causing changes in various aspects of social trends including policy, popular will, and finance. Within this trend, initiatives are being created that will put pressure on fossil fuel companies (see Table 2).

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[1] Ministry of Economy, Trade and Industry, Fuel Oil Working Group, Oil Demand Assumption Study Group, March 29, 2019. Accessed October 19, 2020. https://www.meti.go.jp/shingikai/enecho/shigen_nenryo/sekiyu_gas/sekiyu_shijo/pdf/006_02_00.pdf.

[2] The Institute of Energy Economics, Japan (2019). "IEEJ Outlook2020."

[3] The Reference Scenario is a scenario in which the trending changes thus far are continued amidst the background of energy and environmental policies to date. There is no radical energy conservation or low carbon policy launched (business as usual). The Advanced Technologies Scenario is a scenario in which each country sets out robust energy and environmental policies in order to secure a stable energy supply and strengthen climate change countermeasures, leading to maximizing the success of the policies.

Table 2 Examples of Decarbonization and Low Carbonization Initiatives

Initiative	Detail
RE100	An initiative launched in 2014 with the objective for member corporations to switch to 100% renewable energy in powering their business operations. The trend for businesses to urge their suppliers and clients to switch to renewable energy, in addition to their own companies, is also seen.
Science Based Targets (SBT)	An initiative that involves establishing a carbon dioxide emissions reduction target based on scientific evidence in order to limit the rise in the global average temperature to well below 2°C above pre-industrial levels.
Climate Action100+	A global initiative for institutional investors to conduct constructive dialogue on information disclosure and efforts aimed at reducing greenhouse gas emissions with corporations that possess large influence in addressing global environmental issues.
Carbon Disclosure Project (CDP)	The project strives to disclose the status of environmental initiatives undertaken by businesses using a common measure through the collection of information via the survey on emissions reduction and climate change related initiatives of major global companies, and analysis and evaluation of the survey responses. Its focus is on the collection and disclosure of climate change-related information of concern to institutional investors.
Task Force on Climate-related Financial Disclosures (TCFD)	The TCFD was established by the Financial Stability Board (FSB) at the request of the G20 in order to examine how to disclose climate-related information and the response of financial institutions. It issued recommendations to companies regarding governance, strategy, risk management, and metrics and targets concerning climate-related risks and opportunities.

Source: Compiled by the author based on various reference materials

3. Future Growth Markets

3-1. Energy Demand Trends of Japan

The previous section shed light on the risks facing Japanese oil companies. Next, this paper will identify the growth fields in Japan while reviewing the situation for each energy source from IEEJ Outlook 2020. First to focus on is electricity. The ratio of electricity in final energy consumption (electrification rate, hereinafter) is growing by a substantial amount, and it will increase for both the Reference Scenario and Advanced Technologies Scenario up to 2050. This ratio will rise from 28% in 2017 to 32% by 2030, 34% to 35% by 2040 and 38% to 39% by 2050, showing that the importance of electricity will continue growing.

Next, the outlook for primary energy consumption in Japan indicates that it will continue declining following the country's declining population. Also, the usage amount of fossil fuels will fall due to measures to combat climate change. Oil demand will decline from 176 Mtoe in 2017 to 105 Mtoe by 2050 (92 Mtoe in the Advanced Technologies Scenario), representing a 40 to 50% drop. Coal demand will drop from 116 Mtoe in 2017 to 79 Mtoe by 2050 (39 Mtoe in the Advanced Technologies Scenario), or between 30 and 70%. Natural gas demand will fall from 111 Mtoe in 2017 to 72 Mtoe by 2050 (38 Mtoe in the Advanced Technologies Scenario), or between 40% and 60%. Meanwhile, among renewable energies, solar and wind power will increase from 5.5 Mtoe in 2017 to 16 Mtoe (38 Mtoe in the Advanced Technologies Scenario), for an increase of between 3 and 7 times (see Fig. 5).

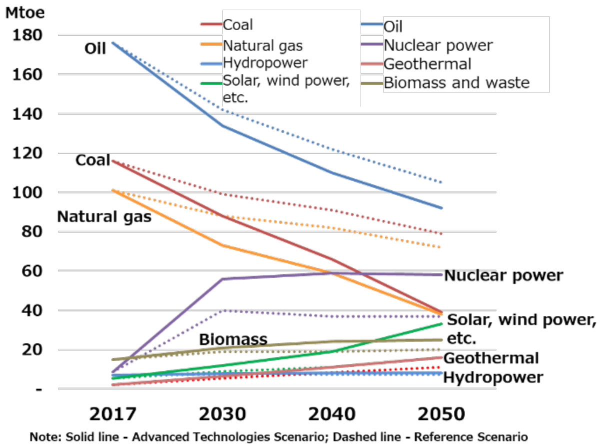

Fig. 5 Long-term Outlook for Primary Energy Consumption (Japan)

Source: Compiled by the author based on IEEJ Outlook 2020

Japan's declining population and depopulation of rural areas will make it difficult to maintain its energy network. However, this trend will further promote the use of electricity and may further grow demand for solar and wind power (offshore wind power in the future) as distributed energy.

Demand for fossil fuels will decline largely, but even in the Advanced Technologies Scenario, oil will remain the largest energy source as of 2050. For this reason, consideration will need to be given to the point that oil will retain its importance.

Based on the above, Table 3 shows the results of an evaluation and summary of the growth potential of each energy source. The importance of oil will remain, but in Japan electrification of demand will rise, and renewable energy, which is expected to grow, will become a growth field.

Table 3 Evaluation of Growth Potential by Energy Source (Japan)

	Evaluation (Growth potential)	Outlook for 2050	Challenges
Renewable Energy	Excellent	Growing demand, especially large growth in solar power and wind power	Decrease in suitable land Output volatility, integration cost
Nuclear and Water Power	Poor	Nuclear power: Increase Hydro power: Marginal change	Maintenance and updates New investment Safety and economic efficiency
Natural Gas	Poor	While demand is expected to increase due to the possibility of alternatives to coal-fired power and demand for city gas, it will gradually decrease in the long run.	Alternatives to coal-fired power City gas demand supplement View of gas as a fossil fuel
Oil	Poor	Downward trend due to decreasing population, increasing fuel cost and stronger EV growth. Slight decrease also expected in demand for petrochemicals.	Speed of EV development Competitiveness of refineries
Coal	Bad	Large decrease due to increased replacement of non-efficient coal-fired power	Decreased coal-fired power generation Divestment of steel manufacturing process

Source: Compiled by the author based on various reference materials

3-2. Worldwide Energy Demand Trends

Next, this section will look at worldwide demand. The outlook differs for Japan and international markets, and demand trends for energy also vary by region. In the Reference Scenario, primary energy consumption grows on the back of rising populations around the world. Natural gas demand is expected to increase from 3,107 Mtoe in 2017 to 5,165 Mtoe by 2050, up about 1.7 times, and oil demand is also forecast to increase by a large amount from 4,449 Mtoe in 2017 to 5,707 Mtoe, up about 1.3 times. In the Advanced Technologies Scenario, energy conservation and climate change measures will cause primary energy consumption to decline by 2,842 Mtoe compared to the Reference Scenario for 2050, but still, increase overall. In addition, while demand for renewable energy will increase, coal demand will drop substantially. Demand for oil will peak in 2030 and for gas in the first half of the 2040s. Nevertheless, similar to Japan, oil will remain the largest energy source even as of 2050 (see Fig. 6).

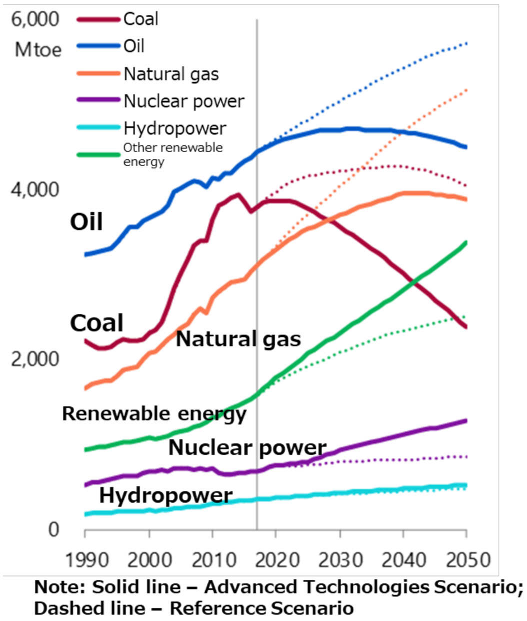

Fig. 6 Long-term Outlook of Primary Energy Consumption (World)

Source: IEEJ Outlook 2020

The driver of demand will be Asia with its huge population and high growth potential. In contrast, demand will decline in developed countries including the OECD. The importance of electricity will continue to grow worldwide. The amount of power generation in the world will continue to increase from 25,606 TWh in 2017 to 45,361 TWh by 2050 in the Reference Scenario, representing an increase of about 1.8 times. The electrification rate of demand also will rise from 19% in 2017 to 26% by 2050. This trend remains largely the same as with the Advanced Technologies Scenario. The increase in power generation will see electricity demand covered by natural gas-fired thermal power and renewable energy, with the role of coal remaining in emerging countries.

Let us now look at the cost structure of renewable energy covering this increase in electricity. According to IRENA, power generation cost by renewable energy is declining worldwide[4]. Photovoltaic power has declined around 80% from 0.378 USD/kWh in 2010 to 0.068 USD/kWh. Similarly, onshore wind power has fallen from 0.086 USD/kWh to 0.053 USD/kWh, or down around 40%. Installed capacity from renewable energy will continue to rise due to declining costs and climate change measures.

[4] International Renewable Energy Agency (2019). "Renewable Power Generation Cost in 2019," pp. 22-23.

However, the large-scale introduction of renewable energy faces the challenges of cost for addressing the variable nature of output and difficulty in satisfying demand for high temperature heat required by industry. Renewable energy is an extremely important energy source for decarbonization, but it is not the only countermeasure. Initiatives other than renewable energy will become necessary.

Table 4 presents the results of an evaluation by energy source based on future growth potential. The overarching trend will be for coal to be replaced by renewable energy. As such, renewable energy will continue to grow going forward. Meanwhile, particularly in Asia, demand for fossil fuels including coal will grow and oil will continue to increase in importance. Since the situation will differ by energy source and region, it will be necessary to consider strategy with a good understanding of areas and energy sources.

Table 4 Evaluation of Growth Potential of Each Energy Source (World)

Energy Source	Reference Scenario	Advanced Technologies Scenario	Outlook for 2025	Challenges
Renewable Energy	Excellent	Excellent	Major growth as the pillar of measures against climate change, also partly due to declining cost.	Excessive competition Integration cost
Nuclear and Hydro Power	Good	Good	Demand expands with switch to electricity, but not at the same level as renewable energy. Development of new nuclear power plants such as SMR.	Maintenance and updates Difficulty in establishing new facilities Safety and economic efficiency
Natural Gas	Excellent	Good	Demand expected to increase as a relatively clean fossil fuel.	Adaptation in developing countries View of gas as a fossil fuel
Oil	Excellent	Good	Demand remains in the transportation sector, especially in developing countries.	Development of fuel efficient vehicles and EV
Coal	Poor	Bad	Solid demand in Asia. Possibility of a sudden decrease due to the pressure to reduce.	Non-coal fired power Divestment

Source: Compiled by the author based on IEEJ Outlook 2020

4. Examples of Responses by the World's Fossil Fuel Companies

As pressure for lower carbon and decarbonization increases, what types of strategy will the world's fossil fuel companies implement? This section will examine their responses to change and identify the options that the Japanese oil industry can model their initiatives going forward.

4-1. Oil Majors[5, 6]

First, the main responses of the world's oil majors focused on this section are summarized below (see Table 5).

(1) Shell

Shell is moving ahead with energy conversion, having established ambitious decarbonization targets and policy. It announced a target to achieve net zero emissions of greenhouse gases by 2050 (Scope 1 and Scope 2 – aiming to achieve net zero emissions from its own product manufacturing). In this manner, Shell appears committed to strengthening initiatives to address climate change issues. Furthermore, it aims to reduce GHG emissions from energy products it sells (Scope 3) 30% by 2035 and 65% by 2050.

[5] Koto, Taihei (JOGMEC Research Department) (May 2020). "Energy Transition Strategy of Major Companies."
[6] Furukawa, Rie (JOGMEC Research Department) (May 2018). "Portfolio Strategy of Major Companies.

Upstream, Shell is strengthening its gas business in particular, shifting from oil to gas. In 2016, it acquired BG Group of the UK, enhancing its trading functions and expanding its value chain to the mid and downstream. Shell accounts for the world's largest share of LNG supply as a private-sector company.

In renewable energy, Shell is focusing particularly on wind power, with projects being promoted in North America and the Netherlands. In 2020, it commenced construction of an offshore wind farm in the Netherlands without subsidies together with Eneco (the Netherlands). Recently, Shell has also been moving ahead with the development of floating offshore wind power.

Shell is working to grow its EV charging network as well. In 2017, it acquired NewMotion (the Netherlands) and now owns Europe's largest charging network.

Shell is also actively moving ahead with its carbon capture and storage (CCS) business, implementing projects and research and development in Australia, Canada and Norway, among other countries. Shell also participates in The Oil and Gas Initiative (OGCI)[7] through which it promotes carbon storage and utilization.

Table 5 Initiatives of Oil Majors

	Shell	BP	Total	ExxonMobil	Chevron
Decarbonization target	2050 Net Zero Scope 1-3 Targets	2050 Net Zero Scope 1-3 Targets	2050 Net Zero Scope 1-3 Targets	Scope 1-2 Targets	Scope 1-2 Targets
Natural gas business	Acquired BG Group (UK) Enhancing value chain	Emphasis on focus areas, profitability and low GHG emissions	Acquired Engie (France) Strengthening value chain	Stepping up efforts	Stepping up efforts
Wind and solar power business	Increasing offshore wind power Solar power in the U.S. and Brazil	Strength in wind power in the U.S. Acquired Lightsource,(France) the largest solar company in Europe	Focusing on solar business Acquired Eren (France) and a joint project with Macquarie (Australia) in the wind power business	No prominent assets	Stepping up efforts through a partnership with Algonquin (Canada)
Bio-fuel business	Initiatives in Brazil	Initiatives in Brazil	Bio diesel Bio jet fuel	Algae refining project	Bio diesel Bio jet fuel
EV, storage battery and hydrogen	Largest EV charging network in Europe Expanding hydrogen sales network	Expanding charging network with DiDi (China) and joint venture with Reliance (India) Expanding investment in hydrogen	Acquired Saft (France) Constructing the largest battery storage facility in France	Research on hydrogen power generation with fuel cells	Development of hydrogen stations
CCS business	Stepping up efforts Northern lights project	Stepping up efforts	Stepping up efforts Northern lights project	Stepping up efforts	Major CCS initiative in Australia, and research on direct air capture (DAC)
Alliance affiliation	OGCI member	OGCI member	OGCI member	OGCI member	OGCI member
In-house carbon pricing	Implemented	Implemented	Implemented	Implemented	Implemented
Compensation-linked environmental targets	Present	Present	Present	Not present	Present

Source: Compiled by the author based on various reference materials.

(2) BP

BP has also set ambitious targets. It aims for net zero emissions of greenhouse gases across all of its businesses by 2050. In addition, BP is working to reduce carbon intensity of the energy products it sells by 50%. Furthermore, according to its

7 Oil and Gas Climate Initiative (OGGI) is an initiative launched by global major oil and gas companies to promote measures against climate change. There is a total of 13-member companies, including BP, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental Petroleum, Pemex, Petrobras, Repsol, Saudi Aramco, Shell, and Total.

clean energy transformation plan announced in August 2020, BP plans to cut oil and gas output by 40% by 2030 compared to 2019.[8] Also, it plans to expand investment in fields such as renewable energy, CCS, and hydrogen to 5 billion US dollars per annum.

Upstream, BP positions natural gas and LNG as core sectors, while focusing on production at assets with high profitability and low greenhouse gas emissions.

In regard to renewable energy, BP has become the main player in wind power in the United States. In 2020, BP acquired wind power assets on the East Coast from Equinor (Norway), strengthening its wind power business.

In addition, BP is also focusing on EV related businesses. BP established a joint venture company with DiDi, a major vehicle hire app in China, and is working to expand its charging network. In 2019, BP entered the fuel retailing business in India and established a joint venture company with Reliance, with a plan to build EV charging stations in the country. In 2020, it was working to build rapid charging stations in Germany as well.

BP's new CEO Bernard Looney, who took over in February 2020, is stepping up initiatives toward decarbonization and carbon reduction in rapid succession. He has announced a concept of shifting from an International Oil Company (IOC) to an Integrated Energy Company (IEO).

(3) Total

The total has also established ambitious targets. With the goal to become net zero in its operations around the world by 2050 (Scope 1 and 2), it aims to achieve net zero emissions in Europe including emissions from customer use of the products it sells (Scope 3).[9]

In 2017, Total acquired Engie, a French utility company. It is seeking to grow and optimize in each domain of the LNG value chain, and is committed to expanding its gas business in all domains from upstream, including gas-fired thermal power generation and bunkering, to downstream.

As for the renewable energy business, Total is focusing on the solar business in particular, and in 2011 it acquired SunPower of France, which at the time was the third largest solar company in the world. It is also developing the business in the United States, Mexico, South Africa, Chile, and other countries. In 2019, Total approved a large-scale project with Marubeni in Qatar in the Middle East, and it has made inroads into Spain as well. It has also entered the solar power generation market in Japan. Furthermore, Total entered the wind power business in 2017 with its acquisition of Eren of France. In 2020, it announced that it would take part in an offshore wind farm project of South Korea together with Macquarie of Australia. In October 2020, Total announced that it would spend 3 billion US dollars with the aim of increasing investment in its power division including renewable energy to more than 20% of total capital investment.[10]

Total also has a storage battery business. In 2019, it commenced construction on the largest storage battery facility in France. In 2020, Total created a joint venture company for in-vehicle storage batteries with Groupe PSA of France, which is a global car manufacturer. Total is strengthening its presence in EV charging networks, with the acquisition of the UK's

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[8] British Petroleum PR (August 2020). "Strategy Overview." Accessed October 19, 2020. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/investors/2q-strategy-2020-bernard-looney-strategy-overview.pdf.

[9] Total (May 2020). "Total adopts a new climate ambition to get to net zero 2050." Accessed October 19, 2020. https://www.total.com/media/news/total-adopts-new-climate-ambition-get-net-zero-2050

[10] Total PR (September 2020). "2020 strategy & outlook presentation." Accessed October 19, 2020. https://www.total.com/media/news/press-releases/2020-strategy-outlook-presentation

largest EV charging network (Bluepoint London) in 2020 and other initiatives. Total is also actively working on CCS and CCUS, having identified their importance.

Total's CEO Pouyanne says, "Total aims to sell energy," indicating the company is seeking to become a supplier of a wide range of energy.

(4) ExxonMobil

ExxonMobile is taking a somewhat different approach than European oil majors. It is focusing on deep sea resource exploration and development as well as upstream development for LNG, etc. In addition, it does not have any prominent assets in terms of renewable energy.

As a response to the environment, ExxonMobile is focusing on the development of low carbon technologies and bio fuels. As for low carbon technologies, it is working to reduce greenhouse gases in upstream oil and natural gas exploration and development processes. Among these, ExxonMobile is developing methane emissions monitoring technology and emission reduction technology. In terms of bio fuels, it is conducting R&D into algae-derived bio fuels, continuing research aimed at large-scale production. It is also conducting CCS research and development.

(5) Chevron

Chevron is investing in CCS technology, including large-scale CCS for an LNG project in Australia, becoming actively involved in this area. It has also established targets for reducing flaring during development processes and lowering methane emissions. With an eye on the future, Chevron is engaging in EV charging station networks and direct air capture (DAC) of CO2. In addition, Chevron is involved in the technological development of renewable fuels such as bio diesel and bio jet fuel.

4-2. Oil Refinery Companies

Next, this section will look at developments among the world's refiners. First is SK Innovations, South Korea's largest refiner. This company engages in businesses from upstream exploration and development to refining, chemicals, and lubricants. In recent years, SK Innovation has begun manufacturing batteries for EVs, making it the first in South Korea to establish a mass production system. Its production bases are located not only in South Korea, but also in China, Hungary and other locations. It plans to expand its manufacturing bases in Europe and China, while constructing a manufacturing base in the United States. It is also focusing on other businesses including information and electronic materials. In this manner, SK Innovation is offering new materials while utilizing its technical process from existing businesses.

Reliance of India is a conglomerate that engages mainly in petrochemicals but is also involved in oil and gas exploration and development, retail, infrastructure, and bio-technology, among other businesses. In retailing, it has become a leading player and India's largest retailer spanning foods, home electronics and fashion, etc. Reliance has also made inroads into other fields as well including digital services, media and entertainment. It has a presence in mobile data networks, contents, and movie-related entertainment domains, which have grown to the point of accounting for around 20% of the company's earnings (FY2018). In this manner, Reliance is building up its business portfolio by expanding into fields outside of its core oil and chemicals businesses.

Finally, there is Valero of the United States. Valero is a dedicated oil refining company, with the largest oil refining capacity in the entire United States. It also operates refineries in Canada and the UK, and has a total capacity of 3.1 million b/d, making this single company on par with the 3.51 million b/d capacity of all Japanese refiners combined. Utilizing this refining capacity and operational capabilities, Valero is not only selling products downstream, but also optimizing product exports to demand areas from its portfolio across the Atlantic. In this way, Valero has built a business model that generates massive profits by trading with regions including Europe and Latin America. Valero is also focusing on biodiesel and bioethanol businesses. It supplies these to California, with its growing environmental awareness, as well as to premium low carbon markets in Canada and Europe. Valero is using existing assets of its own business for trading, etc. to generate profits.

4-3. Mineral Resource Companies

As a reference for the response to coal assets, this section reviews the moves of mineral resource companies. Starting with Glencore of Switzerland, it is a multinational company engaging in mine development and commodity trading. Its business fields are wide ranging and include metals (copper, zinc, lead, nickel and alloys, etc.), energy (coal and oil) and agricultural products. Up to 2018, the company had expanded its coal business around the world, but in 2019 it announced the plan to restrict its current level of coal production output and not to expand it any further. It has also not denied the possibility of divesting its coal assets. Glencore foresees growth fields to be mineral and metals to satisfy the demand for fuel cells and EVs.

Peabody of North America is the largest coal company in the United States. After filing for bankruptcy in 2016, Peabody restructured and emerged in 2017 after shrinking the size of its operations. The reason for its bankruptcy was the increased use of natural gas following the shale boom in the United States, causing the shift from coal to natural gas in power generation, and an increase of renewable energy following a decline in prices. Peabody is working to promote understanding about the role of coal in electricity and steel making, and intending to expand usage of progressive coal-related technologies including HELE technology[11] and develop CCUS technologies. Until now, the thermal coal business in the United States has been Peabody's core business, but it plans to expand the coking coal business going forward.

Rio Tinto is a multinational corporate group based in the UK and Australia engaged in mining and resource fields. It is an integrated resource company with operations in coal, uranium and diamonds, etc., in addition to iron ore and non-ferrous metals. Its coal business was located in Australia, the United States and Mozambique in Africa. However, citing little hope for stable profits, it exited the United States in 2011 and sold off its Mozambique coal assets in 2014. In 2018, it sold all of its coal concessions in Australia, marking the complete exit from the coal business. Rio Tinto was the first major mineral resource company to exit the coal business. Rio Tinto says it will allocate its portfolio to fields such as lithium used as a raw material for storage batteries and aluminum for vehicle development, leading to improved fuel economy.

BHP Billiton, based in the UK and Australia, is the world's largest mining company. It has operations in iron, coal, oil, other metals such as bauxite, and mining products. BHP Billiton is the world's largest supplier of coking coal, and it has thermal coal operations in Australia and Colombia. In 2019, it indicated that it would exit the thermal coal business in the near future.

Mineral resource companies have shown their future direction in the form of exiting the coal business, restricting production output, and shifting to coking coal, indicating they are attempting to respond to environmental concerns and rising pressure for decarbonization. In addition, it has also been found that these companies are paying closer attention to minerals related to fuel cells and EVs.

5. Review of Countermeasures of the Japanese Oil Industry

The above overview of the initiatives promoted by each company has provided several options that Japanese oil companies should consider. European companies are carrying out a broad range of efforts toward long-term goals while

[11] HELE are technologies that offer high-efficiency and low emissions.

announcing ambitious targets. In terms of other refiners, companies are engaging in new materials such as storage batteries and electronic materials, strengthening surrounding domains such as retailing and digital services, and carrying out initiatives utilizing existing assets, such as trading. As for coal, companies are shifting to coking coal or restricting production output, or exiting altogether, indicating a direction of the restraining business while working on higher value products. Implementing all of these options at the same time is unrealistic, so the priority ranking of these initiatives for the Japanese oil industry will be considered in the sections below.

5-1. Review of Countermeasures Based on the Market Potential of Each Sector

Section 1 and Section 2 of this paper revealed the major regional differences in the market potential of each energy form. In light of this point, the current section will put a new focus on the market potential of each energy source. Looking at compatibility with the resources of the Japanese oil industry at the same time, the keys to success for the industry will be explored in terms of which region and sector the industry should prioritize.

Table 6 contains the regional market potential of each energy source and the compatibility of low carbon and decarbonization technologies with the oil industry. Regarding compatibility, naturally, oil has the greatest compatibility, while for natural gas, coal and renewable energy, evaluations are "poor to good" because of the different situation of each oil company. The evaluation for important low carbon and decarbonization technologies is "poor" because they are still not superior as of the current point in time. Looking at the market potential, oil will decline in Japan, but the scale of the oil business in Japan is large and its importance will continue to remain. In addition, in Asia forecasts predict growth in oil demand, indicating Japanese oil companies should expand into the region. Meanwhile, given the market potential and compatibility of natural gas and coal, these sectors do not offer good options as countermeasures. Although compatibility is not high for renewable energy and low carbon technologies, growth in these sectors is expected in Japan, Asia and developed countries, so Japanese oil companies should look to these sectors.

Table 6 Regional Growth Potential and Compatibility of the Oil Industry by Energy Source

Field/Region	Future growth potential			Compatibility with oil industry resources
	Japan	Asia	Developed countries	
Oil	Poor	Good	Poor	Excellent
Natural gas	Poor	Good	Poor	Poor to Good
Coal	Bad	Poor	Bad	Poor to Good
Renewable energy	Excellent	Excellent	Good	Poor to Good
Low/decarbonization technology/products	Excellent	Excellent	Excellent	Poor

Source: Compiled by the author based on various reference materials

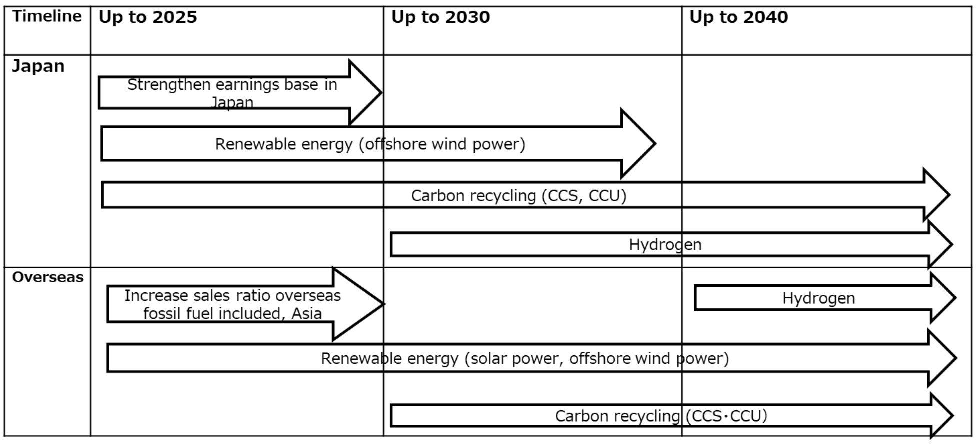
The key to the Japanese oil industry is strengthening its earnings base in Japan, its core market, despite declining demand, and at the same time selling oil product, which is still growing in the Asian market and increasing sales in overseas markets. Furthermore, the Japanese oil industry will need to address electrification while stepping up initiatives in the renewable energy sector which is expected to offer great market potential. As for renewable energy, the companies in the industry should focus particularly on offshore wind projects in Japan and making inroads into suitable markets mainly in Asia. Working on low carbonization and decarbonization technologies is essential to continue selling fossil fuels. Since technological development takes time, they should get involved from an early stage. Particularly, carbon recycling (CCS and CCU) not only reduces CO2, but is also considered to be an important initiative for the effective use of assets already owned by the oil industry.

5-2. Prioritization of Countermeasures

Next, the prioritization of countermeasures will be considered. Looking at the timeline, the time until 2025 will be classified as short-term, until 2030 medium-term and until 2040 long-term (see Table 7).

First, over the short term, Japanese oil companies should strengthen their earnings through their domestic oil product business. At the same time, to increase the share of overseas sales, they should expand into Asia in particular. In renewable energy, they should focus on offshore wind power in Japan, and address renewable energy and electrification. In addition, while it takes time for technological development, they should start on carbon recycling (CCS and CCU) with the expectation of long-term growth. Through these efforts, they can increase the share of overseas sales over the medium term and increase efforts for renewable energy and electricity. During this period, a certain timeline will be established for carbon recycling and the commercialization of hydrogen. In this manner, over the long term, Japanese oil companies should establish a corporate structure where new technologies and new businesses offset the decline in sales of fossil fuels.

Table 7 Prioritization of Countermeasures



5-3. SWOT Analysis

In this paper, SWOT analysis was conducted in order to consider which strengths specifically the Japanese oil industry should utilize in response to these countermeasures, and the results are summarized in Table 8. Utilizing the strengths outlined here will provide an important perspective in implementing countermeasures.

Table 8 SWOT Analysis of the Japanese Oil Industry

■Opportunity	・Increased demand in Asia ・Renewable energy ・Decarbonization, low carbonization technology (CCS, CCUS) ・Enhanced efficiency and customer contact points through digitization
■Threat	・Decreased demand due to population decline, EV, and switch to electrical power ・Pressure on fossil fuels from decarbonization
■Strength	・Track record of fulfilling responsibility of stable supply ・Nationwide service station network and distribution network ・Supplied energy together with the community ・Experience with handling complex process treatment and large volume of hazardous materials such as petroleum and petrochemicals ・Many years of business transactions with the Middle East ・Examples of expansion in Asia (lubricant, petrochemicals, fuel oil) ・Sales results overseas
■Weakness	・ Refinery: Aging facilities, which are also smaller than neighboring countries ・ Business scale: Inferior in scale to major companies ・ Response to change since it had enjoyed stable long-term demand and handled products without quality deterioration ・ Small business scale in sectors beside petroleum

Source: Compiled by the author based on various reference materials

6. Examination of Important Countermeasures

6-1. Domestic Oil Business

This section will delve deeper into several countermeasures that deserve attention. First, is the domestic oil business cited as a short-term initiative. The major underlying assumption will be the promotion of further enhancements of efficiencies following progress in business integration and an improved business environment. In addition, the utilization of digital technology and IoT will be necessary. For example, digital technology and IoT can be used to sustain oil supply of service stations required as a lifeline to marginal communities. In order to supplement oil demand of each household, sensors can be attached to each tank (heating oil, LP gas, etc.) to gather data. This data can, in turn, be analyzed to understand demand and carry out efficient delivery, which will secure a certain degree of demand for the supply side. Japanese oil companies will be able to explore the possibility of supply from locations with a slight distance from depopulated areas. For the demand side, there is also the merit of product delivery. Since regular communication will be created, there is the latent potential of regional revitalization and promoting peripheral businesses (i.e., businesses for seniors, etc.) through myriad consultative activities. With sensor performance and lower costs, if a system and agreement on data acquisition and cooperation with the community can be established, this will open the door to potential initiatives. Similarly, another possibility is that sensors can be attached to vehicle fuel tanks on a construction site to refuel those vehicles running low on fuel.

Even in urban centers, one approach may be to use service stations to appeal to people who find it inconvenient to fuel up. There is also the potential for marketing using customer contact points. Coupons can be utilized for each target using an app to encourage customers to visit service stations. In addition, there is the potential for data analysis to be used to conduct tailored approaches for each customer, leading to cross selling (which is to have customers purchase other products together) of non-oil products, car washes and vehicle inspections to increase sales. Customer time can be shortened as well by advancing digital payments and building a mechanism to complete payment when finished filling by linking the vehicle and pump at the time of filling.

6-2. Offshore Wind Power

The long-term outlook indicates that renewable energy is expected to grow, but within this sector, offshore wind power is an area of particular interest. Under the Fifth Strategic Energy Plan, Japan will aim to make renewable energy a mainstay power source while securing adjustment capabilities in response to lowering costs, grid constraints and the variable nature of output from renewable energy. Within this, wind power is expected to account for around 1.7% of the country's energy mix in 2030, with the installed capacity forecast being 10 GW, of which offshore wind power will account for 0.8 GW. With sites suited to the introduction of onshore wind power in short supply, the plan states that it will be vital to expanding the introduction of offshore wind power generation.[12]

The target for installed capacity in the Fifth Strategic Energy Plan is conservative, but Japan has the world's sixth largest exclusive economic zone, meaning there is a high potential for wind power in Japan. According to the Japan Wind Power Association, the potential for fixed offshore wind power is 128GW, while the potential for floating is 424GW.[13]

In Europe, the market leader, the cost of offshore wind power is declining due to the establishment of rules on the use of territorial waters and the introduction of a tender system. In Japan, the development of rules on the use of territorial waters had been an issue, but in 2019, the Act on Promotion of Use of Territorial Waters for Offshore Renewable Energy Generation Facilities (Offshore Wind Promotion Act) was established, providing positive headway in the development of the business environment. The Offshore Wind Promotion Act secures business stability by designating areas where the implementation of offshore wind power projects is feasible, selecting operators by public auction, creating a system enabling long-term exclusivity, and ensuring an exclusivity period (30 years) required including FIT period and necessary construction period before and after that. In addition, a committee was established to facilitate coordination with local communities. For designated development zones, discussions are held with relevant ministries and agencies, and the national government is involved in the coordination of first use, improving the predictability of business operators.[14] Moreover, the Act aims to lower costs through competition to make prices subject to public offering selection criteria. In July 2020, Noshiro City, Mitane Town, and offshore Oga City in Akita Prefecture, offshore Yurihonjo City (north and south) in Akita Prefecture, offshore Choshi City in Chiba Prefecture, and offshore Goto City in Nagasaki Prefecture were designated as four promotion areas.[15] The maximum tender price for three of these promotion areas was set at 29 yen/kWh in September 2020.

(1) Overview of Suggestion for Japanese Oil Companies

Offshore wind power is a technology with a small track record outside of Europe. Even in Europe, bottom-mounted offshore wind turbines are the mainstream (because of the geographic characteristic of extensive shallow waters), and there are few floating offshore wind turbine projects with the technology not having been established. The potential for wind power generation in Japan established by the Japan Wind Power Association suggests that floating offshore wind turbine is expected to become the mainstream because of the limited amount of shallow territorial waters with strong winds. Japanese oil companies should quickly establish a track record in Japan where it is easy for them to conduct business, and then expand into Asia because of its locational advantages. There are expected needs in Asia's developing countries because of growing interest in the environment and climate. The potential for expanding offshore wind power includes (1) supply of renewable

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[12] Ministry of Economy, Trade and Industry (July 2018). "The Fifth Strategic Energy Plan." Accessed October 19, 2020. https://www.meti.go.jp/press/2018/07/20180703001/20180703001-1.pdf

[13] Japan Wind Power Association (July 2020). "Making Offshore Wind Energy the Primary Source of Energy." Accessed October 19, 2020. https://www.meti.go.jp/shingikai/energy_environment/yojo_furyoku/pdf/001_04_01.pdf

[14] Ministry of Economy, Trade and Industry (December 2019). "Act on Promotion of Use of Territorial Waters for Offshore Renewable Energy Generation Facilities." Accessed October 19, 2020. http://www.pref.hokkaido.lg.jp/kz/kke/yojoshiryou1.pdf

[15] Ministry of Economy, Trade and Industry PR (July 2020). "Sea Areas as Project Target Areas Designated under the Act on Promotion of Use of Territorial Waters for Offshore Renewable Energy Generation Facilities." Accessed October 19, 2020. https://www.meti.go.jp/press/2020/07/20200721005/20200721005.html

electricity; (2) lower carbon emissions of oil business; and (3) hydrogen production. Lowering carbon emissions of the oil business involves supplying electricity to oil fields at the time of upstream exploration and development. In addition, hydrogen production is a potential long-term approach that uses electricity generated for hydrogen production even when there are grid connectivity constraints.

(2) Specific Action Plan

At the current point in time, the Japanese oil industry lacks the knowledge to engage in the development of offshore wind projects on a standalone basis. Therefore, it will need to find the right partners while utilizing its relationships with existing businesses to form a consortium. It will also be beneficial to participate in investments in overseas projects to increase experience and gain know-how while working with European companies including those bottom-mounted offshore turbine projects. At the same time, Japanese oil companies will need to build a track record in domestic projects. Additionally, using M&A could be an effective approach to accelerate initiatives by purchasing technologies and experience.

Key points of interest in moving ahead with this business will be the availability of transmission line connections and approaches. Given current challenges, the government is taking the lead in forming push-type transmission networks, and developments in this regard should be closely monitored. In addition, the economics will also need to be closely monitored as the transition from the FIT to FIP systems is making progress.

(3) Reason for the Japanese Oil Industry to Engage in Wind Power

In addition to business opportunities and the large potential of Japan, there are several areas promoting affinity with the Japanese oil industries' involvement in offshore wind power generation. Companies already have knowledge in onshore wind power, and the oil business is not area specific and companies have engaged in business nationwide, meaning they are capable of pursuing offshore wind power anywhere in Japan. They also have strengths in having engaged in business together with local companies and communities at their manufacturing bases including refineries throughout Japan. This experience is considered to be an advantage when engaging in the offshore wind power business in which one key point for success is to realize close working relationships with local stakeholders. As indicated in Table 9 below, there are examples of Japanese oil companies participating in offshore wind power projects both within and outside of Japan. These are expected to grow going forward.

Table 9 Examples of Wind Power Generation Projects involving the Japanese Oil Industry

Company	Examples
Idemitsu Kosan	・2019 Developed a 88,000 kW floating offshore wind turbine in Norway (also supplies power to the oil field of which the company holds rights)
ENEOS	・2019 Participated in offshore wind power generation project in Taiwan with an investment in a 640,000 kW offshore wind turbine (investment rate 6.75%) ・2020 Invested with Tohoku Electric Power in the Japan Renewable Energy offshore wind power generation project in Akita (tentatively 155,000 kW)
Cosmo Eco Power	・2019 Began environmental evaluation process for offshore wind power generation project off the coast of Ishikari, Hokkaido, 1 million kW

Source: Compiled by the author based on promotional materials of each company

6-3. Carbon Recycling

Carbon recycling is a medium- to long-term initiative worth noting. In this initiative, CO_2 emissions released into the atmosphere are reduced by separating, recovering and storing CO_2, and then the recovered CO_2 is considered as a resource that can be converted into materials or fuel by mineralization, artificial photosynthesis and methanation for reuse. As the reduction in CO_2 emissions is required in order to continue selling fossil fuels, carbon recycling is believed to be a necessary approach for the Japanese oil industry that contributes to climate change measures. Since it takes time to develop the technology, it is ideal to strengthen approaches at an early stage, leading to realizing the sale of carbon neutral oils in the future.

As outlined in the road map of the Carbon Recycling Promotion Office under the Ministry of Economy, Trade and Industry, there are two types of initiatives, namely short-term initiatives with the aim to achieve early penetration of carbon recycling, and other initiatives aiming for its medium- to long-term penetration.[16] Short-term initiatives include lowering costs for CO_2 separation, recovery, utilization, and storage, utilization in EOR,[17] as well as separation and recovery by each plant. Moreover, from a short-term perspective, it is desirable to begin replacements with alternatives that have a high added-value, with the sectors of chemicals (e.g. polycarbonates), liquid fuel (e.g. jet fuel), and concrete products (e.g. roadblocks) offering the most potential. In the medium- to long-term, it is viewed that initiatives will be expanded in general-purpose products with high demand.

(1) Required Steps and Approaches for Actualization

Looking strictly at CCS alone, there are only two cases of implementation in Japan. The first example is a demonstration test conducted in Nagaoka City, Niigata Prefecture in which 10,000 tons of CO_2 was stored in an aquifer during the period of 18 months starting in 2003.[18] The second example is a demonstration test conducted in Tomakomai, Hokkaido, which involved injecting CO_2 released from a hydrogen production facility within the Hokkaido Refinery of Idemitsu Kosan into a reservoir. A cumulative total of 300,000 tons has been injected and stored between 2016 and 2019, and the storage in the reservoir was confirmed to have remained stable even after the injection had stopped.[19] Going forward, the number of demonstration tests should increase with the development of technology for CO_2 separation, recovery and storage. Simultaneously, the development of conversion technology for CO_2 recovered should also be undertaken. During the stage of technological development, efforts to enhance economic efficiency, such as lowering the recovering cost of CO_2, are also sought after. At the same time, since CCS does not generate any profit, it is necessary to consider incentives for introducing CCS based on economic efficiency, as well as reviewing legal and tax structures, to support it.

(2) Other Challenges

It is possible to inject recovered CO_2 into oil wells after mining in countries that produce resources. However, since Japan is not a country that can conduct resource mining in its surrounding areas, there is limited space for CO_2 storage. Looking for a suitable storage location in the inland area of Japan, would require obtaining consent from the residents in the community, and incur a large cost, such as construction costs. For this reason, it is essential to also develop technology for undersea injection. Rather than seeking suitable locations for storage within Japan, it is also crucial to expanding businesses and cooperation with other oil producing countries. CCS will be implemented in oil producing countries to offset the imported crude oil. This allows oil companies to sell low carbon gasoline through carbon neutral crude oil. In addition, this

[16] Ministry of Economy, Trade and Industry Website (June 2019). "Roadmap for Carbon Cycling Technologies." Accessed October 19, 2020. https://www.meti.go.jp/press/2019/06/20190607002/20190607002-1.pdf

[17] EOR, short for Enhanced Oil Recovery, is an advanced recovery technology represented by CO2 injection method.

[18] The Research Institute of Innovative Technology for the Earth (RITE) Website. "Nagaoka CO2 Injection Demonstration Test." Accessed October 19, 2020. https://www.rite.or.jp/co2storage/safety/nagaoka/

[19] Ministry of Economy, Trade and Industry, NEDO, Japan CCS Survey (May 2020). "Report on Large-scale CCS Demonstration Test in Tomakomai City as of the Successful Injection of 300,000 tons of CO2 Underground (Comprehensive Report)." Accessed October 19, 2020. https://www.meti.go.jp/press/2020/05/20200515002/20200515002-2.pdf

initiative can be a win-win approach that enables oil producing countries to improve their crude oil recovery rate by using CO_2 in enhanced oil recovery technology, while avoiding stranded oil assets.

(3) Accessible Strengths of the Japanese Oil Industry

The Japanese oil industry has a long-standing business relationship with oil producing countries in the Middle East. The implementation of CCS and CCU with these countries, taking advantage of the trust relationship built through long-term transactions, is considered an approach that harnesses the strength of the oil industry. In addition, their long-standing experience in handling a large amount of petroleum products, as well as refining and manufacturing petrochemical products should serve as strengths leading to the development of CCU technology. Therefore, the Japanese oil industry should work more actively on CCS and CCU, enhance relevant expertise for future demand, and be involved in developing necessary technologies and systems.

6-4. Required Actions of Each Player

What initiatives are required of each relevant player in order to carry out the effective methods for improving the situation described above? Companies are first and foremost expected to make the best efforts in carrying out the activities that they can undertake as individual entities. To start, Japanese oil companies should actively engage in demonstration tests of carbon recycling, which requires long-term implementation. From there, with the development of technologies, these companies should sort out the systems needed to ensure profitability. Each company should also take a flexible approach in addressing their areas of deficiency (technical or financial) through collaboration with other companies (beyond their industry). In addition, it is necessary to consider forming partnerships and establishing a system with oil producing countries and overseas players. Moreover, these companies need an approach toward more actively communicating and collaborating with the government.

The commercialization of carbon recycling technology, which requires long-term efforts, is important not only for the Japanese oil industry but also the country's manufacturing industries as a whole. Therefore, the government should provide assistance to foster the advancement of technology. Some examples for consideration include, increasing the amount of research and development support, expanding the scale of demonstration test projects, and making arrangements for international demonstration test projects. Moreover, measures such as applying emissions reduction and making carbon pricing evaluation to carbon recycling can be effective in promoting commercialization. The government may also play the role of coordination (cases involving local governments, contents shared between ministries, projects across countries) and intermediary (for private companies to overcome obstacles in capital or human resources) in providing essential policy support.

7. Conclusion

The operating environment for Japan's oil industry is undergoing enormous change, with growing pressure on implementing measures for climate change and decarbonization. While domestic demand for oil decreases, the need for electricity and renewable energy is expected to grow in Japan. Globally, the outlook of demand differs by each region. In Asia, the increased demand will be met with fossil fuel, while renewable energy also increases.

Although there are various responses from fossil fuel companies, it is unrealistic to take measures addressing all directions. Therefore, it is desirable to implement measures in the order of priority with respect to time. For the short term, companies should secure their earnings base in Japan, where the industry has been reorganized. At the same time, companies can expand overseas to increase the share of overseas sales. From there, they should expand their efforts in renewable energy with particular attention to offshore wind power generation.

For the medium- to long-term, as efforts must be put into carbon recycling, companies need to carry out long-term initiatives to address various challenges in technical, geographical, and economic aspects. Collaboration on initiatives with the government and other companies both in Japan and overseas will become essential in order to overcome these challenges. The future of the Japanese oil industry lies in developing sustainability while working on each initiative, leveraging each company's strengths.

A Study on the Effects of Negative Emission Technologies on Alleviating the CO_2 Abatement Cost◆

Yasuaki Kawakami*

Abstract

As global attention increasingly turns to a decarbonized energy system, the government of Japan has set a long-term greenhouse gas reduction target of realizing a carbon-neutral energy system as soon as possible in the second half of the century. Since some energy sectors such as industry and transport are heavily dependent on fossil fuels and cannot easily switch to electricity, negative emission technologies such as bio-energy with carbon capture and storage (BECCS) and CO_2 direct air capture and storage (DACS) have attracted attention as a means of accomplishing carbon neutrality. This paper presents the effects of negative emission technologies on alleviating the CO_2 abatement cost using a bottom-up energy system optimization model which incorporates a high-temporal-resolution power sector. Seven scenarios for a decarbonized energy system ranging from 80% to 100% CO_2 reduction in Japan are modeled for 2050. Simulation results reveal that the use of BECCS could alleviate the CO_2 marginal abatement cost in 2050 by 10,000 yen per tonne of CO_2 in the 80% reduction scenario and that the effect would grow as severer decarbonization targets are imposed. Furthermore, it is found that to reduce CO_2 by more than 90%, it is essential to install negative emission technologies.

Key words: BECCS, DACS, Battery Installation, Variable Renewables, Energy System Optimization Model

1. Introduction

Japan has presented a goal of reaching carbon neutrality as soon as possible in the second half of this century under its Long-Term Strategy under the Paris Agreement released in 2019, and in October 2020, Prime Minister Suga declared a goal of achieving net-zero greenhouse gas emissions (GHG) by 2050. While Japan is heading toward large-scale decarbonization of its energy system, abandoning fossil fuels is not easy for sectors such as transport (particularly aviation) and parts of industry (such as steel). To achieve carbon neutrality while allowing CO_2 emissions from those sectors where it is extremely difficult to eliminate emissions, it is essential to introduce negative emission technologies such as biomass-fired power with CCS (BECCS). Thus, it is important to quantitatively analyze their roles in pursuing carbon neutrality of Japan's energy system.

In addition to being a negative emission technology, another notable feature of BECCS is that it is a thermal power source that allows dispatchable operation and provides synchronous inertia and can therefore contribute to power system stability when large amounts of variable renewable electricity (VRE) sources are introduced in the future. However, steam power generation, a widely-used generation technology for solid biomass fuels, has a somewhat lower output adjustment capability compared to gas turbine generation. In analyzing the role of BECCS in decarbonizing the energy system, it is important to consider these characteristics of BECCS as a thermal power source and its ability to replace and/or complement other zero-emission power sources, and vice versa. Using an energy system optimization model suited for this purpose, this study analyzes the roles of BECCS and other negative emission technologies in achieving the reduction target and alleviating the abatement cost as Japan pursues large-scale decarbonization of its energy system by 2050. Previous studies on BECCS as a decarbonization technology include an analysis on Japan using a TIMES model with a relatively simplified power sector[1],

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[1] E. Kato, A. Kurosawa: Evaluation of Japanese energy system toward 2050 with TIMES-Japan – deep decarbonization pathways, Energy Procedia, 158(2019), pp. 4141–4146.

and analysis on the feasibility of achieving a carbon-neutral power system in Europe, using a mixed integer programming model and targeting only the power sector[2]. The novelty of this study is that it analyzes the large-scale decarbonization, including 2050 carbon neutrality, of Japan focusing on negative emission technologies using an energy system optimization model that incorporates a highly detailed power sector, as Japan becomes increasingly committed to reaching carbon neutrality in reality.

2. Analytical Framework

This analysis used an energy system optimization model[3,4] which the author has developed and used in previous studies, with a more detailed biomass power generation model incorporated for this analysis. It is a dynamic linear programming model that minimizes the discounted total energy system costs, which is the objective function, over the analysis period under multiple constraints. The power sector and electrolyzed hydrogen supply were modeled with an hourly time resolution (8,760 time slices per year). The analysis was conducted for the period up to 2050 (at 5-year intervals starting from 2015) for 5 regions (Hokkaido, Tohoku, Kanto, West Japan, and Kyushu).

One type of steam power generation was adopted for biomass thermal power assuming the use of solid fuel, and, as with other thermal power technologies, the minimum output constraint, annual maintenance scheduling, load-following capability constraint, and percentage of DSS operation, etc. were taken into account. Since the total CO_2 emissions from biomass over its lifecycle are considered to be neutral regardless of combustion, the emissions from biomass would be net negative by collecting and storing the emissions from combustion.

Other negative emission technologies such as the combination of direct air capture (DAC) and storage (hereafter, DACS) were also considered. Furthermore, CCU technologies such as FT synthesis, methanation, and methanol production were considered though they are not negative emission technologies. CCU technologies for non-energy use were not considered.

3. Assumptions

3-1. Assumptions about biomass power

The following assumptions were made regarding the performance of the biomass power technology based on Reference 2 and others: maximum load-following capability (versus rated output) of 36% hour^{-1}, generator-end efficiency of 38%, minimum output rate of 30% and DSS operation of 0%. Generation costs and the service life of facilities were set based on Reference 5. The cost for domestic biomass supply was set based on Reference 6, and the maximum amount of supply was set to 90 PJ year^{-1}. The cost for imported biomass supply was set to 831 yen/GJ^{-1} [7] and the maximum amount of supply to 406 PJ year^{-1}. This maximum amount is equivalent to 24 million tonnes[8], which equals the global trade quantity of wood pellets in 2018. We assumed that this amount of wood pellets would be available in Japan by 2050 because wood pellet production is growing and supplies are likely to increase as demand rises, and considering that other biomass fuels also exist. See Reference 4 for other assumptions for the power sector (such as the specifications of power generation and storage technologies, maximum new VRE capacities, transmission line capacity, and constraints on the use of nuclear power).

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[2] W. Zappa, M. Junginger, M. van den Broek: Is a 100% renewable European power system feasible by 2050?, Applied Energy, 233–234(2019), pp. 1027–1050.
[3] Y. Kawakami, R. Komiyama, Y. Fujii: Development of a bottom-up energy system model with high-temporal-resolution power generation sector and scenario analysis on CO2 reduction in Japan, IEEJ Transactions on Power and Energy, 138-5(2018), pp. 382–391.
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[6] T. Kinoshita, T. Ohki, Y. Yamagata: Woody biomass supply potential for thermal power plants in Japan, Applied Energy, 87(2010), pp. 2923–2927.
[7] Agency for Natural Resources and Energy: *Cost data for geothermal power, small- and medium-sized hydraulic power, and biomass power,* Materials for the 50th Procurement Price Calculation Committee (2019).
[8] FAO: Global Forest Products Facts and Figures 2018 (2019).

3-2. Other assumptions

For DAC, another negative emission technology, the capital expenditure for DAC plants for collecting 1 million tonnes of CO_2 (2050) was estimated about US$780 million based on the energy intensity and costs described in Reference 9. Natural gas and unutilized heat energy were specified as the heat sources for collecting CO_2. The CO_2 from burning the natural gas used as the heat source will also be collected.

We assumed that 95% of the CO_2 from power plants and the industry sector will be collected, and set the CO_2 storage potential in 2050 to 91 million t-CO_2/year[10] as the reference case. For assumptions on other promising key decarbonization technologies such as imported hydrogen, hydrogen production by electrolysis, hydrogen storage, and methanation, see Reference 4. In this paper, the maximum amount of ammonia import was set to half the amount set for hydrogen (under Japan's basic hydrogen strategy) in calorific terms (30 million tonnes).

3-3. Scenarios

Seven scenarios were formulated as shown in Table 1. CO_2 constraints were applied only to energy-related emissions, and reduction rates by 2050 were set to 80%, 90%, and 100% from FY2013 levels. The 2030 emissions were set to the level indicated in the Long-Term Energy Supply-Demand Outlook and the emissions for each year up to 2050 were set through linear interpolation. Under each CO_2 target scenario, the impact of using or not using BECCS on technological options and CO_2 abatement cost was analyzed. For the 100% CO_2 reduction scenarios, a scenario with a higher annual CO_2 storage potential (150 million tonnes) in 2050 was also formulated.

Table 1 Scenarios

Scenario name	CO_2 reduction rate	Net negative emission technology	Maximum CO_2 strorage capacity
C80	80%	BECCS, DACS	91 Mt yr^{-1}
C80_NoBECCS	80%	DACS	91 Mt yr^{-1}
C90	90%	BECCS, DACS	91 Mt yr^{-1}
C90_NoBECCS	90%	DACS	91 Mt yr^{-1}
C100	100%	BECCS, DACS	91 Mt yr^{-1}
C100_NoBECCS	100%	DACS	91 Mt yr^{-1}
C100_CCS+	100%	BECCS, DACS	150 Mt yr^{-1}

4. Results

4-1. Decarbonization of the power sector

To reduce CO_2 emissions by at least 80% by 2050, it is important to reduce the CO_2 emissions from the power sector by accelerating its progress toward zero or negative emissions while advancing electrification in the final demand sector. However, a feasible solution for reaching carbon neutrality (a 100% reduction of CO_2) was not obtained under the reference CO_2 storage potential regardless of the use of BECCS, and was achieved only under the higher storage potential scenario.

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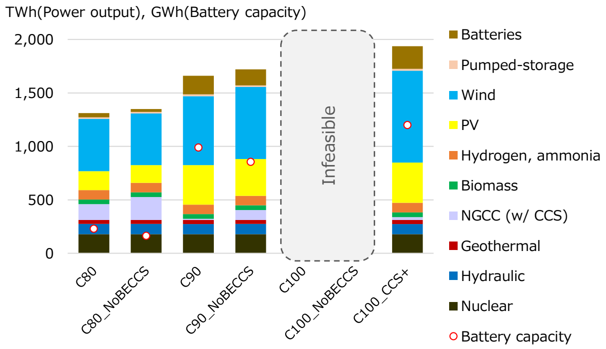


Fig. 1 Power output and battery introduction (2050)

For 80% CO_2 reduction scenarios, the share of natural gas-fired thermal power with CCS (NGCC) will exceed 10% (16% for the NoBECCS scenario), and, along with biomass thermal power and ammonia-fired thermal power, decarbonized thermal power with adjustment capability will account for approximately 25% of the output in 2050 (Fig. 1). Meanwhile, coal-fired thermal power with CCS, despite having low generation costs, will not be selected from the perspective of using the limited storage potential efficiently, since it has a small output relative to the amount of CO_2 collected. Since even a small amount of uncollected CO_2 emissions will become impermissible as CO_2 reduction requirements become stricter, the output of NGCC with CCS will start to decrease and VRE power sources will increase instead. For the at least 90% reduction scenarios, the share of VRE power will surpass 60%, making it necessary to introduce a massive battery capacity of approx. 1000 GWh for adjusting power supply and demand because of limited thermal power operation. However, since it is possible to collect 100% of CO_2 from thermal power if costs permit, further analysis should be conducted regarding the pace of increase in this cost and its impact on the operation of thermal power with CCS in the context of large-scale decarbonization.

In all scenarios, biomass thermal power will be used to the limit of fuel supply availability. For other decarbonized thermal power sources, ammonia power will also be developed to the limit of fuel supply availability, while hydrogen will not be consumed for generation but will be used instead for FCV and FT synthesis in the final demand sector, thus reducing CO_2 in that sector (Fig. 2). Hydrogen has a relatively high fuel cost, which hinders its widespread use in the power sector where it must compete with other power sources. However, its use will be economically rational in the final demand sector where the means for large-scale CO_2 reduction are limited. Note that hydrogen production by electrolysis will hardly be introduced since losses associated with conversion to hydrogen must be avoided as electricity demand rises driven by the need to accelerate electrification in the final demand sector.

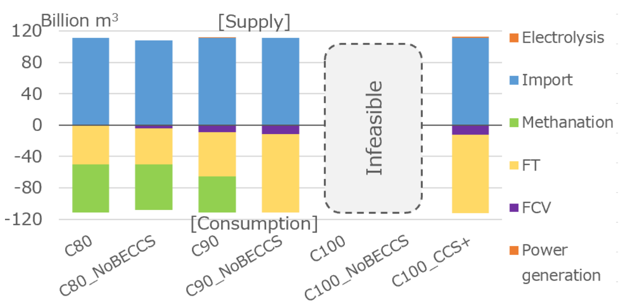
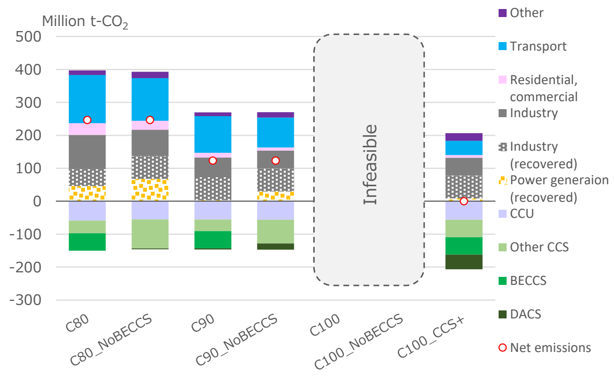
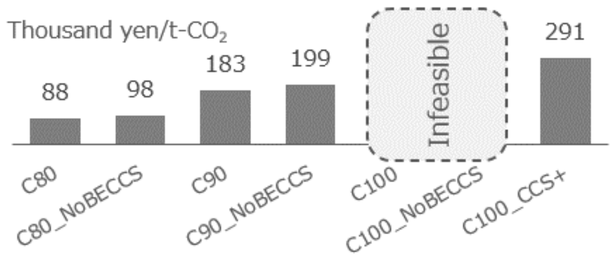


Fig. 2 Supply-demand balance of hydrogen



(a) CO_2 balance



(b) CO_2 marginal abatement cost

Fig. 3 CO_2 balance and marginal abatement cost (2050)

4-2. CO_2 balance and marginal abatement cost

The CO_2 balance and marginal CO_2 abatement cost in 2050 are shown for each scenario in Fig. 3. In all scenarios, industry and transport are the key CO_2 emitter sectors, suggesting the relative difficulty of decarbonizing those sectors. In contrast, the residential and commercial sector, which is relatively easy to electrify, will be electrified nearly 100% and will account for a very small portion of CO_2 emissions.

CO_2 emissions will decrease even in hard-to-decarbonize sectors through electrification and energy conservation as the CO_2 reduction target rises, but there are limits. To overcome these limits, it is necessary to introduce negative emission technologies such as BECCS and DACS. If available, BECCS will reduce CO_2 by a net 50 million tonnes even for the reduction target of 80%. It is suggested, however, that this reduction can be achieved without negative emission technologies for the 80% reduction scenarios, since the introduction of DACS will be limited even if BECCS is not available. However, these technologies will be indispensable for reduction rates of over 90%. Without BECCS, achieving a 90% reduction involves reducing approx. 20 million tonnes of CO_2 in net terms using DACS, which is relatively more costly. For the 100% reduction scenarios, the amount of net CO_2 reduction from these technologies will amount to almost 100 million tonnes.

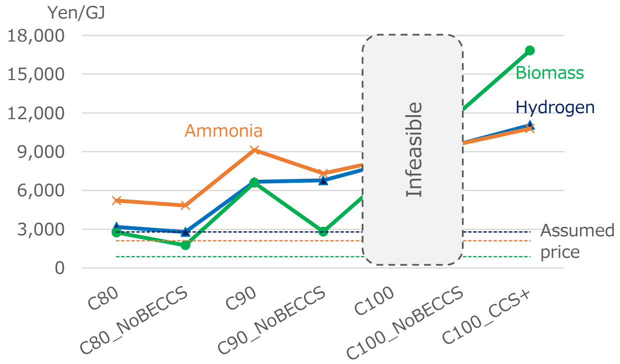


Fig. 4 Implicit value of each decarbonized energy in 2050 (Assumed prices + shadow prices on limited supplies)

The amount of CO_2 used for CCU will be around 55 million tonnes for all scenarios, the primary purpose being decarbonizing the transport sector through FT synthesis. The amount used for CCU will be the same for all scenarios presumably because of limits in the availability of hydrogen.

It has been suggested that large-scale decarbonization of energy systems, including achieving carbon neutrality, is technically possible by introducing negative emission technologies, but this would inevitably impose a heavy economic burden. The marginal CO_2 abatement cost in 2050 would be almost 100,000 yen/t-CO_2 for the 80% reduction scenarios, almost 200,000 yen/tonne for 90% reduction, and almost 300,000 yen/tonne for 100% reduction. The results for the 80% and 90% scenarios suggest that using BECCS has a marginal cost reduction effect of approximately 10,000–15,000 yen/tonne and that the effect grows with the CO_2 reduction rate. This point is also suggested by the shadow prices associated with the restrictions in the amount of biomass fuel imports. Fig. 4 indicates the implicit value of imported hydrogen, imported ammonia, and imported biomass in 2050, calculated based on the shadow prices of the energies associated with the limits in their supply and their set import prices. The value of imported biomass is lower than that of ammonia for CO_2 reduction rates of 80% and 90% due to the low generation efficiency of biomass thermal power. However, since negative emission technologies will be indispensable for achieving carbon neutrality, if BECCS is available, the potential value of imported biomass will be about 55% higher than that of hydrogen and ammonia for the same scenarios.

5. Conclusion

This paper discussed the extent to which BECCS and other negative emission technologies would be introduced to reduce CO_2 by 80–100% by 2050 in Japan and their impact on the alleviation of CO_2 abatement cost, using an energy system optimization model which incorporates a high-temporal-resolution power sector. The results showed that introducing BECCS would reduce the marginal CO_2 abatement cost by approximately 10,000 yen/tonne in the 80% reduction scenario. It was suggested that negative emission technologies such as BECCS and DACS are indispensable for achieving reduction rates of 90% and higher. To achieve carbon neutrality, around 150 million tonnes of CO_2 must be stored, in addition to around 100 million tonnes of negative emissions using negative emission technologies. Accordingly, the value of biomass energy used for BECCS will exceed those of hydrogen and ammonia. The tasks going forward include considering biomass gas GTCC generation, studying the import price of biomass and the amount available for import, verifying CO_2 storage potential in and outside Japan, and analyzing the impact of high CO_2 abatement cost on the economy.

Competitive Landscape After Three and Half Years of Japan's City-Gas Market Full Retail Competition◆

Daisuke Masago[*]

1. Introduction

More than three and half years have passed since Japan's city-gas retail market for all the market segments was opened for competition on 1 April 2017. Judging from the author's analysis of the number of switching cases and switching rates, the rate of progress in the full retail liberalization of city-gas differs between rural and urban areas. The author has also analyzed the impact of changes in consumer behavior due to the expansion of COVID-19 infection on the competition for customers, and the 'start-up wholesaling' launched in FY2019 as an initiative to promote the new entrants into the gas retail business from the perspective of the purpose of its introduction.

2. Course and objectives of the full retail liberalization of city-gas

The liberalization of the city-gas business in Japan has been proceeding in stages since 1995. The domestic sales volume of city-gas has been steadily expanding along with the increase in demand due to industrial development. However, at the beginning of the liberalization history, the city-gas business was vertically integrated and licensed in each of more than 200 franchised regions, and the retailing and maintenance and operation of the network were carried out by a specific company as a regional monopoly. Under the then Gas Business Act, it was not possible to set rates for each customer, and industrial customers with large gas consumption expressed a strong demand for liberalization to enable price negotiations. As a result, liberalization began in 1995 for large users with annual gas consumption of 2 million cubic meters on more, such as large factories and large hospitals. After that, the threshold volume for liberalized gas sales was lowered in stages, and the scope of liberalization was expanded. In the wake of the Great East Japan Earthquake in March 2011, as the electric power system was being reformed, the full liberalization of the retail market for city-gas was considered with the aim of "ensuring a stable supply of natural gas," "maximizing the control of gas prices," "diversifying usage menus and expanding business opportunities," and "expanding the ways of using natural gas". In April 2017, the full liberalization of the city-gas retail market was launched for small offices and residential customers.

Table 1 Course toward the full liberalization of Japan's city-gas

Start	Liberalization target	Liberalization rate to gas sales volume
1995～	Consumers with annual gas consumption of 2,000,000 cubic meters and over < Large-scale factory, Large-scale hospital >	49%
1999～	1,000,000 cubic meters and over < Large-scale hotels >	53%
2004～	500,000 cubic meters and over < Medium-scale factories, medium-scale hospitals >	57%
2007～	100,000 cubic meters and over < Mid-scale hotels >	64%
2017～	All consumers <office, residential customers>	100%

◆ This article is a presenting paper at the 37th Conference on Energy, Economy, and Environment that Japan Society of Energy and Resources (JSER) hosted.

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3. Analysis of economics

3-1. New Entrants

Prior to the full liberalization of gas retailing, general gas utilities operated under a "license system," with each utility operating exclusively in areas licensed by the Minister of Economy, Trade and Industry (METI). However, with the enforcement of the revised Gas Business Act on 1 April 2017, the gas retail business after the full liberalization of gas retailing was revised to a "registration system" that requires registration and certification by the METI or the Director-General of the Bureau of Economy, Trade and Industry. New entrants to the gas retail market include a diverse range of businesses, mainly former general gas utilities, former general electric power utilities, and LPG retailers. As of 20 October 2020, the number of registered gas retail suppliers was 82. However, not all registered suppliers have necessarily entered the gas retail market, and only 35 suppliers (43% of the total number of registered suppliers) are supplying or planning to supply gas. Although the timing of liberalization and the size of the markets differ, the number of new entrants is much smaller than 420 in the low-voltage electric power sector.

Fig. 1 shows the number of companies that are registered as gas retailers and that are supplying or planning to supply gas. The number of new entries by former general gas utilities and former general electric power utilities has not necessarily increased. On the other hand, there has been a significant increase in the number of entries by "others" service suppliers, which include internet service providers and new power producers and suppliers. This is due in large part to the "city-gas platform" provided by the Tokyo Energy Alliance (TEA). The company launched its platform business in October 2017. The company provides gas procurement, security, and customer management systems to companies that are considering entering the gas retail business. TEA is a joint venture between TEPCO EP and NIPPON GAS, with TEPCO EP taking over gas procurement and NIPPON GAS taking over safety technologies and customer management systems accumulated in the propane industry. Currently, there are 16 "others" suppliers that are supplying or planning to supply gas, and 11 of them have adopted the TEA's city-gas platform. Some propane gas retailing companies have also adopted TEA's city-gas platform. The number of new entrants using the platform is expected to increase in the future.

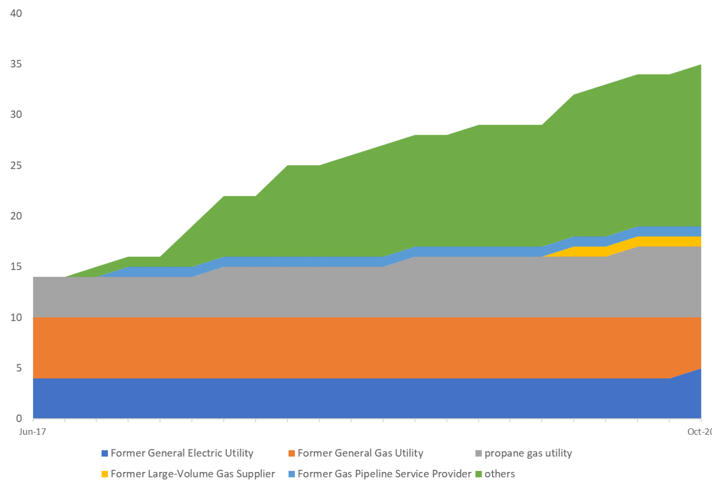

Fig. 1 Change in the number of new entrants that are supplying or planning to supply gas

Fig. 2 shows the actual retail supply areas applied for by the 35 new entrants. When a prospective new entrant applies for gas retail registration to the METI or the Director-General of the Bureau of Economy, Trade and Industry, it is necessary to apply for the area of the general gas pipeline utility to which it plans to supply retail gas, in addition to the gas retail business system and complaint handling system. After aggregating the retail supply area applications of each company, the author has found that the new entrants have entered a total of 21 prefectures. Characteristically, the areas of entry are mainly the supply areas of the four major city gas companies (Tokyo Gas, Toho Gas, Osaka Gas, and Saibu Gas (the Fukuoka area only)), which have a large number of city-gas customers, and competition for customers are fierce between existing city-gas companies and new entrants. On the other hand, there are 26 prefectures where no new entrants have entered the market. The main reason for this is the inability to ensure sufficient business profitability for new entrants. In this case, the city-gas customers in the 26 prefectures where no new entrants have entered the market will not be able to fully enjoy the benefits of liberalization unless the existing city-gas companies voluntarily set new price menus and expand their services.

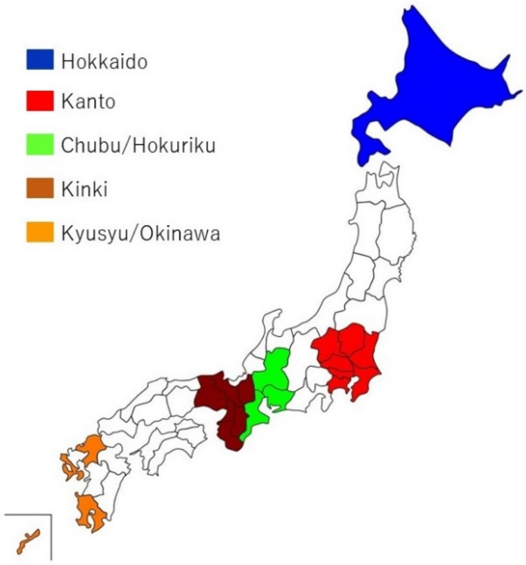

Fig. 2 Entry areas of new entrants that are supplying or planning to supply gas

3-2. Customer switching

The number of switching is used as a typical indicator to evaluate the competition trend and progress of the liberalization of gas retailing. As of the end of August 2020, the number of switching applications published monthly by the Agency for Natural Resources and Energy was approximately 3.8 million (an increase of 44% or 1.15 million compared to the same month in 2019), and the number of applications for switching has been steadily accumulating. However, the number of applications for switching published by the agency is a cumulated value, and further analysis is needed to determine whether switching is expanding its use as an option for city-gas consumers.

Fig. 3 shows the monthly number of switching applications in the four regions where switching is occurring (Kanto, Chubu/Hokuriku, Kinki, and Kyushu/Okinawa). In the three regions (Chubu/Hokuriku, Kinki, and Kyushu/Okinawa), the number of switching applications has stagnated, with the largest monthly number of approximately 51,000 recorded in the Kinki region in April 2018. On the other hand, in the Kanto region, approximately 135,000 city-gas customers applied for switching in April 2020, which is the largest number for a month since the statistics started.

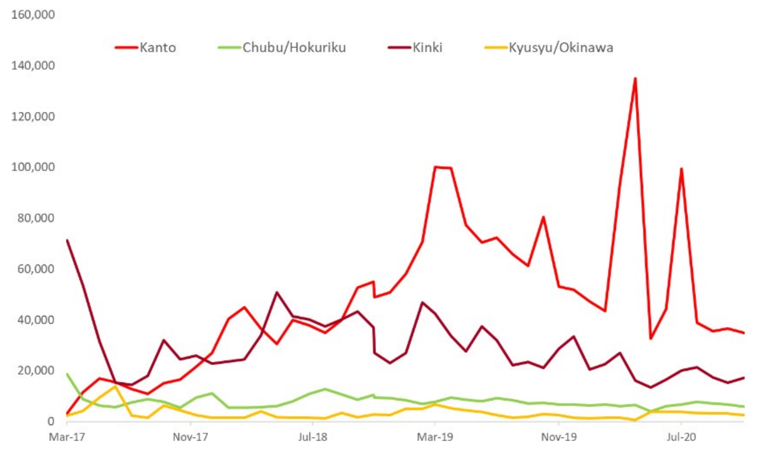

Fig. 3 Monthly switching by region

Fig. 4 shows the switching rates, which is the ratio of switching applications to the number of city-gas customers by region. As of July 2020, the Kanto region had the largest number of customers in Japan, with approximately 13.64 million, which is 52% of Japan's total. This is 2.1 times more than the Kinki region, 5.5 times more than the Chubu/Hokuriku regions, and 9.5 times more than Kyushu/Okinawa. In terms of the number of switching applications, the Kanto region has been at a higher level than the other three regions since September 2018. However, the switching rates are less than 1% due to a large number of city-gas customers. In Kinki, the rate was 1.15% in March 2017This is assumed to be a transitory increase due to the introduction period of liberalization.

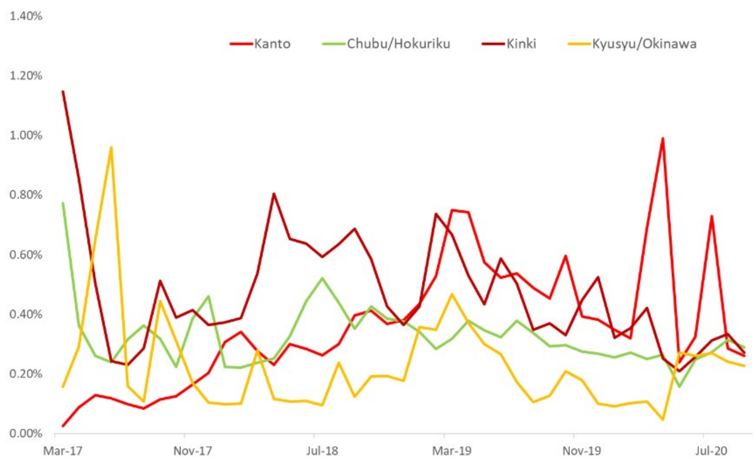

Fig. 4 Monthly switching rate by region

Table 2 shows a comparison of switching rates between Japan and the United Kingdom over the last two years. As in Japan, the United Kingdom has been liberalizing the gas market in stages, and full liberalization began in 2002 with the removal of gas price regulations. The average monthly switching rate in the United Kingdom for 2019 was 1.7%, while the rate in Japan was 0.4%. There is a large difference in the number of switching cases and switching rates when comparing the two countries. However, it should be noted that there are differences in the awareness of switching among customers due to the different start dates of liberalization, the number of gas retails companies, the installation status of pipelines, and the density of customers, etc.

Table 2 Monthly switching rates for Japan and the UK

	Japan			Great Britain		
	Switching Cases	Total Gas Customers	Switching Rates	Switching Cases	Total Gas Customers	Switching Rates
Apr-18	89,313	25,795,510	0.35%	372,000	23,240,000	1.60%
May-18	90,790	25,771,973	0.35%	399,000	23,257,000	1.72%
Jun-18	90,455	25,758,127	0.35%	389,000	23,280,000	1.67%
Jul-18	86,552	25,765,991	0.34%	365,000	23,296,000	1.57%
Aug-18	94,183	25,763,155	0.37%	394,000	23,312,000	1.69%
Sep-18	106,362	25,760,949	0.41%	433,000	23,330,000	1.86%
Oct-18	105,241	25,799,228	0.41%	470,000	23,347,000	2.01%
Nov-18	88,276	25,831,047	0.34%	382,000	23,371,000	1.63%
Dec-18	85,649	25,892,974	0.33%	338,000	23,386,000	1.45%
Jan-19	98,857	25,907,627	0.38%	291,000	23,397,000	1.24%
Feb-19	129,370	25,904,185	0.50%	350,000	23,417,000	1.49%
Mar-19	157,046	25,938,582	0.61%	486,000	23,492,000	2.07%
Apr-19	148,152	26,040,077	0.57%	522,000	23,509,000	2.22%
May-19	117,924	26,047,511	0.45%	381,000	23,528,000	1.62%
Jun-19	119,818	26,037,719	0.46%	336,000	23,548,000	1.43%
Jul-19	116,117	26,017,666	0.45%	402,000	23,568,000	1.71%
Aug-19	97,920	26,035,947	0.38%	391,000	23,588,000	1.66%
Sep-19	93,732	26,032,165	0.36%	436,000	23,606,000	1.85%
Oct-19	111,851	26,061,138	0.43%	431,000	23,632,000	1.82%
Nov-19	91,133	26,091,118	0.35%	378,000	23,653,000	1.60%
Dec-19	93,291	26,146,136	0.36%	418,000	23,670,000	1.77%
Jan-20	75,317	26,154,317	0.29%	340,000	23,682,000	1.44%
Feb-20	74,251	26,156,936	0.28%	406,000	23,700,000	1.71%
Mar-20	128,217	26,188,923	0.49%	457,000	23,716,000	1.93%

Due to the spread of COVID-19 infection, which is still raging around the world, many industries are experiencing changes in customer behavior. In the gas industry, the sales volume of gas for industrial use decreased significantly due to the economic recession, while sales volume of gas for residential use generally remained at the same level as in 2019. However, the number of applications for switching in May 2020 decreased by 53% compared to May 2019, the largest decrease ever recorded. One of the reasons for the decrease is thought to be that customers' motivation for switching decreased due to the restriction of unnecessary face-to-face sales activities caused by the request to refrain from going out, especially in the metropolitan area.

In addition, due to the restraint in going out, the attention to the latest gas appliances with improved convenience is increasing, especially in the generation for child rearing. Among these, the gas clothes dryer "Kanta-kun" has met the needs of customers for its ability to dry clothes in a short time and at low cost, and its sales have increased rapidly. The attention of consumers to the latest gas appliances may lead to their interest in the services and gas prices of gas suppliers and may also increase their interest in switching.

4. Start-up wholesaling

A new initiative for wholesale supply called "start-up wholesaling" was launched in FY2019. The purpose of the initiative is to promote the entry of new entrants in the Hokkaido, Tohoku, and Chugoku regions, where switching has not yet occurred, and in regions where new entrants have already entered the market but the number of switching has not increased. Start-up wholesaling is positioned as a voluntary initiative by former general gas utilities, based on the "proactive wholesale supply of gas" described in the "Guidelines for Appropriate Gas Transactions" published by the Fair Trade Commission and the METI in January 2019. The participating companies are classified according to their gas procurement capacity and supply facilities. There are nine companies in the first group (Tokyo Gas, Osaka Gas, and Toho Gas) and the second group (Hokkaido Gas, Sendai City Gas Bureau, Shizuoka Gas, Hiroshima Gas, Saibu Gas, and Nihon Gas), and the target area is within the city-gas supply area of these companies. The wholesale system is based on "one-touch wholesaling," in which the wholesaler delivers gas to the gas retail supplier (new entrant) at the point of demand. The terms "start-up wholesaling" and "one-touch wholesaling" are sometimes used interchangeably, but the former refers to the name of the initiative and the latter to the wholesale supply system. By making the wholesale supply system "one-touch wholesale," the wholesaler will be responsible for the "balancing operations" of managing the volume of gas dispatched from the gas pipeline and the volume of gas injected in the consignment supply, which has been one of the issues for new entrants, and the workload of new entrants will be reduced. The system is also designed to set the contract period, method of setting the wholesale price, and maximum usage volume, etc. However, new entrants who do not have strong bargaining power in bilateral trading will be able to lower the entry bar by using start-up wholesaling.

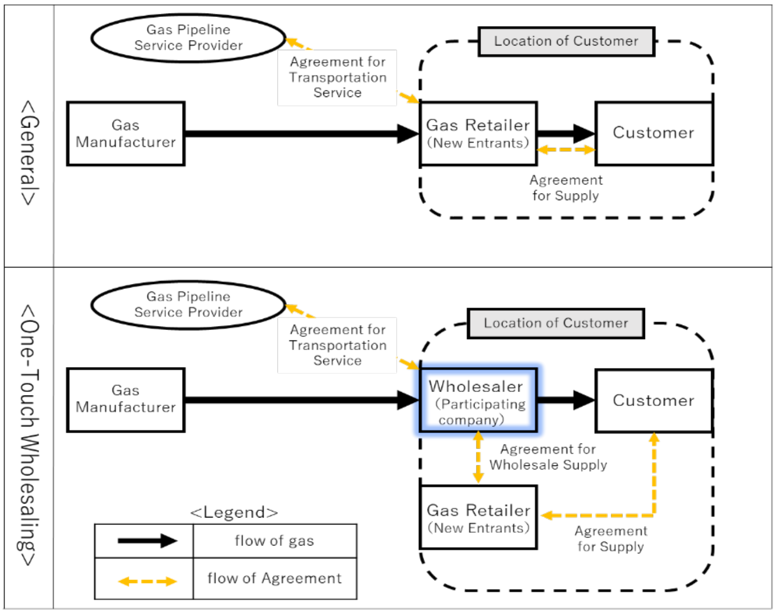

Fig. 5 Supply image of one-touch wholesaling

METI published a report on start-up wholesalers in July 2020, in which it announced the number of inquiries to start-up wholesaling from companies that are considering entering the market. The total number of inquiries was 58, including some cases in which a sole company made inquiries to more than one participating company. Because there are 35 new entrants who supply or plan to supply gas as mentioned above, the potential new entrants are showing a high interest in this initiative. However, as of 1 October 2020, there were only three new entrants utilizing start-up wholesaling, and the start has been slower than expected after a detailed system design. In April 2020, Ichitaka Gas One entered the area supplied by Hokkaido Gas, and Koa Gas Nihon entered the area supplied by Nihon Gas in Kagoshima. In addition, in October 2020, Hokkaido Electric Power Company became the first former general electric utility to take advantage of the initiative entering the Hokkaido Gas supply area. Considering that the purpose of the introduction of start-up wholesaling is to promote the entry of new entrants into the market, the fact that areas where no new entrants have appeared so far have observed some interest in entering the market can be appreciated. The three new entrants are also striving to create benefits for customers by setting up "set discounts" for contracts that combine electricity and kerosene. Ichitaka Gas One has been steadily increasing the number of customers and has acquired 47 customers as of the end of June 2020. On the other hand, while Kyushu Electric Power Company and other companies have already entered the Kyushu-Okinawa region, the number of customers of Koa Gas Nihon is unknown.

The challenge for the future is to follow up on the large number of companies that decided not to enter the market despite a large amount of interest in start-up wholesaling. The reason why companies are abandoning their efforts to enter the market is presumably due to their inability to ensure the profitability of their business. It may be difficult for prospective retailers to differentiate their retail gas prices offered to gas customers from those offered by general gas utilities with the wholesale prices offered by the wholesaler (the participating company) to the prospective retailers.

The method of setting wholesale prices for start-up wholesaling is as follows: the wholesaler (participating company) prepares an "upper limit wholesale price list" and presents individual wholesale price lists to the prospective retailers for negotiation at or below the upper limit wholesale price. The upper limit wholesale price list and calculation basis have been submitted to the Agency for Natural Resources and Energy, allowing the prospective retailers to compare and reconcile the wholesale prices as necessary. In other words, governance over the wholesalers is ensured. In the case of a standalone gas contract, Koa Gas Nihon has a superior rate structure to that of Nihon Gas. On the other hand, Ichitaka Gas One offers the same price as the general rate structure of Hokkaido Gas for a standalone gas contract. In addition, Hokkaido Electric Power Company does not offer standalone gas contracts, so it is necessary to combine gas contracts with other fuels to differentiate gas retail prices.

5. Conclusion

The media coverage of the full liberalization of gas retailing is often based on the cumulative number of switching applications and switching rates in the seven regional categories (1) Hokkaido, (2) Tohoku, (3) Kanto, (4) Chubu/Hokuriku, (5) Kinki, (6) Chugoku/Shikoku, and (7) Kyushu/Okinawa, as published by the Agency for Natural Resources and Energy. In this report, gas retail supply areas where new entrants have applied for registration are summarized, and is the author has shown that the areas where the competition among the entrants arises due to the full liberalization of gas retailing are the urban areas where the economic scale is large, and the number of consumers is large. Although the Agency for Natural Resources and Energy publishes the number of applications for switching in each of the seven regional divisions, it does not mean that new entrants have entered the market in all the sub-regions under the regional division. For example, in the Chubu/Hokuriku regions, new entrants have entered the market in the three prefectures in the Toho Gas area (Aichi, Gifu, and Mie), but there have been no entrants in the remaining six prefectures, and it should be noted that there is no competition for residential consumers.

To create and expand the benefits to customers from the full liberalization of gas retailing, it remains important to promote the entry of new entrants. Although the city-gas platform business provided by TEA is expected to be widely used and expanded, it is assumed that the areas where companies will enter the market will be concentrated in urban areas. There are only three new entrants using start-up wholesaling, but it is significant that new entrants have entered Hokkaido and Kagoshima, which were previously areas with no entrants. There is no target set for the number of new entrants to the market through this initiative, but by further brushing up the design of the system for start-up wholesaling, it is expected that other areas that have not yet entered the market (Sendai City Gas Bureau, Shizuoka Gas, Hiroshima Gas area, etc.) will also take advantage of this initiative.

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Renewable Energy Situation and Challenges in Asian Countries◆

Takahiro Nagata* Masato Yoshida* Sichao Kan*

Abstract

More countries are aiming to achieve carbon neutral in 2050 and Japan's prime minister also pledged that the country would be carbon neutral by 2050 target on October 26, 2020. Renewable energy will be of even more importance. We can also expect that under the new 2050 target energy cooperation between Japan and developing countries will be increasingly focused on clean energy technologies, especially on applying Japanese technologies in these countries to help them reduce their GHG emissions. This paper is based on a study conducted on the status of energy and renewable energy, including a detailed study on renewable energy policy, in selected Southeast Asian (ASEAN) countries: Viet Nam, Thailand, Malaysia, Indonesia, and the Philippines.

These ASEAN countries, especially Viet Nam, Thailand and Malaysia, have seen substantial expansion of renewable energies. However, increasing PV and wind power generation may also lead to grid instability. Japanese technologies, such as battery, demand response (DR) and demand side management (DSM) can help to solve grid integration challenges. Financial and institutional design for supporting the introduction of renewable energies is also important in cooperation with these countries.

1. Introduction

In recent years, Japan has been making progress on initiatives to increase the use of renewable energy. The Japanese government positions renewable energy as one of the main power sources, and it is also advancing efforts to expand the use of offshore wind power. A growing number of companies has also become members of the RE100 initiative, which aims to achieve 100% renewable electricity and implement initiatives toward the realization of net zero CO2 emissions by 2050 or earlier. In October 2020, Prime Minister Suga declared Japan's goal to achieve carbon neutrality by 2050, and this is expected to stimulate greater activity in the move to expand the use of renewable energy.

The Institute of Energy Economics, Japan (IEEJ) has, for many years, been engaged in projects commissioned by the Ministry of Economy, Trade and Industry (METI) to promote the adoption of renewable energy in ASEAN and other developing countries. It has also been involved in projects introducing Japan's clean energy technologies and systems to these target countries.

This paper focuses on the following five countries: Viet Nam, Thailand, Malaysia, Indonesia, and the Philippines. Based on a comparison of the energy situation in each country and an organization of information related to their renewable energy policies, the paper examines future renewable energy business development in this region.

2. Energy situation in the Southeast Asian countries

First, in order to understand the energy situation in the five countries, we summarized the relationships between GDP per capita and primary energy consumption and electricity consumption by country in Fig. 1, based on data from the IEA.[1] Energy consumption increases with GDP growth. To present this trend even more clearly, Fig.2 shows GDP on the horizontal axis, and primary energy consumption and electricity consumption on the vertical axis. It is clear that a positive correlation exists between these two factors.

◆ This article is a presenting paper at the 37th Conference on Energy, Economy, and Environment that Japan Society of Energy and Resources (JSER) hosted.

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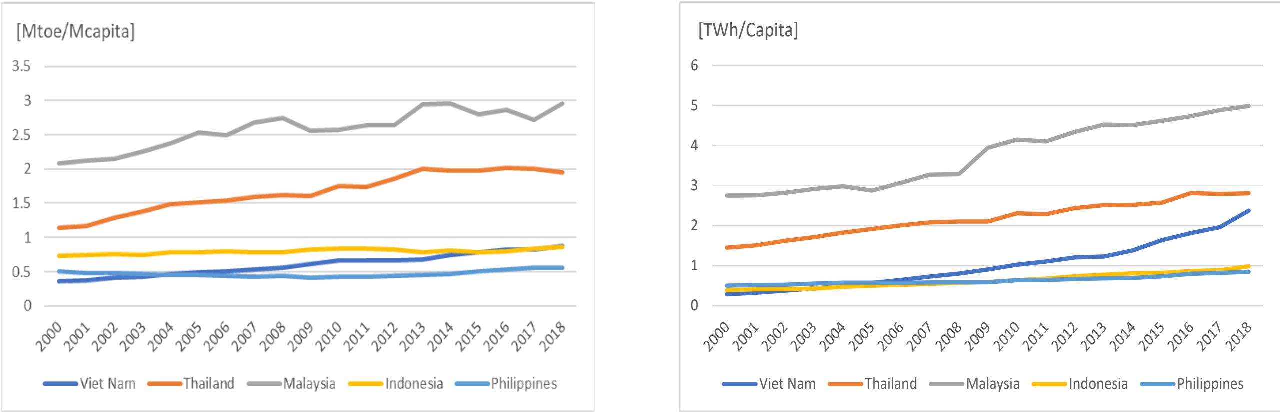
1 IEA, World Energy Statistics and Balances 2020



a. Primary energy

b. Electricity

Fig. 1 Yearly energy consumption per capita

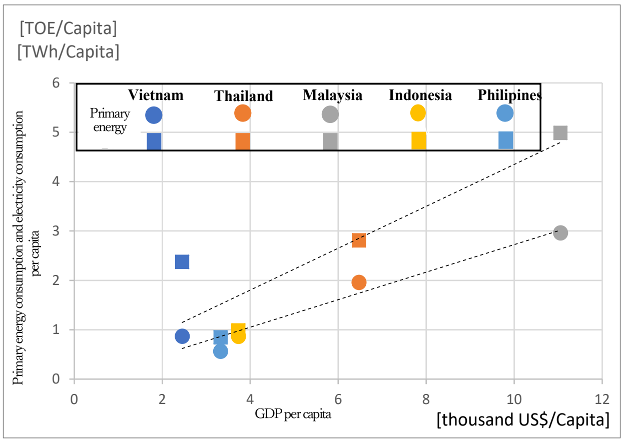


Fig. 2 Relationship between per capita GDP and energy consumption

3. Status of the development of renewable energy

3-1. Overall status of the deployment of renewable energy

We also summarized the status of the deployment of renewable energy in each country. Fig. 3 shows the share of renewable energy power generation in each country, including hydropower. In 2018, the country with the highest share was Viet Nam with approximately 35%, followed by the Philippines with approximately 23%. The share of renewable energy was about 17% in the remaining countries. Fig. 4 shows the breakdown of the types of renewable energy power generation. Hydropower is the main source of renewable energy in most of the countries, particularly in Viet Nam and Malaysia. As for other types of renewable energy, geothermal power generation is an important source in the Philippines and Indonesia, while biomass power generation is popular in Thailand and Indonesia.

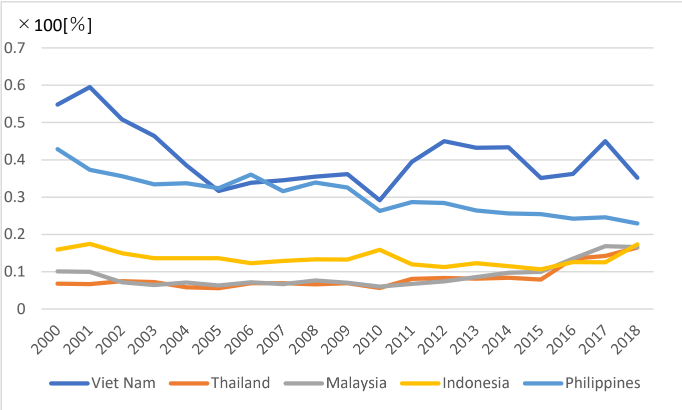


Fig. 3 Changes in the market share of renewable energy (including hydropower)

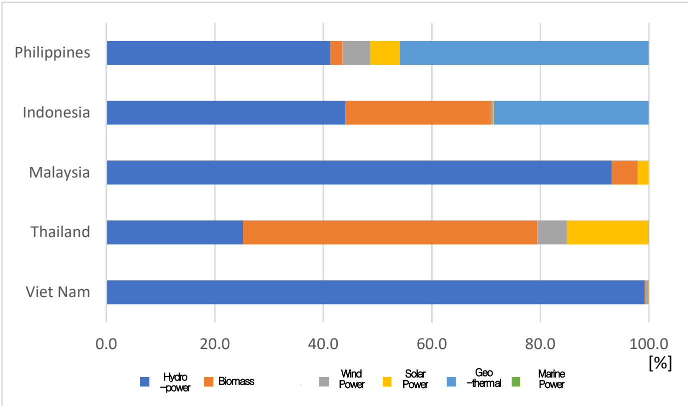


Fig. 4 Breakdown of types of renewable energy (including hydropower)

3-2. Status of the deployment of solar power and wind power generation

This section summarizes the status of the deployment of solar power generation, which has seen large cost reductions in recent years in tandem with its growing popularity worldwide, as well as wind power generation, for which offshore wind development is anticipated in Japan. Both solar power and wind power generation are variable power sources, the output of which varies depending on the condition of solar radiation and wind speeds. In Japan, system designs and grid stabilization technologies have been developed in order to accommodate expanding variable renewable energy sources. These designs and technologies can be applied in ASEAN countries where variable renewable energy will expand in the near future. This will drive needs for support measures and business development involving relevant technologies.

The power generation capacity of solar and wind power is summarized in Fig. 5, based on consolidated data from IRENA[2] on power generation capacity through 2019. In recent years, there has been significant growth in power generation capacity in Thailand for both solar and wind power generation. Viet Nam also showed prominent growth in solar power generation in 2019.

No correlation was observed between increased deployment and GDP for renewable energy in general, or either for solar power generation or wind power generation Hence, economic development is not a key factor for the increase of renewable energy.

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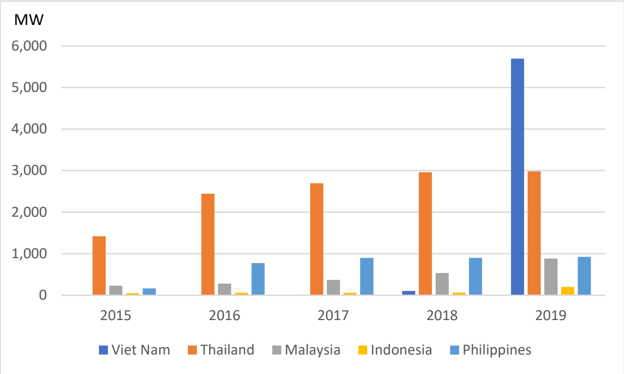
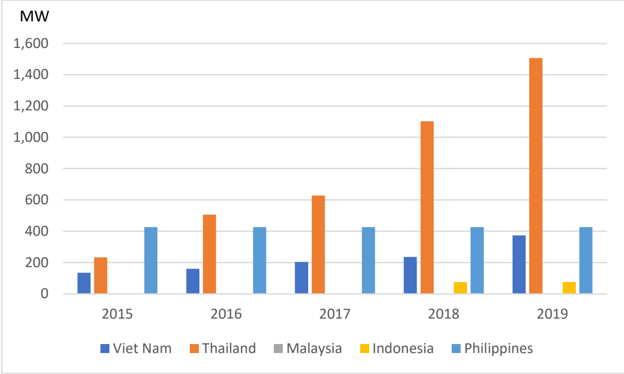
2 IRENA, Renewable Energy Statistics 2020



a. Solar power generation



b. Wind power generation

Fig. 5 Changes in power generation capacity for solar power and wind power generation

4. Factors affecting the deployment of solar power generation

The potential for developing geothermal, biomass, and wind power generation varied greatly among the five countries because of widely varying potential, and various factors for the deployment of these technologies. However, with regard to solar power generation, there is little variation among the potential for each country as they are all located near the equator; and therefore, the level of deployment is greatly influenced by the policy of each country.

To identify factors leading to the current status of solar PV deployment and to examine the prospects for solar PV deployment, solar power policies and electricity prices in each country are evaluated in this section.

Table 1 summarizes the feed-in-tariff (FIT) system in each country.

Table 1 Overview of FIT scheme for solar power generation in each country

Country	Year of introduction	FIT rate [US cent/kWh]*
Viet Nam	2017	2017: 8.34 July 2019: 6.58–8.33
Thailand	2013	Rooftop: 19.7–22.3 Ground-mounted: 14.4–18.1
Malaysia	2011	Large-scale: 4.32–13.9** Other: 7.68–16.1**
Indonesia	2006	3.19–3.92***
Philippines****	2012	18.5

There are differences in the purchase prices and the initial introduction of FIT. To examine the impact of the FIT on the deployment of solar PV, the cost of solar power generation (or Levelized Cost of Electricity (LCOE))[3] and the electricity tariff (tariff for the commercial use of electricity)[4] were evaluated for each country. The results are shown in Fig. 6.

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* Calculated based on the conversion rate in October 2020.
** Calculated based on the purchase prices from 2018 and after.
*** Calculated based on 65%–80% of PNL power generation cost. Power generation cost is assumed to be 70% of commercial charges (7¢/kWh (study by JETRO)).
**** Certification ended in February 2018
3 BloombergNEF, Levelized Cost of Electricity
4 Jetro, "Comparison of Investment Costs," https://www.jetro.go.jp/world/search/cost.html. (Accessed on October 20, 2020)

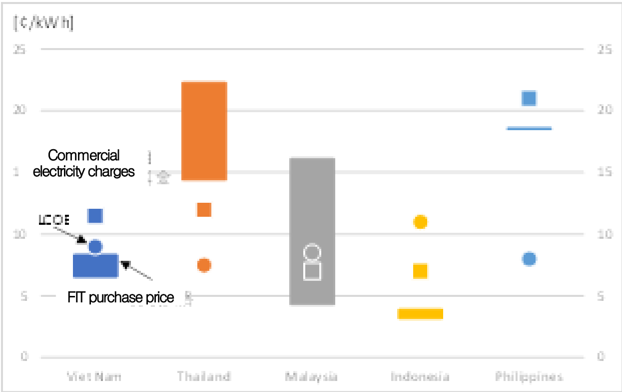

Fig. 6 Relationship between FIT purchase price, LCOE, and commercial electricity charges

In Thailand, the FIT rate is more than double that of LCOE, and is also higher than the commercial electricity tariff. This provides incentives to both developers as well as companies that wish to introduce on-site solar power generation systems, and is considered to be the reason for the fast growth of solar power in this country. On the other hand, although Indonesia introduced the FIT as early as 2006, it fixes the FIT rate at about 65%–80% of LCOE. This makes the FIT rate lower than LCOE and the electricity tariff, and therefore offers little incentive for adoption. This is presumably the reason behind the sluggish deployment rates. In the Philippines, the FIT pricing is higher than LCOE, thus incentivizing solar power generation developers. However, as the target deployment level was achieved in 2018, further FIT approval for solar power generation and wind power generation was suspended. As a result, the Philippines has seen little growth since then. In Viet Nam, although the FIT rate is lower than LCOE and the commercial electricity tariff, power generation capacity increased significantly in 2019 for reasons unclear. Malaysia has a wide range of FIT rates; and therefore, the deployment level of solar power generation is lower in comparison with Thailand. However, it has steadily increased the deployment rate year on year, recording particularly significant growth from 2018 to 2019.

5. Future deployment of renewable energy in the selected countries, and examination of Japan's contributions

We organized the energy situation and deployment status of renewable energy in each country, and examined the factors behind the growth of solar power with a focus on the FIT system. In this chapter, we consider the future development of renewable energy in the selected countries and Japan's contributions, as well as the potential for business development.

5-1. Viet Nam

5-1-1. Current situation and prospect for renewable energy

Viet Nam has recently registered prominent growth in both solar power and wind power generation. It revised the FIT rate for solar power generation in 2020 as shown in Table 2. FIT pricing varies depending on the installation form and region.

Table 2 FIT purchase prices from July 2020 to February 2021[5]

Solar power generation technology	Purchase price	
	VND/kWh	US cent/kWh
Floating solar power	1,783	7.69
Ground-mounted solar power	1,644	7.09
Grid-connected solar power in the Ninh Thuan region	2,086	9.35
Roof-top solar power	1,943	8.38

In addition, the country has also made remarkable advancements in the development of wind power generation technology since 2019. An important factor behind this is the expansion of foreign capital into the Vietnamese wind power generation market (in particular, offshore wind power). Viet Nam and Denmark are deepening their cooperative relationship in the wind power generation sector, and estimates from both countries place the potential of offshore wind power at 160GW.[6] In 2020, two European leading wind power generator manufacturers were actively engaged in business in Viet Nam.[7] In July, Siemens Gamesa Renewable Energy (Spain) received an order for 36 wind power generators for two offshore wind farms (total output of 165MW) to be built in the southern part of Viet Nam, while Vestas Wind Systems (Denmark) delivered 50MW wind turbines to a wind farm in the southern part of Viet Nam. Similarly in July 2020, Copenhagen Infrastructure Partners (CIP), a Danish offshore wind power corporate group, concluded a basic agreement with regional partners in Viet Nam on a 3.5GW offshore wind power generation project.[8]

In March 2016, the government of Viet Nam published a revision of the National Power Development Plan VII (hereafter, "PDP 7 rev."), which is drawn up every five years. The renewable energy targets set out in this plan are summarized in Table 3.

Ambitious targets have been established for wind power and solar power generation towards 2030. In addition, FIT rates have also been raised for wind power generation—from 7.8 US cents/kWh in 2018 to 8.55 US cents/kWh for onshore wind power, and to 9.85 US cents/kWh for offshore wind power[9]. Rates for solar power generation were also raised as shown in Table 2. In these ways, the Viet Nam government is strengthening its support for the sector. Combined with the proactive entry of foreign capital into the market, the growth of renewable energy in Viet Nam is expected to accelerate in the future.

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[5] Decision No. 13/2020/QD-TTg on the mechanism of encouraging development of solar power in Vietnam

[6] NNA Asia, June 17, 2020, "Viet Nam and Denmark Cooperate on Wind Power Development."

[7] The Denki Shimbun, July 29, 2020, "Two Leading European Wind Turbine Manufacturers Get Serious about Developing the Viet Nam Market – 11 million kilowatt Development Plan"

[8] Recharge, July 22, 2020, CIP plans 3.5GW Vietnam offshore wind project, https://www.rechargenews.com/wind/cip-plans-3-5gw-vietnam-offshore-wind-project/2-1-846588 (Accessed on October 20, 2020)

[9] VIET JO, July 11, 2020m https://www.viet-jo.com/news/column/200708162238.html (Accessed on October 20, 2020)

Table 3 Renewable energy targets set out in PDP 7 rev.

	2020	2025	2030
Hydropower (including micro hydropower)	21,600MW (29.5%)	24,600MW (20.5%)	27,800MW (15.5%)
Wind power	800MW (0.8%)	2,000MW (1%)	6,000MW (2.1%)
Solar power	850MW (0.5%)	4,000MW (1.6%)	12,000MW (3.3%)
Biomass	750MW (1%)	1,824MW (1.2%)	3,281MW (2.1%)

5-1-2. Potential for business development

In Viet Nam, projects related to solar power and wind power generation, among other forms of renewable energy, have become increasingly active in recent years because of the rise of FIT prices and other factors. However, some entities are advancing renewable energy projects that exceed the power transmission capability, so it would be desirable to improve technologies and systems in order to provide output control. It would also be desirable to strengthen and sophisticate the power transmission and distribution systems to match the rapid growth in power demand and the expansion of power generation. Technologies that are related to grid stabilization and smart communities should be an important area of cooperation for both Viet Nam and Japan.

While the World Bank and other organizations are providing support for studies on aspects such as the distribution of renewable energy resources in Viet Nam, in view of the fact that the height of required wind conditions also change alongside the increase in the size of wind turbines, and given the growing activity in the area of offshore wind power generation, it would be effective to re-evaluate the resource distribution in order to understand the latest situation and introduce the technologies necessary in the updated context.

5-2. Thailand

5-2-1. Current situation and prospect for renewable energy

The adoption of solar power in Thailand has been increasing rapidly thanks to the FIT scheme. The target for solar power (6,000MW by 2036) established in the Alternative Energy Development Plan (AEDP) 2015 (which is the development plan for alternative energy from 2015 to 2036) was revised upward to 15,574MW in AEDP 2018 (Alternative Energy Development Plan covering the years from 2018 to 2037). In order to achieve this new target, it will be necessary to implement measures for promoting increased deployment. Further growth of solar power is projected to cause increased cost burden related to grid stabilization. To solve the problem, there are plans to launch peer-to-peer (P2P) transactions of surplus electricity between solar power generation businesses in 2021, among other measures. In August 2018, BCPG Public Company Limited, a renewable energy corporation in Thailand, together with Power Ledger (Australia), began conducting P2P trials using blockchain technology in the T77 district of Bangkok. This initiative made use of rooftop solar power generation facilities with total capacity of 700MW, installed at schools, apartments, hospitals, and other buildings, making it the largest project of its kind in the world. It is also expected to be applicable to microgrid systems.[10]

[10] "Medium" website
https://medium.com/power-ledger/case-study-learn-more-about-our-live-project-with-bcpg-in-bangkok-thailand-ab7a31c8b464
(Accessed on October 20, 2020)

5-2-2. Potential for business development

Given its remarkable economic growth Thailand is no longer a developing country, but has reached the stage of a semi-developed country. Its energy demand is increasing rapidly driven by economic growth and urbanization, and it is becoming increasingly important for the country to harness renewable energies that will effectively serve to improve its energy self-sufficiency and counter global warming. Therefore, Thailand's needs in this sector are expected to grow rapidly.

Thailand aims to introduce more renewable energy with a focus on solar power generation. However, as it also faces challenges in power grid development and policy design for further facilitation of solar power installation, Japan's leading technologies and experiences in these fields are likely to be effective in business development.

Moreover, while initiatives in areas such as "smart grid" and "smart city" can be seen in Thailand, there are inadequacies in the details of policy design. Hence, consultations on the master plans for these initiatives should also be helpful.

5-3. Malaysia

5-3-1. Current situation and prospect for renewable energy

Since the introduction of the FIT scheme, the renewable energy sector in Malaysia has seen steady expansion. As of October 2020. the cumulative amount of renewable energy introduced as a result of the FIT has reached 604.44MW, of which solar power generation accounts for the largest portion at 380.24MW, followed by biomass power generation at 82.7MW, and biogas power generation (biogases from landfills and agricultural waste) at 62.94MW.

Various measures were rolled out for solar power generation, including shifting to competitive bidding for large-scale solar power generation and launching the Net Energy Metering (NEM) from 2016. Malaysia is currently implementing a large-scale solar power generation project with a capacity of more than 1.6GW, of which 690MW started operation by the second quarter of 2020.

Policies supporting the solar power generation industry include subsidies for research and development, industry-government-academia cooperation, tax incentives, financing, and land adjustment for power plants. Malaysia ranks third in the world in terms of solar panel production (for both cells and modules).[11] Local governments have launched policies to attract investment from foreign solar panel manufacturers, and many world-leading manufacturers have set up manufacturing lines while using Malaysia as the production hub for the Asian market.

5-3-2. Potential for business development

Malaysia advocates the "Look East Policy" (learning about technologies, strong labor ethics, and work motivation from the countries of East Asia), the scope of which covers areas such as green technologies, renewable technologies, and biotechnologies.[12] "Japan-Malaysia Joint Statement on Strategic Partnership,"[13] issued after the Japan-Malaysia bilateral summit meeting held in May 2015, sets out clearly, "Both leaders affirmed the pressing need [...] to address climate change through the transfer of climate and environment-friendly low and zero-emission technologies for power generation from renewable sources and through the transfer of technologies needed to enhance energy efficiency across all sectors." Hence, technological support in the Malaysian renewable energy sector is an important area for Japan.

5-4. Indonesia

5-4-1. Current situation and prospect for renewable energy

Hydropower, biomass, and geothermal power generation account for a large part of the renewable energy sources in Indonesia. Solar power and wind power generation are limited, and the installed capacity of both of these energy sources is about 150MW in 2019. This is probably impacted by the price ceiling in regions where the regional LCOE rate exceeds the

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[11] International Energy Agency (2018) "Trends 2018 in Photovoltaic Applications," p.57.

[12] Ministry of Foreign Affairs (March 2011), "Country Assistance Evaluation of Malaysia (Third-party Evaluation)," p.45 https://www.mofa.go.jp/mofaj/gaiko/oda/shiryo/hyouka/kunibetu/gai/malaysia/pdfs/kn10_03_01.pdf (Accessed on October 20, 2020)

[13] Ministry of Foreign Affairs (May 25, 2015), "Japan-Malaysia Joint Statement on Strategic Partnership," p.3. http://www.mofa.go.jp/mofaj/files/000081944.pdf (Accessed on October 20, 2020)

national average LCOE of Perusahaan Listrik Negara (PLN), the national electric power corporation. In such regions, the FIT rate must not exceed the LCOE of the region.

Little future growth is expected for hydropower, biomass, and geothermal power generation. On the other hand, solar power is expected to increase to 6.4GW by 2025 according to the Indonesian government. There is high potential for solar power on islands and in remote regions, where diesel power generation is currently the main power source and power generation costs are high.

5-4-2. Potential for business development

While islands and remote regions in Indonesia rely on diesel power generation, which is expensive, central regions such as Java and Bali have introduced large amounts of cheap coal-fired power; and therefore, the cost of power generation varies greatly among regions, depending on the local power generation mix. Due to changes made to regulations on the purchase of renewable energy in 2017, the upper limit of purchase prices has been kept below the average power generation cost of each region. However, this has resulted in higher purchase prices for renewable energy on islands and in remote regions, where power generation cost is high, compared to the Java and Bali regions. From the perspective of economic efficiency, islands and remote regions could be attractive destinations for investing in renewable energy.

On the other hand, in terms of technological constraints, the electric power load is small on islands and in remote regions, where the electricity supply systems are often independent. As a result, they are not suited to the large-scale introduction of renewable energy with rapid output fluctuations. Measures to address the output fluctuation issue include installing energy storage equipment, backup power supply system, as well as comprehensive grid management technologies. Moreover, from the perspective of realizing an independent, stable, and resilient energy supply for islands, systems combining renewable energy and hydrogen, which is ideal for relatively long-duration energy storage, are also effective. There is potential for the application of such innovative technologies.

In addition, the Ministry of Energy and Mineral Resources (MEMR) is also actively engaged in initiatives related to coal and biomass co-firing in order to promote the utilization of existing coal-fired thermal power generation facilities and renewable energy. Japanese power generation developers have rich experience in the operation of biomass co-combustion plants; and therefore, there are opportunities for cooperation between the two countries in the biomass-coal co-firing power generation-related area, including fuel production and the operation of power plants.

5-5. Philippines

5-5-1. Current situation and prospect for renewable energy

The Philippines has greatly increased the amount of solar power and wind power (as of 2019, solar power generation: 922MW, wind power generation: 427MW) thanks to the feed-in-tariff (FIT) scheme introduced at the recommendation of the National Renewable Energy Board (NREB). However, as the FIT ended after reaching its target in 2018, little growth has been recorded in recent years.

The key to further increase renewables in the future lies in reviewing the FIT scheme, and resuming the purchase mechanism.

5-5-2. Potential for business development

After the introduction of the FIT, sufficient advancements have been made in the deployment of variable renewable sources, such as solar power and wind power to achieve NREP targets. However, due to the weak power transmission lines between solar and wind power generation sites and the load center in Manila, it is difficult to control the fluctuation of electricity. Therefore, it would be desirable to strengthen the power transmission networks. In addition, as the Philippines is an island country, the introduction of microgrid systems can also be considered for securing electricity supply in small island regions. Japan's grid stabilization technologies and systems can also contribute to addressing the intermittency issue of variable renewable energy technologies.

6. Conclusion

This paper mapped out and set out in parallel the energy and renewable energy situations for five Southeast Asian countries. In particular, it examined the FIT policy's impact on the development of solar power generation. In addition, it also looked at the systems and the situation of renewable energy in each country in detail, and identified the implications for Japan's business development in these countries.

In response to the declaration by Prime Minister Suga on achieving carbon neutrality by 2050, UN Secretary-General Antonio Guterres issued the following statement: "The Secretary-General has no doubt that Japan has all the necessary technological, financial and engineering tools to get to net zero emissions by 2050. He is confident that Japan will also assist developing countries to reach that same objective, including through technological assistance and its public and private financing for renewable energy." Chinese and European manufacturers have been working on reducing the costs of solar power and wind power generation, and thus it is difficult for Japan to expand such technologies to developing countries. It is crucial to put effort into contributing to the roadmap for increasing renewable energy in the target country through proposing technology packages, including grid stabilization technologies, that meet the needs of the country, and providing low-interest loans and loan guarantees to promote investment in systems that contribute to grid stabilization, as well as investment in renewable energy sources that entail high initial investment costs but low operation and maintenance costs.

Interactions between Tipping Elements in an Integrated Assessment Model of Climate Change: Modeling and Analysis with a Focus on Melting of the Greenland Ice Sheet and Collapse of the Atlantic Meridional Overturning Circulation◆

Takashi Otsuki* Yuji Matsuo** Soichi Morimoto***

Abstract

This paper presents a cost-benefit analysis on climate change with a focus on two tipping elements: melting of the Greenland ice sheet (GIS) and collapse of the Atlantic meridional overturning circulation (AMOC). We employ an integrated assessment model based on the DICE-2016R2 framework. Interactions of GIS and AMOC are newly modeled. Simulation results show that interaction between GIS and AMOC largely increases the social cost of carbon and lowers the optimal CO_2 emissions compared to a "no interaction" case. The optimal global CO_2 emissions reach zero by around the year 2090 in some cases, much earlier than the original DICE-2016R2, implying the importance of low-carbon and negative emissions technologies to manage the impacts and risks of tipping elements. The estimated global average temperature rise in 2100 from pre-industrial levels is also lowered from 3.5°C in the original DICE-2016R2 to 3.2°C in some cases with interacting tipping elements. Our results indicate that tipping elements and their interactions could be important factors for designing long-term climate strategies.

Key words: Tipping Element, Greenland Ice Sheet, Atlantic Meridional Overturning Circulation, Integrated Assessment Model

1. Introduction

Rising interest in climate change has spurred international discussions on ambitious greenhouse gas (GHG) reduction targets in recent years. The Paris Agreement adopted a target to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels." In 2018, the IPCC released the Special Report on Global Warming of 1.5°C[1], pointing that the average temperature has already risen by about 1°C, and that to limit the temperature rise to 1.5°C or 2°C, global human-generated emissions must be reduced to net zero by around 2050 and 2075, respectively. Meanwhile, it has also been reported that the current Nationally Determined Contributions are insufficient for reaching these goals.[2]

A decarbonized society is one of the target end-states that humans should pursue. However, temperatures have already risen by almost 1°C and may rise further to a certain extent, and so another important perspective for climate change policy is to what level humankind should allow temperatures to rise and what kind of GHG emission path is optimal for humans. This type of study is conducted using cost benefit analysis (CBA). CBA considers three factors, namely: the mitigation cost, the adaptation cost and the damages, to determine the GHG emission paths and temperature levels that would minimize the sum of these costs (or maximize the benefits for humans). Note that this is different from cost effectiveness analysis which presents a picture of a cost-optimum society for a given emissions reduction target. CBA is conducted using an Integrated

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1 Intergovernmental Panel on Climate Change (IPCC): Summary for policymakers. In V. Masson-Delmotte et al. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018), World Meteorological Organization.

2 United Nations Environment Programme (UNEP): Emissions Gap Report (2019), UNEP.

Assessment Model (IAM)[3], and models such as DICE[4], FUND[5], and PAGE[6] have been developed. IAM is used not only for obtaining the optimal path but also for assessing the Social Cost of Carbon (SCC).[7]

However, there are also many criticisms of CBA and SCC estimates using IAM[8], particularly the high uncertainty associated with estimating the three costs listed above (especially the estimate for damages). Damages are estimated using physical process modeling, structural economic modeling, and empirical modeling[9, 10], but it is difficult to cover the impact of climate change comprehensively, convert some impacts into monetary terms, and so forth. To address these issues, there are ongoing attempts to update the models and assessments of these techniques using the latest knowledge[11, 12]. In addition, the possible existence of tipping elements—processes of irreversible and drastic changes in the earth's system—has been identified in recent years, and incorporating these elements into damage projections has become an important research topic. This study focuses on tipping elements, particularly the melting of the Greenland Ice Sheet (GIS) and the collapse of the Atlantic Meridional Overturning Circulation (AMOC) to quantify their interactions. Many CBAs take tipping elements into account, as noted in Section 2-2, but few have addressed their interactions. Focusing on the interaction between GIS and AMOC, this study aims to refine cost-benefit analyses and acquire knowledge on the damage from the impact of tipping elements.

This paper consists of five chapters. Chapter 2 presents an overview of tipping elements (particularly GIS and AMOC) and summarizes previous studies on them. Chapter 3 describes the DICE-2016R2 model and the modeling of GIS and AMOC adopted in this paper. Chapter 4 presents and discusses the analysis results, followed by Chapter 5 which outlines the conclusions and research themes for the future.

2. Overview of tipping elements and previous cost-benefit analyses

2-1. Overview of tipping elements, the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation

The earth's climate is considered to have originally maintained an "equilibrium"[13, 14, 15]. That is, disturbances up to a certain level (such as rises in atmospheric CO_2 concentration) were counterbalanced by a negative feedback effect, preventing major deviation from the equilibrium. However, it has been pointed out that when these disturbances surpass a certain level, the earth's system reacts with positive feedback, accelerates the deviation and ultimately transitions to a new equilibrium at a higher temperature level. That is, the earth's system may have a saddle point (or a critical point called a tipping point), beyond which conditions transition at an accelerated rate. The mechanisms that induce a tipping point are called tipping elements and include the loss of the Amazon rain forests, collapse of the West Antarctic Ice Sheet, frequent

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[3] Also called cost-benefit-type IAM (CB-IAM) to distinguish from cost effectiveness analysis.

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[7] S. K. Rose, D. B. Diaz and G. J. Blanford: Understanding the social cost of carbon: A model diagnostic and inter-comparison study, Climate Change Economics, 8(2) (2017), 1750009.

[8] D. Diaz and F. Moore: Quantifying the economic risks of climate change, Nature Climate Change, 7 (2017), pp. 774–782.

[9] Physical process modeling is a model in which specific impacts and damage caused by climate change are described and evaluated. An example is the "produce model," which evaluates the impact of quantities of temperature, humidity, CO_2 concentration, etc. on the productivity of produce. Structural economic modeling describes the relationship between climate change and behaviors of the economy and the market, and is used to assess economic impact, for example, the impact, damage, and costs caused by climate on labor productivity and demand for air-conditioning. The empirical model describes the relationship between meteorological and climatic changes and the ecological response of humans based on past data. For example, it is used to estimate the relationship between temperature exposure and death rate.

[10] National Academies of Sciences, Engineering, Medicine: Valuing climate damages: Updating estimation of the social cost of carbon dioxide (2017), The National Academies Press.

[11] S. Hsiang, et al.: Estimating economic damage from climate change in the United States. Science, 356(6345) (2017), pp. 1362–1369.

[12] J. Takakura et al.: Dependence of economic impacts of climate change on anthropogenically directed pathways, Nature Climate Change, 9 (2019), pp. 737–741.

[13] T. M. Lenton et al.: Tipping elements in the Earth's climate system, PNAS, 105(6) (2008), pp. 1786–1793.

[14] R. E. Kopp et al.: Tipping elements and climate–economic shocks: Pathways toward integrated assessment, Earth's Future, 4(8) (2016), pp. 346–372.

[15] W. Steffen et al.: Trajectories of the Earth System in the Anthropocene, PNAS, 115(33) (2018), pp. 8252–8259.

occurrence of the El Nino-Southern Oscillation, melting of GIS and collapse of AMOC. This paper focuses on the latter two since it is relatively clear that there is an interaction between them (melting of GIS may accelerate the collapse of AMOC) compared to other elements.

GIS contains enough freshwater to raise the earth's sea level by 7 meters were it to melt, and its melting could trigger feedback effects associated with a global rise in sea level, weaker Atlantic Meridional Overturning Circulation through an inflow of freshwater into the Atlantic Ocean (described later), and changes in the albedo of the earth's surface. It should be noted here that the melting of GIS exhibits a hysteretic behavior. That is, the relationship between the average global temperature and the volume of the ice sheet is not unique; if the Greenland ice sheet melts extensively, a new ice sheet will not form immediately even if the temperature goes down again. Thus, the melting can be considered almost irreversible.

Deep sea circulation is driven by density gradients in seawater determined by temperature and salt content and hence is called thermohaline circulation. A surface limb of AMOC flowing from south to north is cooled off the coast of Greenland, sinks to the bottom of the sea as it cools, and travels in deeper layers, gradually moving up to the surface again. This surface limb is considered to contribute to the warm climate of the North Atlantic region by transporting heat energy from sub-tropical regions to the northern hemisphere. Further GIS melting could weaken the thermohaline circulation by prompting an inflow of freshwater and lowering the salt concentration (i.e., the density), resulting in extensive effects including a cooler North Atlantic region and warming of the sub-tropical regions, in addition to fiercer cyclones, changes in vegetation, and shifts in river flow rates.

It is suggested that AMOC has a critical point. The strength of AMOC is expressed in units of volumetric rate of transport of seawater per unit time (Sv, 1 Sv = 10^6 m^3/s). A drop in this strength below the critical point, once it occurs, would prompt positive feedback, possibly weakening AMOC sharply and irreversibly. Using CLIMBER-2, an earth system model of the Potsdam Institute for Climate Impact Research, Reference 16 postulated "multiple rates of change in the inflow of freshwater associated with rises in temperature" (unit: Sv/°C; called h in this paper) and analyzed the long-term impact on the strength of AMOC (Fig. 4 in the Reference document). The results showed a tendency for AMOC to collapse once h surpasses a certain level. While the value of h depends on the melting of GIS and Arctic sea ice, among others, Reference 16 treated it as an exogenous value and conducted a sensitivity analysis. (In this study, the effects of the melting of GIS were considered endogenously, as described in Chapter 3.) Note that the contribution of melting of GIS on h was estimated to range between 0.002–0.01 Sv/°C, suggesting it has a degree of uncertainty.

2-2. Cost-benefit analysis taking account of tipping elements, and their challenges

There have been many attempts to incorporate tipping elements into CBA. Some studies up to around 2016 modeled the occurrences (on/off) of tipping elements probabilistically and analyzed them using dynamic planning. As specific examples, Reference 17 analyzed thermohaline circulation, Reference 18 the West Antarctic ice sheet, and Reference 19 GIS and AMOC, to determine the optimal path, also taking other events into account. Furthermore, Reference 20 grouped tipping elements into three types: those with impact on the carbon cycle, those on radiative forcing, and those inflicting direct damage, and analyzed them also using dynamic planning. Meanwhile, in recent years, some studies described the occurrence of tipping elements as a simple process rather than a binary on/off. Examples include studies on AMOC[21, 22],

[16] K. Zickfeld, T. Slawig and S. Rahmstorf: A low-order model for the response of the Atlantic thermohaline circulation to climate change, Ocean Dynamics, 54 (2004), pp. 8–26.
[17] K. Keller, B. M. Bolker and D. Bradford: Uncertain climate thresholds and optimal economic growth, Journal of Environmental Economics and Management, 48(1) (2004), pp. 723–741.
[18] D. Diaz and K. Keller: A potential disintegration of the West Antarctic ice sheet: Implications for economic analyses of climate policy, American Economic Review, 106 (5) (2016), pp. 607–611.
[19] Y. Cai, T. M. Lenton and T. S. Lontzek: Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction, Nature Climate Change, 6 (2016), pp. 520–525.
[20] D. Lemoine and C. P. Traeger: Economics of tipping the climate dominoes, Nature Climate Change, 6 (2016), pp. 514–519.
[21] D. Anthoff, F. Estrada and R. S. J. Tol: Shutting down the thermohaline circulation, American Economic Review, 106(5) (2016), pp. 602–606.
[22] M. Belaia, Integrated assessment of climate tipping points, (2017).
https://pure.mpg.de/rest/items/item_2472743_4/component/file_2472742/content (Date of access: 2020.8.30)

GIS[23], and methane emissions from permafrost[24, 25, 26]. Note that the process description model apparently tends to underestimate the impacts of tipping elements compared to the binary approach; the impact of melting of GIS on SCC was reported to be minor by Nordhaus[23].

While studies have progressed, as described above, many CBAs covered single tipping elements, and the interactions between them have been ignored as out-of-scope. Among the studies in the previous paragraph, Reference19 considered many tipping elements and their interactive coefficients. However, it adopted a binary equation, and the processes of interaction were not clearly described.

3. Model formulation

3-1. Overview

In this study, the melting of GIS and collapse of AMOC was incorporated into the DICE-2016R2 model[4], and their impact on the optimal path was assessed. The source code of the model is open and has been used in many studies[27]. DICE-2016R2 is written in GAMS but was ported to Pymo[28] in this study.

3-2. Modeling of the Greenland Ice Sheet (GIS)

GIS was modeled by drawing on Nordhaus[23]. Specifically, the model consists of an equation for defining the "equilibrium ice sheet volume ratio $V^*(t)$" (equation (1)) and a motion equation representing the "ice sheet volume ratio $V(t)$" (equation (2)). Here, t represents a point in time, and $T(t)$ in equation (1) the average global temperature at time t. The ice sheet volume represents the volume of GIS at time t, and the equilibrium ice sheet volume the volume at which GIS reaches a state of equilibrium at temperature T. These elements expressed as a ratio of the initial ice sheet volume are called the "ice sheet volume ratio $V(t)$" and "equilibrium ice sheet volume ratio $V^*(t)$" and both take a value between 0 and 1 (the starting point of DICE-2016R2 is 2015, therefore $V(2015) = 1$). We assumed that GIS transitions to equilibrium $V^*(t)$ from $V(t)$ at temperature T, and modeled the change in the volume ratio based on the difference between $V(t)$ and $V^*(t)$ (equation (2)).

$$V^*(t) = 1 - \alpha_1 T(t) \tag{1}$$

$$\frac{\Delta V(t)}{\Delta t} = \beta_1 \mathrm{sign}\big(V^*(t) - V(t)\big)\big(V^*(t) - V(t)\big)^2 \tag{2}$$

In formulating the motion equation corresponding to equation (2), Nordhaus[23] defined the equilibrium temperature based on the ice sheet volume ratio, the reverse of what happens in equation (1), but the approach adopted in this study is mathematically equivalent to that of Nordhaus[23] (we adjusted the form of the equation for consistency with the equation for AMOC). Parameters were also set based on Nordhaus as $\alpha_1 = 0.294$ and $\beta_1 = 0.000122$. The rise in sea level when the ice sheet melts completely was set at 7 meters, and was assumed to rise in proportion to the volume of GIS that has melted away. The economic damage caused by a rise in sea level of 1 meter was estimated at 1% of global GDP[23].

3-3. Modeling of the Atlantic Meridional Overturning Circulation

Equations to describe the state of equilibrium and the motion, respectively, were also formulated for AMOC. Hereafter, $X(t)$ represents the strength ratio of AMOC at time t (the strength of AMOC at time t relative to the initial strength), and $X^*(t)$ the equilibrium strength ratio. The values of $X(t)$ and $X^*(t)$ at the initial point (2015 value) are 1. The strength of AMOC was

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[23] W. Nordhaus: Economics of the disintegration of the Greenland ice sheet, PNAS, 116(25) (2019), pp. 12261–12269.
[24] L. Kessler: Estimating the economic impact of the permafrost carbon feedback, Climate Change Economics, 8(02) (2017), pp. 1–23.
[25] H. Wirths, J. Rathmann and P. Michaelis: The permafrost carbon feedback in DICE-2013R modeling and empirical results, Environmental Economics and Policy Studies, 20 (2018), pp. 109–124.
[26] D. Yumashev et al.: Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements, Nature Communications, 10 (2019), Article Number: 1900.
[27] M. Hänsel et al.: Climate economics support for the UN climate targets, Nature Climate Change, 10 (2020), pp. 781–789.
[28] W. E. Hart, C. Laird, C. J.-P. Watson and D. L. Woodruff: Pyomo – Optimization Modeling in Python. Springer Optimization and Its Applications, 67 (2017), Springer.

set to 22.6 Sv.

As described in Section 2-1 above, the possible existence of a critical point has been suggested regarding the strength of AMOC. Equations for equilibrium strength ratio $X^*(t)$ were formulated so that negative feedback would be generated when $X(t)$ declines but is still above the critical point X_{th} (the critical point is not passed), while positive feedback would be generated when X_{th} is passed (equations (3-1) and (3-2)).

When $X^*(t) > X_{th}$:

$$X^*(t+1) = X^*(t) - \alpha_2\big(T(t+1) - T(t)\big) + \gamma_{up}\big(1 - X^*(t)\big) \qquad (3\text{-}1)$$

When $X^*(t) < X_{th}$:

$$X^*(t+1) = X^*(t) - \alpha_2\big(T(t+1) - T(t)\big) - \gamma_{down}X^*(t) \qquad (3\text{-}2)$$

The section up to the second term on the right-hand side of equations (3-1) and (3-2) indicates that the state of equilibrium is proportional to the average global temperature $T(t)$, and is similar in essence to equation (1). The transitional state before and after passing the critical point is simulated by adding a third term to the equations (the feedback effect intensifies near the critical point). The motion equation for the strength of AMOC $X(t)$ was defined as equation (4) below:

$$\frac{\Delta X(t)}{\Delta t} = \beta_2\big(X^*(t) - X(t)\big) \qquad (4)$$

In equation (2) for GIS, the transitional speed was set to be proportional to the square of the difference between the equilibrium ice sheet volume and the ice sheet volume based on Reference 23. On the other hand, in equation (4) above, parameters were set assuming that they are proportional to their values raised to the power of one[29], to ensure consistency with AMOC analysis results for CLIMBER-2[16]. Specifically, parameter $\alpha 2$ was defined as $\alpha 2 = ah + b$, $a = 1.67$, and $b = 0.0517$, using h as the rate of change in freshwater inflow; other parameters were set as follows: $\beta 2 = 0.043$, $\gamma up = 7.23\times10^{-6}$, and $\gamma down = 2.56\times10^{-6}$. h was set differently depending on the analysis case: in cases in which interactions between GIS and AMOC were not considered (cases a and c in Section 3-5), it was defined as the sum of three constants, as shown in equation (5) below.

$$h = h_{GIS} + h_{SI} + h_0 \qquad (5)$$

where, h_{GIS} is the effect of melting of GIS on the rate of change in freshwater inflow, h_{SI} the impact of melting of the Arctic sea ice, and $h0$ other impacts. The impacts of Arctic sea ice and other factors (h_{SI} and h_0) were set to h_{SI} = 0.0125 Sv/°C, h_0 = 0.03 Sv/°C based on the reference case in Reference 22. The assumptions for the impact of the melting of GIS h_{GIS} are described in the section on case settings (Section 3-5). The assumptions for h_{GIS} when considering the interactions between GIS and AMOC (case d) are described in the next section. The economic damage caused by the collapse of AMOC was estimated to be worth 3% of global GDP[22].

3-4. Modeling of interactions

The rise in global temperature based on the optimal solution of DICE-2016R2 (the original model that does not consider tipping elements) shown in Fig. 1a was fed into the model described in Section 3-2 to obtain the ice sheet volume ratio $V(t)$, as shown in Fig. 1b (section for 2015–2070). The chart indicates that $T(t)$ tends to be linear while the change in $V(t)$ accelerates. The rate of freshwater inflow into AMOC $H(t)$ (unit: Sv) is considered to be largely proportional to the change

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[29] Classically, the behavior of AMOC has been assessed using a two-box model* simulating two sea areas, the north and the south. Meanwhile, Reference 16 presents a four-box model and argued that the model can simulate the critical point when freshwater inflow increases (i.e., it is possible to simulate the accurate AMOC analysis result from CLIMBER-2). However, an examination of the result by the authors suggested that the response of the four-box model was remarkably faster than CLIMBER-2 (Fig. 4 and 5 of Reference 16). Thus, this study set up equations and parameters by referring not to the four-box model proposed in Reference 16 but the result of CLIMBER-2 used for verification. Fig. 4 of Reference 16 indicates multiple responses of AMOC for multiple freshwater inflow change rates h (0.013–0.06). A simulation of AMOC behavior done by feeding those change rates into the equations in this study produces mostly the same result as Fig. 4.

* H. Stommel: Thermohaline convection with two stable regimes of flow, Tellus, 13(2) (1961), pp. 224–230.

in $V(t)$, and if so, the change in the rate of freshwater inflow should also gradually increase as temperature rises. This tendency of gradual change could not be captured if h_{GIS} was set as a constant in Section 3-3, possibly resulting in the inadequate assessment of the impact on AMOC.

With this point in mind, equation (3-1), which defines the state of equilibrium, was expanded as represented by equations (6) to (8) to account for the interaction between GIS and AMOC. The same was done for equation (3-2), though not described here.

$$X^*_1(t) = 1 - \alpha'_2\big(T(t) - T(2015)\big) - a\big(H(t) - H(2015)\big) \quad (6)$$

$$X^*_2(t+1) = X^*_2(t) + \gamma_{up}\big(1 - X^*(t)\big) \quad (7)$$

$$X^*(t) = X^*_1(t) + X^*_2(t) \quad (8)$$

Equation (6) corresponds to the two terms on the right-hand side of equation (3-1) and indicates the change in $X^*(t)$ as temperature rises. The impact of GIS is removed by defining $\alpha'2 = a(h0 + hSI) + b$, and instead, the rate of freshwater inflow $H(t)$ calculated based on GIS volume is accounted for with the last term of the equation. $T(2015)$ is the average rise in global temperature at the starting point (2015), estimated at 0.85°C. $H(2015)$ was set to 0.0006 Sv based on an estimate by the IEEJ. The value of $X^*_1(t)$ at the starting point is 1. Furthermore, equation (7) represents the third term on the right-hand side of equation (3.1) which indicates the behavior near the critical point, and the initial value of $X^*_2(t)$ is 0. $X^*(t)$ in equation (8), which adds up the previous two equations, representing the state of equilibrium of $X(t)$.

In the optimal solution for DICE-2016R2, the temperature would rise by 1°C from 2015 to around 2045 (Fig. 1a). An estimate of the rate of freshwater inflow $H(t)$ based on the change in GIS volume ratio (Fig. 1b) shows that the rate of freshwater inflow increases from 0.0006 Sv to 0.0024 Sv during this period, suggesting that the change per 1°C increase would be: 0.0024 − 0.0006 = 0.0018 Sv/°C. This value corresponds to h_{GIS} in the previous section and is hereafter called "h_{GIS} of the GIS model."

3-5. Cases for assessment

In this study, the following four cases were established for modeling the tipping elements, each with five values of h_{GIS} (0.002, 0.004, …, 0.01 Sv/°C) to allow for the uncertainty in the rate of freshwater inflow associated with melting of GIS (described at the end of Section 2-1).

・Case a: DICE-2016R2 with only AMOC considered
・Case b: DICE-2016R2 with only GIS considered
・Case c: DICE-2016R2 with both GIS and AMOC incorporated but their interactions not considered
・Case d: DICE-2016R2 with both GIS and AMOC
incorporated and their interactions considered

As for the details on h_{GIS} settings, for case a in which only AMOC was considered, the five constants above were assigned to h_{GIS} in equation (5), and equations (3-1) and (3-2) were used to obtain the optimal path. For case b in which only GIS was considered, h_{GIS} in the GIS model was set in line with the assumptions above in conducting an analysis (the amount of change in the ice sheet volume ratio $V(t)$ obtained from equations (1) and (2) was mechanically multiplied by the constants so that the change in the rate of freshwater inflow between 2015 and 2045 matched the assumed values). For case c, the assumptions for cases a and b were put together. For case d, only h_{GIS} in the GIS model was adjusted, and the state of equilibrium of AMOC was expressed using equations (6) to (8).

4. Evaluation results and discussions

4-1. Change in the social cost of carbon (SCC)

Fig. 2 shows the SCC for each of the cases in 2015. In the chart, the horizontal axis represents the estimated rate of freshwater inflow into AMOC, and "without TEs" noted in the chart legend shows the analysis results for DICE-2016R2 without tipping elements (TE) considered. The SCC for the case "without TEs" for 2015 was determined to be \$30.7/tCO_2 (hereafter, \$ represents the value of U.S. dollars at 2010 price levels). Cases a to d have higher SCC compared to the "without TEs" case due to the modeling of tipping elements. In case a, in which AMOC was considered, h_{GIS} had limited impact on SCC when it was low, but the rise in SCC accelerated as h_{GIS} increased as shown by the convex curve, and SCC was estimated at \$32.8/tCO_2 for $h_{GIS} = 0.01$. This nonlinearity is considered attributable to the critical point of AMOC—that is, the risk of AMOC collapsing is low when h_{GIS} is low but rises sharply once h_{GIS} passes a certain level. Meanwhile, for case b, in which only GIS was considered, SCC rose linearly with the increase in h_{GIS}. The shape of the curve seems to reflect the absence of any clear critical point being considered for GIS. SSC reached \$33.1/tCO_2 at $h_{GIS\_0} = 0.01$ for case b, suggesting that the damage from the impact of the melting of GIS may be greater compared to the collapse of AMOC. This result disagrees with Reference 30, and the difference may arise from the assumptions for h_{GIS}. Reference 30 assumes a low h_{GIS} for GIS but a far higher h_{GIS} for AMOC, and therefore, when the assumptions are adjusted to match, as was done in this study, the impact of melting of GIS would be greater compared to the collapse of AMOC.

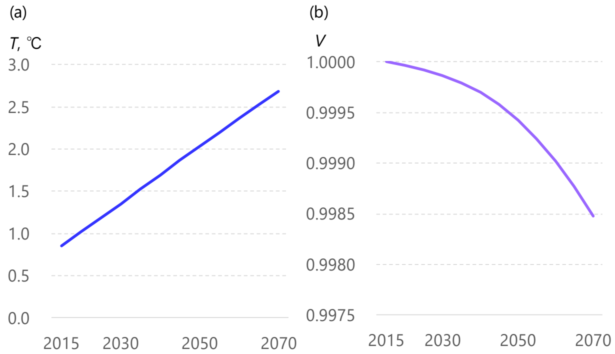

Fig. 1 (a) Average global temperature for the optimal path from DICE-2016R2 , and the estimated change in GIS volume ratio based on (b)

Note: Only 2015–2070 indicated.

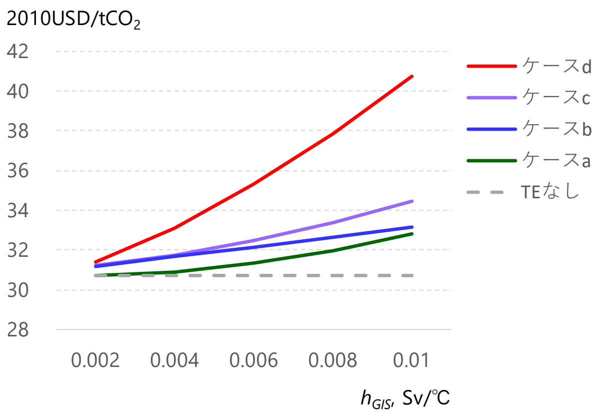

Fig. 2 Social cost of carbon (SCC) in 2015

In the case where both GIS and AMOC were considered, but without their interactions (case c), the increase in SCC was greater than in the cases in which either GIS or AMOC was modeled, but was smaller than when the increases in cases a

[30] S. Dietz, J. Rising, T. Stoerk and G. Wagner: Tipping points in the climate system and the economics of climate change, (2020). https://www.aeaweb.org/conference/2020/preliminary/paper/bSttrkyz (access date: 2020.8.30)

and b were simply added together (\$34.4/tCO_2 for h_{GIS} = 0.01 Sv/°C). This can be understood from the nature of the critical point for AMOC. For the case "without TEs," the path which would eventually pass the AMOC critical point became the optimal path, but for the case with AMOC only (case a), the path in which emissions were reduced until collapse would be avoided was selected. Meanwhile, when the optimal path is sought by first taking GIS into account, the optimal path would be one with lower emissions than when GIS is not considered. Therefore, by incorporating AMOC into the case with GIS, it would be possible to prevent AMOC from collapsing with a smaller additional reduction than when AMOC is incorporated into the case "without TEs." This is why the difference between the case with GIS (case b) and the case with AMOC and GIS (case c) is smaller than the difference between the original optimal solution (the case without TEs) and the case with only AMOC (case a).

In contrast, SCC rose significantly in case d in which the interaction between the two TEs was considered, to \$40.7/tCO_2 under h_{GIS} = 0.01. The difference between case a and case d (the impact of GIS melting and the interaction) was \$7.9/tCO_2, more than triple the impact of GIS melting alone (the \$2.4/tCO_2 difference between case b and the case "without TEs"). This suggests that the interactions between tipping elements may cause consequences that are more serious than when their impacts are considered individually.

4-2. Changes in optimal emission paths

Fig. 3 shows the amount of CO_2 emissions for each case in 2050. As with SCC, the impact of GIS (case b) was largely linear to h_{GIS_0} while the impact of AMOC (case a) was nonlinear. However, unlike the trend of SCC, the amount of emissions reduction under h_{GIS} = 0.01 for the GIS-only case (case b) was smaller than that of the AMOC-only case (case a).

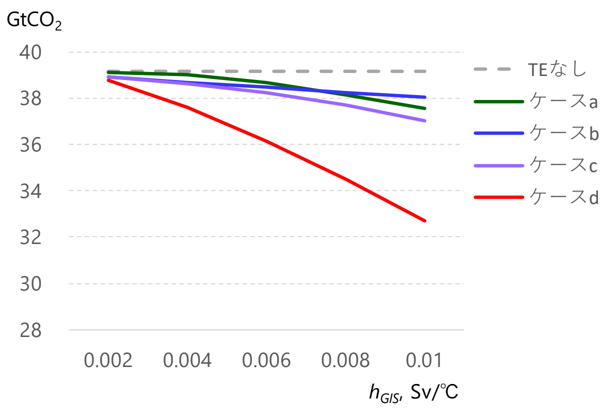

Fig. 3 CO_2 emissions for the optimal path in 2050

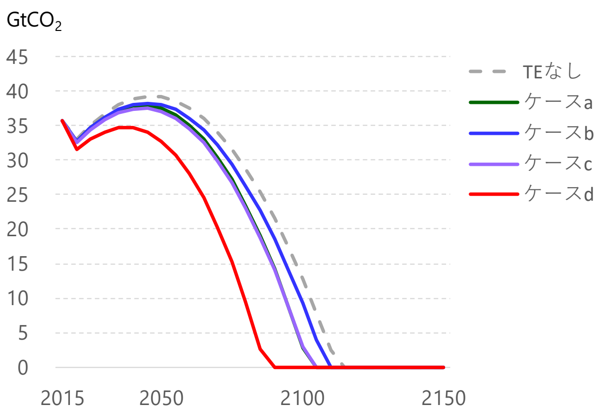

Fig. 4 The optimal global CO_2 emission path (h_{GIS} = 0.01)

This was because while the optimal path for case a opted for a relatively large emissions reduction to prevent AMOC from collapsing, for case b, the path which allows a certain level of damage and therefore has a relatively small reduction became the optimal path. Case d showed a remarkable change in the amount of CO_2 emissions as well, suggesting the importance of addressing interactions.

Fig. 4 shows the optimal CO_2 emission paths for $h_{GIS} = 0.01$ up to 2150. Emissions decrease for all cases between 2015 and 2020, but this is due to a feature of the DICE-2016R2 model, in which the optimal path would be to reduce emissions to a certain extent even at the very initial stage, rather than a reduction rate of zero. For the optimal solution for "without TEs," emissions rise gradually from 2020, reaching 39.1 $GtCO_2$ in 2050 (up 9.5% from 2015). In contrast, the emission paths for cases a to c are lower as the risk of GIS melting and AMOC collapsing are reduced.

As shown in Fig. 3, in 2050, a slight gap remains between the optimal emission volumes of cases a and c, but the gap thereafter becomes narrower toward 2100 (but will not close up completely). This would be because the combined effects of two tipping elements will not be a simple sum of the two (without modeling their interactions), and will diminish as reduction makes progress.

For case d, for which interaction was modeled explicitly, emissions decreased dramatically. The reduction would not be so striking in the relatively near future as in 2030 through 2050 (with a reduction of just 8.5% from 2015 in 2050), but the effects would be remarkably prominent in the second half of this century. The amount of optimal emissions would reach zero in the 2090s, about 10 to 20 years earlier than cases a to c or the case without TEs. This is presumably because it would become rational to introduce larger amounts of decarbonizing technologies to mitigate the damage from interactions between tipping elements.

4-3. Change in rise in temperature

Fig. 5 shows the rise in the average global temperature for each case when $h_{GIS} = 0.01$. For the optimum solution for the case "without TEs," the temperature will rise by 3.5°C by 2100 and by 4.1°C by 2165, hitting the peak, and thereafter gradually decrease. By comparison, the rise in temperature was estimated to be somewhat more moderate for cases a to c, rising by 3.4°C by 2100 and even more moderate for case d, rising by 3.2°C.

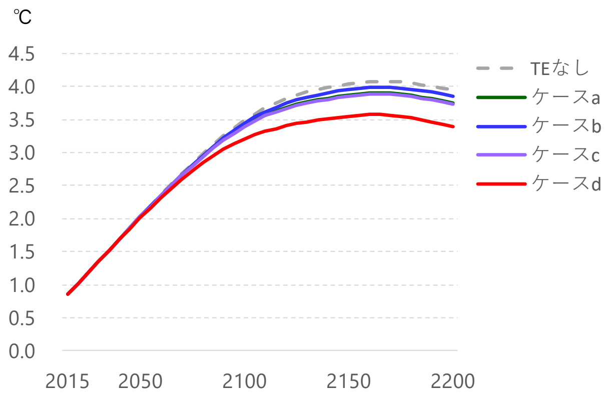

Fig. 5 Rise in temperature up until 2200 ($h_{GIS} = 0.01$)

5. Conclusion

In this study, a cost-benefit analysis was conducted by incorporating the behavior of GIS and AMOC into DICE-2016R2. The result showed that the impact of interaction becomes prominent when h_{GIS} is relatively high, significantly affecting SCC and the amount of optimal CO_2 emissions. Interactions between tipping elements will be essential factors in considering climate policies in the future. When interactions were taken into account ($h_{GIS} = 0.01$), zero emissions became the optimal solution in 2100. In terms of mitigating the damage of tipping elements and managing their risks, developing technologies for achieving zero or negative carbon emissions and implementing them in society will become crucial.

However, even under the optimal emission path for case d ($h_{GIS} = 0.01$) analyzed in this study, the temperature will rise by some 3.2°C in 2100. The DICE model is known to produce optimal temperature rises greater than 2°C or 1.5°C envisioned by the Paris Agreement. However, there are analysis results[19] indicating that it would be optimal to keep the rise in temperature within 2°C by changing the damage function and discount rate. These subjects need to be discussed in greater depth in order to assess the scientific rationality of climate change targets.

Topics requiring further research include the modeling and analysis of tipping elements other than GIS and AMOC. As mentioned above, the results of this analysis are dependent on numerous conditions including the discount rate, availability of technologies that contribute to "negative emissions," and a decrease in reduction costs toward the future. How the results of this analysis would change based on these conditions must also be examined.

Comparative Economics of Hydrogen and Carbon-neutral Methane Blending into the Existing City Gas Network◆

Yoshiaki Shibata* Takahiro Nagata**

This study evaluated decarbonization impact and cost of hydrogen blending and carbon-neutral methane (CN methane) blending into the existing city gas network. These two gases are produced from renewable energy. Larger scale of variable renewables deployment allows to curb the scale of facilities like electrolyzer and methanation and can reduce CO_2 abatements cost in both cases. Decarbonization impact of hydrogen blending is limited, though the CO_2 abatement cost is smaller than CN methane blending. On the other hand, CO_2 abatement cost of CN methane is higher than hydrogen blending, though CN methane blending can bring about larger decarbonization impact on the city gas network. These results come from the fact that hydrogen blending can receive the benefit in using the existing infrastructure that is regarded as an advantage inherent to CN methane. However, it should be noted that in reality blending hydrogen or CN methane into city gas causes adjustment of calorie and combustion performance in equipment at consumers, and the adjustment cost incurred by hydrogen blending is supposed to be much higher than CN methane blending. This factor will be included in the future studies.

Key words: Decarbonization, City gas, Blending, Hydrogen, Methanation

1. Introduction

The activities toward expanding the utilization of hydrogen for decarbonization have been accelerating throughout the world. As hydrogen can be produced from a wide range of resources, it is expected to improve energy security through the diversification of supply sources. On the other hand, demand creation is a challenge, and promotion of hydrogen utilization is under consideration for areas such as power generation, transportation, and industry. Of these, hydrogen blending into the existing city gas infrastructure is drawing attention mainly in Europe. However, it has been pointed out that hydrogen blending into existing city gas infrastructure poses various technological difficulties,[1] and in order to circumvent these issues, the blending of carbon-neutral methane (CN methane) into the infrastructure is also being studied.[2, 3] Prior research [4] has shown that CN methane, which can be used as it is in existing infrastructure, offers an economic advantage over hydrogen that needs new infrastructure.

However, blending hydrogen into existing city gas infrastructure means that it would be possible to avoid building new infrastructure for the distribution of hydrogen to consumers, which would bring about similar advantages as those offered by CN methane.

This study carried out a comparative analysis on the economics and contribution to city gas decarbonization between hydrogen blending and CN methane blending.

◆ This article is a presenting paper at the 37th Conference on Energy, Economy, and Environment that Japan Society of Energy and Resources (JSER) hosted.

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1 Shibata, "Power-to-gas with a view to realizing a low carbonization society – The role of methanation," Inorganic Membranes Research Center Symposium to Explore the Future, Research Institute of Innovative Technology for the Earth (RITE). November 7, 2019.

2 Japan Association of Carbon Capture and Reuse (https://ccr-tech.org/)

3 NEDO, "Development of Power-to-gas System to Synthesize Methane from Renewable Hydrogen and Exhaust CO_2 for Supplying via Conventional Gas Grid," Hitachi Zosen Corporation

4 Shibata, "Potential and Economics of Carbon Neutral Methane; Combination of PtG and CCU," The 35th Conference on Energy, Economy, and Environment. January 2019.

2. Roles and challenges of hydrogen and CN methane blending

Europe, firstly, aims to convert existing hydrogen demand derived from fossil fuels (primarily used for industrial feedstock) to hydrogen produced from renewable energy.[5] As this demand is small-scale and distributed, and involves the procurement of hydrogen at a high cost, there is a possibility that even hydrogen produced from renewable energy, which is estimated to be expensive, can compete with the existing hydrogen. At the same time, the hydrogen market will gradually be expanded toward energy applications, such as large-scale industries. This strategy implies the intention to utilize existing infrastructure and equipment (Fig. 1).

The hydrogen blending into existing city gas infrastructure has been addressed as one of the measures for creating hydrogen demand not only in Europe,[6,7] but also in Australia[8] and the IEA.[9]

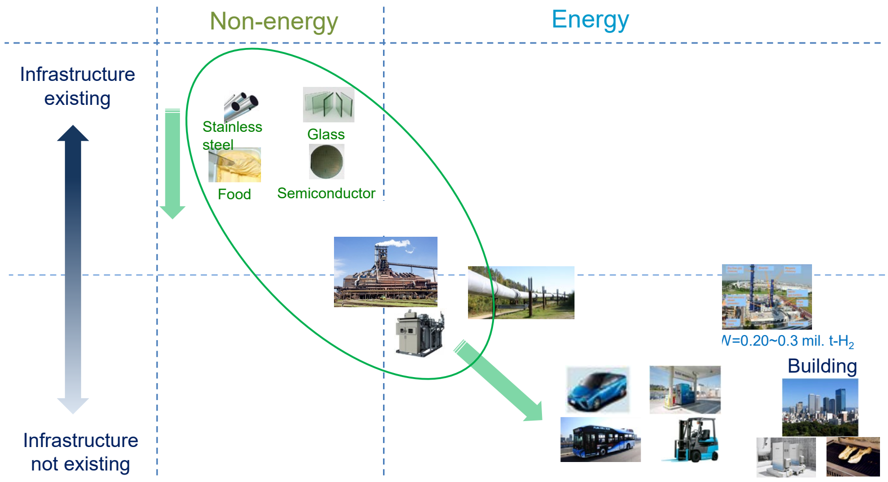

Fig. 1 Difference in Hydrogen Demand Expansion Measures between Europe and Japan[10]

However, there are many challenges in blending hydrogen into city gas infrastructure. These include changing the current measurement method based on volume to calorific value, calorific and combustion performance (combustion speed and Wobbe Index) adjustment of consumers' equipment, ensuring safety in the use of hydrogen, and specific arrangement for special industrial applications such as super high-temperature heating furnaces and carburization, which require carbon in their processes. These challenges are addressed also in Europe, and it has been pointed out that differences in the hydrogen blending rate among regions can be a barrier to the smooth transportation of city gas. Hence, the future development of infrastructure dedicated to hydrogen has also been taken into consideration.[6]

Although hydrogen blending is expected to have an impact on the decarbonization of city gas, from the viewpoint of the city gas infrastructure that will accept the hydrogen, calorific value per unit volume of hydrogen (12.8MJ/Nm^3 LHV) is extremely low at less than one-third of that for city gas in the main regions (45MJ/m^3). As such, even if 2vol% of hydrogen were blended into the city gas infrastructure, the decarbonization impact on city gas would be no more than about 0.6%. In reality, there is also a need to address the abovementioned issues. Therefore, it must be recognized that the hydrogen blending into city gas is aimed at accelerating the creation of initial demand for hydrogen, which is a hydrogen-oriented viewpoint, and in this respect, neglects the circumstances of the side receiving the hydrogen.

In view of that, the blending of CN methane is a potential candidate. Methane is one of the main feedstocks for city gas,

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[5] Plan de déploiement de l'hydrogène pour la transition énergétique, Ministère de la Transition Ecologique et Solidaire, France, 6/2018
[6] An EU Strategy for Energy System Integration, European Commission, 7/2020
[7] A hydrogen strategy for a climate-neutral Europe, European Commission, 7/2020
[8] Australia's National Hydrogen Strategy, 11/2019
[9] The Future of Hydrogen, IEA, 6/2019
[10] Shibata, "Reconsidering the Significance of Carbon-Neutral Methane – Based on Discussions Overseas," Japan Association of Carbon Capture and Reuse. August 2020.

and the blending of CN methane can significantly lower the barriers related to the adjustment of the calories and combustion performance. Furthermore, as the calorific value, at 39.8MJ/Nm^3 (LHV), is considerably close to that of city gas, it offers a higher blend tolerance (on the basis of calorific value) compared to hydrogen. Therefore, decarbonization effect is about 19 times higher than that of hydrogen blending (CO_2 emissions from LPG addition that would be necessary for the adjustment of calorific value for city gas and energy input for CO_2 capture are disregarded).[11]

3. Structure of Analysis

This research uses a model that incorporates city gas demand module into a simple power generation mix simulator,[12] to specify the volume that can be blended into city gas and the decarbonization impact for the cases in which hydrogen and CN methane, respectively, are produced from surplus variable renewable energy, and to analyze the economics.

3-1. Structure of the simulation model

For the sake of simplicity, the study is conducted based on the assumption that Japan is a single virtual region. Base load power generation (nuclear, hydro, biomass and geothermal) and Load Frequency Control (LFC) thermal power generation are set on "must-run" status. Scenarios are established for variable renewable energy (solar PV and wind), and the surplus electricity is identified by simulating the hourly power generation mix. The volume of hydrogen and CN methane that can be produced every hour is figured out based on the surplus electricity. The volume of CO_2 required for CN methane production takes into consideration the hourly emissions based on prior research,[4] and include only intensive emissions from thermal power generation, biomass power generation, and large-scale industries. On the other hand, the hourly volume of hydrogen and CN methane respectively that can be blended into city gas is specified based on an assumption of city gas calorie tolerance. However, it is assumed that a volume of hydrogen and CN methane exceeding the blend tolerance is not produced. Even if the calorific value of blended city gas were the same, hydrogen blending has a greater impact on combustion performance than CN methane blending, and incurs a greater cost in relation to the adjustment of consumers' equipment. However, as there are too many uncertainties concerning the level of this cost, it is disregarded in this study.

With regard to hydrogen, this study also considers the introduction of a hydrogen tank, based on the assumption that the aim is to blend a greater volume of hydrogen into city gas. On the other hand, about CN methane, it is assumed that existing gas holders/pipelines can be used as CN methane storage facilities. Based on the results of the simulation, the volume of gas blended per year and the CO_2 reduction effect achieved through the substitution of natural gas, and the required facility scale, are analyzed.

3-2. Assumptions

(1) Electricity demand, power generation capacity, city gas demand

Based on possible long-term electrification trends and electricity saving, it is assumed that power demand will increase by 10% from the current level to 1040 TWh. Nuclear is assumed to be the same level for 2030 set out in the Long-term Energy Supply and Demand Outlook, while small and medium-scale hydro, biomass, and geothermal are assumed to be slightly higher than the level for 2030 (13GW, 8GW, 3GW respectively). No new large-scale hydro and no pumped-storage hydro will be added. Thermal power generation is assumed to be completely LNG-fired from a long-term perspective. Solar PV is set at 300GW, and wind power generation is set at 100GW and 300 GW.

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[11] The Second Research Group on the Gas Industry for 2050, Material 5, Ministry of Economy, Trade and Industry. October 6, 2020.
[12] Shibata, "Grid Flexibility Offered by Distributed Combined Heat and Power Using Carbon-neutral Methane Produced from Renewable Surplus Electricity," The 36th Conference on Energy, Economy, and Environment. January 2020.

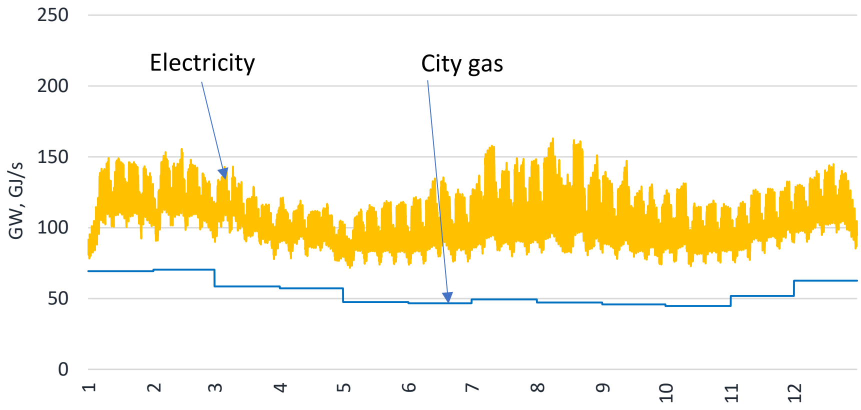


Fig. 2 Hourly Load Profile of Electricity and City gas

City gas demand is assumed to be 35.1 billion m^3 (45MJ/m^3 equivalent) based on the demand in FY2016 of the former General Gas Utilities. Demand varies monthly, but the hourly demand within each month is assumed to be constant. Fig. 2 shows the hourly electricity and city gas demand per year.

(2) Assumptions for blend tolerance of city gas (Case setting)

Although the current calorific value for city gas differs depending on the region, the calorific value of 45MJ/Nm^3 for the metropolitan area is applied uniformly for the whole of Japan. As the maximum amount of calories that can be tolerated through hydrogen and CN methane blending is unknown, the range of 44–39.8MJ/Nm^3 is established as the setting for various cases (Table 1). As the calorific value of methane is about three times that of hydrogen, the methane blend tolerance ratio (vol%) is about six times more of hydrogen. Note that 39.8MJ/ Nm^3 is the figure for the case in which 100% methane is blended, the blend tolerance ratio for hydrogen, in this case, is 16.1%.

Table 1 Blending Cases

Acceptable calorific value (MJ/m^3)	Acceptable H_2 blending ratio (vol%)	Acceptable CH_4 blending ratio (vol%)
39.8	16.1%	100.0%
41.0	12.4%	76.9%
42.0	9.3%	57.7%
43.0	6.2%	38.5%
44.0	3.1%	19.2%

(3) Assumptions for technological specifications and cost

In the case where hydrogen is blended directly into the city gas infrastructure, pressure is assumed to be 1MPa. In the case where it is blended via a hydrogen tank, pressure is assumed to be 20MPa through compression tank. Table 2 shows the technological specifications. In the case of CN methane, pressure is assumed to be 1MPa as the pressure of city gas holders is usually 0.85MPa. Table 3 shows the technological specifications, including CO_2 capture and methanation. The scale of energy storage in the city gas infrastructure is estimated using the geometric volume and pressure of gas holders and pipelines, based on the Gas Industry Handbook (Table 4). While there is room for debate on whether pipelines can be used as storage facilities, as city gas does not require instantaneous supply-demand balancing as electricity does, the pipelines are also assumed to have storage capacity. LNG price is assumed to be 50,000 yen/ton (0.92 yen/MJ) based on trends in recent years. Table 5 shows the assumptions of facility costs that are used in the economic analysis.

Table 2 Assumptions for Hydrogen Production

	Electrolyzer	Compressor	Total	Unit
Direct blending (1MPa)	4.50	0.076	**4.58**	kWh/ Nm^3-H_2
Blending through compressed tank (20MPa)	4.50	0.224	**4.72**	kWh/ Nm^3-H_2

Source: Based on[4] and[13].

Table 3 Assumptions for Methanation

Electrolysis+Methanation	18.0	kWh/Nm^3-CH_4
Auxiliary	0.32	kWh/Nm^3-CH_4
Electricity for CO_2 capture	0.02	kWh/Nm^3-CH_4
Compressor (1MPa)	0.074	kWh/Nm^3-CH_4
Total	**18.42**	kWh/Nm^3-CH_4
Heat for CO_2 capture	**3,549**	kJ/Nm^3-CH_4
	(1,800)	MJ/t-CO_2
CO_2 capture ratio	90%	
Boiler efficiency	80%	

Source: Based on[4] and[13].

Table 4 Storage Capacity of City Gas Infrastructure

Gas tank	34	million Nm^3-CH_4
Pipeline	38	million Nm^3-CH_4
Total	72	million Nm^3-CH_4

Source: Estimated from "Gas Utility Handbook".

Table 5 Assumptions for CAPEX

Electrolyzer	215	1000JPY/(Nm^3-H_2/h)
Methanation	500	1000JPY/(Nm^3-CH_4/h)
CN-methane production	1360	1000JPY/(Nm^3-CH_4/h)
CCU(CO_2 capture and boiler)	134	million JPY/(t-CO_2/h)
	0.26	million JPY/(Nm^3-CH_4/h)
Hydrogen compressor	120	1000JPY/kW
Hydrogen tank	2.2	1000JPY/Nm^3

Source: Based on[12, 13] and [14].

3-3. Direct blending and blending via storage facilities

The approaches to direct blending into the city gas infrastructure and, and blending via storage facilities (new hydrogen compression tank in the case of hydrogen, and existing gas holders/pipelines in the case of CN methane), are shown below.

[13] "Evaluation of Hydrogen Cost," Japan Atomic Energy Research Institute. July 2005.
[14] "FY2005 CO_2 Fixation and Effective Utilization Technology, etc. Countermeasure Project - Report on the Results of R&D on CO_2 Underground Storage Technology" (March, 2006), Research Institute of Innovative Technology for the Earth (RITE)

(1) Hydrogen blending

1) Direct blending

The capacity of the water electrolyzer is identified based on the correlation of the hourly producible hydrogen volume from surplus electricity and the blend tolerance (minimum water electrolysis facility capacity).

2) Blending via a hydrogen tank

As the blending volume is likely to be limited in case of direct blending of hydrogen, consider increasing the capacity of the water electrolyzer as larger as possible to produce a large amount of hydrogen, temporarily storing hydrogen that cannot be blended directly in a hydrogen tank, and blending this stored hydrogen at a different time. Firstly, the capacity of the water electrolyzer (maximum water electrolyzer capacity) that can produce a volume of hydrogen equivalent to the volume that can be blended yearly (Yearly city gas demand (Nm^3) × Blend tolerance ratio (%)) is specified. Next, using the water electrolyzer capacity as a variable (from minimum water electrolyzer capacity to maximum water electrolyzer capacity), the maximum capacity of the hydrogen tank that is required is identified through a simulation. However, in cases where surplus electricity is limited and a volume of hydrogen equivalent to the volume that can be blended yearly cannot be produced, all the surplus electricity is utilized for hydrogen production (in such cases, the capacity of the water electrolysis facility will be extremely large).

(2) CN methane blending

1) Direct blending of CN methane

The capacity of the CN methane production facility (water electrolyzer, methanation, CO_2 capture) is identified based on the correlation of the hourly producible CN methane volume from surplus electricity and the blend tolerance (minimum capacity).

2) Utilization of holders, etc.

It is assumed that existing gas holders and pipelines can be used for the storage of CN methane, and simulation is carried out by using CN methane production capacity as a variable.

4. Results of analysis

4-1. Blending volume

Fig. 3 shows the relationship between the annual producible volume, blend tolerance, and blend volume, while Fig. 4 and 5 are examples of the simulation results for a typical one-week period in summer. Both Fig. 4 and 5 are based on the assumption of large-scale variable renewable energy deployment, "Solar PV + Wind = 300GW + 300GW". Fig. 4 shows the case in which blend tolerance at H_2 3.1vol%=CH_4 19.2 vol%, while Fig. 5 shows the case in which blend tolerance is at H_2 16.1vol%=CH_4 100 vol%.

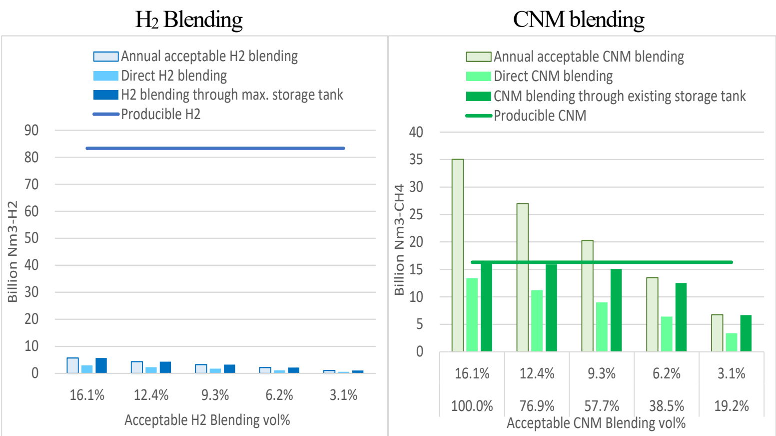


Fig. 3 Producible amount, acceptable blending amount, and blending amount

Note: In case of "Solar PV + wind = 300GW + 300GW"

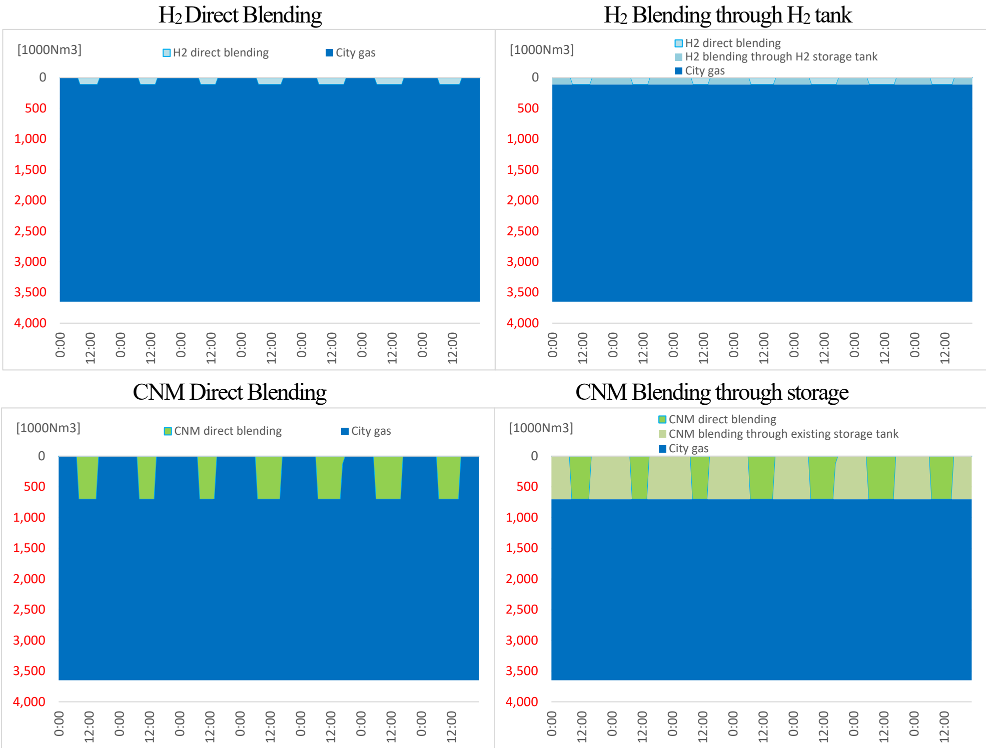


Fig. 4 Blending profile (H_2 3.1vol%=CH_4 19.2 vol%)

Note: Example of a representative week in summer. "Solar PV + wind = 300GW + 300GW". Electrolyzer capacity is 0.16 million Nm^3-H^2/h for direct H_2 blending. Electrolyzer capacity is 0.24 million Nm^3-H_2/h and H_2 storage tank capacity is 64 million Nm^3-H_2 for H_2 blending through H_2 tank. Methanation capacity is 1 million Nm^3-CH_4/h for direct CH_4 blending and 1.45 million Nm^3-CH_4/h for CH_4 blending through the existing city gas storage tank.

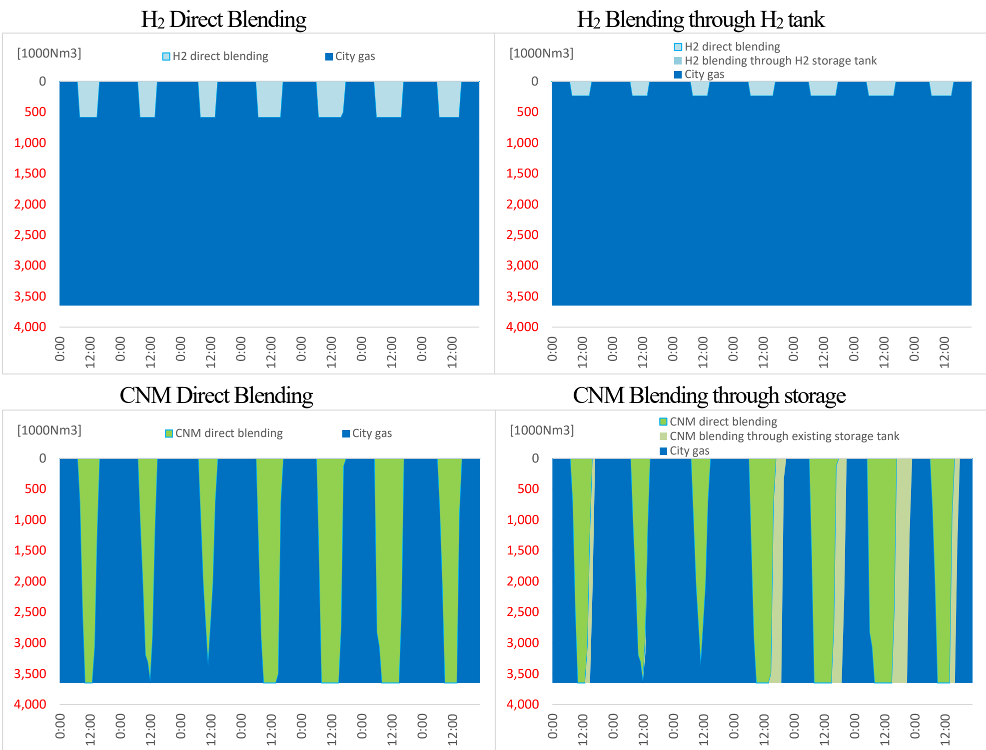


Fig. 5 Blending profile (H_2 16.1vol%=CH_4 100 vol%)

Note: Example of a representative week in summer. "Solar PV + wind = 300GW + 300GW". Electrolyzer capacity is 0.84 million Nm^3-H_2/h for direct H_2 blending. Electrolyzer capacity is 1.26 million Nm^3-H_2/h and H_2 storage tank capacity is 330 million Nm^3-H_2 for H_2 blending through H_2 tank. Methanation capacity is 5.2 million Nm^3-CH_4/h for direct CH_4 blending and 7.24 million Nm^3-CH_4/h for CH_4 blending through the existing city gas storage tank.

While the hydrogen blend tolerance of city gas is considerably small in comparison with the scale of surplus renewable energy, the CN methane blend tolerance is at the almost same level as the scale of surplus renewable energy (Fig. 3), which demonstrates the potential for accepting a large amount of surplus renewable energy. In the case of H_2 3.1vol%=CH_4 19.2 vol% (Fig. 4), it is possible to keep blend volume mostly flat every hour through the introduction of new storage facilities for hydrogen blending, and through the utilization of existing storage facilities for CN methane blending. However, in the case of H_2 16.1vol%=CH_4 100 vol%, blend volume is flat for hydrogen blending, but does not remain flat in the case of CN methane blending as blend tolerance is high (Fig. 5).

4-2. Facility scale

Fig. 6 shows the facility scale and hydrogen blend volume in the case of hydrogen blending. In the case where only a small scale of renewable energy is introduced (Solar PV + Wind = 300GW + 100GW), direct blend volume is also low due to the smaller amount of surplus electricity. If a hydrogen tank is used in an attempt to increase blend volume, a larger scale of water electrolyzer would then be required (it would be necessary to use extremely low frequency and high output surplus power). At the same time, a large-scale hydrogen tank would also be required. Expanding the scale of renewable energy introduced (Solar PV + Wind = 300GW + 300GW) would increase the frequency for the emergence of surplus power, resulting in a greater amount of surplus power. Hence, it would be sufficient to keep the scale of the water electrolyzer and hydrogen tank small. At the respective blend tolerance ratios (hydrogen 16.1%, 12.4%, 9.3%, 6.2%, 3.1%), the introduction of the largest possible hydrogen tank would make it possible to carry out blending up to the blend tolerance almost throughout the year (5.66 billion, 4.36 billion, 3.27 billion, 2.18 billion, and 1.09 billion Nm^3-H_2 respectively).

Fig. 7 shows the facility scale and blend volume in the case of CN methane blending. The direct blend volume (dots in the figure) for the respective blend tolerance ratios (CN methane 100%, 76.9%, 57.7%, 38.5%, 19.2%) does not lie in linear as it is in the case of hydrogen blending. This is because of the relative magnitude between the scale of surplus power and blend tolerance. In the case of hydrogen blending, the scale of blend tolerance is extremely small in comparison with the amount of surplus electricity (the amount of hydrogen that can be produced). For this reason, the frequency and scale of the emergence of surplus power are not significantly impacted, and the increase in water electrolyzer capacity accompanying the increase in blend tolerance has a mostly linear relationship with the increase in the volume that can be blended. On the other hand, as blend tolerance is high in the case of CN methane, even if methanation facility capacity were expanded to accompany the increase in blend tolerance, it would only have the effect of absorbing the surplus electricity that is generated at extremely low frequency, and the marginal volume of CN methane that can be blended decreases gradually.

In this study, it is assumed that renewable energy is introduced on a large scale, and the scale of surplus electricity exceeds blend tolerance. As such, methanation facility capacity in direct blending is dependent only on the blend tolerance ratio (in the figures, the position of dots of the same color in the horizontal direction is the same, regardless of the scale of renewable energy introduced). However, blend volume (vertical direction of dots) increases corresponding to the scale of renewable energy introduced.

When holders/pipelines are utilized, lines other than the 19.2% blend overlap in the scenario where the scale of renewable energy introduced is small (Solar PV + Wind = 300GW + 100GW). This is because it is dependent only on methanation facility capacity, regardless of blend tolerance ratio, since the scale of surplus power is small and the yearly producible amount of CN methane falls below the yearly blend tolerance when blend tolerance ratio is 38.5%.

If the scale of renewable energy introduced was expanded (Solar PV + Wind = 300GW + 300GW), the producible amount of CN methane also increases. In this situation, increasing the blend tolerance ratio enables a larger volume of CN methane to be blended (deviation of each line).

When blend tolerance ratio is small, the upper limit of the blend tolerance would be achieved faster even if the methanation facility capacity were increased. On the other hand, when blend tolerance ratio is large, the producible volume of CN methane would be reached before the upper limit of blend tolerance if the methanation facility capacity were increased (Blend tolerance > producible volume of CN methane).

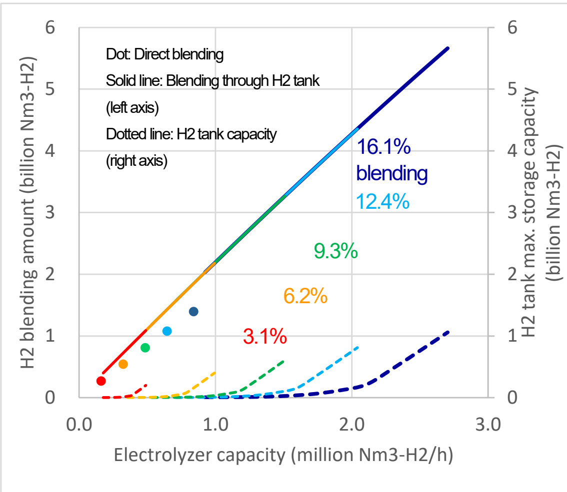
4-3. Economics

Fig. 8 shows the amount and cost of CO_2 abatement in the cases of hydrogen blending and CN methane blending. The procurement cost of electricity from renewable sources is assumed to be 5 yen/kWh.

The level of CO_2 abatement is the substitution effect of city gas through hydrogen/CN methane blending on the basis of calorific value, but in the case of CN methane, the incremental city gas consumption for supplying the necessary heat for CO_2 capture is deducted. Cost is obtained by deducting the reduction in LNG procurement from renewable energy procurement costs and facility costs. Facility costs comprise the cost of water electrolyzer, compressors, and hydrogen tank (where necessary) in the case of hydrogen blending, and water electrolyzer, methanation equipment, CO_2 capture equipment, and compressors in the case of CN methane blending.

Hydrogen blending incurs about half of the CO_2 abatement cost in comparison with CN methane blending; however, the degree of CO_2 abatement is extremely small.

[Solar PV + Wind = 300GW + 100GW]



[Solar PV + Wind = 300GW + 300GW]

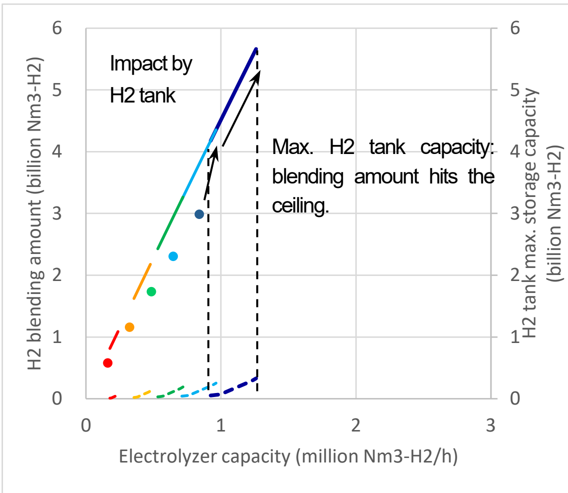


Fig. 6 Electrolyzer Capacity and H_2 Blending Amount

Even with the expanded use of hydrogen tanks, it would still only be approximately 4 million tons. This is considerably limited when compared to the current level of CO_2 emissions from city gas, which is about 80 million tons. On the other hand, as CN methane has a high blend tolerance ratio and calorific value that is about three times that of hydrogen, it produces a significant reduction in CO_2 emissions. However, while a certain degree of cost reduction can be achieved through the utilization of existing storage facilities such as holders, CO_2 abatement cost is higher. However, for both hydrogen and CN methane, the greater the scale of renewable energy introduced, the lower the cost of CO_2 abatement.

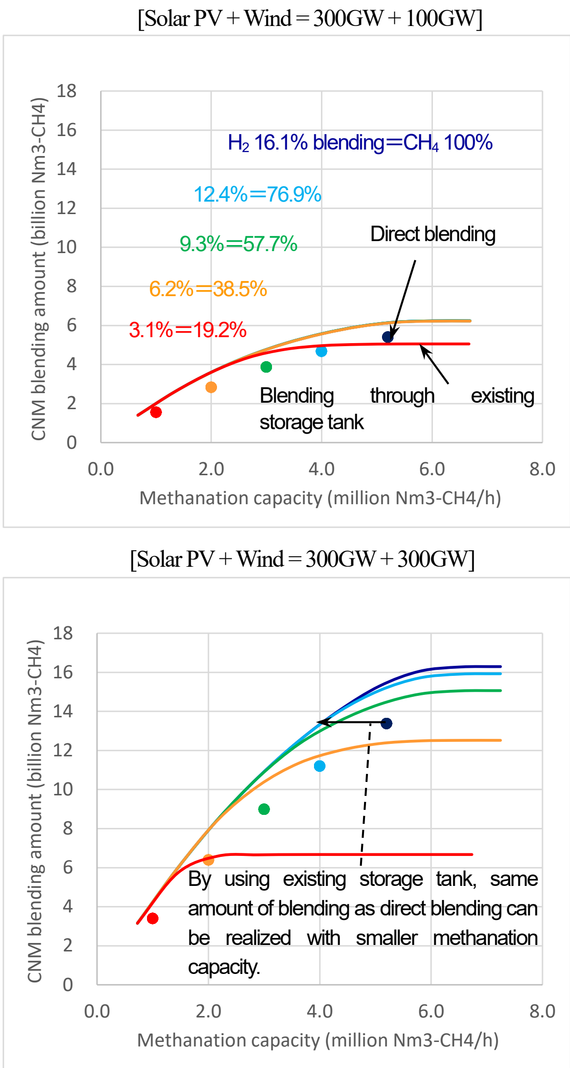
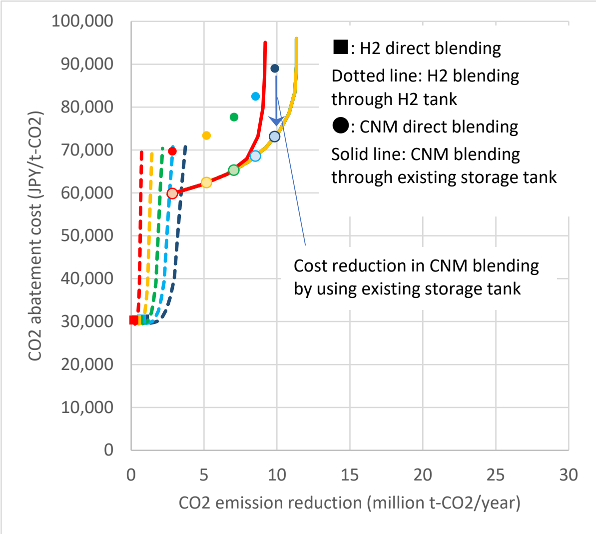


Fig. 7 Methanation Capacity and CNM Blending Amount

[Solar PV + Wind= 300GW + 100GW]



[Solar PV + Wind= 300GW + 300GW]

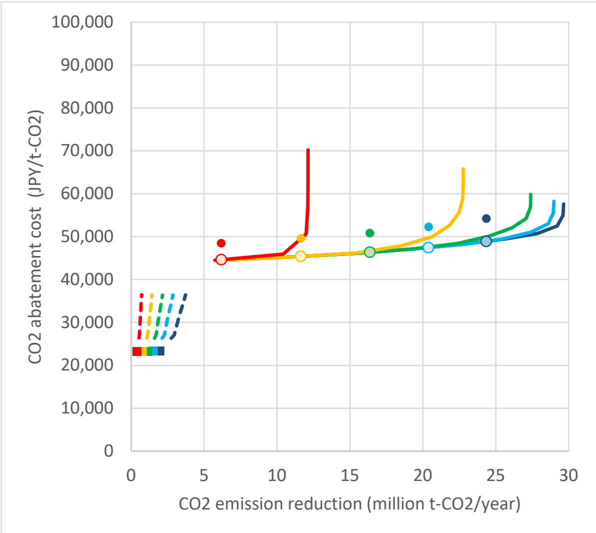


Fig 8 CO_2 Emission Reduction and CO_2 Abatement Cost

Note: Costs incurred on calorific adjustment for customers equipment by blending are ignored. Note that these costs incurred by hydrogen blending are larger than CNM blending.

5. Conclusion

This research provided a simple evaluation of the amount and costs of CO_2 abatement through the blending of hydrogen and CN methane, respectively, into city gas. For both scenarios, a larger scale of renewable energy introduced is more capable of suppressing the scale of facility per unit of blend volume, and of reducing CO_2 abatement cost. While CO_2 abatement cost is lower for hydrogen blending than for CN methane blending, its decarbonization impact on city gas is limited. On the other hand, while CN methane blending can be expected to produce a greater decarbonization impact, it poses the challenge of incurring a higher CO_2 abatement cost than hydrogen blending. This is because the economic advantage from the utilization of existing infrastructure, which is the inherent characteristic of CN methane, can also be applied to hydrogen blending.

In this study, the analysis was carried out based on the premise that standard calorific value can be changed without causing any technical issues. However, in reality, it is necessary to adjust calorific value and combustion performance of consumers' equipment by adding LPG into city gas that has been blended with hydrogen or CN methane. In the case of hydrogen blending, the costs involved in this respect are presumed to be higher than those for CN methane blending. Moreover, the production and injection of gas at a stable volume and properties are stipulated based on the current gas utility supply service provisions. This poses institutional issues for hydrogen blending and CN methane blending. An analysis that considers these factors will be a subject for the future.

Utilization of existing infrastructure is an advantage for CN methane blending, However, when the time comes to update infrastructure in the future, it will also be worth considering the establishment of infrastructure dedicated for hydrogen, depending on the region.

Study on Market Price Based Dynamic Renewable + Battery Control to Maximize Market Revenue◆

Sichao Kan*

Under the FIP mechanism renewable developers are expected to sell their electricity through the electric power exchange market in the future. To hedge market price fluctuations and to counter the so-called "Cannibalism" issue, batteries could be utilized. This study discusses how to dynamically control battery operation based on market price signals to maintain high market revenue for the renewable + battery system. Battery operation control is disaggregated into 2 steps: control of charging/discharging, and decision of electricity discharging amount. A method of using the previous day's market price signal to conduct the control process is examined and the simulation results suggest that this method could help increase market revenue when battery installation happens to an extend that affects market prices. The study also attempted reinforcement learning for battery control and found that though the reinforcement learning could help bring higher market revenue, the results highly rely on the pre-set learning conditions and more study on this method will be needed in the future.
Key words: Electricity Exchange Market, Renewable Energy, Battery Operation

1. Background

The subsidy mechanism for large scale solar PV and wind will be changed from feed-in tariff (FIT) to feed-in premium (FIP) in Japan. Under the FIP system, renewable energy electricity will be sold in the Japan Electric Power Exchange, with a premium on top of the market price.

Under the FIP system, renewable developers' revenue becomes vulnerable to market price fluctuations. Batteries are one of the options for developers to maximize their market revenue. As too much electricity from solar PV and wind, the marginal costs of which is low, flows into the market, the market prices in certain hours could plunge and result in the decrease of the renewable developers' revenue from the market. The so-called cannibalism phenomenon[1, 2] is one of the issues with the FIP system. A previous study[3] analyzed batteries' role in mitigating the cannibalism phenomenon.

This study considers a method to control battery operation in response to electricity market price fluctuations to maximize revenue from electricity sales in the market. As is the case with the previous study[3], the analysis is carried out with a case study of the Kyushu region which is one of the largest solar PV market in Japan.

2. Defining the Problem

According to the previous study[3], the installation of batteries allows electricity from solar PV to be sold in the evening when electricity market prices are high, which can mitigate the impact of the cannibalism phenomenon. However, in the simulation of the previous study, the hours for electricity sales from solar PV-battery systems were fixed between 17:00 and 21:00 (Fig. 1). Under this case, if solar PV-battery systems continue to increase, a large amount of low-cost electricity from solar PV-battery system could in turn cause market prices during the evening hours to drop (Fig. 2).

◆ This article is a presenting paper at the 37th Conference on Energy, Economy, and Environment that Japan Society of Energy and Resources (JSER) hosted.

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[1] Kenji Asano, Kenji Okada, Yu Nagai, Masahiro Maruyama; An Analysis of Renewables Market Integration Policies in the European Liberalized Electricity Market, Central Research Institute of Electric Power Industry (2016)

[2] Hirth Lion, The Market Value of Variable Renewables, Energy Policy 38 218-236, (2013) https://www.neon-energie.de/Hirth-2013-Market-Value-Renewables-Solar-Wind-Power-Variability-Price.pdf. (Accessed on 2020/11/05)

[3] Sichao Kan & Yoshiaki Shibata, Study on FIP Policy Design by Using Multi-agent Based Electric Power Market Simulation Model, 36th Conference on Energy Systems, Economy and Environment Conference, Session 22 (2020)

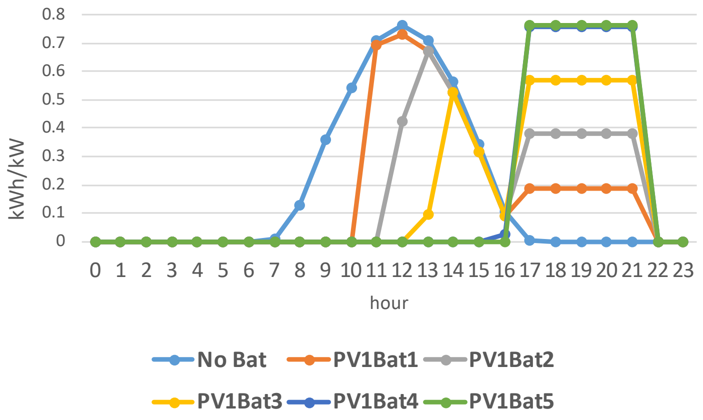

Fig. 1 Assumption on the output of solar PV-battery system in the previous study

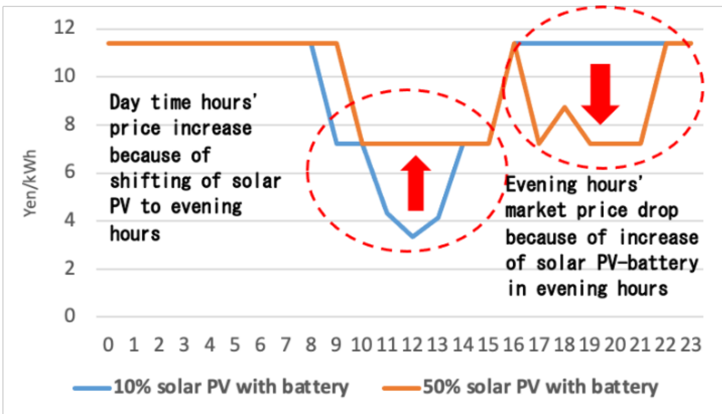

Fig. 2 Market price drop caused by the increase of solar PV-battery system

Source: Simulation results from the previous study[3]

To resolve this problem to improve market sales revenue, battery operation is required to be dynamically controlled in response to market price fluctuations.

3. Methodology and key assumptions

This study uses the same multi-agent-based electricity market simulation model as in the previous study[3]. Simulation case is Kyushu Electric Power Company's service area. All power generators in the area are assumed to participate in the market. The simulation assumes one buyer agent and multiple seller agents for each power generation technology. As in the previous study[3], because of data availability interval for market settling is assumed to be 1-hour.

The previous study[3] assumed two cases for solar PV generation capacity – 7,850 MW (actually installed capacity) and 16,673 MW (approved capacity at the end of FY2017). However, this study only covers the 16,673 MW case.

As is the case with the previous study[3], the bidding block of the buy agent is calculated based on hourly electricity demand (2017)[4] disclosed by Kyushu Electric Power Company. Seller agents' bidding block, the volume is considered equal to installed capacity for non-variable renewable power generation technologies. For each variable renewable energy technology, the quantity of electricity to offer to be bid is calculated by the installed capacity and the output curve estimated

[4] Information disclosed by Kyushu Electric Power Company
https://www.kyuden.co.jp/td_service_wheeling_rule-document_disclosure. (Accessed on 2020/11/09)

from the historical output data. Output from solar PV-battery systems depends on battery operation control (the operation control method is detailed in 3-1). Table 1 shows assumed battery configurations. Assumptions for each power generation technology are the same as in the previous study[3] (Table 2).

Table 1 Assumptions on battery configuration

Item	Assumption
Battery Capacity	3 kWh battery per 1 kW solar PV
Rated Output	Battery capacity（kWh）/hour
Charging Efficiency	95%
Discharging Efficiency	95%
Selfdischarging	0.2%/hour

Table 2 Assumptions on the power generation cost and capacity of various technologies

	Hydro	Nuclear	Coal	Gas	Oil	Biomass	Geothermal	Solar PV	Wind	Solar PV + battery
Generation cost（Yen/kWh）	2.3	5.4	7.2	11.4	26.7	25.2	12.5	3.34	4.15	3.34
Capacity（MW）	1,901	1,780	3,983	4,981	3,560	52	192	7,850	500	scenario

Source: Same with the previous study[3]

3-1. Battery operation control

Given that revenue from electricity sales in the market depends on the price and volume of electricity sold, to increase revenue, it is desirable for solar PV-battery systems to charge during hours with low market prices and to discharge when the market price is high. Therefore, this study assumes that battery operation is controlled in two stages: (1) determining the timing for charging and discharging (a charging or discharging command signal for each hour) and (2) deciding the amount of electricity for charging or discharging. Although there are various logics to link market price with the decision making of the charging/discharging timing as well as the charging/discharging amount, this study assumed a method using indicators calculated by market prices of the previous day.

(1) Timing for charging and discharging

It is assumed that charging and discharging do not happen at the same time, no discharging is assumed during the hours between 10:00 and 18:00 when there is solar PV output. So, the decision making for charging/discharging timing is only required for the remaining hours. Although the market price may change from day to day, there are some common trends for high- and low-price hours. This study uses market price of the previous day to decide on the charging and discharging timing of the current day. First the previous day’s average market price is calculated. For the same hours, when the previous day’s market price is higher than the average price, command signal for battery discharging is issues. For the other hours, the command signal is charging.

(2) Amount of electricity to be charged or discharged

In response to a charging command signal, the battery will be charged up to its full capacity. If there is still solar PV electricity generation when the battery is charged full, the electricity will be sold to the market.

In response to a discharging command signal, the desirable amount of electricity to be discharged is first calculated based on market prices to maximize electricity sales during high-price hours. The actual discharging amount will be limited by the electricity stored in the battery and battery's rated output power. This study calculated the economically desirable discharging amount by multiplying the battery's rated output power by the ratio calculated from the previous day's market prices. To calculate the ratio of a given discharging hour, first, the sum of the price gaps between discharging hours' market prices (previous day) and the previous day's average market price is calculated. For a certain discharging hour, the hour's discharging ratio is the ratio of the hour's price gap divided by the price gaps sum (Fig. 3). The actual discharging volume is smaller between the economically desirable discharging amount electricity stored in the battery.

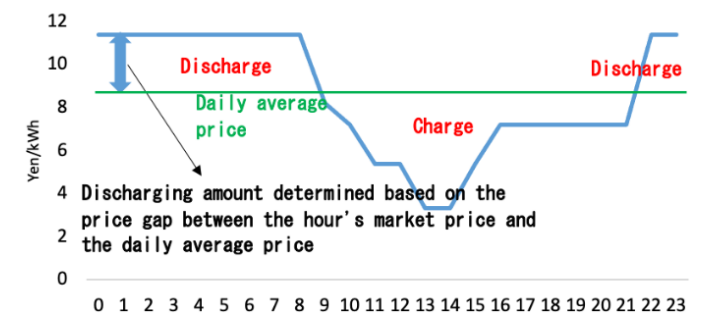

Fig. 3 Control of battery's charging/discharging

4. Results

4-1. Market sale revenue

The previous study[3] showed that if massive solar PV electricity is flowed into the market (solar PV capacity increases from 7,850 MW to 16,673 MW), the solar PV developer's annual revenue from electricity market will decline from 11,845 yen/kW to 6,714 yen/kW because of the cannibalism phenomenon. If batteries are installed to shift solar PV electricity sales to evening hours, annual market revenue could be increased by 4,232 yen/kW (Fig. 4). As noted above, however, revenue for solar PV-battery systems would decline if there are too many such systems, which will result in lower market price in evening hours. If the share of solar PV-battery systems expands from 10% to 50% in terms of total solar PV capacity, revenue for solar PV-battery systems will decrease by 2,400 yen/kW (Fig. 4).

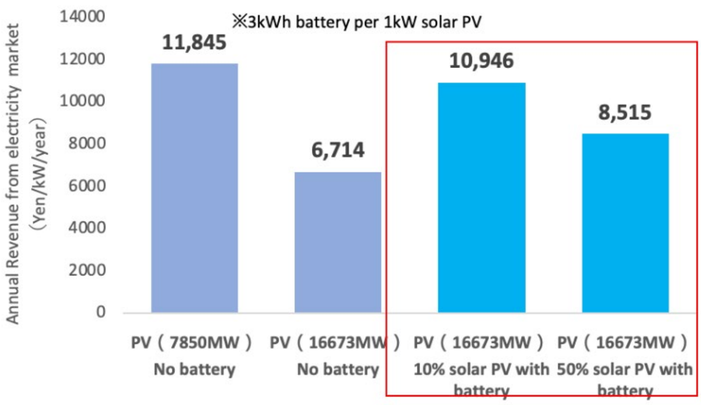

Fig. 4 Change of market revenue with installation of battery

Source: results from the previous study[3]

The effectiveness of the battery operation control method discussed in this study can be shown from the results of the two cases: batteries are installed for 10% of solar PV capacity (Fig. 5) and for 50% of solar PV capacity (Fig. 6).

The simulation results suggest that the battery operation control discussed in this study is effective in improving the solar PV-battery system's market revenue when the penetration of battery high (capacity of solar PV with battery accounts for 50% of total solar PV capacity) (Fig. 6). However, when the installation of battery is relatively small (solar PV-battery accounts for 10% of solar PV capacity) the system's market sales revenue benefits little from dynamic control of battery (Fig. 5).

Electricity market price is usually high in evening hours, which means that to increase revenue selling electricity in these hours is desirable. As stated before, when the installation of batteries increases because of the concentration of electricity selling from solar PV-battery systems in evening hours, market price in these hours will decline, resulting in the decrease of market revenue. In this case, dynamic battery operation control to shift the output of battery from evening hours to other high-market-price hours will improve market sales revenue.

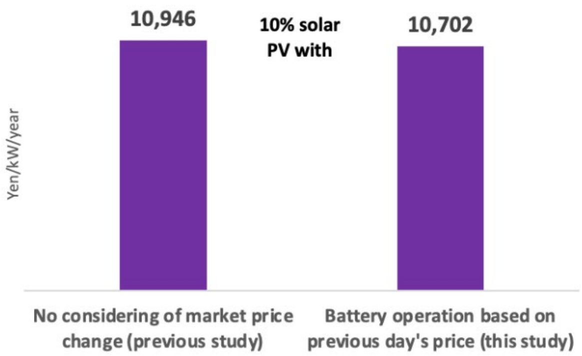

Fig.5 Change of market revenue by dynamic battery operation (solar PV with battery accounts for 10% of total capacity)

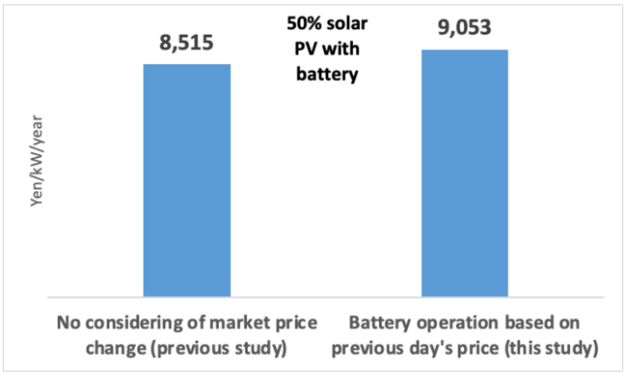

Fig.6 Change of market revenue by dynamic battery operation (solar PV with battery accounts for 50% of total capacity)

4-2. Considering reinforcement learning for battery control

This study also tested using reinforcement learning for battery control. Reinforcement learning allows an agent (batteries in this study) to select profit-maximizing option from multiple options through learning. This study applied reinforcement learning in the process of decision making of the amount of electricity to be discharged. Multiple options of discharging amount are assumed in advance and through a learning strategy, the solar PV-battery agent will select the one that is expected to maximize market sales revenue.

Simulation results suggested that how to set the discharging amount options has great impacts on the results of learning. Fig. **7** shows annual market sales revenue results for two cases. Case 1, the maximum dischargeable amount is 26% of rated battery output, and Case 2, the maximum dischargeable amount is 100% of rated battery output. Even with the same learning strategy, the difference in annual market revenue between the 2 cases is as much as 2,010 yen/kW. Revenue under Case 2 is lower than that under Case 1 because under the assumptions of Case 2, hourly discharging amount is larger and in the learning process, there is still the possibility that options of larger discharging amount are selected even the market price is not the highest. On the other hand, revenue under the assumptions of Case 1 is higher than that using the method discussed in 4-1.

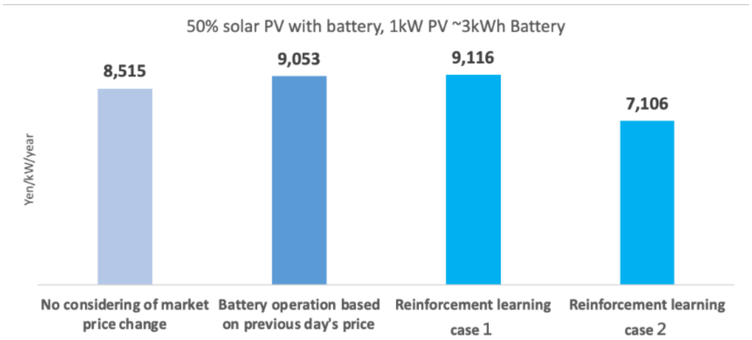

Fig.7 Market revenue results using reinforcement learning

5. Conclusion and implications

This study used a multi-agent market simulation model to analyze the effectiveness of dynamic battery operation in response to the change of electric market price. Simulation results suggested that as solar PV-battery systems expand, dynamic battery operation control based on market price can contribute to the improvement of the system's market sales revenue. This study discussed two battery operation control methods: one based on previous-day market price only and the other based on previous-day market price as well as reinforcement learning. Although reinforcement learning could help to further improve market sales revenue, the result is highly dependent on the pre-set learning conditions.

A Quantitative Analysis of Japan's Optimal Power Generation Mix towards 2050 - Analysis Considering Economic Percussion by Investment in Power Resources –◆

Hideaki Okabayashi* Tomofumi Shibata** Yuji Matsuo***

Abstract

This study performs model analyses assuming the Japanese power supply portfolio in 2050 to evaluate the optimal generation portfolios that contribute to both economic growth and low-cost power supply by 2050. The energy model developed in this paper is an integrated model which combines an optimal power generation mix model and an evaluating econometric model.

Considering the economic ripple effect, portfolios that include zero emission power generation do not necessarily decelerate economic growth, even if the portfolios raise the electric price due to higher system costs. A balanced energy mix using not only zero-emission power generation but also an optimal amount of gas power generation can realize harmonization between the environment and economic growth.

Key words: Nuclear power, Unit cost, Linear programming, Econometrics, Energy mix

1. Introduction

In response to internationally growing interests in global warming prevention, a large number of countries have set national targets regarding greenhouse gas emission cuts.

In June 2019, for instance, the United Kingdom passed a law to reduce GHG emissions to net zero in 2050[1]. In November 2019, France enacted a law to upgrade its national target from a 75% cut in GHG emissions from 1990 by 2050 to carbon neutrality by 2050[2].

Japan as well has enhanced its initiatives to reduce future GHG emissions. In June 2019, the Japanese government made a cabinet decision on the Long-term Strategy under the Paris Agreement[3], proclaiming a "decarbonized society" as the ultimate goal and aiming ambitiously to accomplish it as early as possible in the second half of this century, while boldly taking measures towards the reduction of GHG emissions by 80% by 2050. Japan then became the first country among the Group of Seven industrial democracies to make a decision to proclaim net-zero GHG emissions. In his policy speech[4] in October 2020, Japanese Prime Minister Yoshihide Suga stated, "We hereby declare that by 2050 Japan will aim to reduce greenhouse gas emissions to net-zero, that is, to realize a carbon-neutral, decarbonized society."

While major countries have set ambitious targets of cutting GHG emissions to net-zero, some countries see growing concerns about an increase in costs for global warming countermeasures.

In France, more than 10 citizens were killed with more than 1,000 citizens and police officers injured in citizens' anti-government protest called the "Yellow Vest Movement" which grew from the second half of 2018 to the first half of 2019. One of the factors behind the movement was citizens' discontent with a carbon tax.

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*** Senior Economist, Manager, Energy and Economic Analysis Group (EEA), Energy Data and Modelling Center (EDMC), IEEJ

1 Gov.UK; UK becomes first major economy to pass net zero emissions law (2019). https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (Accessed on 2020/11/30)

2 République française Direction de l'information légale et administrative; Loi du 8 novembre 2019 relative à l'énergie et au climat (2019). https://www.vie-publique.fr/loi/23814-loi-energie-et-climat-du-8-novembre-2019 (Accessed on 2020/11/30)

3 Prime Minister's Office, Long-term Strategy under the Paris Agreement, June 11, 2019 https://www.kantei.go.jp/jp/singi/ondanka/kaisai/dai40/pdf/senryaku.pdf (Accessed on 2020/11/30)

4 Prime Minister's Office, Policy Speech by the Prime Minister to the 203rd Session of the Diet, October 26, 2020 https://www.kantei.go.jp/jp/99_suga/statement/2020/1026shoshinhyomei.html (Accessed on 2020/11/30)

In Japan as well, business leaders have expressed concerns about the economic impacts of some GHG emission reduction measures including a carbon tax. In November 2017, the Japan Business Federation known as Keidanren published an opinion on carbon pricing[5], indicating concern that explicit carbon pricing could affect Japan's international competitiveness.

These cases demonstrate a dilemma between the ideal of net-zero GHG emissions and economic cost hikes accompanying the achievement of the ideal, indicating how important it is to prepare a specific strategy for ambitious GHG emission cuts while minimizing economic impacts.

Given the above, initiatives to analyze the impacts of national energy choices for net-zero emissions on the economy and national burdens have been vigorously implemented at home and abroad.

For instance, many researchers mainly in European countries and the United States have assessed costs for integrating renewable energy and other power sources into electric power systems.

According to a report[6] by the Organization for Economic Cooperation and Development and the Nuclear Energy Agency in 2012, the average cost for integrating variable renewable energy for covering 30% of total power generation differs by country within a 2-8 cents/kWh range. The OECD/NEA estimated the average cost at 2.5-4.0 cents/kWh in a review in a report[7] released in 2018 and at 2 cents/kWh in a model analysis[8] for Europe released in 2019. Cost estimates thus range wide. Many similar estimates have been made mainly in Europe (e.g., Van Zuijlen et al. (2019)[9]) and the United States (e.g., Noel et al. (2017)[10]). Some groups including Jacobson et al. (2015)[11] and a Lappeenranta University group (e.g., Ram et al. (2017)[12]) estimated and published such integration costs for most countries and regions in the world.

Multiple reports exist about VRE integration cost estimates in Japan. For instance, the abovementioned Lappeenranta University group (e.g., Ram et al. (2017) [12]) and WWF Japan (2017)[13] indicated that even if renewable energy covers all power generation in Japan in 2050, total electric system costs including the VRE integration cost would be lower than at present. In contrast, reports by Matsuo et al. (2018)[14] and Matsuo et al. (2020)[15] estimated that electric system costs would increase substantially if fossil-fired power generation is unavailable in 2050 and that a combination of renewable energy and nuclear power would contribute to holding down cost hikes. Ogimoto et al. (2018)[16] estimated that if VRE alone is used for power generation, the unit electric system cost would be far higher than at present.

There are thus numerous studies assessing the economy of the power sector by energy choice. However, most of them focus on the economy of total costs for overall electric system development, maintenance and management. Studies are scarce on a wider range of quantitative macroeconomic impacts including the economic effects of investment in power

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5 Japan Business Federation, "Opinion on Carbon Pricing" October 13, 2017
http://www.env.go.jp/earth/ondanka/cp/arikata/conf05/cp05_mat_keidanren.pdf (Accessed on 2020/11/30)

6 Organisation for Economic Co-operation and Development (OECD)/Nuclear Energy Agency (NEA); Nuclear energy and renewables system effects in low-carbon electricity systems (2012), OECD/NEA, Paris.

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13 WWF Japan, "Long-term Scenario for the Creation of a Decarbonized Society (2017)
https://www.wwf.or.jp/press/475.html (Accessed on 2020/11/30)

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generation equipment, the economic burden of a carbon tax and the multiplier effects of fiscal spending expansion based on carbon tax revenue.

Some studies including the Asia-Pacific Integrated Model (2009)[17] by the Japanese National Institute for Environmental Studies have used applied general equipment models to analyze overall macroeconomic impacts. They base estimation on economic growth assumptions and can express the macroeconomic impacts of carbon tax and other policies as distortions from the equilibrium for a case in which these policies are not introduced. As far as they depend on an assumption that each economic entity would conduct rational behavior based on price information under complete information, however, they fail to indicate recession, market disequilibrium and other gaps. If carbon tax and other constraints are imposed, GDP would decrease under these models. There are some constraints on their applications.

For instance, full employment is assumed for the labor market under the applied general equipment models. Even if the government implements a green new deal to stimulate the economy during a recession, such deal's impacts on GDP would be difficult for these models to analyze.

Given such a situation, this study uses an energy economy model into which we integrated an optimal power generation mix model using linear programming and a macro econometric model to analyze the impacts of energy choices for Japan's electric system on total electric system costs and macroeconomic indicators such as GDP.

Here is the composition of this paper: Chapter 2 describes an overview of the model used in this study and major assumptions. Chapter 3 outlines model analysis results. Based on the results, Chapter 4 considers an optimal power generation mix to balance decarbonization with economic growth and describes this study's policy implications.

2. Assessment method

2-1. Integrated energy economy model

This study developed an integrated energy economy model for estimation to assess the impacts of Japan's energy choices on total electric system costs and macroeconomic indicators through 2050.

The model developed for this study is an integrated energy economy model combining a top-down econometric model and a bottom-up cost-minimizing optimal power generation mix model. The top-down econometric model was developed by Murota et al. (2005)[18] and improved in Yanagisawa (2008)[19] and Komiyama et al. (2012)[20]. The bottom-up cost-minimizing optimal power generation mix model is a Japanese optimal power generation mix model that was developed by Fujii and Komiyama (2017)[21] and improved in Matsuo et al. (2019)[22] and Matsuo et al. (2020)[15].

2-2. Econometric model

The econometric model estimates economic indicators based on assumptions for overseas factors such as global trade, economic policies such as public investment, demographics, and fossil fuel and other energy prices.

As shown in Fig. 1, the econometric model focuses on gross domestic product and its components such as investment, imports and exports and calculates fund flows in the national economy.

The model consists mainly of the real expenditure module, the wage-price module, the income distribution module and

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the labor module and can estimate the impacts of changes in exogenous variables on the economy. See Komiyama et al. (2012) [20] for details of the model.

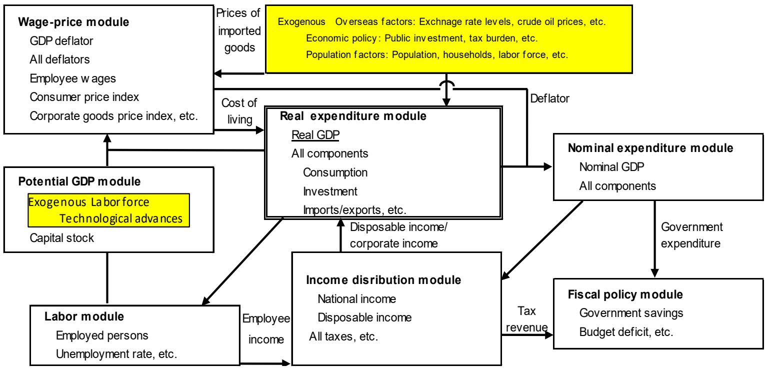

Fig. 1 Econometric model

2-3. Optimal power generation mix model

This study used the optimal power generation mix model to simulate and analyze cost-minimizing electricity supply under multilateral constraints for Japan's power sector in 2050.

The optimal power generation mix model uses linear programming to simulate a country's energy system to determine energy supply and demand and the economically rational size of energy technologies. The target function is discounted total system costs during the computation period. The constraint equation covers constraints on resources, energy supply and demand, etc.

In a geographical division, Japan excluding Okinawa is divided into nine according to the service areas of nine former general power utilities. These areas are assumed as connected through direct or alternating current interconnection cables.

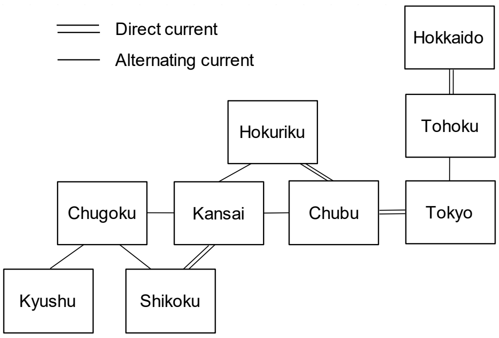

Fig. 2 Geographical division

This study computed and assessed annual electricity supply and demand on an hour-to-hour basis (dividing a year into 8,760 hours by multiplying 24 hours by 365 days).

2-4. Integrated energy economy model structure

The abovementioned optimal power generation mix model can estimate the most efficient cost-minimizing power generation mix under constraints by using linear programming. While a country's energy demand is required to be given exogenously as an assumption, the demand itself is influenced by power source choices.

While heavy dependence on cheap fossil fuels for power generation is likely to be an optimum solution to minimize power supply costs under the optimal power generation mix model, for instance, national wealth outflow through massive fuel oil imports may exert downward pressure on GDP and domestic electricity demand.

While a power generation mix using massive nuclear and renewable energy capacity requires higher total electricity system costs than that depending heavily on fossil fuels under the optimal power generation mix model, a curb on national wealth outflow through fossil fuel imports and an increase in private capital investment in domestic power generation equipment may exert upward pressure on GDP and electricity demand.

To conduct an analysis considering mutual relations between the impacts of changes in the power generation mix on electricity supply costs and macroeconomic indicators, this study developed an integrated energy economy model in which the econometric and optimal power generation mix models share exogenous variables as assumptions and analyzed how energy choices for the electricity system would impact total electricity supply costs and the whole of the Japanese economy.

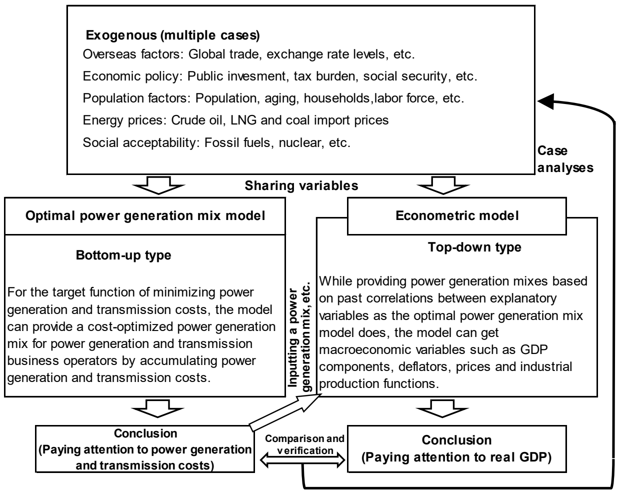

Fig. 3 Integrated energy economy model

The integrated energy economy model used the optimal power generation mix model to estimate cost-minimizing power generation mixes and total system costs under multiple assumptions set for constraints on power source choices.

Then, the model computed variables including total power generation and transmission costs covering capital investment, fuel, carbon tax and other costs for the optimal power generation mix estimated by the optimal power generation mix model and exogenously put the variables into the econometric model to estimate real GDP and other macroeconomic variables. We compared and verified the two models' conclusions and conducted additional case analyses regarding variables, as necessary.

The amount of capital investment refers to NEDO (2014)[23], Ishii (2014)[24], TEPCO (2020)[25], the government's Procurement Price Calculation Committee (2020)[26] and Mitsubishi Research Institute (2020)[27]. As a result, the domestic production rate for the total investment of equipment costs and construction costs will be 95% for nuclear power, 50% for coal / gas-fired power, 40% for batteries, 27% for solar PV, 23% for onshore wind, and 22% for offshore wind. In addition, all carbon tax revenues shall be returned to the domestic economy as government consumption expenditures such as

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[23] NEDO; NEDO Renewable Energy Technology White Paper 2nd Edition(2014).
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[25] Procurement Price Calculation Committee; Opinion on Procurement Prices in FY2020 (2020))
https://www.meti.go.jp/shingikai/santeii/pdf/20200204001_1.pdf(Accessed on 2020/11/30)
[26] Tokyo Electric Power Company Holdings, Incorporated; Look at TEPCO by a mathematical table -Overview of each nuclear power plant- (2020).
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[27] Mitsubishi Research Institute; Ministry of Economy, Trade and Industry 1st Stationary Power Storage System Spread and Expansion Study Group "Awareness of the current situation regarding power storage systems" (2020).
https://www.meti.go.jp/shingikai/energy_environment/storage_system/pdf/001_05_00.pdf (Accessed on 2020/11/30)

environmental measures. When a large amount of carbon tax is introduced in Japan, changes in the international competitiveness of imports and exports due to differences in environmental policies with other countries are not taken into consideration.

2-5. Estimation cases

To consider a wide range of constraints on the electricity system in 2050, this study first developed, compared and developed six basic cases as shown in Fig. 4. Numbers in Table 1 indicate case numbers. The six cases indicate whether the use of fossil fuels for power generation, a carbon tax or new nuclear power plant construction would be socially accepted.

After comparing and verifying the six cases, this study input five more cases into the two models to clarify gaps between the optimal power generation mix model and econometric model assessment results. A total of 11 cases were thus compared and verified, as discussed in Chapter 3.

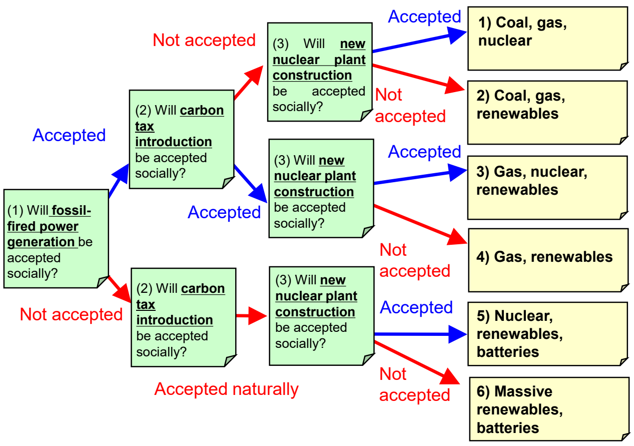

Fig. 4 Estimated cases

Table 1 Presence or absence of basic power sources in estimated cases

Case number	1)	2)	3)	4)	5)	6)
Carbon tax	Present level		$\$120/t\text{-}CO_2$ ※			
Existing coal	○	○	×	×	×	×
Gas	○	○	○	○	×	×
New nuclear	○	×	○	×	○	×

Note: ※ World Bank "State and Trends of Carbon Pricing 2020" 12p. Japan's carbon tax is assumed to reach the Swedish level of $\$119/5\text{-}CO_2$, the highest in the world as of April 1, 2020. Under the optimal power generation mix model, coal-fired power plants will disappear completely at this carbon tax level. The exchange rate is 110 yen/dollar.

2-6. Assumptions

In each case, we set assumptions for Japan's energy mix for 2050 according to IEEJ (2018)[21] and IEEJ (2019)[22]. In line with the objective of this study, however, we set some exclusive assumptions for this study as follows:

(1) Nuclear power generation

The power generation costs and performances of existing large nuclear reactors are used for the estimation. The maximum available nuclear power generation capacity for 2050 covers existing reactors other than those to be decommissioned and under-construction reactors as of October 2020, totaling 42.5 GW. Given a service life of 60 years, 17.0 GW out of the existing capacity will be subjected to decommissioning by 2050. If new reactors are profitable and accepted socially, however, reactors subject to decommissioning will be replaced with new ones with the same or less capacity. Construction costs for existing and under-construction reactors (hereinafter referred to as existing reactors) within 60 years from the launch of operation were deducted as sunk costs for nuclear plant operators from capital costs at the time of estimation.

Table 2 Power generation cost and performance assumptions (large existing and new reactors)

Unit construction cost [1,000 yen/kW]	420
Years of operation	40
Full cost rate	1.00
Captive consumption rate	0.04
Fuel cost [yen/kWh]	1.8
Maximum output growth rate	0.02
Maximum output decrease rate	0.02
Maximum annual capacity factor	0.80
Minimum output level	0.80

(2) Renewable energy power generation

Renewable energy power generation cost reduction targets given by the government's Procurement Price Calculation Committee in February 2020[26] call for cutting the unit power generation cost to 7.0 yen/kWh for solar PV and 8-9 yen/kWh for wind by 2025 or 2030. Since these targets deviate far from the past cost reduction trend in Japan. Therefore, we assumed the unit cost in 2050 at 7.0 yen/kWh for solar PV and at 8.5 yen/kWh for onshore wind. The offshore wind power generation cost is assumed to decline as much as the onshore wind cost. (as shown in Table 3.)

Table 3 Power generation cost assumptions (solar PV and wind power generation)

		Standard
Solar PV	Unit construction cost [1,000 yen/kW]	102
	Years of operation	30
	Full cost rate	0.014
Onshore wind	Unit construction cost [1,000 yen/kW]	190
	Years of operation	30
	Full cost rate	0.021
Offshore wind	Unit construction cost [1,000 yen/kW]	286
	Years of operation	30
	Full cost rate	0.044

Maximum available solar PV and wind power generation capacity was assumed as shown in Table 4. Although Matsuo et al. (2019)[22] as cited above used potential assessment data by the Ministry of the Environment, this study used estimates in Obane, et al. (2019)[28] from the viewpoint of realistic constraints.

[28] H. Obane, Y. Nagai, K. Asano; Evaluating technical potential of ground-mounted solar and on-shore wind energy in Japan, Central Research Institute of Electric Power Industry report Y18003 (2019)
https://criepi.denken.or.jp/jp/kenkikaku/report/detail/Y18003.html (Accessed on 2020/11/30)

Table 4 Maximum available solar PV and wind power generation capacity assumptions

Unit: GW	Solar PV	Onshore wind	Offshore wind
Hokkaido	14.7	16.4	177.1
Tohoku	24.8	2.8	33.9
Tokyo	54.4	0.6	38.8
Hokuriku	9.3	0.2	0.1
Chubu	35.5	0.5	23.3
Kansai	26.0	0.6	0.04
Chugoku	24.2	0.8	0.1
Shikoku	13.1	0.5	1.9
Kyushu	37.5	2.2	2.0
Total	239.3	24.6	277.2

(3) Batteries

Lithium-ion batteries were adopted for a battery cost assumption. The median case of US$150kWh of Cole and Frazier (2019)[29] is assumed as a standard case (Table 5). In line with Matsuo et al. (2019)[22] as cited above, pump-up power generation capacity is separately assumed at the existing level of 163 GWh.

Table 5 Battery cost assumption

	Standard
Battery [US$/kWh] ※	150

Note: ※Calculated at 110 yen/dollar and input to all models.

(4) Fossil-fired power generation

This study assumed the use of existing coal- and gas-fired power plants without giving consideration to hydrogen or CCS-fitted thermal power plants. Table 6 shows assumptions for fossil-fired power plants.

Table 6 Power generation cost assumptions (coal- and gas-fired plants)

	Coal	Gas
Unit construction cost [1,000 yen/kW]	250	120
Years of operation	40	40
Full cost rate	0.037	0.024
Thermal efficiency	0.48	0.57
Captive consumption rate	0.06	0.02
Fuel cost [yen/kWh]	(Table 7)	(Table 7)
Maximum output growth rate	0.26	0.44
Maximum output decrease rate	0.31	0.31
Maximum seasonal capacity factor	0.90	0.95
Maximum annual capacity factor	0.80	0.80
DSS (daily start-stop) operation rate	0.00	0.50
Minimum output level	0.30	0.30

[29] W. Cole and A.W. Frazier; Cost Projections for Utility-Scale Battery Storage (2019), https://www.nrel.gov/docs/fy19osti/73222.pdf (Accessed on 2020/11/30)

Fuel cost assumptions in IEEJ (2019)[30] were used as shown in Table 7.

Table 7 Fuel cost assumptions

	Standard
Coal [US$/t] ※	123
LNG [US$/MMBtu] ※	10.5

Note: ※Calculated at 110 yen/dollar and input to all models.

3. Assessment results

3-1. Power generation mix minimizing power generation and transmission costs under optimal power generation mix model

The optimal power generation mix and its power generation and transmission costs under the optimal power generation mix model are shown in Table 8.

Carbon tax levels will exert great influence on coal-fired power generation. In cases in which the current petroleum and coal tax level will be maintained (see Cases 1) and 2)), the existing coal-fired power generation capacity will be maintained to the maximum extent. Meanwhile, renewable energy power generation capacity in these cases will be far less than in the other cases, losing to cost-competitive coal-fired capacity.

In cases in which the carbon tax will increase substantially (to \$120/t-CO_2 in Cases 3) to 6)), optimal power generation mixes will differ far from the above ones. Coal-fired capacity affected by the carbon tax will disappear completely. In its place, gas-fired, solar PV and wind (onshore and offshore) capacity will increase substantially.

Nuclear power generation capacity will be close to the maximum available level in all cases in principle because of its cost competitiveness. In Case 1) in which the carbon tax will remain at the present level, new nuclear capacity will be 2 GW lower because of coal-fired plants' even higher cost competitiveness.

Under the optimal power generation mix model of which a target function is the minimized power generation and transmission cost level, Case 1) represents the optimal (cost-minimizing) power generation mix. Power generation and transmission costs will rise in cases of curbs on new nuclear plants, higher carbon tax levels and greater restrictions on fossil fuels or any other power source. In Case 6) which represents the toughest restrictions, the costs will be the highest at 18.96 trillion yen (assessed as the worst from the viewpoint of lower costs).

[30] Institute of Energy Economics, Japan; IEEJ Outlook 2020 (2019). https://eneken.ieej.or.jp/data/8645.pdf (Accessed on 2020/11/30)

Table 8 Optimal power generation mixes and ranking of power generation and transmission costs

Optimal power generation mix model (Unit: GW)

Case No.	1)	2)	3)	4)	5)	6)
Existing coal	40	40	-	-	-	-
Gas	82	97	120	137	-	-
Fossil total	122	137	120	137	-	-
Existing nuclear	26	26	26	26	26	26
New nuclear	15	-	17	-	17	-
Nuclear total	41	26	43	26	43	26
Solar PV	-	171	171	188	239	231
Onshore wind	2.5	11	11	12	25	25
Offshore wind	-	-	-	-	155	250
Geothermal/biomass	16	16	16	16	16	16
Renewables total	18	197	197	215	435	521
Hydro	20	20	20	20	20	20
Generation capacity	201	380	380	398	497	567
Batteries (GWh)	0.2	0.1	0.2	0.3	173	150
Generation (GWh)	1,010	1,009	1,017	1,016	1,043	1,043
Carbon tax	Present level		$120/t-$CO_2$			
Power generation and transmission costs (1 trillion yen)	8.68	8.74	10.30	10.78	16.07	18.96
Same as above (yen/kWh)	8.59	8.66	10.13	10.61	15.41	18.18
Cost ranking	1	2	3	4	5	6

3-2. Power generation mix to maximize real GDP under econometric model

Table 9 shows the results of inputting each case's power generation mix into the top-down econometric model developed by the IEEJ. Case 3) represents the optimal power generation mix model to maximize Japan's real GDP. Cases 1) and 2) that posted the first and second lowest costs are ranked fifth and sixth under the econometric model.

Table 9 Real GDP ranking for same cases as in Table 8

Econometric model (Unit: 1 trillion yen)

Case No.	1)	2)	3)	4)	5)	6)
Real GDP	812.6	810.5	814.0	813.7	813.9	812.9
GDP ranking	5	6	1	3	2	4
Private consumption expenditure	413.6	413.8	415.8	415.4	414.9	413.9
Government consumption expenditure	99.7	99.7	100.8	101.1	99.7	99.7
Private nonresidential investment	104.8	107.5	108.5	108.2	114.9	117.0
Fossil fuel imports	35.1	31.7	30.7	31.7	27.6	27.6
Overall unit electricity price (yen/kWh)	24.72	37.60	37.96	38.28	44.43	47.59

3-3. Comparison between optimal power generation mix model and econometric models

Table 10 extracted and compared the power generation and transmission cost ranking under the optimal power generation mix model in Table 8 and the GDP ranking under the econometric model in Table 9, indicating clear differences between the results under the two models.

Table 10 Power generation and transmission cost ranking vs. real GDP ranking

Optimal power generation mix model

Case No.	1)	2)	3)	4)	5)	6)
Carbon tax	Present level		$120/t-$CO_2$			
Power generation/ transmission costs (1 trillion yen)	8.68	8.74	10.30	10.78	16.07	18.96
Same as above (yen/kWh)	8.59	8.66	10.13	10.61	15.41	18.18
Cost ranking	1	2	3	4	5	6
Econometric model						
Real GDP	812.6	810.5	814.0	813.7	813.9	812.9
GDP ranking	5	6	1	3	2	4
(Reference) CO_2 emissions (As coal-fired 0.80kg-CO_2/kWh, gas-fired 0.43kg-CO_2/kWh)						
CO_2 emissions (Mt-CO_2)	320.9	366.5	128.3	169.7	-	-
CO_2 saving ranking	4	5	2	3	1	1

(1) Comparing Cases 1) and 2) with Cases 3) to 6)

Under the optimal power generation mix model, coal-fired power generation will be highly competitive as far as the carbon tax level remains at the present level. In Case 1), it will appear to be a promising power source, with solar PV limited to zero and with new nuclear plant construction restricted. Under the econometric model, however, GDP will fail to grow due to carbon tax revenue's failure to be used for government consumption expenditure, private nonresidential investment's failure to increase amid low unit investment cost and massive existing capacity for coal-fired power generation and massive fossil fuel imports representing national wealth outflow in Cases 1) and 2). Eventually, coal-fired power generation will be given low ratings under the econometric model and run counter to climate change countermeasures.

(2) Comparing Case 1) with Case 2), Case 3) with Case 4), Case 5) with Case 6)

Under the optimal power generation mix model, power generation and transmission costs for nuclear energy will decline (with higher ratings given) in all cases if existing capacity (26 GW) is combined with capacity addition and replacement (17 GW). Even under the econometric model, nuclear capacity addition and replacement will surely push up GDP through massive construction investment, high domestic contents for nuclear equipment and curbs on fossil fuel imports. Therefore, nuclear capacity addition and replacement will be given high ratings under both models.

(3) Comparing Cases 3) to 6)

If the carbon tax assumption is the same for all cases under the optimal power generation mix model, gas-fired power generation will achieve the lowest power generation and transmission costs in Case 3) (massive gas-fired power generation capacity around 120 GW) in which gas-fired capacity will be increased beyond the existing capacity of 83 GW in the Survey of Electric Power Statistics (2020)[31] by the Agency for Natural Resources and Energy. Case 3) will indicate the greatest significance of gas-fired capacity as a power supply-demand balancer among the cases. Under the carbon tax imposition, Case 3) may achieve both the lowest costs for power utilities under the optimal power generation mix model and the highest

[31] Agency for Natural Resources and Energy, "Survey of Electric Power Statistics 1-(1) Number and capacity of power stations of electric power utilities (July 2020)) https://www.enecho.meti.go.jp/statistics/electric_power/ep002/results.html (Accessed on 2020/11/30)

GDP under the econometric model.

By the way, CO_2 emissions are added as reference information, but Case 3) is superior to Cases 1) and 2), which have many coal-fired power plants, in terms of CO_2 saving, and is inferior to Cases 5) and 6), which do not emit CO_2. The purpose of this study is to compare power generation cost and GDP, and three comparative verifications including decarbonization will be the subject of future study.

3-4. Deriving final results through additional case studies

Under the econometric model, however, gas-fired capacity features low construction investment and fossil fuel imports and is expected to produce a relatively smaller GDP-boosting effect than other power sources. Therefore, we thought that additional case studies would be required to verify whether Case 3) may maximize GDP. Then, we set up five gas-fired capacity cases with 20 GW increments between Case 3) (gas-fired capacity at 120 GW) and Case 5) (no gas-fired capacity) that indicated the first and second largest GDP in Table 11 and put the five new cases into the optimal power generation mix and econometric models for additional estimation. Table 12 indicates additional estimation results.

The comparison of the seven cases between Cases 3) and 5) found that Case 3)-2 may maximize GDP while holding down an increase in power generation and transmission costs for power utilities by mixing gas-fired capacity around 80 GW (close to the existing level of 83 GW) with renewable energy and batteries in a balanced manner. The finding indicates that gas-fired, renewable and battery capacity shares in the power generation mix may differ between Case 3) for the lowest costs for power utilities and Case 3)-2 for the largest GDP.

Case 3)-2 for gas-fired capacity at 80 GW will maximize GDP mainly because this gas-fired capacity level will be more useful for maintaining power supply in the absence of wind and sunshine than lower gas-fired capacity cases. If gas-fired capacity is cut to 40 GW or less, renewable energy and battery capacity levels will be far higher, resulting in frequent renewable energy output suppression that would boost costs for power utilities to affect their business performance. In the cases of higher gas-fired capacity, GDP may fail to rise due to low gas-fired capacity construction costs and fossil fuel import expansion, as noted above. Therefore, Case 3)-2 in which renewable energy and batteries will diffuse while refraining from triggering frequent output suppression that could lead to unnecessary power cost hikes would be one of the optimal solutions regarding the best power generation mix for the Japanese economy.

Table 11 Final results

Case No.	Cited again 3)	New 3)-1	New 3)-2	New 3)-3	New 3)-4	New 3)-5	Cited again 5)
Existing coal	-	-	-	-	-	-	-
Gas	120	100	80	60	40	20	-
Fossil total	120	100	80	60	40	20	-
Existing nuclear	26	26	26	26	26	26	26
New nuclear	17	17	17	17	17	17	17
Nuclear total	43	43	43	43	43	43	43
Solar PV	171	189	197	209	208	239	239
Onshore wind	11	11	12	14	19	25	25
Offshore wind	-	-	-	21	60	103	155
Geothermal/ biomass	16	16	16	16	16	16	16
Renewables total	197	215	224	260	303	382	435
Hydro	20	20	20	20	20	20	20
Generation capacity	380	378	367	383	406	465	497
Batteries (GWh)	0.2	24	44	72	110	160	173
Generation (GWh)	1,017	1,018	1,020	1,024	1,030	1,039	1,043
Power generation/ transmission costs (1 trillion yen)	10.30	10.37	10.48	10.68	11.27	12.83	16.07
Same as above (yen/kWh)	10.13	10.18	10.27	10.43	10.95	12.35	15.41
Cost ranking	1	2	3	4	5	6	7
Real GDP	814.0	814.4	814.6	814.2	813.7	813.6	813.9
GDP ranking	4	2	1	3	6	7	5
Private consumption expenditure	415.8	416.0	416.1	415.9	415.4	415.2	414.9
Government consumption expenditure	100.8	100.7	100.7	100.5	100.1	99.8	99.7
Private non residential investment	108.5	108.7	108.8	109.7	111.1	113.1	114.9
Fossil fuel imports	30.7	30.3	30.2	29.3	28.2	27.8	27.6
Overall unit electricity price (yen/kWh)	37.96	38.10	38.03	39.50	41.36	43.19	44.43

(Reference) CO_2 emissions (As coal-fired 0.80kg-CO_2/kWh, gas-fired 0.43kg-CO_2/kWh)

CO_2 emissions (Mt-CO_2)	128.3	119.2	114.0	84.4	43.3	12.0	-
CO_2 saving ranking	7	6	5	4	3	2	1

4. Conclusion

This study finally put 11 scenarios for Japan's power sector in 2050 into the integrated energy economic model combining the optimal power generation mix model adopted by power utilities for considering the best mix of coal-fired, gas-fired, nuclear and renewable energy power generation and batteries with the econometric model used widely for considering energy policies, quantitatively indicating that an optimal solution for minimizing power utilities' power generation and transmission costs differs from that for maximizing Japan's GDP.

Comparison between data within the two thick frames in the lower part of Table 11 indicates that a transition from Case 3) to Case 3)-2 boosts Japan's real GDP by about 600 billion yen and power utilities' power generation and transmission costs by about 200 billion yen. On the contrary, a transition from Case 3)-2 to Case 3) reduces power utilities' costs by 200 billion yen and real GDP by about 600 billion yen. This means that policymakers and power utilities have different optimal solutions regarding the best power generation mix and can cooperate in handling energy and economic policies adequately to produce Japan's virtuous economic cycle.

This study is designed to provide recommendations about power sources that Japan should focus on from now towards 2050 based on feasible technologies and costs at present. In addition to power generation technologies covered by this study, hydrogen and ammonia power generation, and CCS (carbon capture and storage) and CCUS (carbon capture, utilization and storage) technologies are conceivable for the future. However, we have intentionally refrained from considering these new technologies. This is because these new technologies are in the demonstration phase rather than in the commercialization phase, leaving great uncertainties about their commercialization before 2050, their costs and capacity levels for power utilities and their spillover effects on the Japanese economy. The uncertainties could destabilize estimation. If these new technologies' costs conceivable in the demonstration phase are assumed, these technologies, like coal-fired power generation under a high carbon tax, could disappear from a power generation mix through model computation. Given that Japan has shifted the target from a low-carbon society to a decarbonized society as indicated by the prime minister's latest policy address[4], however, these new technologies will become key factors for considering the future power generation mix. As soon as capacity levels, costs and targets for these technologies' commercialization are clarified, we would like to subject them to consideration and comparison.

As for the effect of boosting GDP, if the price of fossil fuels rises, the superiority of gas-fired power generation will decrease. And if renewable energy and batteries become cheaper, their superiority will increase. In these cases, GDP will be maximized to the right of Case 3) -2, that is, to Case 3) -3. The same is true in the opposite direction, and the evaluation results may change.

In addition, the domestic production rate of capital investment is set with reference to the current rate. For this reason, if the rates of various power generations and batteries become higher than expected in the future, private capital investment will increase and GDP will increase according to the amount of their composition ratio, and if the rate decreases, GDP will decrease.

Furthermore, although we assume that a large amount of carbon tax will be levied, we do not currently assume international competitiveness adjustment of products called "border adjustment measures", but we will consider it in the future.

As far as we know, no earlier study has used specific figures to comprehensively discuss correlations between power utilities' cost-based optimization of a power generation mix and economic indicators including real GDP. Therefore, we hope that this study would help provide a useful direction for both power utilities and the Japanese economy. We will continue to consider the relationship between the power generation mix and economic activities from different angles.

A Discussion on Abatement Costs in an Integrated Assessment Model of Climate Change◆

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Abstract

In this study, we conducted a cost-benefit analysis with an Integrated Assessment Model of climate change. Firstly, we incorporated the effects of cost reduction of backstop technologies by RD&D investments into an abatement costs calculation. Secondly, we modeled the time lag between RD&D investments and the reduction of abatement costs brought by them. We call this the inertia regarding time lag, which previous studies did not address. The results show that RD&D investments have little impact on emission reductions in the near-term, but gradually have a significant impact on those in the long-term. Considering the inertia of learning-by-researching, the optimal RD&D investments path shifts lower than the case without inertia, but there is no significant difference in the optimal RD&D investments required in the first half of this century. In the case of imposing a temperature constraint, RD&D becomes much more important and the optimal RD&D investments path shifts significantly higher compared to the case of no temperature constraint. Although it is sometimes pointed out that technological innovation through RD&D investments means a postponement of abatement efforts, our results support the importance of near-term RD&D investments for further emission reduction in the future.

Key words: Integrated Assessment Model, Abatement Cost, RD&D, Inertia

1. Introduction

1-1. Responses to climate change and integrated assessment model

As understanding the natural science of climate change makes progress[1, 2, 3], pressure grows on the world to respond to climate change. However, energy-related CO_2 emissions have increased almost persistently since 1990, albeit with a temporary decline amid a recession in 2009[4]. In a recent bright sign, renewable energy has gradually grown cost competitive against fossil fuels. Nevertheless, actual greenhouse gas emissions have a wide gap with emissions required to achieve the goal of limiting global warming to well below 2°C compared to pre-industrial levels under the Paris Agreement[5].

The world is required to cut GHG emissions to net zero at least by the end of this century to achieve the long-term goal under the Paris Agreement,[6] but present technologies cost too much to or cannot achieve decarbonization such as sectors that are difficult to electrify, including heat utilization in heavy industries and long-range transportation. The International Energy Agency's latest Energy Technology Perspectives[7] pointed out that progress towards net-zero emissions will depend on faster innovation in electrification, hydrogen, bioenergy and CCUS (carbon capture, utilization and storage). It also indicated that some 40% of cumulative CO_2 emissions reductions (from a stated policies scenario) through 2070 in a sustainable development scenario will depend on technologies that are not commercially available today.

One reason why it is difficult to respond to climate change is that inertia works strongly in the global climate system and our social and economic systems. For instance, it is pointed out that the lifetime of several decades for energy system

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infrastructure brings about fossil fuel lock-in[8]. Technological innovation takes much time. Research and development investments would take much time to bring about technology cost cuts and diffusion.

The abovementioned background leads us to think that the abatement of climate change (GHG emissions reductions) is important. Given that GHG emissions are linked closely to economic activities, however, a cost-benefit analysis considering the total balance between climate change and the economy is indispensable as a prerequisite. Integrated assessment models are available for such analysis, including DICE[9], FUND[10] and PAGE[11].

These models that highly integrate relations between climate change and the economy are controversial because of their high sensitivity to parameter changes. There are numerous studies on discount rates[12] and damages[13, 14]. Most of these studies estimate lower discount rates and higher damages and compare these estimates with traditional integrated assessment model estimation results, concluding that the abatement of climate change has become more urgent. Meanwhile, abatement costs that are as important as damages have been discussed less than discount rates or damages. As the abovementioned technological innovation (changes) and the inertia of social and energy systems are apparently required to be considered in regard to abatement costs, the following reviews earlier studies.

1-2. Learning by researching

The neoclassical theory of economic growth had given technological change as a total factor productivity growth rate exogenously, but P. Romer et al.[15] has created a model to internalize technological change. Some studies considered endogenous technology innovation for climate change model analyses. Modeling technological change is generally divided into learning by researching and learning by doing. The learning-by-doing modeling, though frequently used for bottom-up models, leaves the relationship between cumulative technology diffusion and cost falls in a black box, leading to an optimistic assumption that costs would decline even without investments to acquire new knowledge. It is also pointed out that a problem regarding statistical identification could cause overestimation of learning parameters[16]. As it is important to consider costs for bringing about technological change in a cost-benefit analysis, the following literature review focuses on the learning-by-researching modeling.

Some studies[17, 18, 19, 20, 21] applied to learn by researching to cost-benefit analysis of climate change, using different modeling approaches to express the impacts of research, development and demonstration (RD&D) on technological change. Specifically, Goulder and Mathai (2000)[17] gave consideration to a decline in abatement costs, Nordhaus (2002)[18] to a decline in emission intensity, Popp (2004)[19] to a decline in energy intensity, and Popp (2006)[20] and Yin and Chang (2020)[21] to declines in energy intensity and backstop technology costs. They set model calibration criteria based on

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21 Yin, Di, and Youngho Chang; Energy R&D Investments and Emissions Abatement Policy, The Energy Journal, 41-6 (2020).

empirical research, present RD&D investments level and so on. These studies indicate that endogenous technological change would exert impacts on emission paths, however, that given opportunity costs for RD&D investments in energy technologies, the impacts would be limited.

WITCH[22] contributing to scenario analysis in the IPCC AR5 (5th assessment report by the Intergovernmental Panel on Climate Change) used a normal learning curve or a two-factor learning curve combining learning by researching with learning by doing to model specific technologies such as solar photovoltaics and batteries. WITCH is a multi-region model that considers spillover effects of knowledge from other countries when calculating knowledge stock.

In contrast to the abovementioned approaches using empirical knowledge (past data), there is an approach that combines expert elicitation about outlooks on individual technologies with technology-rich model analysis[23]. Studies under this approach used expert elicitation about specific technologies including solar PV power generation to estimate the relationship between RD&D investments and energy technology cost drops. The estimated relationship including uncertainties is put into a model handling specific technologies to analyze the impacts of RD&D investments in those technologies on GHG emission paths and emission reduction costs and consider optimum portfolios for RD&D investments in energy technologies. Such portfolios cover biomass power generation, biofuels, CCS, nuclear power generation, solar PV power generation and their combinations. GCAM[24], WITCH, MARKAL[25] and other models are used to express specific technologies. Some studies[26, 27] conducted cost-benefit analysis by using the GCAM model to express changes in a marginal abatement cost curve through cost drops for specific technologies with simple parameters and reflecting these changes in the abatement cost function in the DICE model.

Studies considering the impacts of learning by researching specific technologies apparently represent an important direction. Given that technologies subject to these studies are limited, however, they have difficulties in considering overall economic impacts that are significant for cost-benefit analysis.

1-3. Social and energy system inertia

Another challenge regarding abatement costs is to consider social and energy system inertia. In the DICE model, for instance, the abatement cost function (marginal abatement cost curve) is given as a prerequisite, indicating that abatement costs in a year depend on the CO_2 emission reduction rate in the year and are not affected by the previous year's rate. In an extreme case, abatement costs for a year would remain unchanged whether the emission reduction rate is raised from 0% or 90% to 100% in a period (five years). This assumption would be adequate if only energy-saving behaviors or fuel switching accompanied by no infrastructural renewal are assumed. However, it is not adequate for abatement means accompanied by the construction of infrastructure including long-life power generation equipment. This problem is naturally taken into account in bottom-up and other models giving consideration to the lifetime of the infrastructure. For these models, the marginal abatement cost curve is not a prerequisite but an estimation result changing depending on the emission path[28].

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[22] Emmerling, Johannes, et al.; The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways, FEEM Working Paper No. 42 (2016).
[23] Anadon, Laura Diaz, Erin Baker, and Valentina Bosetti; Integrating uncertainty into public energy research and development decisions, Nature Energy, 2-5 (2017), pp.1-14.
[24] Calvin, Katherine, et al; GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems, Geoscientific Model Development (Online), 12 (2019), pp.677-698.
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[26] Baker, Erin, and Senay Solak; Climate change and optimal energy technology R&D policy, European Journal of Operational Research, 213-2 (2011), pp.442-454.
[27] Baker, Erin, and Senay Solak; Management of energy technology for sustainability: How to fund energy technology research and development, Production and Operations Management, 23-3 (2014), pp.348-365.
[28] Akimoto, Keigo, et al.; Comparison of marginal abatement cost curves for 2020 and 2030: longer perspectives for effective global GHG emission reductions, Sustainability Science, 7-2 (2012), pp.157-168.

Grubb and Wieners (2020)[29] proposed a simple model to take social and energy system inertia into account regarding the abatement cost function in the DICE model, indicating that the consideration of inertia would lead the optimum emission reduction path to change from a rapid rise in the reduction rate as shown by the DICE model to a moderate change after the initial high rate.

1-4. Purpose of this study

As reviewed above, cost-benefit analysis studies using integrated assessment models have frequently considered discount rates and damages while failing to consider abatement costs, lacking balance.

Key points that should be considered regarding abatement costs include endogenous technological change resulting from learning by researching and social and economic system inertia. However, inertia in learning by RD&D investments has not fully been modeled.

Earlier studies modeled “stock inertia”. Specifically, they introduced the concept of knowledge stock, indicating that knowledge stock growth brings about technological change (cost drops) (Equations (4) and (5)). RD&D investments represent flow bringing about knowledge stock growth and their contribution takes stock inertia into account.

However, in models for earlier studies, RD&D investments in a period contribute to knowledge stock growth in the next period, indicating no time lag beyond a time step. In reality, however, immature technologies naturally take much time to achieve cost cuts and diffusion after RD&D investments. Such “time lag inertia” should be modeled to assess the impacts of RD&D investments more adequately.

Given the above, this study aims to model the effects of learning by researching with time lag inertia taken into account in regard to abatement costs in the DICE integrated assessment model and to assess the impacts of the effects on cost-benefit analysis.

2. Methodology

2-1. DICE

The DICE model developed by W. Nordhaus incorporates climate change adaptation/damage costs and GHG emission reduction costs into the Ramsey-Cass-Koopmans model[30, 31, 32], a standard economic growth theory model, to conduct a cost-benefit analysis to integrally assess the balance between economic growth, and climate change adaptation/damage and abatement. Climate change adaptation/damage costs are expressed as the function of temperature rise, with a simple climate model incorporated to compute a temperature rise through GHG emissions.

In the DICE-2016R2 model as the latest DICE model, the function of abatement costs per emission is given as Equation (1) and the marginal emission reduction cost curve (Equation (1) was differentiated in regard to the reduction rate) as Equation (2). Abatement costs increase exponentially against the emission reduction rate of $\mu(t)$ in the relevant year (θ = 2.6). $p_b(t)$ expresses backstop technology costs (marginal abatement costs at the reduction rate of 100%). The costs stood at US\$550/tCO_2 (in 2010 dollars) and would automatically fall at an annual rate of 0.5% (t in the equation indicates a five-year step, hereinafter the same). See literature[9] for the entire picture of the DICE model.

$$\Lambda(t) = \frac{p_b(t)}{\theta}\mu(t)^{\theta} \tag{1}$$

$$MAC(t) = p_b(t)\mu(t)^{\theta-1} \tag{2}$$

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[29] Grubb, Michael, and Claudia Wieners; Modeling myths: on the need for dynamic realism in DICE and other equilibrium models of global climate mitigation, Institute for New Economic Thinking Working Paper Series, 112 (2020).
[30] Ramsey, Frank Plumpton; A mathematical theory of saving, The Economic Journal, 38-152 (1928), pp.543-559.
[31] Cass, David; Optimum growth in an aggregative model of capital accumulation, The Review of Economic Studies, 32-3 (1965), pp.233-240.
[32] Koopmans, Tjalling C; On the concept of optimal economic growth, Cowles Foundation Discussion Papers 163, Cowles Foundation for Research in Economics, Yale University (1963).

In this equation:

$$p_b(t) = 550 \times (1 - 0.025)^{t-1} \tag{3}$$

2-2. Formulation of learning by researching

Here, we formulate learning by researching without considering time lag inertia. Based on earlier studies[17, 18, 20], the reduction of backstop technology costs through learning by researching is expressed by Equations (4) to (6).

$$p_b(t) = 550/H(t) \tag{4}$$

$$H(t) = H(t-1) + aR(t-1)^b\, H(t-1)^{\varphi} \tag{5}$$

$$Q(t) = C(t) + I(t) + \kappa \cdot R(t) \tag{6}$$

Here, $H(t)$ stands for backstop technology knowledge stock and $R(t)$ for RD&D investments. Backstop technology costs do not decline automatically as time goes by, as shown in Equation (3), but they fall in line with growth in knowledge stock as an endogenous variable according to Equation (4). Knowledge stock is accumulated through contributions from RD&D investments and knowledge stock in the previous period according to Equation (5). Contributions from knowledge stock in the previous period indicate that knowledge accumulation from the past makes present knowledge accumulation easier. Equation (6) balances $Q(t)$ for output, $C(t)$ for consumption, $I(t)$ for capital investments and $R(t)$ for RD&D investments (each in trillions of 2010 US dollars), combining the original DICE equation with the third term of the right side.

In Equation (5), $0 < b$ and $\varphi < 1$ are assumed according to Popp (2006)[20]. Then, parameters b and φ indicate that contributions from RD&D investments and knowledge stock in the previous period to present knowledge stock would decline in proportion to scale. As values around 0.5 are usually adopted for φ, we adopted the value of 0.54 by reference to Popp (2006)[20]. We determined a and b by assuming that the automatic reduction of backstop technology costs in the original DICE model would come as RD&D investments remain at the current level. Specifically, we standardized knowledge stock for the reference year at 1 ($H(1) = 1$) and determined a at 0.0461 and b at 0.19 to make Equations (3) and (4) closer to each other as much as possible (to minimize the square sum of a $p_b(t)$ gap between 2015 and 2510) in case that low-carbon technology RD&D investments' share of GDP would remain unchanged from 0.022% in 2015. As for GDP, we used the results for the optimum solution in the original DICE model. The b value ranged from around 0.1 to 0.2 in calibration for earlier studies[18, 20] indicating that our determination is consistent with the earlier studies.

We determined low-carbon technology RD&D investments' share of GDP at 0.022% for 2015 by multiplying the GDP share at 0.030%[calculated from 33] for RD&D investments in low-carbon technologies (including energy efficiency, CCS, renewable energy, nuclear, hydrogen, fuel cell, other electricity and storage, and other cross-sectoral technologies) in OECD countries by the ratio of the GDP share at 2.31%[34] for RD&D investments in areas including non-energy technologies in OECD countries to the global average GDP share at 1.70%[35] for such investments (covering OECD and non-OECD countries (excluding some)).

The third term of Equation 6 represents opportunity costs for RD&D investments in backstop technologies. Generally, it is known that as RD&D investments generate the positive externality of knowledge spillovers beyond organization boundaries and induce underinvestment, the social return on such investments is at least two to four times as large as the private return[36]. On the other hand, an increase in RD&D investments in some fields may cause a decrease in such

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33 IEA Data Service, Energy Technology RD&D (2020 early edition); http://wds.iea.org/WDS/Common/Login/login.aspx (Accessed on 2020/10/7)

34 OECD Data, Gross domestic spending on R&D; https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm (Accessed on 2020/10/7)

35 UNESCO Institute for Statistics; Global Investments in R&D, Fact Sheet No. 50, UIS/FS/2018/SCI/50 (2018).

36 Jones, Charles I., and John C. Williams; Measuring the social return to R&D, The Quarterly Journal of Economics, 113-4 (1998), pp.1119-1135.

investments in other fields (crowding-out). If \$1 in RD&D investments in backstop technologies induces a \$1 decline in those in other fields (crowding-out at 100%), with a return on the latter being \$4, opportunity costs come to \$4, meaning that κ stands at 4[18]. Popp (2006)[20] assumed crowding-out at 50% by reference to U.S. macro data. Meanwhile, Buonanno et al. (2003)[37] formulated intensified RD&D investments contributing to both cutting emission intensity and raising productivity, assuming no crowding-out. As indicated above, no view has been established on κ assumptions. As this study focuses on changes that occur when time lag inertia is introduced for learning by researching, we assumed no crowding-out ($\kappa = 1$) but conducted a sensitivity analysis.

2-3. Introducing inertia for learning by researching

The formulation of learning by research based on earlier studies expressed stock inertia by introducing the concept of knowledge stock. This means that as knowledge stock rather than RD&D investments (flow) reduces backup technology costs, a large increase in RD&D investments in a period may have a limited impact on the reduction of backstop technology costs.

In Equation (5), RD&D investments in a period contribute to accumulating knowledge stock, or reducing technology costs, in the next period (one period covers five years here). In reality, however, some time lag may emerge between RD&D investments and the reduction of costs, particularly for technologies in the initial RD&D phase. There is also a time lag between the reduction of technology costs and the diffusion of relevant technologies, but this time lag has not been considered.

In this study, we expressed a series of inertia (time lag) impacts from RD&D investments in backstop technologies to the reduction of technology costs and the diffusion of technologies, as shown by Equation (7) against Equation (5) expressing traditional knowledge stock accumulation. In formulating the equation, we introduced parameter p (ranging from 0 to 1) expressing the strength of inertia against knowledge stock by reference to an earlier study[29] that introduced inertia against the abatement cost function, enabling a sensitivity analysis on various p values.

$$\Delta H(t) = (1-p) \cdot h(t-1) + p \cdot \Delta H(t-1) \tag{7}$$

In this equation:

$$\Delta H(t) = H(t) - H(t-1) \tag{8}$$

$$h(t) = aR(t)^b \, H(t)^{\varphi} \tag{9}$$

The formulation allows knowledge stock in a period to depend on not only RD&D investments in the previous period but also on an increase in knowledge stock in the previous period. If p is 0, the equation returns to Equation (5). If p is 1, knowledge stock growth follows the past trend irrespective of RD&D investments in the previous period (a static state if $H(1)$ is equal to $H(2)$).

Here, knowledge stock growth stemming from RD&D investments in a period is accompanied by a time lag. Such investments' contributions to knowledge stock ($h\_lag(t+n)$) after the n period ($n \geqq 1$) are shown in Equation (10). Fig. 1 plots $h\_lag(t+n)$ for $h(t)$ at 1 and p ranging from 0.1 to 0.9 (one period covers five years).

$$h\_lag(t+n) = \left\{(1-p)\sum_{\tau=0}^{n-1} p^{\tau}\right\} h(t) \tag{10}$$

[37] Buonanno, Paolo, Carlo Carraro, and Marzio Galeotti; Endogenous induced technical change and the costs of Kyoto, Resource and Energy Economics, 25-1 (2003), pp.11-34.

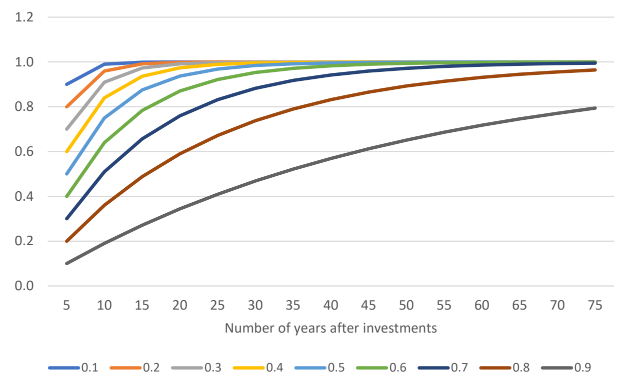

Fig. 1 How RD&D investments bring about knowledge stock growth with a time lag (Plotting parameter p ranging from 0.1 to 0.9)

Note: Potential growth is put at 1

According to Fig. 1, 90% of potential knowledge stock growth through RD&D investments would come in five years if p is 0.1. If p is 0.9, however, 52% of such growth would come even in 35 years. In this study, we assumed a time lag from RD&D investments to the reduction of technology costs and the diffusion of technologies and put p at 0.5 for a case in which more than 90% of potential knowledge stock growth would come in 20 years after such investments. We also conducted a relevant sensitivity analysis.

2-4. Model development and solution

The original DICE model was developed as a nonlinear planning model on the GAMS model, allowing source code to be downloaded from the Nordhaus website. In this study, we replicated DICE-2016R2 as the latest version of the DICE model on a Python (Pyomo) model, replaced Equation (3) with Equation (4), added Equations (7) to (9) and modified Equation (6) (by adding the third term). We solved the model with Ipopt[38].

We combined three cases – absence of RD&D investments, presence of RD&D investments and absence of inertia (p = 0), and presence of RD&D investments and inertia (p = 0.5) – with the presence and absence of temperature constraints (global warming up to 2.5°C) to develop six cases for calculation (hereinafter, inertia refers to that through a time lag). It must be noted that as backstop technology costs are fixed at \$550/tCO_2 for comparative cases where RD&D investments are absent, our solutions differ from optimum solutions in the original DICE model.

3. Results and their consideration

Fig. 2 indicates CO_2 emission estimation results. In cases where no temperature constraints are imposed, emissions in a case with consideration given to RD&D investments will be reduced from a case without consideration given to RD&D investments. Emissions will change little in the near future before the reduction accelerates from 2035. Without consideration given to RD&D investments, emissions will be reduced to zero in 2145. With consideration given to RD&D investments, however, emissions will be cut to zero in 2115. This is because accumulated knowledge stock will gradually reduce backstop technology costs (stock inertia). Not only RD&D investments in a year will reduce backstop technology costs in the year.

In a case with consideration given to time lag inertia from RD&D investments to the reduction of costs and the diffusion of technologies (knowledge stock growth through RD&D investments may not be brought about immediately, but 50% of such growth is here assumed to come in five years from investments and 94% in 20 years), the optimum emission path is

[38] Ipopt Documentation; https://coin-or.github.io/Ipopt/ (Accessed on 2020/10/7)

slightly higher than in a case without consideration given to the inertia.

In a case where a 2.5°C limit on global warming is imposed, emissions will begin soon to rapidly decline and reach zero in 2040. Although the decline looks more rapid than a fall to net zero in 2050 for the goal of limiting global warming to 1.5°C, it must be noted that the DICE model subjects only industry-related CO_2 emissions to the reduction and leaves contributions from other GHG emissions. Under temperature constraints, differences between the cases are slight. However, a comparison between cases with and without RD&D investments indicates that the case with such investments sees lower future abatement costs and is optimal for cutting emissions more rapidly.

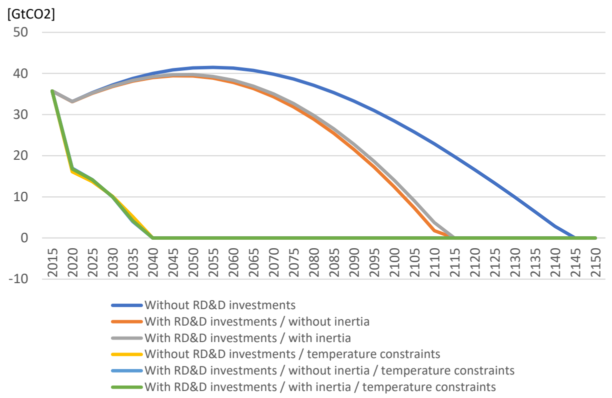

Fig. 2 CO_2 emissions

Temperature rise is shown in Fig. 3. In a case without temperature constraints or RD&D investments, global warming through 2150 will be 4.4°C. RD&D investments will cut global warming by 0.39°C without inertia and by 0.36°C with it. Under temperature constraints, there are few differences in global warming paths between the cases.

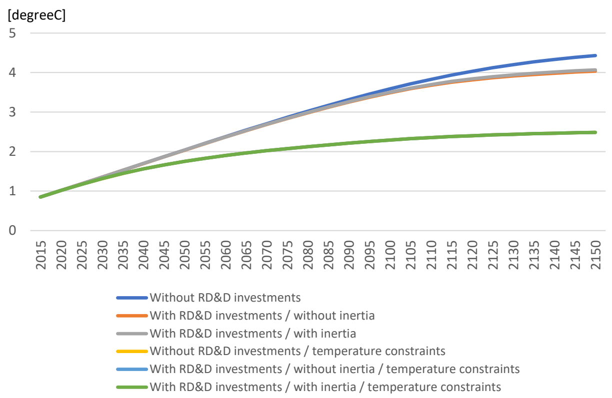

Fig. 3 Temperature rise

Fig. 4 shows RD&D investments. The baseline indicated by a dotted line shows an RD&D investment trend for a case where low-carbon technology RD&D investments' share of GDP is fixed at the present level (2015). In the calibration of parameters related to RD&D investments, we assumed that the annual cost reduction of 0.5% assumed in the DICE model would be achieved if RD&D investments are implemented according to the dotted line. Optimal RD&D investments start at a slightly lower level than in the baseline case and increase more rapidly.

RD&D investment levels and growth rates in a case with consideration given to inertia will be lower than in a case without such consideration. However, no major difference will arise in investment levels in the first half of this century.

This means that even if there is some time lag from RD&D investments to the reduction of technology costs and the diffusion of technologies, the importance of RD&D investments in the first half of this century would remain unchanged.

In a case where temperature constraints are imposed, RD&D investment levels and growth rates will be far higher than in a case without such constraints until 2035 before investment levels remain almost unchanged. As for the effects of RD&D investments shown in Table 1, RD&D investments will cut abatement costs (before discounting) between 2015 and 2100 by 25.0% in a case without inertia and by 22.4% in a case with inertia. Therefore, the importance of RD&D investments in the first half of this century will dramatically increase in a case for seeking the early reduction of emissions. In a case where temperature constraints are imposed, RD&D investments in the near future will decline, if with consideration given to inertia, in contrast to a case without temperature constraints. In a case where early emission and abatement cost cuts are required under temperature constraints, a longer time lag before the emergence of RD&D investments' effects reduces the cost-effectiveness of investments, indicating the relatively greater impacts of inertia. Even with consideration given to inertia, however, optimal investment levels will remain far higher than in a case without temperature constraints.

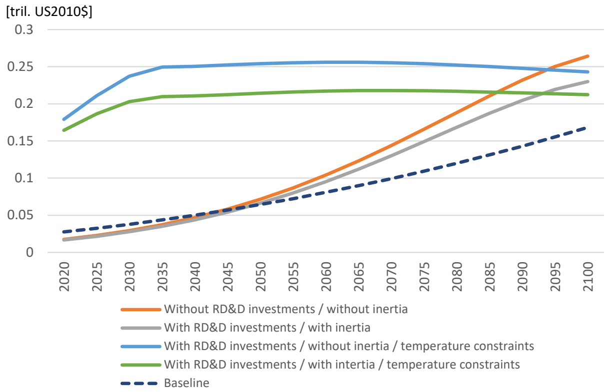

Fig. 4 RD&D investments

Table 1 Abatement cost reduction through RD&D investments under temperature constraints (2015-2100, in comparison with a case without RD&D investments)

Case (under temperature constraints)	Reduction of abatement costs (before discounting)
With RD&D investments/without inertia	-25.0%
With RD&D investments/with inertia	-22.4%

4. Sensitivity analysis

We conducted a sensitivity analysis on the impacts of two highly uncertain parameters on RD&D investments. One is parameter p regarding time lag inertia of knowledge stock in Equation (7). The other is parameter κ regarding opportunity costs for RD&D investments in Equation (6). No temperature constraint is imposed on the following calculation.

Fig. 5 shows parameter p sensitivity analysis results. As p rises, the optimal RD&D investment path gradually shifts downward. If p is up to 0.5 (50% of investments' contributions to knowledge stock will arise in five years from investments and 94% in 20 years), however, the optimal RD&D investment path would change little in the first half of this century.

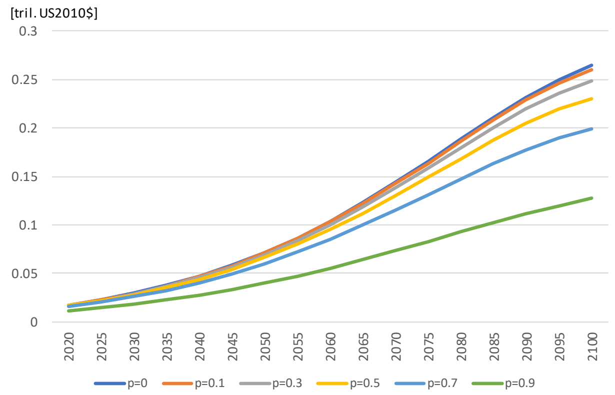

Fig. 5 RD&D investments
(sensitivity analysis on parameter *p*)

Fig. 6 shows parameter κ sensitivity analysis results (p = 0.5 for all cases). The degree of opportunity costs has great impacts on the optimal RD&D investment path. RD&D investments in 2050 in a case for assuming complete crowding-out (κ= 4) are 80% lower than in a case assuming no crowding-out. Given the presence of opportunity costs (the third term of Equation (6)), funds for RD&D investments in low-carbon technologies must be limited with consideration given to the entire economy. However, how much opportunity costs of RD&D investments would be is uncertain in the absence of sufficient knowledge, indicating the need for future relevant studies. Parameter κ has great impacts on an optimal RD&D investment level while exerting no impact on RD&D investment growth. For instance, RD&D investments in 2050 are some four times as large as in 2020 in all cases. This study aimed to assess the impacts of inertia in learning from researching on an optimal RD&D investment path and concluded that the optimal RD&D investment path in the first half of this century remains unchanged even in a case in which inertia is present. This conclusion does not change dramatically depending on parameter κ levels.

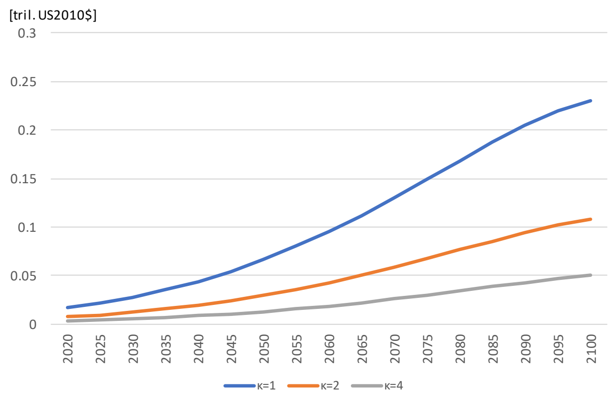

Fig. 6 RD&D investments
(sensitivity analysis on parameter κ)

5. Conclusion

In this study, we conducted cost-analysis analysis after introducing learning by researching regarding abatement costs in the DICE integrated assessment model and reflecting a series of time lag inertia impacts from RD&D investments on the reduction of technology costs and the diffusion of technologies.

RD&D investments exert little impact on emission reductions over the short term but have great gradual impacts on emission reductions over the long term. In a case where time lag inertia is considered, RD&D levels and growth are lower than in a case where inertia is not considered. However, investment levels in these cases do not differ so much, indicating that RD&D investments in the near future would remain important. If temperature constraints are considered, however, RD&D investments in the first half of this century will become even more important.

It is pointed out that the promotion of technological innovation through RD&D investments to accelerate future emission reductions amounts to delaying global warming countermeasures. Given the results of this study, however, the importance of RD&D investments at present remains high even if a time lag before the emergence of the effects of investments is considered. At a time when the world seeks to achieve the long-term target under the Paris Agreement, the importance becomes even greater.

Considering uncertainties regarding the success of RD&D and the possibility that RD&D investments in low-carbon technologies could reduce those in other fields, we find that it is difficult to provide any firm conclusion on how much optimal investments would be. This point remains subject to future studies. In reality, however, sharp emission reductions exceeding 80% may apparently be impossible rather than costly at present. If the world seeks to achieve zero emissions finally, technological innovation and RD&D investments for such innovation would be indispensable irrespective of how emission paths would be.

Transition to Renewable Energy Society in Germany and the U.K.
－ Historical paths to FIP and CfD Introduction and Implications for Japan －

Akiko Sasakawa*

Summary

Renewable energy is attracting attention from the decarbonization trends and the viewpoint of resilience against the COVID-19 disaster. In line with this recognition, this paper considers how best to realize the transition to a society where renewable energy is widespread. Taking up the power sector of Germany and the United Kingdom that have historically depended heavily on fossil fuels, this paper analyzes how the two countries have tried to achieve the transition from a fossil-based system to a renewable-based system for the power sector. The analysis mainly focused on EU and domestic policies, political party trends, and the Parliament discussions.

Interestingly, Germany and the United Kingdom have followed widely different policy paths to their common renewable energy promotion goal. Germany has frequently implemented fine-tuned legislative measures since its initial development of renewable energy promotion systems, adjusting feed-in tariffs and their gradual reduction rates by renewable energy type, capacity range, and activation year. In contrast, the United Kingdom has used market functions as much as possible from the beginning for the cost-efficient promotion of renewable energy.

While following different paths to renewable energy promotion, the two countries commonly experienced twists and turns for handling renewable energy's relations with other energy sources such as coal and nuclear. Also, they continued efforts to advocate national visions and long-term targets to implement renewable energy promotion policies. Climate change, energy security, and other higher-ranked policy agendas have also significantly impacted their renewable energy promotion.

Given such analysis, this paper suggests the need for assessing the impacts of other primary energy sources and high-ranked policy agenda. It also points out the significance of long-term targets and coordination after institutional development to realize a renewable energy-oriented society.

As implications from German and the U.K. policy processes for Japan, this paper emphasizes the importance of developing electricity markets, eliminating grid constraints, securing the supply-demand balancing capacity, and demonstrating the long-term targets for 2050 to promote renewable energy as a major power source. This paper also considers calculation methods for premium prices under the Feed-in Premium (FIP) system.

Introduction

Adopting decarbonization as one of the pillars for economic recovery from the COVID-19 disaster has become a significant trend, especially in Europe. The world seeks to build back better by tackling society-wide challenges like climate change, technological innovation, health, employment, and social gap issues.

In such a situation, renewable energy has attracted attention not only as a low-carbon energy source contributing to decarbonization but also from the perspective of resilience against the COVID-19 disaster. While global electricity demand has plunged into economic stagnation due to the pandemic, renewable energy power generation, mainly from solar photovoltaics and wind, has been growing. In 2020, renewable energy became the only energy source scoring primary energy supply growth[1]. Renewable energy had been viewed as a volatile and costly electricity source. However, given its characteristic position as distributed energy and its cost-competitiveness enhanced through technological development, renewable energy has increasingly been recognized as safer and cheaper than conventional electricity sources for which

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[1] Y. Ninomiya "2020-21 Renewable Energy Trends: How Would Covid-19 Impact Renewable Energy?" 435th Forum on Research Works, IEEJ, 7/14/2020, IEA "Renewables 2020 – Analysis and forecast to 2025", November 2020.

massive labor and fuels are required.

With such recognition, it must be worth reconsidering how to realize a society where renewables are widespread. As the future global energy mix's direction has long been discussed, the significance of policies promoting the transition from a fossil-based society to a renewable-based one has widely been recognized. In an EU Strategy for Energy System Integration released in July 2020, Europe indicated a policy at the EU level to gradually shape a new integrated energy system, *i.e.*, "the energy system as a whole, across multiple energy carriers, infrastructures, and consumption sectors, by creating stronger links between them with the objective of delivering low-carbon, reliable and resource-efficient energy services, at the least possible cost for society"[2]. In Japan, the cabinet decided on the Fifth Strategic Energy Plan in July 2018, adopting a policy of diffusing renewable energy as a primary electricity source for the first time. Since then, institutional designs have been discussed to diffuse renewables as a cost-competitive and long-term stable electricity source.

Based on such trends, this paper reviews the transition from a fossil-based system to a renewable-based one in the power sector, where renewables were actively promoted ahead of other sectors such as heat and transport. In the field of political science, the question of how technologies and institutions that had been locked in society would make a transition to new ones has actively been researched. Some researchers have broken down transition processes into phases and analyzed phase-to-phase changes[3]. Others have considered transition processes by focusing on political trends triggered by external shocks impacting existing systems[4]. Studies on transitions paid attention to the timings when specific policies were taken and clarify processes in which existing systems or institutions transitioned to new ones.

This paper conducts a comparative analysis of German and U.K. cases based on such framework of transition studies. Both countries had historically depended heavily on fossil fuels but have dramatically expanded renewables' presence in the power sector since the 1990s. In Germany, renewables' share of total power generation dramatically increased from 3.5% in 1990 to 39.9% in 2019 and a record 55.8% in the first half of 2020[5]. In the United Kingdom, renewables' share of the power mix soared from only 2.7% in 2000 to 37.1% in 2019. It has reached 47% in the first quarter of 2020. Among EU countries that have promoted cross-border renewable electricity trading through the international grid, the two countries have achieved remarkable renewable expansion[6]. Their power sector's transition from heavy dependence on fossil fuels is worthy of attention.

To analyze how the German and U.K. power sector has promoted transition to renewables, this paper chronologically tracks the two countries' renewable energy policies while keeping trends for other energy sources in sight. It attempts to three-dimensionally identify transition processes by discussing specific policy choices and their background, including EU and domestic policies, political party trends, and Parliamentary discussions. Based on the comparative analysis, implications for Japan to realize a renewable energy-oriented economic society will be considered.

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[2] "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Powering a climate-neutral economy: An EU Strategy for Energy System Integration," COM(2020)299 final, 8th of July 2020., p.2.

[3] Earlier studies regarding the theme of this paper include Geels et al., "The Socio-Technical Dynamics of Low-Carbon Transitions", *Joule* 1, November 15, 2017, pp.463-479; Verbong, Geert and Loorbach, Derk eds., *Governing the Energy Transition: Reality, Illusion or Necessity?* (Routledge, 2012); Grin, John, Rotmans, Jan and Schot, Johan., *Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change* (Routledge, 2010); and Loorbach, Derk, *Transition Management: New Mode of Governance for Sustainable Development* (International Books, 2007)

[4] Aklin, Michaël and Urpelainen, Johannes, *Renewables: The Politics of a Global Energy Transition* (The MIT Press, 2018).

[5] Data for 1990 and 2019 are from IRENA, "Renewable Energy Statistics," 2020. Data for the first half of 2020 are from a story in the Nikkei Sangyo Shimbun newspaper dated July 21, 2020, citing a release from Germany's Fraunhofer Society.

[6] Renewable energy data in the power sector in EU countries are from Agora Energiewende, "The European Power Sector in 2019: Up-to-Date Analysis on the Electricity Transition." According to the report, renewables accounted for 34.6% of total EU power generation in 2019. In Sweden and Austria endowed with rich hydro resources, renewables capture more than 70% of total power generation. Hydro has long been a mainstay power source in these countries. Denmark has boosted its renewable share to around 70% by expanding wind power generation.

1. German institutional building process for renewable energy expansion

Germany has taken the initiative in energy transition for decarbonization, greatly expanding renewable energy's share of the power sector. How has Germany, which has historically depended heavily on fossil fuels, developed renewables in the power sector? This section reviews Germany's power supply and demand trends, tracks its renewable energy expansion policy process from the 1990s, and analyzes its policies.

1-1. German power supply and demand trends

As a country endowed with rich coal resources, Germany has depended heavily on coal for developing manufacturing since the 19th century. Poor with non-coal energy resources, the country has relied on imports for most oil and natural gas supply. When cheap oil began to be imported into Germany in the 1960s, its primary energy supply source shifted from coal to oil. However, the first oil crisis in 1973 led Germany to transition back to coal and give policy protection to the coal industry[7]. As shown in Fig. 1, coal's share of Germany's total power generation stood at 58.7% in 1990 and remained above 50% until 2004. In 2005, it slipped below the level to 48.2% and 30.3% in 2019[8]. While coal's presence in power generation was still significant, in January 2020, the German government announced plans to phase out coal mines and coal-fired power plants by 2038.

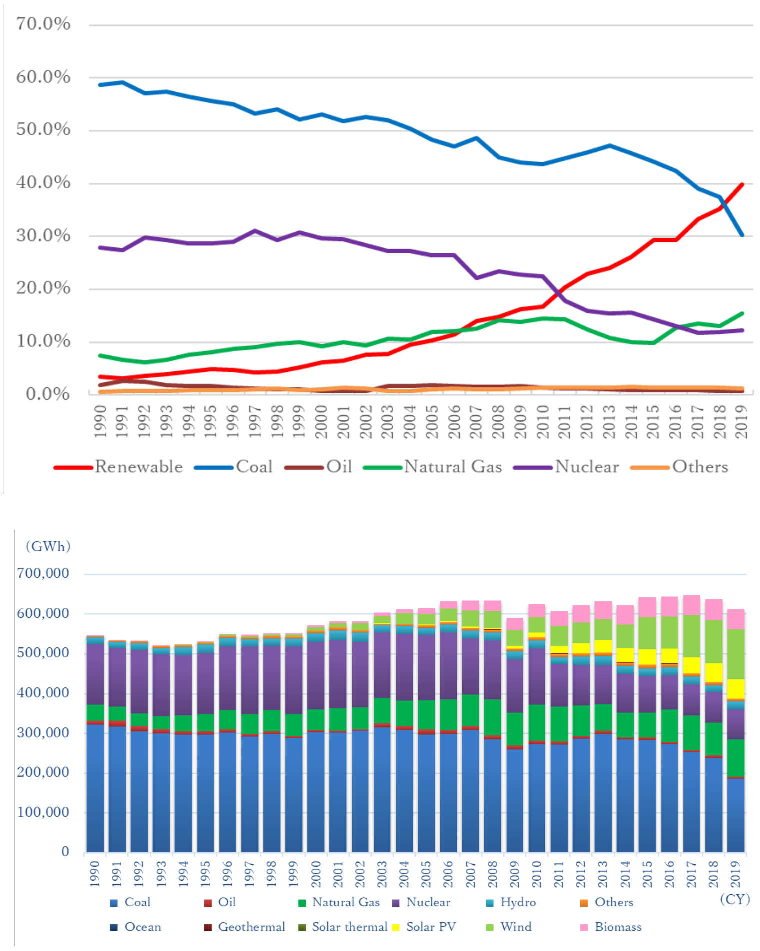

Fig. 1 (Upper) Each energy source's share of total power generation (%), (Lower) German power mix trends

Source: Prepared from IEA, "Energy Statistics and Balance 2020"

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[7] Federation of Electric Power Companies of Japan website, "German Energy Policy Trends (「ドイツのエネルギー政策動向」)" (https://www.fepc.or.jp/library/kaigai/kaigai_jigyo/germany/detail/1231559_4782.html)

[8] IEA, "World Energy Statistics and Balances 2020." According to the statistics, oil accounted for 0.8% of Germany's total power generation in 2019, natural gas for 15.4%, nuclear for 12.3%, renewables for 39.9% and others for 1.3%.

The German government had already announced a nuclear phaseout policy in 2011. Nuclear had accounted for about 30% of total power generation until the early 2000s as the second-largest power source after coal (Fig. 1). Under anti-nuclear campaigns that have been buoyant since the 1970s in Germany, a nuclear phaseout law took effect in 2002 to retire nuclear power plants by 2022. Later, the German government revised the schedule to retain nuclear power plants as it had found that renewable energy alone would not be enough to cover the domestic power demand. In response to the March 2011 Fukushima Daiichi nuclear plant accident, however, the German government swung back to the nuclear phaseout policy. In July 2011, Germany took legislative action to restore a nuclear phaseout plan close to the original one, deciding to phase out nuclear plants by 2022. Under such policy, the nuclear share of total power generation almost halved from 22.4% in 2010 to 12.3% in 2019.

As shown in Fig. 2, renewables' share of the power mix increased substantially from 3.5% in 1990 to 39.9% in 2019. During the same period, renewable power generation output grew about 12-fold from 19,093 TWh to 244,197 TWh. Particularly, wind and solar PV power generation expanded remarkably. Hydro energy had captured most of the total renewable power generation in 1990, while the wind had accounted for only 0.37% of the total, and solar PV for 0.005%. In 2019, however, the share soared to 51.6% for wind and 19.5% for solar PV.

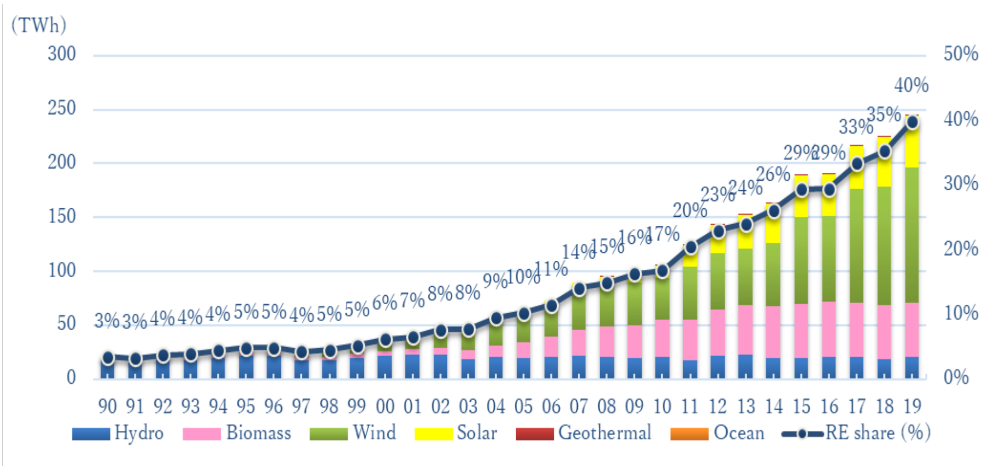

Fig. 2 Renewables' share of total German power generation (1990-2019)

Source: Prepared from IEA, "Energy Statistics and Balance 2020"

Based on the above power supply and demand trends, the following analyzes Germany's policy process to expand renewable energy.

1-2. FIT system creation and evolution

1-2-1. Launching institutional building for renewable energy diffusion

Germany fully launched institutional building for renewable energy diffusion under the Federal Electricity Feed Law (StrEG) that came into effect in 1991. The law required power suppliers to purchase electricity generated from hydro, wind, solar energy, waste gas, sludge gas, and "agriculture or forestry products or biological residue[9]" at rates set as percentages

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[9] This item was revised into "biomass" through the second amendment to the StrEG. This section describes the StrEG, the Renewable Energy Sources Law (EEG), and the EEG 2004 based on T. Watanabe, "German Renewable Energy Sources Law," *Foreign Legislation, no.225,* August 2005, National Diet Library, pp. 61-86.
（渡邊斉志「ドイツの再生可能エネルギー法」『外国の立法』no.225、2005.8、国立国会図書館）

of electricity retail prices in their respective business territories[10].

The law was enacted to help achieve a target adopted by the German Bundestag for cutting greenhouse gas emissions by 30% by 2005 in response to growing interests in the global warming issue[11]. The main support measures for renewable energy were limited to research and development subsidies until the enactment. Then, however, the need was widely recognized for institutional building for promoting renewable energy in place of coal and nuclear energy[12]. It was because the anti-nuclear campaigns since the 1970s gained momentum on the 1986 Chernobyl nuclear plant accident, and global warming was widely seen as a severe challenge in Germany. The Christian Democratic Union of Germany (CDU) and the Christian Social Union in Bavaria (CSU) under the Kohl administration allied with the Green Party and the Social Democratic Party of Germany (SPD), as well as the European Association for Renewable Energies (Eurosolar) founded in 1988, to pass the StrEG through the Bundestag[13]. As a result of such multi-party cooperation, the law was unanimously approved in 1991[14].

The law was amended in 1994 and 1998 before the Renewable Energy Sources Law (EEG) was enacted in April 2000 to reform renewable energy policies thoroughly.

1-2-2. Institutional building for renewable energy diffusion under EEG

The EEG Law can be considered an extension of the StrEG Law because of their common purpose of renewable energy diffusion. However, the EEG differed from the StrEG in the following points. First, the EEG set a numerical target in response to the European Union's renewable energy target. The target called for doubling renewables' share of total energy supply in Germany from 2.6% in 2000 by 2010[15].

Second, the EEG took the initiative in creating the Feed-in Tariff system as a framework for promoting investment in renewable power. As noted above, the StrEG set renewable power purchase prices by some percentages of electricity retail prices, meaning that renewable power purchase prices would fluctuate in line with electricity retail prices, which resulted in failing to secure business predictability for renewable power generators. The EEG guaranteed renewable power purchases at fixed prices to allow renewable power generators to predict their future cash flow, which also encouraged newcomers to invest in renewable power generation.

Third, power suppliers' requirement term to purchase renewable power was set to last for 20 years. It aimed to encourage renewable power generators to increase business efficiency and prevent their profitability from declining over the long term. Forth, as renewables subject to the FIT system, geothermal energy and coal mine firedamp gas were added to wind, solar PV, hydro, waste gas, sludge gas, and biomass. Then, a power output ceiling was set for each renewable power source. Feed-in tariffs, or prices for renewable power purchases, were finely set based on the characteristics and degrees of diffusion for renewable power sources. Thus, the EEG set the numerical target and clarified the FIT system introduction by indicating the system's details to build a framework for accelerating renewable energy diffusion.

In such institutional building, the Social Democratic Party of Germany (SPD) became the largest political party through the 1998 general elections. It formed a coalition with the Green Party promoting climate change measures, renewable energy diffusion, energy efficiency improvement, and other policies related to sustainable development. The Green Party

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[10] Purchase prices were set at 90% of average electricity retail prices for solar PV and wind electricity and 65-75% of such prices for hydro and biomass electricity according to capacity sizes. The ceiling on purchases was put at 5% of each power supplier's local power supply. Electricity from 5 MW or larger facilities among hydro, waste gas, and sludge gas power generators are not subjected to the purchase requirement. T. Watanabe, "German Renewable Energy Sources Law," p. 62, as cited above.（渡邊「ドイツの再生可能エネルギー法」p.62）

[11] K. Oshima, "Germany's Experiences with Renewable Energy Diffusion – Feed-in Tariff System Framework and Realities," *Journal of Ritsumeikan Social Sciences and Humanities,* Vol. 88, pp. 65-91
（大島堅一「再生可能エネルギー普及に関するドイツの経験ー電力買い取り補償制の枠組みと実際ー」『立命館大学人文科学研究所紀要』88 号、pp.65-91）

[12] Aklin and Urpelainen, *op.cit*., pp.146-157.

[13] *Ibid.*

[14] *Ibid.*

[15] T. Watanabe, "German Renewable Energy Sources Law," p. 63（渡邊「ドイツの再生可能エネルギー法」）

participated in a coalition government for the first time in German history. The SPD-Green coalition immediately tackled the nuclear phaseout and the acceleration of renewable energy diffusion. In 2001, it decided on a nuclear phaseout law, providing that existing nuclear power plants would be closed by 2022, with new nuclear plant construction being banned.

Another background for the EEG included the so-called Aachen model launched in 1995 in a German town close to the borders with Belgium and the Netherlands[16]. Under the model, a public water and energy corporation offered to purchase solar PV electricity over 20 years and wind electricity over 15 years at higher prices than market levels while levying a 1% surcharge on electricity rates to raise financial resources for the purchase[17]. The model, which is similar to the FIT system, led to new investment in renewable power generation capacity and became a harbinger system for diffusing renewable energy.

The EEG was implemented in a full-blown manner from 2001. While renewable energy diffusion trends and the suitability of feed-in tariff levels were verified as needed, the law was amended several times[18]. In July 2002, the ceiling capacity for the solar PV electricity purchasing obligation was raised from 350 MW to 1,000 MW in response to smooth solar PV diffusion. It eliminated solar PV power generators' concern that they could lose FIT compensation in the future, encouraging investment in new solar PV power generation projects. In July 2003, preferential treatment for large-lot users[19] was adopted, halving a surcharge for their purchases above 100 GWh. The measure was based on a view that the surcharge for renewable energy diffusion should not seriously affect business operations. In January 2004, an EEG amendment focusing on solar PV expansion was passed. It set feed-in tariffs for solar PV capacity brackets and repealed the solar PV electricity purchasing obligation ceiling.

1-2-3. Setting medium to long-term targets for renewable energy diffusion and evolving the FIT system

In August 2004, the EEG2004[20] was enacted to amend the EEG comprehensively. The EEG2004 reflected an EU directive (EU2001 renewable energy directive)[21] seeking to diffuse renewable energy in the internal electricity market. First, EEG2004 targeted boosting renewables' share of total electricity supply to 12.5% by 2010 and 20% by 2020. The 2010 target share was the same as the EU2001 renewable energy directive. Second, the EEG2004 obliged power transmission and distribution companies to purchase renewable energy electricity and grid operators to connect renewable energy to the grid preferentially[22]. The obligation was regulated in Article 7 (grid system issues) of the EU2001 renewable energy directive.

The EEG2004 also reset feed-in tariffs by renewable energy source and capacity size. Besides, it expanded the scope of large-lot users subject to the preferential surcharge measure introduced under the EEG to ease surcharge burdens on a

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[16] K. Ishikura "Analysis on Germany's Renewable Energy Feed-in Tariff System and Price Transitions," *Hitotsubashi Economics, 7 (1) pp. 33-64, 2013* （石倉研「ドイツにおける再生可能エネルギー買取の制度と価格の変遷に関する考察」『一橋経済学』7(1)、pp.33-64、2013）

[17] K. Yamauchi "Aachen Model Encouraging Solar PV Power Generation Diffusion" 2002 (http://www.genergy.jp/downloads/aachen_model.pdf) （山内浩一「太陽光発電施設普及を促すアーヘンモデルとは」2002 年）

[18] T. Watanabe, "German Renewable Energy Sources Law" （渡邊「ドイツの再生可能エネルギー法」）

[19] Large-lot users are enterprises that consumed more than 100 GWh in electricity on average and paid power charges equivalent to more than 20% of gross added value in the past 12 months. See T. Watanabe, "German Renewable Energy Sources Law," p.64 （渡邉「ドイツの再生可能エネルギー法」p.64）

[20] Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich (BGBl. I 2004 S.1918) (A law to establish a new renewable energy law for the power sector) as translated in T. Watanabe, "German Renewable Energy Sources Law" 渡邊「ドイツの再生可能エネルギー法」 p.69-86. The EEG2004 is a substantially revised version of the traditional EEG, replacing the traditional EEG.

[21] Directive 2001/77/EC of the European Parliament and the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market. The directive calls for setting renewable power diffusion targets and taking renewable energy support measures including green certificates, investment assistance, tax exemption or reduction, tax refund, and direct price maintenance. It also seeks to utilize the guarantee of origin of electricity produced from renewable energy sources and create a framework for grid managment including the preferential connection of renewable power sources to the grid.

[22] Details of the EEG2004 are based on its translation in T. Watanabe, "German Renewable Energy Sources Law" （渡邊「ドイツの再生可能エネルギー法」） p. 69-86.

broader range of enterprises[23].

In this way, the EEG2004 built on the framework and targets for renewable energy support, reflecting the EU2001 target, to enhance Germany's existing measures. Also, it set its own renewable energy diffusion target for 2020 to promote renewable energy diffusion from the medium to long-term viewpoint.

In 2009, the EEG2004 was substantially amended[24] to raise the target for renewables' share of total electricity supply for 2020 from 20% to 30%. A report submitted to the Bundestag in 2007 stated that the renewable share reached 11.6% in 2006 and was expected to top 13% in 2007. It indicated that the target for 2010 in the EEG2004 would be achieved three years ahead of schedule[25]. In March 2007, the European Council, then chaired by Germany, decided on a binding target of 20% for renewables' share of total EU energy consumption in 2020[26]. Based on the new EU target, the EEG2009 raised the renewable share target for 2020 to 30%.

The EEG2009 also unified FIT purchase periods for all renewable energy power generation facilities (other than large hydroelectric power plants) into 20 years (15 years for large hydroelectric power plants) from the start of operation at power generation facilities, and specified conditions of direct electricity sales for renewable power generators[27]. Furthermore, it provided feed-in tariffs by power source, gradual reduction rates, and other details[28]. Given that the fuel costs for biomass power generation were rising though the remarkable growth in the generation was observed in Germany, the EEG2009 lowered the annual reduction rate of feed-in tariff from 1.5% in the EEG2004 to 1.0% for biomass power generation. As for solar PV power generation that rapidly diffused (see Fig. 3), the EEG2009 raised the feed-in tariff's annual reduction rate because solar PV power generation costs were substantially falling on technological development.

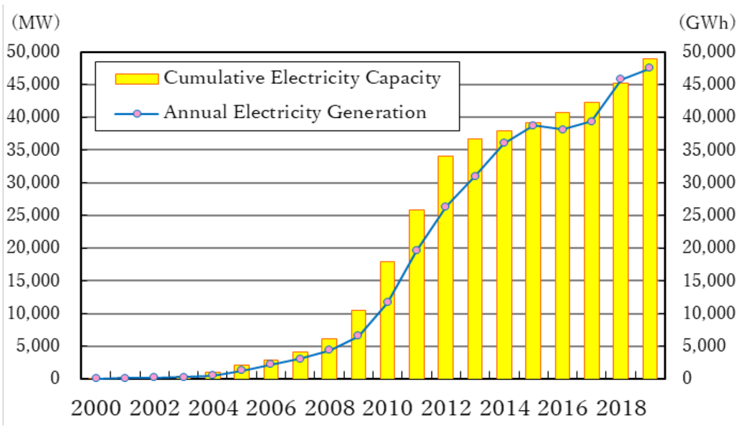

Fig. 3 Solar PV power generation trends in Germany (2000-2019)

Sources: Cumulative electricity capacity data are from IRENA, "Renewable Energy Statistics 2020," and annual electricity generation data from IEA, "World Energy Statistics and Balance 2020."

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23 The burdens were eased on enterprises that consume more than 10 GW in electricity annually and pay electricity charges equivalent to more than 15% of gross added value. See T. Watanabe, "German Renewable Energy Sources Law"（渡邊「ドイツの再生可能エネルギー法」）p. 66.

24 For EEG2004 and EEG2009, see K. Yamaguchi "German Energy and Climate Change Countermeasure Legislation (2) – 2009 Renewable Energy Law," *Foreign Legislation, No.241,* September 2009, National Diet Library, pp. 101-132（山口和人「ドイツのエネルギー及び気候変動対策立法(2)−2009 年再生可能エネルギー法」『外国の立法』no.241、2009.9、国立国会図書館、pp.101-132）

25 K. Yamaguchi "German Energy and Climate Change Countermeasure Legislation (2) – 2009 Renewable Energy Law," *Foreign Legislation, No.241,* September 2009, National Diet Library, p. 103（山口和人「ドイツのエネルギー及び気候変動対策立法(2)−2009 年再生可能エネルギー法」, p.103）

26 "Brussels European Council 8/9 March 2007 Presidency Conclusions," Council of the European Union, 7224/1/07 REV1, Brussels, 2 May 2007.

27 For the EEG2009, see K. Yamaguchi "German Energy and Climate Change Countermeasure Legislation (2) – 2009 Renewable Energy Law," pp. 107-132（山口和人「ドイツのエネルギー及び気候変動対策立法(2)−2009 年再生可能エネルギー法」pp. 107-132). Article 17 of the law provides for conditions on direct sales, stating that power generators can sell electricity generated from their facilities to third parties in each month if they report such sales for a month to power distributors before the start of the previous month.

28 To promote efficient renewable energy investment, feed-in tariffs were set to decline at fixed annual rates. For solar PV, the annual rate of decline in the feed-in tariff was set at 9%, higher than for other renewable electricity sources, because of falling costs.

1-3. Market premium system introduction (EEG2012)

1-3-1. Energy transition policy

As mentioned above, renewable energy diffusion under relevant policies has been a critical policy challenge for Germany to address climate change and promote energy transition in German society[29]. Some 50% of renewable energy facilities installed by 2010 were owned by the private sector[30], and numerous citizens were hoping for an energy transition towards a society that does not depend on fossil fuels or nuclear energy[31]. Meanwhile, the German government was concerned about growing costs for supporting renewable energy diffusion and thought that renewable energy alone would have difficulties meeting electricity demand growth while recognizing the importance of energy transition[32]. As noted in section 1-2-2, the SPD-Green coalition decided on a nuclear phaseout law, providing that existing nuclear power plants would be closed by 2022. However, a new coalition government between the Christian Democratic Union of Germany/Christian Social Union in Bavaria (CDU/CSU) and the Free Democratic Party (FDP), which was formed through the September 2009 general election, thought that the nuclear phaseout schedule would raise the risk of power shortages.

In September 2010, the Merkel cabinet of the coalition government announced an energy transition program called "Energiewende," vowing to transform energy supply in Germany thoroughly[33]. It indicated a policy of using nuclear power generation until developing renewable power supply infrastructure. And the program extended the operating life for 8 years for nuclear power plants launched by 1980 and for 14 years for those found later[34]. It also demonstrated a path of renewable energy diffusion by indicating the target to increase renewables' share of power supply to 35% by 2020, 40-45% by 2025, 55-60% by 2035, and at least 80% by 2050[35].

However, in response to the March 2011 Fukushima Daiichi nuclear power plant accident, the government had no choice but to revise the program substantially. In June 2010, it decided to cancel the previous year's extension of the nuclear plant operating life and restore the policy of terminating nuclear power generation by 2022[36]. Based on the decision, the government recognized the need to accelerate renewable energy diffusion further to cover nuclear plants' closure. From July 2011, it launched efforts to amend the EEG2009 substantially[37].

1-3-2. Integrating renewable electricity into the market

In January 2012, Germany implemented the EEG2012 to accelerate renewable energy diffusion. The law specified targets for renewables' share of power supply through 2050 in line with the energy transition program and called for integrating renewable power into the power supply system[38]. It also revised feed-in tariffs and their reduction rates and included detailed conditions for integrating renewable power into the power market. While renewable power supply expanded under the FIT system, Germany recognized the need to reduce FIT surcharges' burden on consumers and improve

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[29] For EEG2009 amendment history and the EEG2012, see T. Watanabe, "German Renewable Energy Sources Law"（渡辺「ドイツの 2012 年再生可能エネルギー法」）.

[30] Yildiz, Özgür, "Financing Renewable Energy Infrastructures Via Financial Citizen Participation – The case of Germany," *Renewable Energy* 68, 2014, pp.677-685.

[31] Aklin and Urpelainen, *op.cit.*, p.184.

[32] *Ibid.*, pp.184-185.

[33] Agora Energiewende "Energiewende and Economy（「エネルギーヴェンデと経済」）May 29, 2015（https://sekitan.jp/wp-content/uploads/2015/06/Part1_Christoph_JP_final.pdf）.

[34] F. Watanabe, "Germany Accelerates Nuclear Phaseout," Foreign Legislation, May 2011, National Diet Library（渡辺富久子「【ドイツ】脱原発が加速」『外国の立法』2011.5、国立国会図書館）

[35] Agora Energiewende "Energiewende and Economy（「エネルギーヴェンデと経済」） May 29, 2015（https://sekitan.jp/wp-content/uploads/2015/06/Part1_Christoph_JP_final.pdf）.
（Agora Energiewende「エネルギーヴェンデと経済」）

[36] K. Koyama, "Germany Revises Nuclear Power Generation Phaseout, Deciding to Extend Operating Life" Institute of Energy Economics, Japan, September 9, 2010（小山堅「ドイツ、原子力発電フェーズアウト計画を見直し、稼働延長方針を決定」日本エネルギー経済研究所、2010 年 9 月 9 日）（https://eneken.ieej.or.jp/data/3326.pdf）; F. Watanabe, "Germany Accelerates Nuclear Phaseout," *Foreign Legislation*, May 2011, National Diet Library（渡辺富久子「【ドイツ】脱原発が加速」『外国の立法』2011.5、国立国会図書館）

[37] T. Watanabe, "German 2012 Renewable Energy Sources Law"（渡邊「ドイツの 2012 再生可能エネルギー法」）p. 80.

[38] For EEG2012, see T. Watanabe, "German 2012 Renewable Energy Sources Law"（渡邊「ドイツの 2012 再生可能エネルギー法」）

renewable power's market competitiveness, beginning to seek the integration of renewable power into the power market.

The EEG2009 had already provided conditions for direct sales of renewable power in the market, but the EEG2012 featured an independent chapter (Chapter 3a) for details of direct sales and market premiums[39]. First, direct sales of renewable power were divided into three categories – (i) direct sales designed to charge market premiums, (ii) direct sales designed to reduce electric power suppliers' surcharges, and (iii) other direct sales. Renewable power generators were allowed to choose FIT compensation or direct sales and change their direct sales categories.

A market premium is a difference between the average market price and the compensation amount paid as claimed under the FIT system (standard value)[40]. Renewable energy power generators who directly sell renewable power in the market can claim a market premium from grid operators for actual electricity sales in the market and must report the latest monthly market sales volume to grid operators by the 10th day of the following month. A mechanism was introduced to retrospectively calculate a market premium for each calendar month in line with the fourth supplementary provision of the EEG2012. As for biomass power generation, electricity from 750-kW or more extensive facilities launched on January 1, 2014, or later was subjected not to fixed tariff purchases but to direct sales. Biogas-fired power generators that can generate power in line with power demand fluctuations were allowed to claim a flexibility premium in addition to a market premium if they increase capacity and directly sell electricity in the market.

In this way, the EEG2012 further specified the direct sales system created under the EEG2009 and introduced market and flexibility premiums to develop a framework for integrating renewable power into the power market. Renewable power was expected to gradually be integrated into the power market as renewable energy power generators accumulate experiences. The generators take advantage of the direct sales system to gain a more significant profit than FIT compensation by selling electricity when electricity demand and prices are high.

1-4. FIP system introduction (EEG2014)

1-4-1. From protection to competition

The integration of renewable energy into the power market accelerated along with the political transition. After the federal parliamentary election in September, Germany transitioned to a grand coalition between the CDU/CSU and the SPD in December 2013. The new coalition government changed the agency in charge of renewable energy and promoted the amendment of the renewable energy sources law[41].

As renewables' share of total power generation reached 24% in Germany when the new government was inaugurated in 2013 (Fig. 2), the need was recognized for a transition from the policy protection stage to the competitive diffusion of renewables. How to hold down the FIT surcharge growing in line with renewable energy diffusion was viewed as an urgent challenge. The unit surcharge rose from 1.16 euro cents/kWh in 2008 to 3.59 euro cents/kWh in 2012, to 5.28 euro cents/kWh in 2013, and 6.24 euro cents/kWh in 2014 (Fig. 4). In 2014, the total surcharge reached 23.8 billion euros[42]. Until then, FIT compensation for solar PV power generation was lowered to hold down the surcharge growth. However, this measure failed to prevent the surcharge from rising and left power charges, including the surcharge, to increase year by year.

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[39] For direct sales provided in the EEG2012, see T. Watanabe, "German 2012 Renewable Energy Sources Law"（渡邊「ドイツの 2012 再生可能エネルギー法」）

[40] Details of the market premiums are provided in Articles 33g and 33h and the fourth supplementary provision of the EEG2012. For conceptual diagrams of the FIT and FIP systems, see "Comparative conceptual diagrams of renewable energy support measures" at the end of this paper.

[41] For EEG2009 amendment history and the EEG2014, see F. Watanabe, "Enactment of Germany's 2014 Renewable Energy Sources Law," *Foreign Legislation*, *No.262*, December 2014, National Diet Library, pp. 72-109（渡辺富久子「ドイツにおける 2014 年再生可能エネルギー法の制定」『外国の立法』no.262、2014.12、国会図書館、pp.72-109）

[42] F. Watanabe, "Enactment of Germany's 2014 Renewable Energy Sources Law,"（渡辺「ドイツにおける 2014 年再生可能エネルギー法の制定」）, p.76

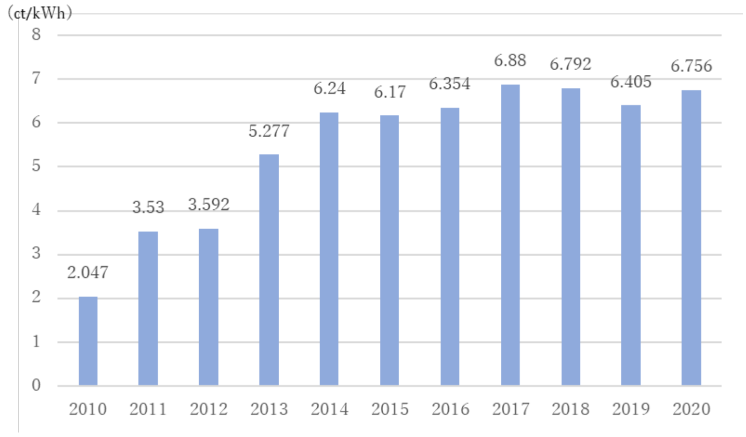

Fig. 4 German FIT surcharge trends (2010-2020)

Source: Prepared from the German grid operator information platform website (EntwicklungderEEG-Umlage) (https://www.netztransparenz.de/EEG/EEG-Umlagen-Uebersicht)

Furthermore, the European Commission issued the Guidelines on State Aid for Environmental Protection and Energy 2014-2020[43], urging EU members to take relevant national measures[44].

The guidelines indicated conditions and standards for subsidization measures in the energy and environment fields to maintain an adequate competitive environment within the European Union. Whether renewable energy support systems under the German StrEG and EEG would be state subsidies banned under EU law had long been an issue mainly in the European Court of Justice[45]. Under such circumstances, the Guidelines on State Aid for Environmental Protection and Energy positioned support measures for renewable electricity as the adequate policy to achieve renewable energy diffusion targets set by the European Union and its members[46]. They also suggested that renewable electricity should be competitive in the grid between 2020 and 2030, and those existing policies of relieving renewable electricity of responsibilities for balancing power supply with demand be phased out. Then, the guidelines required that new renewable energy diffusion support measures be implemented in or after January 2016 to add a feed-in premium to market prices for renewable power generators selling electricity directly to the market[47]. They also required that projects for new support measures to be taken in or after January 2017 be subjected to specific, transparent, and non-discriminatory competitive auctions unless the number of power sources subject to these measures is limited or strategic auctions are expected.

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[43] European Commission, "Communication from the Commission, Guidelines on State Aid for Environmental Protection and Energy 2014-2020 (2014/C 200/01)." The guidelines replaced those in 2008 on state subsidies for environmental protection, covering not only environmental protection but also renewable energy, energy efficiency, cogeneration, carbon capture and storage, and other matters.

[44] Kahles, Markus, and Pause, Fabian, "The Influence of European State Aid Law on the Design of Support Schemes for Electricity from Renewable Energy Sources in Germany and Other Member States" in *The European Dimension of Germany's Energy Transition – Opportunities and Conflicts*, ed. Erik Gawel et al. (Springer, 2019) pp.67-82.

[45] The position of state subsidies in EU law, regulatory requirements, and an outline of the energy and environment guidelines are based on Central Research Institute of Electric Power Industry, Survey Report on "Trends and Challenges Regarding Renewable Energy Diffusion Policy and Renewables' Integration into Power Market in Europe" (「欧州における再生可能エネルギー普及政策と電力市場統合に関する動向と課題」調査報告) : Y15022, May 2016.

[46] Approaches on state subsidies for renewable energy support measures are given by EC (2014/C 200/01) 3.3, Aid to energy from renewable sources (107).

[47] However, FIT system support is admitted for less-than-500-kW power generation facilities or demonstration projects, excluding wind power generation facilities subject to 3 MW or 3-unit capacity. See EC (2014/C 200/01), 3.3 Aid to energy from renewable sources (125). For a conceptual diagram of the FIP system, see "Comparative conceptual diagrams of renewable energy support measures" at the end of this paper.

1-4-2. Enactment of EEG2014 renewable energy expansion law

In response to the EU guidelines and FIT surcharge growth, Germany established the EEG2014 renewable energy expansion law to amend the EEG2012 in August 2014 substantially[48].

The EEG2014 called for raising renewables' share of total electricity consumption continuously and cost-efficiently to 80% or more by 2050, setting the target share at 40-45% for 2025 and 55-60% for 2035. Under these targets, the EEG2014 cited the integration of renewable electricity into the market and the subsequent promotion of renewable electricity's direct sales in the power market as principles. It attracted attention as a sign that Germany transitioned from a traditional renewable energy policy focusing on FIT compensation provisions to a new one pursuing market transactions in renewable electricity.

Specifically, the EEG2014 subjected 500-kW or smaller renewable power generation facilities launched by December 31, 2015, and 100-kW or smaller ones found on or after January 1, 2016, to FIT compensation and required other facilities to sell electricity in the market directly. It also provided that renewable electricity generators engaging in direct electricity sales in the market would be responsible for balancing supply with demand.

Renewable electricity generators were authorized to claim a market premium from grid operators regarding electricity that was subjected to direct sales in the market, supplied to the market, and purchased by third parties. Market premium amounts were planned to be calculated every month, with a standard amount (euro cent/kWh) set for each renewable energy source for computing market premium and compensation amounts. The standard amount was set to gradually fall in line with a diffusion target for each renewable energy source[49].

The EEG2014 also came up with a policy of transitioning to a system for determining subsidies through auctions by 2017. In response to drops in solar PV and wind power generation costs, it recognized that solar PV and wind power could compete with other non-renewable power sources even without policy support and that competitive auctions should allow compensation amounts to decline. The EEG2014 sought to accumulate experiences in which auctions are used for determining compensation amounts for rooftop solar PV power generation projects before auctions are introduced on a full-fledged basis.

In addition to the above-mentioned provisions for integrating renewable electricity into the market and direct sales of renewable electricity in the power market, the EEG2014 included revised provisions for cutting or eliminating the FIT surcharge on large-lot electricity users and private consumers of renewable electricity to hold down surcharge growth[50]. These provisions expanded the scope of those responsible for paying the surcharge to reduce the consumer's surcharge burden.

In this way, the EEG2014 attempted to transition from the traditional FIT system to the Feed-in Premium system to promote direct sales of renewable electricity in the power market and provide the market premium. It also called for introducing auctions, indicating a path to determining compensation levels based on competition principles. The EEG2014 thus demonstrated that Germany transitioned from a protective policy for renewables to a new policy of promoting the integration of renewable electricity into the market under a competitive environment. It represents the base for Germany's current renewable energy promotion policy.

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[48] For Details of the EEG2014, see F. Watanabe, "Enactment of Germany's 2014 Renewable Energy Sources Law"（渡辺「ドイツにおける 2014 年再生可能エネルギー法の制定」）pp.81-109

[49] The standard amount was set to fall every year for hydro, geothermal, and offshore wind facilities, every quarter for biomass and onshore wind facilities, and every month for solar PV facilities.

[50] The 219 sectors subject to surcharge burden cuts were selected as those that intensively consume electricity and could lose international competitiveness by paying the ordinary surcharge. They are listed in the fourth supplementary provision of the EEG2014. The list corresponds to the Guidelines on State Aid for Environmental Protection and Energy. (F. Watanabe, "Enactment of Germany's 2014 Renewable Energy Sources Law"（渡辺「ドイツにおける 2014 年再生可能エネルギー法の制定」）)

1-5. Auction system introduction (EEG2017)

In line with the EEG2014 policy of testing auctions for onshore solar PV power generation projects, test auctions were conducted in 2015 for 500 MW in capacity, in 2016 for 400 MW, and in 2017 for 300 MW. Successful bids slipped below compensation amounts and average successful bid prices dropped gradually. Based on such results, Germany enacted the EEG2017 in January 2017 to amend the EEG2014 and fully introduce the auction system.

The EEG2017 set the target for renewables' share of total electricity consumption at 40-45% for 2025 and 80% or more for 2050[51], which were the same as EEG2014. It also specified annual new capacity installation targets for wind, solar PV, and biomass power generation. It then provided for the introduction of the auction system and renewable energy diffusion, keeping step with grid development.

Regarding how to design the auction system, the EEG2017 called for giving all actors fair opportunities, conducting highly competitive auctions to minimize renewable energy support costs, and setting auction capacity sizes to prevent installed capacity sizes from exceeding or slipping below the EEG2017 targets[52].

Under these policies, new facilities of wind, solar PV, and biomass power generation were subjected to auctions. However, less-than-750-kW wind and solar PV facilities and less-than-150-kW biomass facilities were excluded from auctions with consideration given to administrative costs and small power generators. Other renewable energy facilities, including hydro and geothermal plants, were also excluded from auctions and left subject to support under the FIT or FIP system. Furthermore, under transitional measures, onshore and offshore wind facilities meeting some requirements were excluded from auctions[53]. The auction system is being phased into cost-efficiently diffuse renewable power generation through such trials.

1-6. Analysis of German institutional building processes

This section has reviewed how the German power sector has tried to transition to a system where renewable energy is widespread. Germany launched institutional building for renewable energy diffusion as historical German movements against nuclear power generation gained momentum on the 1986 Chernobyl nuclear plant accident and global warming started to be considered a key policy challenge. Under such a background, political parties shared the view that renewable energy power generation should be promoted to replace nuclear and coal-fired power generation, leading to the enactment of the Federal Electricity Feed Law (StrEG) in 1991.

Germany has promoted renewable energy diffusion on a full scale since the Renewable Energy Sources Law (EEG) was enacted in 2000 to introduce the FIT system and institutionalize a framework for stepping up investment in renewable energy power generation. Under the FIT system, the German government has taken fine-tuned legislative actions in line with renewable energy technology advancement and diffusion, adjusting feed-in tariffs and their gradual reduction rates by renewable energy source, capacity bracket, and year of starting operation.

Since the 2011 Fukushima Daiichi nuclear power plant accident, Germany has accelerated renewable energy diffusion and led the country to reaffirm its nuclear phaseout policy. It has recognized the need to reduce the FIT surcharge and improve renewable electricity's market competitiveness to further diffuse renewable energy, seeking to integrate renewable electricity into the power market. The EEG2012 introduced an option to directly sell renewable electricity to the market and receive a market premium.

A new administration that came into being in 2013 changed the agency in charge of renewable energy and substantially amended the renewable energy law to institutionalize renewable electricity integration into the power market explicitly.

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51 F. Watanabe, "German 2017 Renewable Energy Sources Law," *Foreign Legislation*, January 2017, Research and Legislative Reference Bureau, National Diet Library（渡辺富久子「【ドイツ】2017 年再生可能エネルギー法」『外国の立法』(2017.1)、国立国会図書館調査及び立法考査局）

52 Tokio Marine & Nichido Risk Consulting Co. "FY2018 Research Report on Projects Contributing to Rationalizing Energy Use in Emerging Market Economies (Survey on Overseas Renewable Energy Trends) (for release)" March 2019, p. 112（東京海上日動リスクコンサルティング「平成 30 年度新興国におけるエネルギー使用合理化等に資する事業（海外における再生可能エネルギー等動向調査）調査報告書（公表用）」2019 年 3 月、p.112）

53 *Ibid*., p.95. Conditions for participation in auctions based on the EEG2017 are detailed in this research report.

During this period, the European Commission issued the Guidelines on State Aid for Environmental Protection and Energy 2014-2020, indicating that renewable electricity should be competitive in the grid and that the existing policy of relieving renewable electricity generators of the responsibility for balancing supply with demand should be phased out. To institutionalize such approaches into the domestic policy, the German government came up with integrating renewable electricity into the market and the relevant promotion of direct sales of renewable electricity to the power market. It indicated a turning point from the renewable energy protection policy under the FIT system to a new policy of developing a competitive environment for renewable electricity. Then, Germany fully introduced the FIP system.

As mentioned above, Germany has persistently implemented fine-tuned policies to diffuse renewable electricity in the power sector amid the tremendous energy transition challenge. Germany has frequently amended the renewable energy law during the policy process, specifying long-term renewable energy diffusion targets and conditions for support to each renewable energy source. This resulted in providing business operators and investors with a framework to invest in renewable energy projects confidently. By establishing such a framework from the beginning of institutional building and continuing to make adjustments in response to emerging challenges, Germany has dramatically diffused renewable energy.

Although green political forces have historically been influential in Germany, not only green parties but also multi-party alliances and coalitions have promoted renewable energy policies during the past policy process. Domestic initiatives have been combined with domestic responses to EU directives to lead Germany's renewable energy policies to transition to a new phase. Backed by domestic and external initiatives, Germany is achieving a transition to a society in which renewable energy is widespread.

2. U.K. institutional building process for renewable energy expansion

How has the United Kingdom attempted to transition to a society where renewable energy has been promoted after historically depending heavily on fossil fuels along with Germany? This section reviews the United Kingdom's power supply and demand trends, tracks its renewable energy expansion policy process from institutional building launched in the 1990s, and analyzes its policies.

2-1. U.K. power supply and demand trends

The United Kingdom has been rich with coal resources and has promoted oil and natural gas development in the North Sea since the 1960s, depending on fossil fuels for most of its energy supply. In the 1990s, however, the country rapidly expanded gas-fired power generation by taking advantage of the North Sea oil field amid power industry deregulation while keeping away from additional investment in coal-fired power generation[54]. Oil and natural gas production peaked in the North Sea in the second half of the 1990s and saw a gradual production decline due to the depletion of resources later. In 2004, the United Kingdom became a net energy importer[55].

As energy choices became complicated in this way, the United Kingdom began to give policy priority to climate change. Coal-fired power plants operating during the 2000s in the country were inefficient subcritical ones that started operation in the 1960s or 1970s. Many of them failed to meet EU environmental standards regarding air pollutants[56]. Feeling a sense of crisis about such a situation, the U.K. government formulated the Climate Change Act in 2008, setting a target of cutting greenhouse gas emissions by 80% from 1990 until 2050. While promoting institutional building for climate change countermeasures, the government positioned nuclear power generation, which had been viewed as one of the promising

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54 Y. Ito "EU Decarbonization Policy Background and Realities," IEEJ, August 2017
(https://eneken.ieej.or.jp/data/7504.pdf)
(伊藤葉子「EU における"脱炭素"の政策的背景と実情」日本エネルギー経済研究所、2017 年 8 月)

55 Federation of Electric Power Companies of Japan, "U.K. Energy Policy Trends"
(https://www.fepc.or.jp/library/kaigai/kaigai_jigyo/britain/detail/1231567_4785.html)
(電気事業連合会、「イギリスのエネルギー政策動向」)

56 Y. Ito "EU Decarbonization Policy Background and Realities," IEEJ, August 2017
(伊藤葉子「EU における"脱炭素"の政策的背景と実情」2017 年)

energy options, as a major energy source contributing to both stable energy supply and climate change countermeasures[57]. It came up with a policy of promoting nuclear power generation in January 2008. Under the policy, nuclear power plants have been maintained as an electricity source covering about 20% of total power generation in the United Kingdom (Fig. 5).

The U.K. power mix amid such trends indicates that coal's share of total power generation has remarkably changed. The coal share stood at as high as 65% in 1990, peaked at 65.8% in 1991, and plunged to 34.8% in 2001. It roughly remained above 30% until 2014 but has rapidly fallen since the then U.K. energy and climate change minister in November 2015 vowed to close all coal-fired power plants by 2025[58]. In 2019, the coal share stood at only 2.4%[59]. The United Kingdom was the first major European country to clarify a target for closing all coal-fired power plants, followed by France and Portugal in 2016, by the Netherlands and Italy in 2017, and by Germany in 2020. The U.K. government has indicated the coal phaseout policy and measures to give priority to natural gas-fired power plants, enhance offshore wind power generation, and promote a transition to a smart energy system[60].

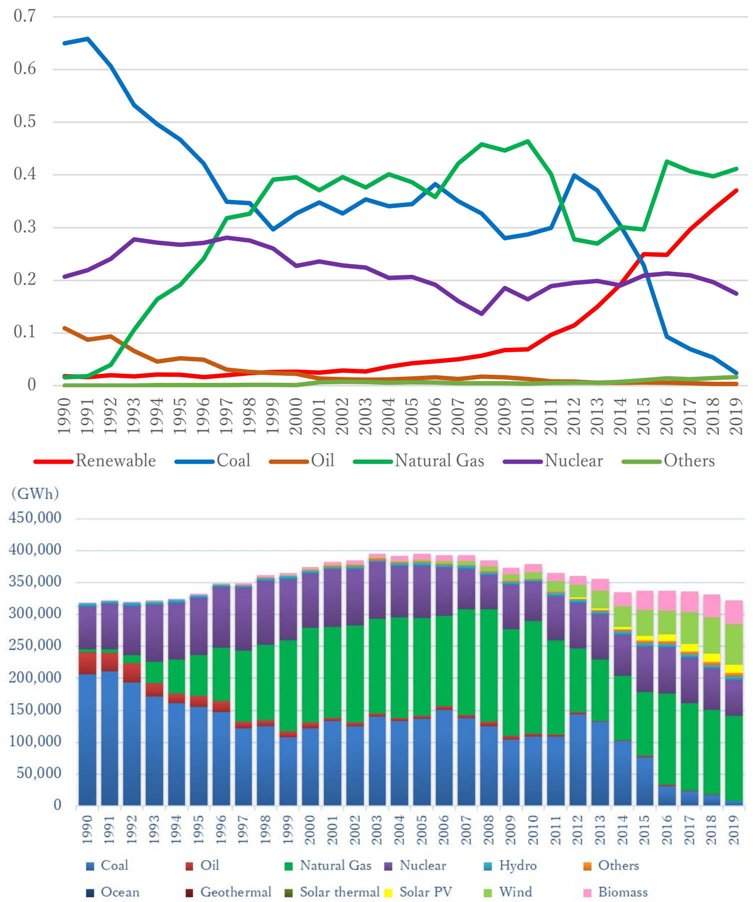

Fig. 5 (Upper) Each energy source's share of total power generation (%), (Lower) the U.K. power mix trends (GWh)

Source: Prepared from IEA, "Energy Statistics and Balance 2020"

[57] UK Department of Trade and Industry, "The Energy Challenge: Energy Review Report 2006," July 2006.
[58] GOV.UK, Press release published November 18, 2015, "New Direction for UK energy policy" (https://www/gov.uk/government/news/new-direction-for-uk-energy-policy)
[59] IEA, "World Energy Statistics and Balances 2020" According to the IEA statistics, oil accounted for 0.3% of the U.K. power mix in 2019, natural gas for 41.1%, nuclear for 17.5%, renewable energy for 37.1%, and others for 1.6%.
[60] GOV.UK, Press release published November 18, 2015, "New Direction for UK energy policy"

Renewables' share of total U.K. power generation expanded from only 2.7% in 2000 to 37.1% in 2019 (Fig. 6). Renewable power generation grew about 12-fold from 9,970 TWh to 119,334 TWh. Notably, wind power generation posted a remarkable increase, boosting its share of renewable power generation from 0.15% in 1990 to 9.5% in 2000 and 53.7% in 2019. The biomass share increased from 10.2% in 1990 to 30.6% in 2019 and the solar PV share from almost zero to 10.6%.

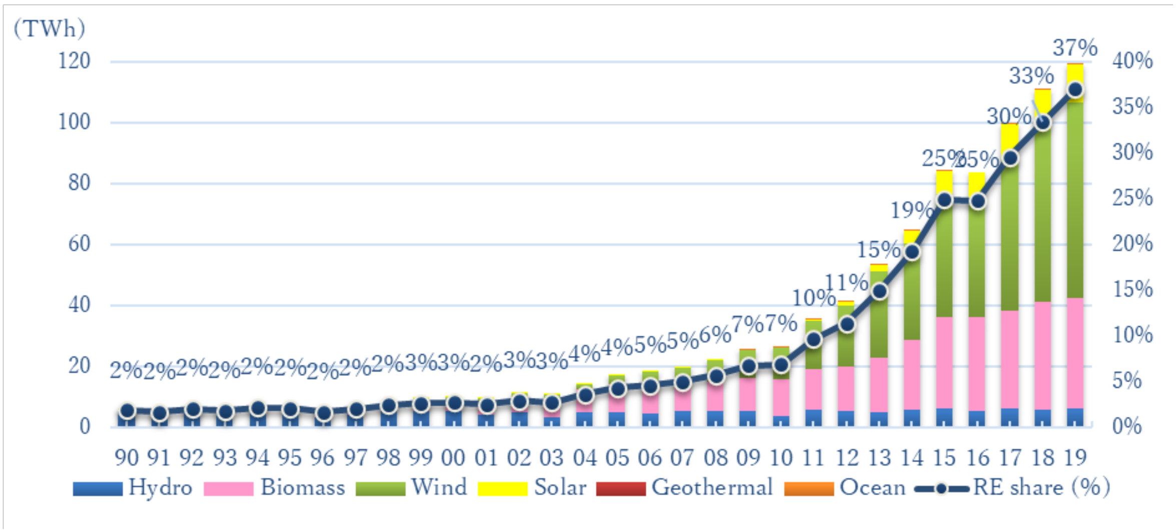

Fig. 6 Renewables' share of total U.K. power generation (1990-2019)

Source: Prepared from IEA, "Energy Statistics and Balance 2020"

Based on the above power supply and demand trends, the following analyzes the United Kingdom's policy process to expand renewable energy.

2-2. Renewables Obligation system introduction

2-2-1. Launching institutional building for renewable energy diffusion

The United Kingdom privatized its power sector under the Electricity Act 1989 enacted under the Thatcher administration, completing the power sector's deregulation ahead of any other country in the world. It had driven the global power system deregulation since 1990, giving priority to the realization of a deregulated power market. As U.K. policy priority for climate change increased; however, the country revised its policy and began to think that it should build institutions to provide incentives for investment in renewable energy projects instead of leaving market forces to work fully. It was also required to achieve renewable energy diffusion targets under the EU directive to promote electricity produced from renewable energy sources in the internal electricity market (EU2001 renewable energy directive) formulated by the European Council in 2001.

Then, the United Kingdom launched institutional building for renewable energy diffusion nearly 10 years later than Germany. The Utility Act 2000 was put into force in 2000. It introduced the Renewables Obligation (RO) system[61] that placed an obligation on power generators to source some proportion of their electricity from renewable sources. In April 2002, the Renewables Obligation Order [Statutory Instrument 2002 No.914] was issued to clarify and fully implement the system.

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[61] The Renewables Obligation was introduced to replace the Non-fossil Fuel Obligations (NFFO) provided in Article 32 of the Electricity Act 1989. The NFFO system obliged public electricity suppliers to purchase electricity from renewable power generators and sell renewable electricity at fixed prices under 15-year contracts (Ofgem (Office of Gas and Electricity Markets), "The Renewables Obligation: Ofgem's first annual report," February 2004, p.8). This system was initially designed to diffuse renewables. Later, however, it was interpreted as a financial system to maintain nuclear power generation (H. Nagayama, "U.K. Renewable Energy Policy," p.110; K. Ueda & K. Yamaka, "International Comparison of Renewable Energy Policies," Kyoto University Press, 2017) （長山浩章「イギリスの再生可能エネルギー政策」p.110、植田和弘、山家公雄編『再生可能エネルギー政策の国際比較』京都大学学術出版社、2017 年）

The "Energy White Paper: Our energy future -- Creating a low carbon economy" published in February 2003 set out the following four targets[62]. First, carbon dioxide emissions should be cut by 60% from 1990 by 2050 to contribute to climate change countermeasures. Second, energy supply stability should be maintained in preparation for the depletion of domestic resources. Third, domestic and overseas competitive markets should be promoted to sustain economic growth and improve productivity. Fourth, sufficient heating should be secured for all households at fair prices.

Renewables were expected to play a vital role in accomplishing these targets. For example, the white paper noted that renewables should cover 30-40% of total power generation by 2050 to achieve the first target[63].

In January 2000, the U.K. government announced a target of increasing renewables' share of total power generation to 10% by 2010. This target was imposed on the United Kingdom under the EU2001 renewable energy directive[64]. Then, the United Kingdom featured a lower renewable energy diffusion rate than other major European countries. According to the white paper, renewables, excluding large-capacity hydro and waste-fired power plants, accounted for only 1.3% of total power generation in the United Kingdom in 2000, against 16.7% in Denmark, 4% in the Netherlands, 3.2% in Germany, and 3.4% in Spain[65]. The United Kingdom was required to install about 10,000 MW in new renewable power generation capacity by 2010 to accomplish the renewable share target for the year[66]. Then, the RO system was introduced to accelerate renewable energy diffusion.

2-2-2. RO system

The RO system obliges electricity suppliers to source a proportion of electricity sales from renewable sources at prices that would not be too burdensome for consumers[67]. Electricity suppliers receive annual RO orders, or renewable electricity sales quotas, from the government at least six months before every business year starts[68]. Accredited renewable electricity generators report power generation volume to the Office of Gas and Electricity Markets (Ofgem) every month and acquire relevant Renewables Obligation Certificates (ROCs). Ofgem administers the RO system by issuing ROCs and accrediting generating stations capable of generating electricity from eligible renewable energy sources, monitoring compliance with RO orders' requirements, and calculating and receiving the buy-out price[69].

Electricity suppliers are required to purchase ROCs amounting to renewable electricity sales quotas and pass ROC purchasing costs on to electricity charges. In this way, renewable electricity generators can sell electricity at higher prices than wholesale electricity prices by selling ROCs issued by Ofgem to electricity suppliers. Renewable electricity generators have an incentive to receive a premium on wholesale electricity prices. Electricity suppliers can demonstrate their compliance with their sales obligations by presenting ROCs to Ofgem[70].

If electricity suppliers fail to procure sufficient ROCs, they are deemed to have met their obligations by paying about 33 pounds per 1,000 kWh shortfall as the buy-out price to Ofgem. Buy-out price payments are used for Ofgem operation. Surplus payments are paid back to electricity suppliers according to how many ROCs they have presented[71].

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[62] U.K. Department of Trade and Industry, "Energy White Paper: Our energy future -- Creating a low carbon economy" CM5761, February 24, 2003.
[63] *Ibid*., p.44.
[64] Country-by-country targets were specified in Directive (2001/77/EC), *op.cit*., Annex. The target for Germany was 12.5% as mentioned above.
[65] Department of Trade and Industry, "Energy White Paper: Our energy future -- Creating a low carbon economy", *op.cit*., p.45.
[66] *Ibid*.
[67] New & Renewable Energy Group, New Energies & International Cooperation Unit, Institute of Energy Economics, Japan, "U.K.: Accelerating CfD introduction to hold down renewable subsidy growth" January 2016（日本エネルギー経済研究所 新エネルギー・国際協力支援ユニット 新エネルギーグループ「英国：CFD 制度の導入時期を早め、再エネ補助金増大の抑制を図る」2016 年 1 月（https://eneken.ieej.or.jp/data/6528.pdf））
[68] The RO system is described based on the Policy Paper by the U.K. Department of Energy & Climate Change; the Annual Report by Ofgem; and M. Yamaguchi "U.K. Power Market Reform and Implications for Japan's Renewable Energy Policy" July 28, 2014, a study published at the Society for Environmental Economics and Policy Studies in 2014 （山口光恒「イギリスの電力市場改革と日本の再エネ政策への示唆」2014 年 7 月 28 日、2014 年環境経済政策学会発表論文）
[69] Ofgem, "Guidance for generators that receive or would like to receive support under the Renewables Obligation (RO) system," April 2019.
[70] Department of Energy & Climate Change (DECC), "Policy Paper: 2010 to 2015 government policy: low carbon technologies" updated May 8, 2015.
[71] Ofgem website (https://www.ofgem.gov.uk/environmental-programmes/ro/about-ro)

Renewables subject to the RO system are solar PV, wind, tidal energy, geothermal energy, biomass, hydro, waste, landfill gas, and sewerage gas. When the RO system was initiated, a ROC per 1 MWh was issued for all renewables. Under a statutory instrument implemented in April 2009, more ROCs were issued for priority renewables than for others under banding.

In 2009, for example, the number of ROCs per MWh was raised to two for offshore wind, solar PV, tidal, and wave energy power generators, while being unchanged at one for onshore wind and fossil/biomass mix generators[72]. From 2013 to 2015, the number was left unchanged at two for offshore wind generators but cut to 0.9 for onshore wind generators and 1.7 for solar PV plants[73]. In this way, priority was given to technologies under development or critical areas, with aid levels diversified.

Under the RO system, renewable power generation increased year by year. Notably, wind power generation posted remarkable growth. From 534 MW in 2002 when the RO system was launched, cumulative installed wind power generation capacity soared to 933 MW in 2004 and 5,421 MW in 2010, increasing more than 10-fold under the RO system[74] (Fig. 7). Remarkably, cumulative installed offshore wind capacity expanded dramatically from 4 MW in 2002 to 1,342 MW in 2010[75].

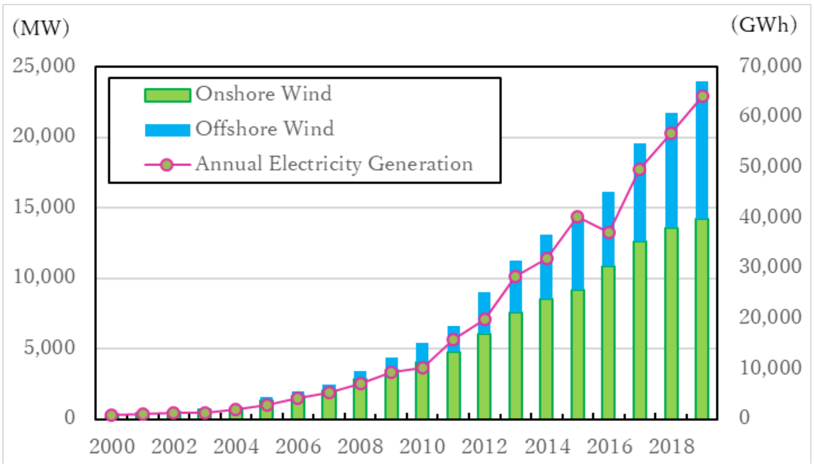

Fig. 7 the U.K. installed wind power generation capacity trends
(Left scale for cumulative installed capacity and the right scale for annual power generation)

Sources: Prepared from IRENA, "Renewable Energy Statistics 2020," and IEA, "World Energy Statistics and Balances 2020"

2-2-3. Phasing out the RO system

In 2011, renewable electricity's share of total electricity supply in the United Kingdom reached 10% for the first time, with renewable power generation totaling 35 TWh. This meant that the country achieved a target announced in January 2000, one year behind schedule. In this way, the RO system to take advantage of RO orders for promoting renewables brought about some achievement in the United Kingdom.

Given that ROCs tradable under the RO system were left to be priced through negotiations between electricity suppliers and renewable power generators and according to the changing supply-demand balance, it was difficult for renewable power generators to make future business plans. Particularly, RO system procedures were cumbersome for small-capacity power generators, preventing small-capacity facilities from spreading. Furthermore, the United Kingdom lacked fine-tuned support measures for each renewable technology, as seen in Germany[76]. Due to these problems, the U.K. government

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[72] DECC, "UK Renewable Energy Roadmap Update 2013," November 2013, p.30.
[73] *Ibid.*
[74] Data from IRENA, "Renewable Energy Statistics 2020"
[75] *Ibid.*
[76] M. Yamaguchi "U.K. Power Market Reform and Implications for Japan's Renewable Energy Policy" July 28, 2014, a study published at the Society for Environmental Economics and Policy Studies in 2014 (山口光恒「イギリスの電力市場改革と日本の再エネ政策への示唆」) p.13

decided to exclude new renewable power generation facilities built on or after March 31, 2017, from the RO system while leaving the existing facilities subjected to the system until 2037[77].

While the problems forced the RO system to be phased out, the United Kingdom was required to introduce additional measures to increase renewables' share of final energy consumption from less than 2% in 2009 to 15% by 2020 under the EU2009 renewable energy directive[78]. Then, it introduced the FIT system as a new renewable energy promotion measure.

2-3. FIT system introduction

2-3-1. Discussions towards FIT system introduction

Before introducing the Feed-in Tariff (FIT) system, the then Labor administration created the Renewables Advisory Board and implemented a consultation on a renewable energy strategy to verify the direction of renewable energy diffusion. In June 2008, the Renewables Advisory Board published a policy recommendation paper titled "2020 Vision – How the U.K. can meet its target of 15% renewable energy," indicating that renewable energy's share of final energy consumption would be limited to around 6% until 2020 in a reference scenario, although the Renewables Obligation (RO) system contributed to diffusing renewables[79]. The paper recommended that the United Kingdom place renewable energy diffusion initiatives at the heart of its energy policy and promote innovative economic, policy, and social initiatives as a drive to achieve the target of 15% renewable energy. It then called for introducing a financial aid measure to allow investors to become confident that the renewable energy market would support new renewable energy investment. A report titled "Consultation on the Renewable Energy Strategy," released in June 2008 after such consultation, pointed out the significance of grid network enhancement and new renewable energy technology development and the need for positive support for small-scale renewable power generators[80].

2-3-2. Launching the FIT system

Based on such discussions, the United Kingdom decided to introduce the FIT system under the Energy Act 2008 in November 2008. The system was put into operation under an April 2010 statutory instrument (No. 678). Under the title "Feed-in tariffs for small-scale generation of electricity," Section 41, Chapter 32 of the Energy Act 2008 empowers the Secretary of State (for energy and climate change) to establish and operate a system of financial incentives to encourage a small-scale low-carbon generation of electricity[81]. Subjected to the FIT system under the Energy Act from April 2010 were 50 kW or smaller generators powered by solar PV, wind, anaerobic digestion (A.D.) gas, hydro, and micro combined heat and power (CHP), or 50 kW to 5 M.W. generators launched on or after July 15, 2019[82].

The U.K. FIT system is designed for licensed electricity suppliers to purchase electricity from small-scale renewable electricity generators at fixed tariffs. Under the system, renewable electricity generators receive generation tariff payments for every kWh generated and export tariff payments for surplus electricity sold[83]. This means that renewable electricity generators can receive payments at fixed tariffs according to total power generation even if they consume electricity on their own without selling it to the grid and can sell surplus electricity at guaranteed tariffs. Small-scale private electricity generators can receive generation and export tariffs and benefit from bill savings by consuming electricity they generate to cut electricity purchases[84].

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[77] DECC, "Digest United Kingdom Energy Statistics 2019," Chapter 6 Renewable sources of energy, p.125.
[78] Directive (2009/28/EC) *op.cit.*
[79] Renewables Advisory Board, "2020 VISION-How the UK can meet its target of 15% renewable energy," June 2008, p.3.
[80] Regarding the consultation on a renewable energy strategy, I referred to a relevant document released in June 2008 by the Department of Energy and Climate Change under the then Labor administration. (https://www.gov.uk/government/consultations/progressing-our-renewable-energy-strategy)
[81] The Energy Act 2008 provides for renewable energy diffusion and carbon capture and storage methods and how to decommission nuclear, renewable energy, and other power plants. Regarding details of the act, see U.K. government's legislation information site (http://www.legislation.gov.uk/ukpga/2008/32/part/2.)
[82] Ofgem website (https://www.ofgem.gov.uk/environmental-programmes/fit/about-fit-system/) Generators with 50 kW or smaller capacity were excluded from the RO system and covered by the FIT system. Generators with capacity between 50 kW and 5 MW were allowed to choose to remain subject to the RO system or transition to the FIT system. Generators with capacity of more than 5 MW remained subject to the RO system.
[83] DECC, "Digest United Kingdom Energy Statistics 2019", *op.cit.*, p.125.
[84] Electricity generators are required to install electricity meters for receiving support for their own consumption in principle and pay for the installation.

Generation tariffs are finely fixed by capacity and year of starting operation for each renewable energy technology[85]. Generation tariffs are indexed to the Retail Price Index and revised annually in principle[86]. Tariffs are fixed at levels expected to achieve a return of 5-8% on the investment for facilities in desirable locations[87]. Renewable electricity generators can choose to sell electricity at guaranteed export tariffs or market prices. As well as generation tariffs, export tariffs are indexed to the Retail Price Index and adjusted annually[88].

2-3-3. Adjustments under the FIT system

When the FIT system was introduced, the government indicated a policy of keeping generation tariffs unchanged until 2013 before revising them every five years. In less than one year after the introduction, however, it came up with a plan to revise them[89]. This was because far-more-than-expected facilities, especially solar PV generators, were registered for the FIT system, with their power generation exceeding predicted levels. Furthermore, large-scale solar PV power generation with 0.25-5.0 MW generators increased faster than predicted[90]. The rapid increase in large-scale solar PV generation prompted the FIT budget to be spent fast and threatened to exert pressure on budget spending on other renewables[91]. The results did not necessarily meet the FIT system's objective of diffusing small-scale renewable electricity generation. In August 2011, the government substantially revised generation tariffs for 50 kW or larger solar PV generators and biomass (A.D.) facilities to improve cost efficiency[92]. Even since the revision, however, generation tariffs and capacity brackets have been revised several times per year.

In this way, solar PV, which had failed to diffuse under the RO system, rapidly spread after the FIT system introduction thanks to prompt adjustments responding to progress in the diffusion under the system (Fig. 8). Cumulative installed solar PV capacity was limited to 4 MW in 2002 when the RO system was introduced, to 8 MW in 2004, and 95 MW in 2010. After the FIT system introduction, however, such capacity expanded more than 10-fold during 2011[93] and continued robust expansion later.

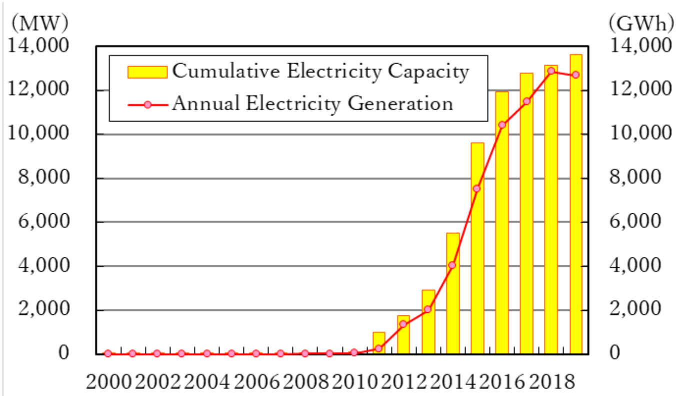

Fig. 8 the U.K. solar PV capacity trends
(left scale for cumulative installed capacity, right scale for annual power generation)

Sources: Prepared from IRENA, "Renewable Energy Statistics 2020" and IEA, "World Energy Statistics and Balances 2020"

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[85] Details of tariffs from April 2010 are available on Ofgem's website (https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates/).
[86] *Ibid.* Tariffs from April 1, 2020, to March 31, 2021, were revised on March 31, 2020.
[87] DECC, "Feed in Tariffs: Government's Response to the Summer 2009 Consultation," February 2010, p.6.
[88] Details of tariffs are available on Ofgem's website (https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates/).
[89] DECC, "Feed-in Tariffs System: Summary of Responses to the Fast-Track Consultation and Government Response," June 9, 2011.
[90] *Ibid.*, p.5.
[91] *Ibid.*
[92] *Ibid.*, p.6. The generation tariff was substantially lowered to 19.0 pounds/kWh for 50-150 kW facilities, 15.0 pounds/kWh for 150-250 kW facilities, and 8.5 pounds/kWh for 0.25-5.0 MW facilities and ground installed ones.
[93] Cumulative installed capacity data are from IRENA, "Renewable Energy Statistics 2020."

2-4. FIT-CfD system introduction

2-4-1. Electricity market reform

As mentioned above, the FIT system launched in 2010 accelerated renewable energy diffusion in the United Kingdom by promoting solar PV generation that had failed to grow under the RO system. However, the U.K. government recognized that more innovative measures would be required to further push climate change countermeasures as a policy priority and achieve a target of increasing renewables' share of final energy consumption to 15% by 2020 under the EU renewable energy directive.

In July 2011, Chris Huhne, the then secretary of state for energy and climate change, presented the Parliament with a policy paper titled "Planning our electric future: A white paper for secure, affordable and low-carbon electricity[94]." According to the paper, 20 GW or a quarter of total installed power generation capacity was planned to be retired due to aging and other problems within 10 years, requiring the country to urgently take measures to secure a stable power supply[95]. Then, there was a target of cutting carbon dioxide emissions by 80% from 1990 until 2050. It was recognized that the power sector would have to dramatically promote decarbonization by 2030[96]. Furthermore, total U.K. power demand was expected to double by 2050, with prices rising, as the transport and heat sectors are electrified further.

Following consultation in December 2010, the policy paper came up with an electricity market reform to address the situation. The U.K. government recognized that new low-carbon generators often had to overcome relatively high barriers to market entry and that market illiquidity made it more difficult for a low-carbon generation to compete with fossil fuels and impeded market access[97]. It was estimated that up to 110 billion pounds would have to be invested in electricity generation and transmission by 2020 to simultaneously achieve the low-carbon economy and stable electricity supply objectives[98]. The government acknowledged that the electricity market would have to be reformed to attract the necessary investment and cost-effectively achieve the objectives.

Under the recognition, the primary objectives of the electricity market reform were (1) to ensure the future security of electricity supply, (2) to drive the decarbonization of electricity generation, and (3) to minimize costs to the consumer. The government set out four measures to realize these objectives[99]. The first measure called for "long-term contracts for both low-carbon energy and capacity, the second for institutional arrangements to support this contracting approach, the third for continued grandfathering, supporting the principle of no retrospective change to low-carbon policy incentives, within a clear and rational planning cycle, and the fourth for ensuring a liquid market that allows existing energy companies and new entrants to compete on fair terms". These measures were designed to form a market environment to secure long-term business predictability and attract proactive investment in low-carbon projects.

2-4-2. Discussions on FIP and FIT-CfD systems

For the first measure for the electricity market reform, the policy paper proposed the Feed-in Tariffs with Contracts for Difference (FIT-CfD) system. The system was one of the key issues in the December 2010 consultation. At issue was whether the FIT-CfD system or the FIP system should be introduced[100]. As the FIP system was similar to the RO system in that electricity generators would receive some payments in addition to electricity sales income from the electricity wholesale market, renewable electricity generators supported the FIP system that they saw as understandable for investors and suitable for smooth implementation. Meanwhile, the FIT-CfD system was widely viewed as a framework to cost-efficiently promote the low-carbon generation, despite concern that the system would be too complex to implement.

After hearing such opinions from various stakeholders, the U.K. government concluded that the FIT-CfD system was

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[94] DECC, "Planning our electric future: a white paper for secure, affordable and low-carbon electricity," July 2011.
[95] *Ibid.* pp.5-6.
[96] *Ibid.*
[97] *Ibid.*
[98] *Ibid.*
[99] For the four measures, see *Ibid*., p.7.
[100] For discussions on the CfD and FIP systems in the consultation, see *Ibid*, pp.17-22. For a conceptual diagram of the FIT-CfD system, see "Comparative conceptual diagrams of renewable energy support measures" at the end of this paper.

more desirable. The FIT-CfD system was viewed as more suitable for minimizing electricity price fluctuation risks over the long term and promoting investment in low-carbon electricity sources. The system was packaged with (1) the capacity market, (2) the carbon price floor, and (3) the emissions performance standard to cost-effectively achieve a low-carbon society and stable electricity supply. Renewable energy diffusion for a low-carbon economy would naturally increase intermittent power sources vulnerable to weather changes, threatening to destabilize the power supply. To address this problem, the U.K. government combined renewable energy diffusion measures with the effective utilization of highly adjustable fossil-fired power generation. Simultaneously, as the capacity to cover supply shortages was secured through the capacity market, the emission performance standard per installed capacity and the carbon price floor was set for new fossil-fired power plants to promote low-carbon electricity.

2-4-3. Parliamentary discussions on the FIT-CfD system

Edward Davey, appointed as the new secretary of state for energy and climate change in February 2012, announced a draft energy bill[101] taking over the institutional design in May 2012. The draft bill was considered by a group of lawmakers from the House of Commons Energy and Climate Change Committee and the House of Lords.

Regarding the FIT-CfD system, one of the key issues was what kind of scheme should be used to execute payments between electricity generators and suppliers to contribute to forming an investment environment that would be stable over the long term[102]. The Department of Energy and Climate Change (DECC) proposed a scheme called the "Multiparty Payment" model. The model, inspired by the existing imbalance system, called for assigning Elexon, a National Grid subsidiary that served as a Balancing and Settlement Code Company (BSCCo) and accumulated experiences with calculating and settling imbalance costs, to undertake FIT-CfD payment services[103]. The model assumed that Elexon would mediate interactive payments under the individual contracts for the difference between electricity generators and suppliers. DECC thought that combining regular payment to electricity generators with suppliers' establishment of collateral to hold down default risks would be effective for minimizing the credit risk, or the risk that contractors could fail to collect credits due to their trading partners' financial deterioration. It is believed that Elexon, well versed in complex computation and settlement services, should be used for realizing the model.

The House of Commons Energy and Climate Change Committee criticized that the DECC-proposed Multiparty Payment model would hold electricity suppliers finally responsible for payments and fail to eliminate credit risk concerns or form a solid base for investment[104]. Then, it proposed the Alternative (central, single) Counterparty model[105].

The alternative model called for creating a credible CfD Counterparty Body that alone would conclude contracts for difference with electricity generators. Under the model, the CfD Counterparty Body would undertake electricity suppliers' payments to electricity generators and clearing services and be controlled by the government and National Grid. It attempted to develop an environment in which electricity generators would conclude contracts only with the government-backed body to eliminate credit risks taken by electricity generators and attract investment at lower finance costs.

The House of Commons Energy and Climate Change Committee strongly recommended the government to adopt the Alternative (central, single) Counterparty Model, while noting that whether the model could unduly work to the

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[101] "Draft Energy Bill," Presented to Parliament by the Secretary of State for Energy and Climate Change by Command of Her Majesty, May 2012, CM8362. When the draft bill was announced, the Department of Energy and Climate Change released a policy paper titled "Electricity market reform: policy overview," detailing the draft institutional design. (https://www.gov.uk/government/publications/electricity-market-reform-policy-overview)
[102] Minutes of deliberations on the Draft Energy Bill at the House of Commons Energy and Climate Change Committee are available at the U.K. Parliamentary Archives. For deliberations on the CfD, see "Draft Energy Bill: Pre-legislative Scrutiny- Energy and Climate Change Contents, 3. Contracts for Difference" (https://publications.parliament.uk/pa/cm201213/cmselect/cmenergy/275/27506.htm) in the Archives (https://publications.parliament.uk/pa/cm201213/cmselect/cmenergy/275/27502.htm).
[103] For the DECC-proposed model, see DECC, "Electricity market reform: policy overview, Annex B, Feed-in tariff with contracts for difference: draft proposal framework," May 2012, p.68-72.
[104] See "Draft Energy Bill: Pre-legislative Scrutiny- Energy and Climate Change Contents, 3. Contracts for Difference" in the abovementioned U.K. Parliamentary Archives.
[105] For details of the Alternative (central, single) Counterparty Model, see "Draft Energy Bill: Pre-legislative Scrutiny- Energy and Climate Change Contents, 3. Contracts for Difference" in the abovementioned U.K. Parliamentary Archives.

disadvantage of small electricity suppliers should be sufficiently considered.

2-4-4. U.K. government response to the parliamentary proposal

In response to the parliamentary proposal, DECC discussed FIT-CfD designs, including the Multiparty Payment model and the Alternative (central, single) Counterparty model, with relevant actors such as grid operators and electricity generators[106]. In November 2012, it adopted the Alternative (central, single) Counterparty model for payments and a limited company owned by the government as the CfD Counterparty Body[107]. In this way, DECC developed a FIT-CfD framework in which low-carbon electricity generators would conclude contracts for difference with the government-backed CfD Counterparty Body that would mediate payments between electricity generators and suppliers. DECC then believed that the FIT-CfD system would be operated through transparent procedures to win investors' confidence in the system and vitalize investment in low-carbon electricity generation projects[108]. To realize highly transparent procedures, it defined the roles of and relations between the government, the National Grid, and the CfD Counterparty Body[109].

2-4-5. FIT-CfD system

Under the Energy Act 2013, the U.K. government decided to implement the FIT-CfD system designed in this way. The act authorized the secretary of state for energy and climate change to make regulations about contracts for differences to be concluded between low-carbon electricity generators and the CfD Counterparty Body[110]. Based on the act, the secretary of state has set up regulations concerning the FIT-CfD system, designated the CfD Counterparty Body, and formulated CfD application and quota allocation procedures since 2014[111]. In this process, fine-tuned operational adjustments based on realities have been made, including slight revisions to CfD management procedures and a temporary suspension on CfD payments for a period in which electricity sale prices are negative.

Under the FIT-CfD system, renewable electricity generators provide National Grid with information such as project outlines, construction approvals, and operation start dates in the initial phase of their respective projects before concluding contracts for difference, under which they would be given strike prices over 15 years. Under CfD contracts, renewable electricity generators would receive the strike price's excess over a reference price[112] calculated by the average wholesale electricity price or pay the difference in case the reference price exceeds the strike price. The system allows electricity generators to hedge spot price fluctuation risks.

The Electricity Market Reform Delivery Plan released in December 2013 stated that there was a set of factors to consider in setting the strike price, covering technology-specific factors such as capital, operating, and financing costs; market conditions such as wholesale prices; and policy considerations[113]. The plan also published the strike prices by energy source and by operation start year for facilities starting operation between 2014/15 and 2018/19[114]. The first auctions regarding the strike prices took place in February 2015, resulting in successful bid prices that slipped below the government-set strike prices for solar PV, onshore wind, and offshore wind power generation facilities[115].

Auction results have been steadily accumulated, with successful bid projects registered in the CFD Register managed by

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[106] DECC, "Electricity Market Reform (EMR): Alternative Payment Model for Contract for Difference" (undated).
[107] DECC, "Electricity Market Reform: policy overview," November 2012, p.17.
[108] *Ibid*., p.21.
[109] *Ibid*., pp.21-22.
[110] Legislation.gov.uk,"Energy Act 2013" (https://www.legislation.gov.uk/ukpga/2013/32/part/2/chapter/2/enacted)
[111] There are numerous regulations including the Contract for Difference (Counterparty Designation) Order 2014 and the Contract for Difference (Definition of Eligible Generator) Order 2014. They are available in the above-cited Legislation.gov.uk archive.
[112] The reference price for intermittent renewable electricity sources is based on the wholesale electricity price for each time zone on the day-ahead market and that for baseload electricity sources on the average price set for each season on the futures market (see the above-cited Tokio Marine & Nichido Risk Consulting Co. 2019, p.181)
[113] DECC, Policy Paper "Electricity Market Reform Delivery Plan" published December 19, 2013 (https://www.gov.uk/government/publications/electricity-market-reform-delivery-plan)
[114] *Ibid.*
[115] Institute of Energy Economics, Japan, "U.K.: First auction results under the CfD system" March 2015
（日本エネルギー経済研究所「英国：CfD 制度による第一回オークション結果が発表」2015 年 3 月
(https://eneken.ieej.or.jp/data/5995.pdf)

Low Carbon Contracts Company[116]. The register specifies project names, project operator names, technology types, contract types, and current strike prices. Under the current U.K. system, auctions have been used to promote renewables at as competitive prices as possible. Information on successful bid projects disclosed timely, indicating that the system has been managed in a highly transparent manner.

2-5. Analysis of U.K. institutional building processes

This section has reviewed how the U.K. power sector has tried to transition to a system where renewable energy is widespread. As well as Germany, the United Kingdom historically featured the dominant presence of fossil fuels. However, the U.K. government prioritized climate change countermeasures alongside stable energy supply, while it became more complex for the country to make energy choices facing the decline of oil and natural gas reserves and outdated inefficient coal-fired power plants from the second half of the 1990s. In breaking away from the economy dependent on fossil fuels, the government first focused on institutional building to diffuse renewable energy. As nuclear power generation was more accepted in the United Kingdom than in Germany, the U.K. government also gave priority to nuclear power generation as one of the low-carbonization initiatives.

Characteristically, the United Kingdom has tried to take advantage of market forces to cost-efficiently diffuse renewable energy from the initial stage of institutional building. Under the RO system introduced in 2002, renewable electricity generators and electricity suppliers traded unpriced ROCs to determine prices. When it was recognized that aid levels should be diversified to support specific renewable technologies under development, the numbers of ROCs per power generation were increased for these renewable technologies, setting a priority order of renewables. Under some government guidelines, the United Kingdom has persistently maintained pricing mechanisms that exploit market forces as much as possible.

Given that the RO system made it difficult for electricity generators to make future business plans and failed to promote the spread of small-capacity renewable power sources because of cumbersome procedures for small-scale electricity generators, the U.K. government introduced the FIT system for small-scale electricity generators in 2010. Under the system, renewables steadily diffused thanks to quick adjustments responding to diffusion trends.

When it was recognized that an innovative reform would be required to achieve the target of increasing renewables' share of final energy consumption to 15% by 2020 under an EU directive, the U.K. government set out a bold electricity market reform. The government took leadership in the reform process, including consultations and a parliamentary debate over whether the FIT-CfD or FIP system should be introduced. Consequently, it decided to introduce the FIT-CfD system as a framework to cost-efficiently promote low-carbon electricity sources. Auctions have been conducted to determine strike prices under the system, indicating the U.K. attitude of taking advantage of market forces as much as possible to cost-efficiently diffuse renewables.

While giving priority to realizing a free market historically, the United Kingdom has made flexible policy adjustments in the process to diffuse renewables. Instead of depending entirely on market forces, the country has persistently pursued how best to cost-efficiently realize an environment offering long-term investment prospects to provide incentives for promoting investment in renewable energy projects. In introducing the FIT-CfD system, it considered the efficient utilization of fossil-fired power generation and adopted a policy of achieving both a low-carbon economy and stable electricity supply. Though launching institutional building for renewable energy diffusion nearly 10 years later than Germany, the United Kingdom has established a system where renewables have been diffusing under the long-held culture of taking advantage of market forces as much as possible.

Conclusion and implications for Japan

1. Implications from German and U.K. policy processes

This paper analyzed how Germany and the United Kingdom diffused renewable energy in the power sector from the

116 CFD Register (https://www.lowcarboncontracts.uk/cfds)

viewpoint of institutional building. The following discusses interesting points of their policy processes and their implications.

(1) Impacts of other primary energy sources and priority policy agenda

First, renewable energy policies have received impacts from other major energy sources such as coal and nuclear in both countries. Germany launched institutional building for diffusing renewables in place of nuclear and coal as anti-nuclear movements gained momentum on the 1986 Chernobyl nuclear power plant accident and global warming was increasingly viewed as a severe challenge. When the Fukushima Daiichi nuclear plant accident occurred in 2011, Germany quickly reversed its decision in the previous year to extend the operating life for nuclear power plants, restored an earlier plan to phase out nuclear power generation by 2022, and launched revisions to its renewable energy law to accelerate renewable energy diffusion.

Meanwhile, the United Kingdom has positioned nuclear as an energy source contributing to both stable energy supply and climate change countermeasures and maintained a nuclear promotion policy. Simultaneously, however, it has gradually reduced coal's share of power generation, becoming the first major European country to announce a target for closing all coal-fired power plants. Behind the coal phaseout policy, climate change countermeasures became a priority policy challenge for the country. Thus, it has promoted policies to diffuse renewables as an energy source to play a vital role in breaking away from the economic dependence on fossil fuels.

In this way, renewable energy policies have been positioned in relation to other primary energy sources and relevant industrial policies in each country. The priority policy agenda including climate change countermeasures and energy security, greatly impacts renewable energy policy promotion, indicating that it is important to assess such policy agenda accurately.

(2) Offering long-term targets

Second, it is remarkable that both countries have continued efforts to set specific long-term targets and national visions for renewable energy diffusion. They have come up with some such targets under the EU directive umbrella and others independent from the umbrella. Both countries have offered long-term targets for 2050 since the second half of the 2010s, taking steps towards a renewable energy society.

By offering long-term targets, governments can encourage enterprises, investors, financial institutions, research institutes, and other various actors to develop bold strategies and new technologies while sharing long-term prospects. This would help any country enhance its competitiveness in the fields, such as storage batteries, hydrogen development, and next-generation renewable energy technologies, in which initiatives beyond existing frameworks or ideas would be required. It would also help invigorate domestic markets and industries and increase chances to take leadership in international cooperation towards decarbonization.

(3) Institutional adjustments

Third, it is noteworthy that institutional building for renewable energy diffusion included continuous adjustments to cope with challenges arising after the introduction of original institutions. Both countries introduced a system that obliged electricity suppliers to adopt renewable electricity as a certain portion of electricity sales. When it was recognized that such a system failed to secure the predictability of business for renewable electricity generators, the two countries introduced the FIT system that employed feed-in-tariff compensation to allow renewable electricity generators to predict their future cash flow. When the need was recognized for reducing costs for the FIT system and integrating renewable electricity into the power market, Germany transitioned to the FIP system and the United Kingdom to the CfD system. Both systems are designed for renewable electricity generators to hedge risks regarding electricity wholesale price fluctuations, securing investment incentives and future business predictability.

In this way, both countries have taken over the helm of policy support for renewable energy diffusion while making adjustments to challenges arising after introducing the original institutions. Adjustments are required for evolving renewables into energy sources that can compete with other electricity sources. Renewable or any other electricity sources cannot be expected to steadily diffuse over the long term unless policies are adequately adjusted in response to challenges arising in the market after the introduction of those policies for diffusing any electricity sources.

2. Towards a renewable energy society

In addition to the abovementioned points, it was confirmed that Germany and the United Kingdom have combined extensive renewable energy support measures, such as priority connection of renewables to the grid, transmission and distribution network development, and electricity market reform, with the FIT or FIP system to diffuse renewable energy.

On the other hand, when we turn our eyes to the trajectory that Japan has followed so far, Japan implemented the Act on the Promotion of New Energy Usage (also known as the New Energy Act) in 1997 and the Act on Special Measures Concerning New Energy Use by Operators of Electric Utilities (also known as the Renewable Portfolio Standard Act) in 2003, proceeding with institutional building for renewable energy diffusion almost at the same time with Germany. Since the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities (also known as the Renewable Energy Act) took effect in 2012, Japan has promoted renewable energy under its Feed-in Tariff system. In 2010, renewables accounted for 9.5% of the power mix, with non-hydro renewables' share limited to 2%. In 2018, the renewables share increased to 17%, and the non-hydro renewables share to 9%. While renewable electricity generation expanded steadily, FIT costs totaled 3.1 trillion yen in 2018, with FIT surcharge aggregating 2.4 trillion yen, indicating that how to ease the surcharge burden on consumers was an urgent challenge[117]. As solar PV generation increased remarkably because of low business entry barriers and shorter lead times for development, Japan was required to address the FIT surcharge growth dependent on solar PV.

In such a situation, the cabinet formulated the Fifth Strategic Energy Plan in July 2018 and called for renewable power generation to evolve into a major long-term stable source of electricity. It also indicated that for growing into a primary electricity source sustaining Japan's energy supply, renewable energy should be independent of the FIT system and become an electricity source that is integrated along with other electricity sources into the power market[118].

Under the FIT system, renewable electricity generators have been guaranteed to have all their generated electricity bought at fixed feed-in tariffs without market trading. This has secured their business predictability and promoted investment in renewable power generation projects. However, it has failed to provide incentives for renewable electricity generators to become conscious of market prices or have their generated electricity integrated along with other electricity into the market. Then, Japan has decided to introduce the market-indexed Feed-in Premium system in April 2022 for allowing renewable energy generators to maintain their business predictability and become conscious of electricity market prices under the Act of Partial Revision of the Electricity Business Act and Other Acts for Establishing Resilient and Sustainable Electricity Supply Systems, which passed the National Diet in June 2020[119]. In this way, Japan aims to implement the FIP system

[117] Ministry of Economy, Trade and Industry "Document 2 for a combination of the 18th meeting of a subcommittee on massive renewable energy diffusion and next-generation networks, Electricity and Gas Industry Committee, Committee on Energy Efficiency and Renewable Energy, and the sixth meeting of a subcommittee on institutional reform to make renewable energy a major electricity source, Strategic Policy Committee, under the Advisory Committee for Natural Resources and Energy," July 22, 2020
（経済産業省「総合エネルギー調査会 省エネルギー・新エネルギー分科会／電力・ガス事業分科会 再生可能エネルギー大量導入・次世代ネットワーク小委員会（第 18 回）基本政策分科会 再生可能エネルギー主力電源化制度改革小委員会（第 6 回）合同会議 資料 2」2020 年 7 月 22 日）

[118] Ministry of Economy, Trade and Industry "Third interim report by a subcommittee on massive renewable energy diffusion and next-generation networks, Electricity and Gas Industry Committee, Committee on Energy Efficiency and Renewable Energy, Advisory Committee for Natural Resources and Energy," August 2019
（経済産業省「総合資源エネルギー調査会 省エネルギー・新エネルギー分科会/電力・ガス事業分科会 再生可能エネルギー大量導入・次世代電力ネットワーク小委員会 中間整理（第 3 次）」2019 年 8 月）

[119] Ministry of Economy, Trade and Industry "Document 2 for a combination of the 18th meeting of a subcommittee on massive renewable energy diffusion and next-generation networks, Electricity and Gas Industry Committee, Committee on Energy Efficiency and Renewable Energy, and the sixth meeting of a subcommittee on institutional reform to make renewable energy a major electricity source, Strategic Policy Committee, under the Advisory Committee for Natural Resources and Energy," July 22, 2020
（経済産業省「総合エネルギー調査会 省エネルギー・新エネルギー分科会／電力・ガス事業分科会 再生可能エネルギー大量導入・次世代ネットワーク小委員会（第 18 回）基本政策分科会 再生可能エネルギー主力電源化制度改革小委員会（第 6 回）合同会議 資料 2」2020 年 7 月 22 日）

likewise Germany to secure investment incentives for renewable energy generators by providing them with the premium, which is calculated based on the difference between the standard price and the market reference price when they sell electricity in the wholesale electricity market or bilateral trading.

Given that the FIP system is a transitional measure before renewables are integrated with other electricity sources into the market, it is essential to take comprehensive measures for evolving renewables into a primary electricity source while carefully designing the FIP system. The following discusses measures that are viewed as particularly important among those that Japan should tackle, based on German and U.K. experiences.

(1) Detailed FIP system design

As for the FIP system's detail, how to design a method for calculating a premium price is important. In Japan, the government has indicated that a unit premium price, obtained by subtracting the market reference price from the standard price, would be multiplied by renewable electricity supply volume to compute a premium amount for every certain period[120]. The FIP system is classified into "fixed FIP" in which a fixed premium is added to the market reference price and "floating FIP" in which the premium is calculated as the difference between standard price and market reference price[121]. Japan plans to adopt the "floating FIP" system, which Germany and other European countries also introduced. One of the critical issues for the floating FIP system is how to set the length of the reference period that will determine the frequency at which a market reference price would be changed. If the reference period is as short as 30 minutes or one hour, renewable electricity generators may be able to flexibly absorb market price fluctuations and ensure the FIP standard price. However, this may make the FIP system similar to the FIT system, failing to encourage renewable electricity to be integrated into the market. On the other hand, if the reference period is as long as one year, the premium may be almost fixed to lead renewable electricity generators' income to become vulnerable to short-term market fluctuations, affecting renewable electricity generators' business predictability and investment.

As reviewed by this paper, Germany has set the reference period at one month, and a mechanism has been introduced to retrospectively calculate a market premium for each calendar month in line with the fourth supplementary provision of the EEG2012. This might have been designed to allow renewable electricity generators to become conscious of market price fluctuations to some extent and secure the predictability of investment conditions. While there is an argument for Japan to set the reference period at one month in line with the German case, whether one month would be adequate as Japan's reference period should be considered cautiously, based on the extent of renewable energy diffusion and market development conditions in Japan. On the precondition that renewable electricity generators should make a step forward from protection under the FIT system to independence, policymakers should consider whether price fluctuations within specific periods would prevent excess risks for renewable electricity generators.

Next, I would like to emphasize the following four measures that are considered to be particularly important to be combined with the FIP system design for evolving renewable energy into a primary electricity source.

(2) Developing electricity markets

First, electricity markets should be developed. Currently, in Japan, discussions have been underway in the direction that

[120] Ministry of Economy, Trade and Industry "Document 1 for a combination of the 19th meeting of a subcommittee on massive renewable energy diffusion and next-generation networks, Electricity and Gas Industry Committee, Committee on Energy Efficiency and Renewable Energy, and the seventh meeting of a subcommittee on institutional reform to make renewable energy a major electricity source, Strategic Policy Committee, under the Advisory Committee for Natural Resources and Energy," August 31, 2020
（経済産業省「総合エネルギー調査会 省エネルギー・新エネルギー分科会／電力・ガス事業分科会 再生可能エネルギー大量導入・次世代ネットワーク小委員会（第 19 回）基本政策分科会 再生可能エネルギー主力電源化制度改革小委員会（第 7 回）合同会議 資料 1」2020 年 8 月 31 日）

[121] Y. Ito "Transition of Renewable Energy Support Measures – Implications from Domestic and Foreign Cases for Japan's FIT Revision" IEEJ, August 2015
（伊藤葉子「再生可能エネルギー支援策の変遷～国内外の制度事例から得る日本の FIT 見直しへの示唆～」日本エネルギー経済研究所、2015 年 8 月）

the markets in which FIP electricity to be traded are the electricity wholesale market, non-fossil value trading market, and supply-demand balancing market[122]. Under the FIP system, renewable electricity generators will be allowed to receive income from trading their generated electricity in relevant markets while being required to shoulder costs for adjusting planned and actual values of their electricity if these values fail to be identical. There is concern that if the penalty on such value imbalance is excessive for renewable electricity generators, they would be discouraged from taking part in markets. In this respect, the hour-ahead market design should be made flexible as much as possible to suppress such imbalance. Market designs and policy processes reviewed in this paper, differ from country to country depending on national conditions and historical contexts and may have to be considered in detail in a separate article. It may be useful to analyze what measures have been taken in Germany or the United Kingdom and what challenges have been recognized as results from specific actions. In Germany and the United Kingdom where hour-ahead market designs are less flexible than in Italy or Spain, for example, it is pointed out that renewable electricity generators could be forced to shoulder imbalance risks to the disadvantage of renewable energy diffusion[123].

(3) Eliminating grid constraints

Next, grid constraints should be eliminated. In Japan, electricity sources connected to the grid are given transmission capacity quotas first under the first-come-first-served rule. It results in forcing renewable and other new electricity sources to remain unconnected to the grid through congested transmission lines until transmission capacity is increased. The elimination of such grid constraints under traditional grid operation rules is one of the significant challenges for promoting renewable energy as a primary electricity source. Japan is now considering the promotion of Japanese connect & management arrangements for the maximum utilization of existing grids, the development of new grids, the revision of power transmission rules, and other measures[124]. As reviewed by this paper, in Europe, the 2001 EU renewable energy directive included grid system issues, providing for priority connection of renewable electricity sources to the grid. This rule has helped to encourage investment in renewable energy but has been insufficient to pursue a renewable energy society. In Germany, for example, a long-pending issue has been the enhancement of transmission capacity connecting the northern region featuring robust wind power development to the southern region with heavy electricity demand. Transmission line construction has remained far behind schedule. So, Germany introduced a grid reserve system as a transitional measure for stable electricity supply in 2012. In Japan, the enhancement of power transmission capacity including the installation of wide-area transmission networks has been recognized as necessary but is expected to cost much time and money. Therefore, Japan needs to promote the enhancement of transmission capacity as much as possible in parallel with the acceleration of the revision of rules for renewable electricity sources' priority connection to the grid and the maximum utilization of existing transmission capacity to eliminate obstacles to renewable energy diffusion.

(4) Securing supply-demand balancing capacity

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[122] Ministry of Economy, Trade and Industry "Document 1 for a combination of the 19th meeting of a subcommittee on massive renewable energy diffusion and next-generation networks, Electricity and Gas Industry Committee, Committee on Energy Efficiency and Renewable Energy, and the seventh meeting of a subcommittee on institutional reform to make renewable energy a major electricity source, Strategic Policy Committee, under the Advisory Committee for Natural Resources and Energy," August 31, 2020
（経済産業省「総合エネルギー調査会 省エネルギー・新エネルギー分科会／電力・ガス事業分科会 再生可能エネルギー大量導入・次世代ネットワーク小委員会（第 19 回）基本政策分科会 再生可能エネルギー主力電源化制度改革小委員会（第 7 回）合同会議 資料 1」2020 年 8 月 31 日）

[123] Presentation by J. Ogasawara at an IEEJ forum on research works
（小笠原潤一（日本エネルギー経済研究所）による研究会発表資料）

[124] Ministry of Economy, Trade and Industry "Document 1 for a combination of the 19th meeting of a subcommittee on massive renewable energy diffusion and next-generation networks, Electricity and Gas Industry Committee, Committee on Energy Efficiency and Renewable Energy, and the seventh meeting of a subcommittee on institutional reform to make renewable energy a major electricity source, Strategic Policy Committee, under the Advisory Committee for Natural Resources and Energy," August 31, 2020
（経済産業省「総合エネルギー調査会 省エネルギー・新エネルギー分科会／電力・ガス事業分科会 再生可能エネルギー大量導入・次世代ネットワーク小委員会（第 19 回）基本政策分科会 再生可能エネルギー主力電源化制度改革小委員会（第 7 回）合同会議 資料 1」2020 年 8 月 31 日）

As intermittent renewable energy such as solar PV and wind diffuses, it is widely recognized that supply-demand balancing capacity should be secured efficiently and effectively[125]. Fossil-fired power generation has so far played a main role in balancing supply with demand. In Germany and the United Kingdom that have decided to phase out coal-fired power generation towards a decarbonized society, how to secure supply-demand balancing capacity has become an urgent issue. Coal-fired and other conventional power sources have used their kinetic energy or inertia to offset any rapid change in the power supply-demand balance in the event of an unexpected accident. This nature has contributed to stabilizing the power system. While Germany that belongs to the continental grid has no inertia problem, the United Kingdom has proactively introduced devices and mechanisms to provide inertia to absorb fluctuations in the power supply-demand balance. In this way, it must be noted that constraints on renewable energy diffusion in the United Kingdom differ from those in Germany due to the power grid system difference. In the future, in addition to the active utilization of geothermal and biomass power generation, storage batteries and IoT technology-based Virtual Power Plants (VPP) for using distributed power sources would have to be applied as balancing capacity that could maintain inertia. In Japan, fossil-fired and pumped hydropower generation may be used as a balancing capacity for the immediate future. As decarbonization makes further progress, however, demonstration tests and technological development to secure new balancing capacity will become even more critical.

(5) Sharing specific long-term targets

Finally, Japan should demonstrate long-term targets through 2050, leading a wide range of actors to share a path to a society where renewables are widespread. Japan's fifth Strategic Energy Plan has set out an initiative for the more advanced 3E's + S (environmental protection, economic efficiency, energy security plus safety), providing four long-term energy choice guidelines – decarbonization, industrial competitiveness enhancement, diversified energy choices, and innovation of safety through technological and governance innovation. However, it has fallen short of specifying long-term targets and energy mix. While coming up with a policy of developing renewable energy into a major economically independent, decarbonized electricity source, the plan has failed to clarify a path to the development or a specific strategy. To diffuse renewable energy further, Japan will have to develop markets, enhance the grid, and accelerate technological innovation at much cost of time and labor. To sustainably stimulate investment in renewable energy and technical development for a transition to a society where renewables are widespread, Japan should set specific targets beyond 2030 and encourage various actors to take bold actions while sharing a long-term direction.

As indicated by German and U.K. policy processes, renewable energy diffusion has been promoted by renewable energy policies while being shaken by other energy policies and revised occasionally. Although paths to a renewable energy society vary depending on national energy mixes and economic conditions, the two countries' processes for developing systems and market conditions to enhance business predictability provide implications for Japan's institutional designing. It is expected that Japan will take steady steps to diffuse renewable energy under clear paths and institutions.

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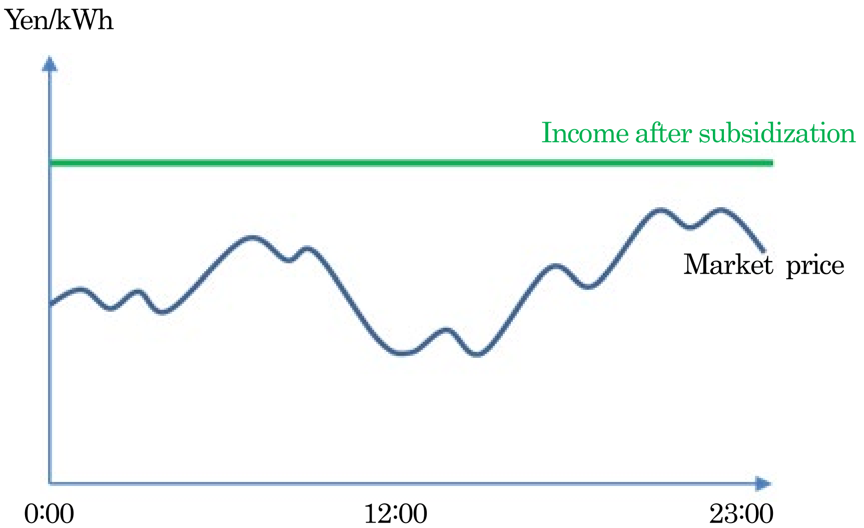
[125] *Ibid.*

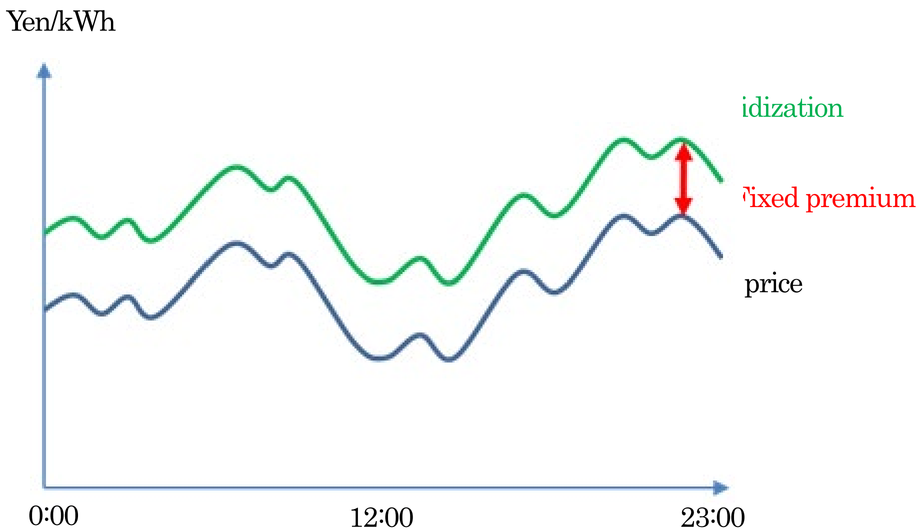
Comparative conceptual diagrams of renewable energy support measures[126]

FIT system



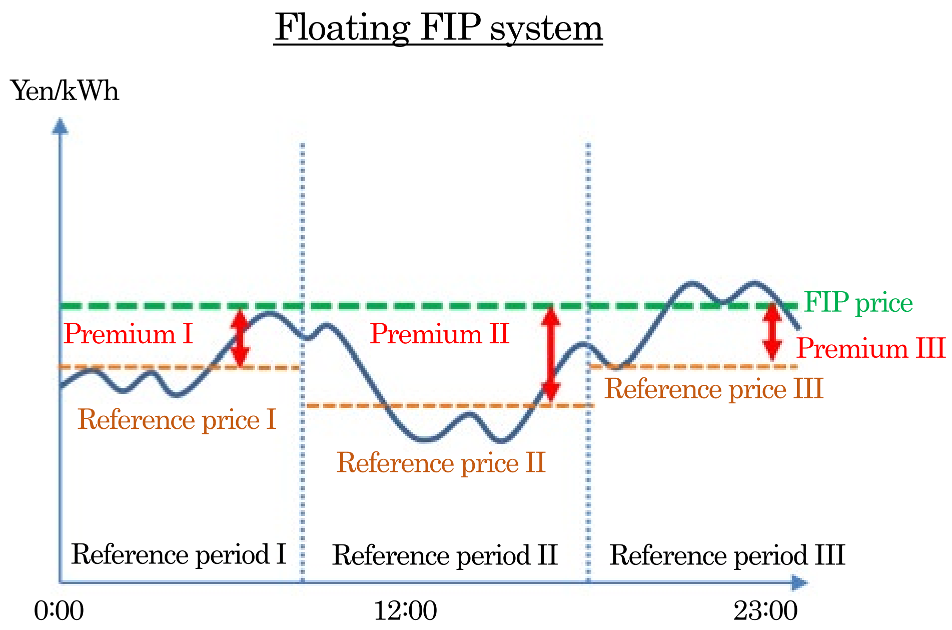
* Feed-in tariffs are fixed irrespective of market prices

Fixed FIP system



* A fixed premium is put on the market price

126 *Ibid.* Referred other various documents



* The FIP price is fixed over a delivery period.
* The reference price is computed every certain period based on average market prices during a reference period.
* The premium price is computed every certain period according to reference price fluctuations.

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