博 士 論 文

STUDY ON THE LIMITATION OF RENEWABLE ENERGY PERFORMANCE AND ITS IMPACT ON PUBLIC GRIDS UNDER DIFFERENT POWER SUPPLY SYSTEM

再生可能エネルギーの導入における地域の受入限界や系統電力への影響に関する研究

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Study on the Limitation of Renewable Energy Performance and Its Impact on the Public Grids Under Different Power Supply System

ABSTRACT

In the context of energy shortages and safe supply requirements, renewable energy has been developing steadily in recent years. Among them, the power sector plays an important role in energy conservation and emission reduction. The development of renewable energy can not only reduce the use of fossil energy, but also increase the rate of energy self-sufficiency. Japan's current energy self-sufficiency rate is only 8%. After the implementation of the FiT system in 2011, renewable energy has experienced explosive growth. Among them, PV and wind energy have shown a leading position in growth. Photovoltaic and wind energy are also called variable renewable energy because of their variable power generation characteristics. Their large-scale introduction affects the stability of the grid, so this research is dedicated to studying the interaction between renewable energy, power demand, grid, and energy storage system to maximize the use of VRE.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. The research backgrounds of energy resources are introduced in Chapter1, which is including the current status and bottleneck of integrational energy development. As well as the significant of developing variable renewable energy. Then, the development and status of renewable energy in world and Japan is well introduced. It is essential to developing renewable energy in the power generation sector to dealing with the problem of energy security and fossil fuel shortage. At last, the research purpose and logical framework is shown in order to support reviewers understand the content of this paper.

In Chapter 2, LITERATURE REVIEW OF VARIABLE AND RENEWABLE ENERGY. The relevant research of this paper is well reviewed in this Chapter. The development of renewable energy in power systems, including the variable renewable energy studies and its hybrid with pumped storage system studies. Besides, the evaluation indicator used in this paper is also well explained further. At lase, the energy management tool of EnergyPLAN models is reviewed. According to the previously study, the current paper contributes to combined them and promote it in the integration potential of renewable energy.

In Chapter 3, METHODOLOGY. The keyword of this paper is load in demand side, electricity generator in supply side, power grid, and storage system. Therefore, the methodology employed including, evaluation indicators of VRE on the power grid, PHS installed capacity prediction, and EnergyPLAN model are summarized in Chapter 3. It helps us to understand the interplay of load in demand side, electricity generator in supply side, power grid, and storage system to seek a ideal electricity production compositions.

In Chapter 4, DATA RESOURCE AND ENERGY CONVERSION ANALYSIS. The data resource mainly focus on the distribution of research area, the composition of power generation in research area, electricity production profiles, and economic cost. Kyushu, Tokyo, Kansai, and Hokkaido with different power proportions, electricity demand profiles, and renewable energy resources are selected to compared and analysis. The energy conversion of fossil fuel to renewable energy is adopted whist.

In Chapter 5, ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE. This chapter evaluated the impact of PV and wind on the public electricity supply system when they are introduced into the grid. A method of predict the maximum penetration of renewable energy and its impact on the public electricity supply system is explained in Chapter 3, which is capacity credit and dynamic investment payback period. The results indicate that the capacity credit increases with an increase in PV and wind shares in the grid. However, it seems to be saturated when the share of PV and wind power in the grid reaches 25% and 60%, respectively. Compared with the wind integration in Kansai and Hokkaido, the PV penetration in Kyushu and Tokyo reaches saturation more rapidly. In addition, PV shows more power suppression, which prolongs its payback period compared to wind energy. The significant difference in the results of capacity credit and DIPP is limited by the characteristics of power demand in mixed regions and the relevance of renewables distribution.

In Chapter 6, ASSESSMENT OF DEMAND SIDE IN VRE INTEGRATION. The impact of a reduction in load demand on renewable energy in the Japan public power grid under a state of emergency declaration (April to May 2020) is compared. Research area is distributed in Kyushu, Tokyo, Kansai, and Hokkaido. The results are shown that the consumption profiles and amounts of power consumption reduction are different in different areas. Tokyo shows the largest share of reduced load, followed by Kansai, Kyushu, and Hokkaido. The load reduction was mainly seen during the day, which reflects the differences in people's activities relative to the same period in 2019. Different means of power dispatch, including power generators, energy storage systems, and transmission lines are used and compared in terms of responses to the changes in electricity consumption profile. Besides, the overall fall in total load demand and the change in load sequence affected the integration and curtailment of PV power generation and consequentially caused the electricity price to drop. This Chapter clarifies the effects of COVID-19 on the public power grids of Japan. Further, it establishes the impact on policymakers in relation to the development of renewable energy.

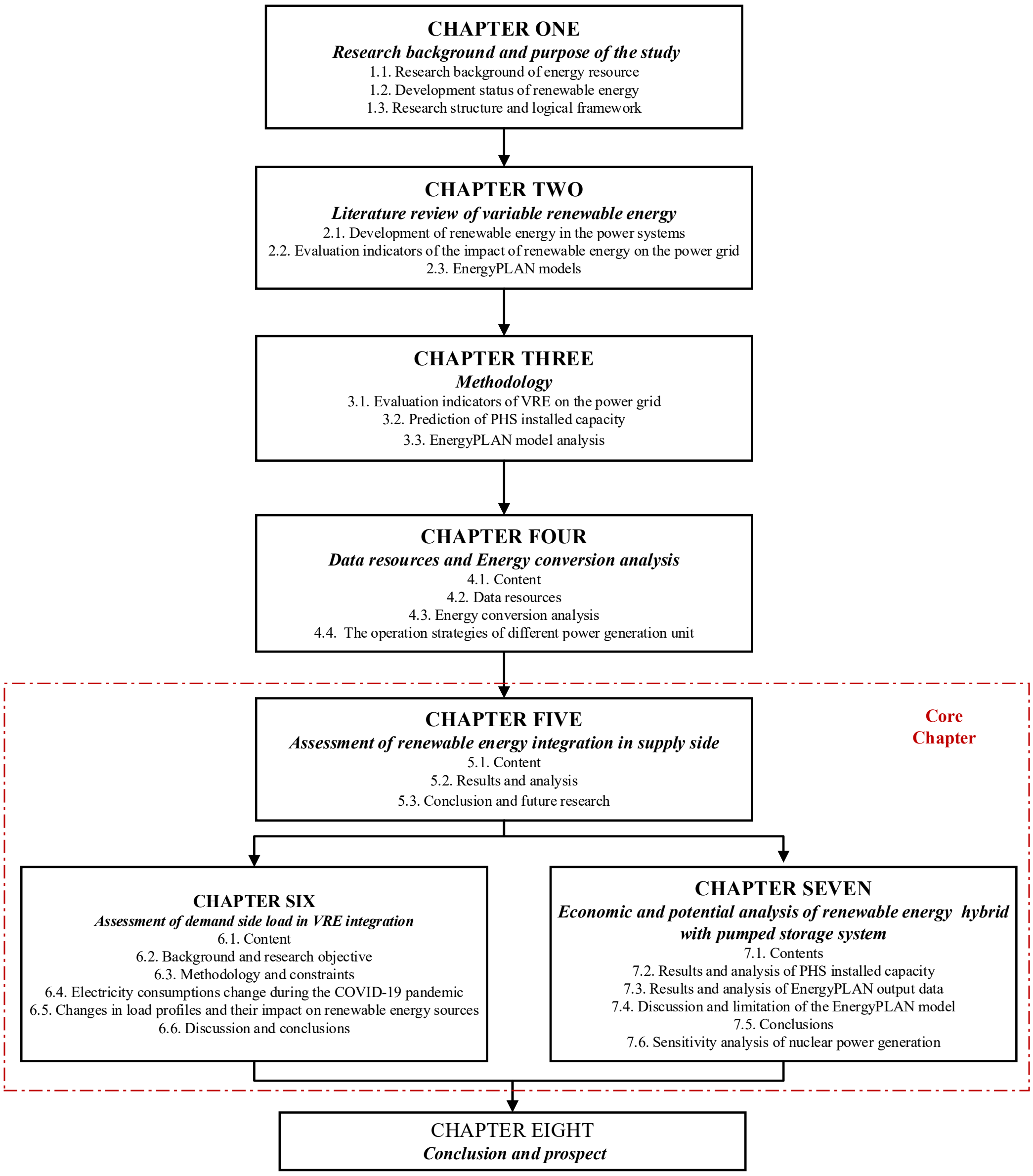
In Chapter 7, ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM. The pumped storage system is used in the energy management system in order to promote the integration of renewable energy integrations. the existing small and medium-size dams in Japan is exploited to expend the capacity of PHS installed.

Combining with the phase-out of thermal power, analyze the basic load power supply equipment contributes to regional VRE penetration. Its energy conversion analysis is introduced in Chapter 3. Kyushu and Hokkaido power grids with different power generation structure and electricity demand profiles as case study. Scenario settings are based on hourly power demand and supply curves using the EnergyPLAN tool. The result shown that the installed capacity potential of small and medium-sized pumped storage in Kyushu and Hokkaido is 18GW and 20GW, respectively. PHS can reduce RES suppression and thermal power operation while providing a share of grid stability. The reduction of the initial installation of thermal power improves the penetration of RES and the operation rate of PHS. the average power generation cost decreases with the reduction of thermal power installation capacity. Besides, the addition of PHS is first higher and then lower than the scenario without energy storage equipment. Under the same RES share, the maximum cost of Kyushu is 16yen / kWh and that of Hokkaido is 26yen / kWh. Attributed to the nuclear power in Kyushu, which accounts to 25% share of power generation. The penetration of VRE in the future public grid and its impact on other power generation units are covered.

In Chapter 8, CONCLUSION AND PROSPECT. A summarized of each Chapter is concluded.

徐 婷婷 博士論文の構成

Study on the Limitation of Renewable Energy Performance and Its Impact on the Public Grids Under Different Power Supply System



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Nomenclature

Label	Unit	Description
IEA	-	International energy agency
LNG	-	Liquefied natural gas
GDP	-	Gross domestic product
RPS	-	Renewable portfolio standard
ITC	-	Investment tax credit
PTC	-	Production tax credit
FiT	-	Feed-in tariff
FIP	-	Feed-in premium
DIPP	-	Dynamic investment payback period
VRE	-	Variable renewable energy
PHS	-	Pump storage system
FY	-	Fiscal year
RPS	-	Renewable Portfolio Standard
EIA	-	National Environmental Impact Assessment
LCOE	-	Levelized cost of energy or electricity
RLDC	-	Residual load duration curves
LDC	-	Load duration curve
CRL	-	Cumulative residual load
PtG	-	Electricity-to-gas
PES	-	Primary energy supply
PV	-	Photovoltaic
DSM	-	Demand-side management
MGSS	-	Minimum grid stability share

Label	Unit	Description
MGSPS	-	Minimum grid stabilization production share
CEEP	-	Critical Excess Electricity Production
RE	-	Renewable energy
JHU	-	Johns Hopkins University
UHV	-	Ultra-high voltage
PRC	-	Polynomial regression curve
X	-	Guaranteed load reduction without PV integration
Y	-	Guaranteed load reduction with PV integration
P	Yen/kWh	Electricity price
$\mathrm{P_b^t}$	MWh	Power flow from base-load plants
$\mathrm{P_m^t}$	MWh	Power flow from flexible plants
VRE_{direct}	MWh	Directly integrated VRE power generation
$\mathrm{load_{grid}^t}$	MWh	Total grid load
$\mathrm{P_{VRE}^t}$	MWh	Total VRE production
$\mathrm{overproduction(t)}$	MWh	Curtailed VRE production
T2	h	Starting hours of excess electricity
T1	h	Finishing hours of excess electricity
$\mathrm{RLDC(t)}$	MWh	Residual load demand
P_t	Year	Dynamic investment payback period of PV or wind
i_t	%	Annual interest rate
t	h	Time unites
C_0	Yen/kWh	Initial investment
C_1	Yen/kWh	Annual revenue
η	%	Total efficiency of PHS power generation

Label	Unit	Description
η_{TG}	%	Efficiency of turbine generator
η_{TP}	%	Efficiency of pumping facility
V_0	10^3m^3	Effective water storage capacity
V_1	10^3m^3	Potential pumped storage
H	M	Head conditions
S	MW	Capacity of installed capacity
P	MWh	Capacity of power generation
P_y	MWh/y	Total power generation for a year
$PHS_{storage}$	kWh	Storage capacity of electricity power
V	m^3	Volume of upper reservoir,
g	m/s^2	Gravitational acceleration
h	m	Head between upper and lower reservoir
C	kW	Rated power generation
η	%	Overall efficiency
E_{out}	MWh	Total electricity produced from the research objective
E_{in}	MWh	Total electricity consumed
e_{stab}	MWh	Total electricity production from grid stabilizing units
d_{stab}	%	Minimum grid stabilization production share
i	h	Time unit
$dispatch^i$	MWh	Flexible thermal power generators
$discharge^i$	MWh	The amount of electricity pumped by PHS
$charge^i$	kWh	The amount of electricity generating by PHS

Label	Unit	Description
η_{pump}	%	Water pump efficiency
$\eta_{turbine}$	%	Turbine efficiency
C_{pump}	MW	Maximum capacity of pump
$C_{turbine}$	MW	Maximum capacity of turbine
$supply^i$	MWh	Total electricity generation by all power sectors
$nuclear^i$	MWh	Power generated by nuclear energy
RES^i	MWh	Power generated by RES energy
ρ	kg/m^3	Density
$Price$	Yen	Average price of fuel at per unit
LHV	MJ/kg	Lower heating value of coal, oil, and LNG
θ	%	Efficiency of thermal power plant electricity generation
P_{cons}	MWh	Power generation from base-load plants
P_{flex}	MWh	Flexible generators that can adjust their output to adapt to the situation of the PV and power grid
PV_{direct}	MWh	Directly accommodated PV
$Load_{direct}$	MWh	Total electricity demand
P_{PV}	MWh	Total PV power generation
$output$	MWh	Total electricity generation on the supply side
$trans$	MWh	Flow of power transferred across regional transmission lines

Chapter 1

RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

CHAPTER ONE: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

1.1 Research background of energy resource

1.1.1 Current status and bottleneck of international energy development

①. The tendency of worldwide energy development

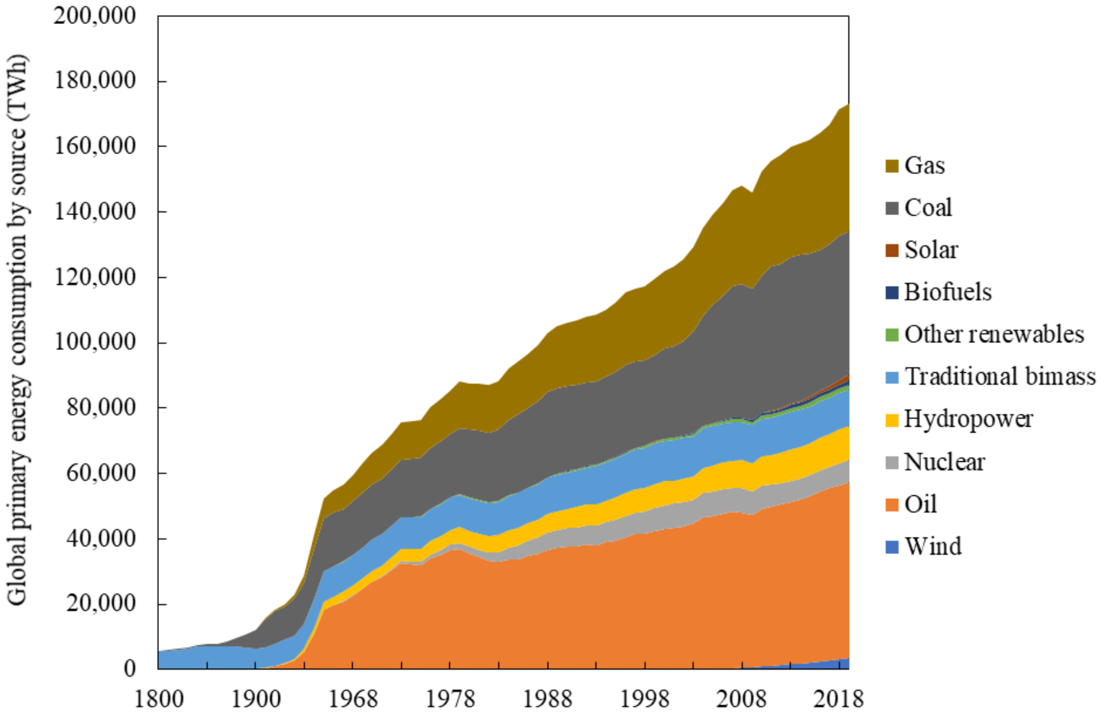


Fig. 1-1 Trends in global primary energy consumption [1]

(Note: Primary energy is calculated based on the substitution method which take account on the inefficiency in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels)

Fig.1-1 shows that the world energy consumption continues to increase over time, and the consumption ratio of different energy over the years is described in Fig. 1-2. From the perspective of energy consumption, coal, oil, and natural gas have always been the center of energy consumption. Oil consumption increased at an average annual rate of 2.1% from 1965 to 2019, accounting for the largest share of overall energy consumption (33.1% in 2019). During this period, coal energy increased at an average annual rate of 1.8%, especially in the 2000s, due to the Asia Pacific region with significant economic growth and other Asian regions seeking cheap power generation fuels. However, because of the passivation of energy demand in some countries and the reduction of natural gas substitution demand in the United States recently, the coal consumption has decreased compared with last year after 2015. And the coal consumption has stagnated accordingly. The results show that the share of coal is 27.0% (as of 2019). On the other hand, the consumption of natural gas exceeds that of oil and coal energy. Natural gas, especially in developed countries that strongly demand to deal with climate change. During the same period, the largest growth rate was atomic energy (8.9% year-on-year) and other renewable energy such as wind and solar energy (12.6% year-on-year), however, the share in 2019 was 4.3% and 5.0% respectively, accounting for a small proportion of the overall energy consumption. On the contrary, the cost of solar power generation and wind power generation has decreased in recent years, and the proportion of renewable energy is expected to further expand in the future.

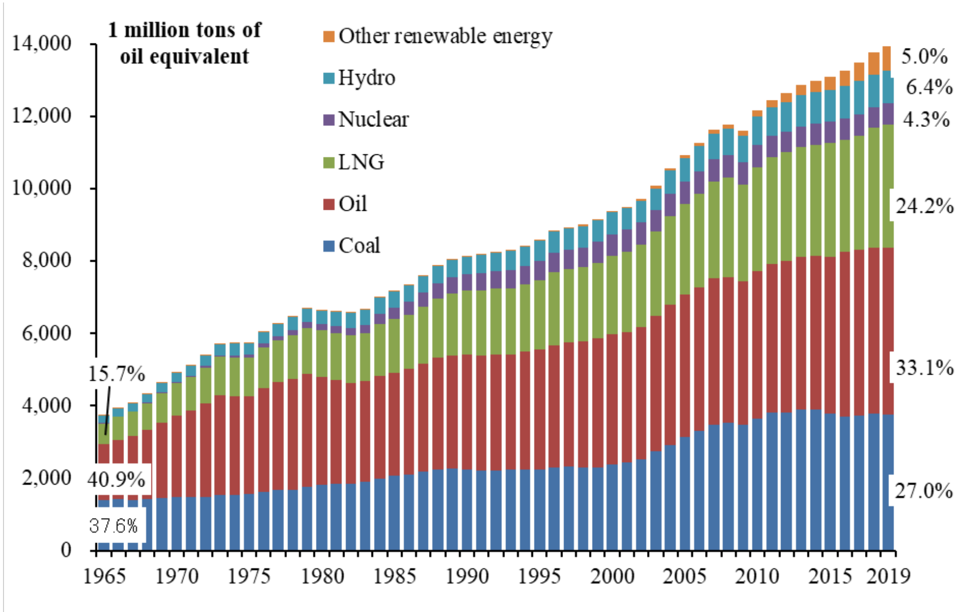


Fig. 1-2 Proportions of the trends in global primary energy consumption

② Current and future prospect of global greenhouse gas (GHG) emissions

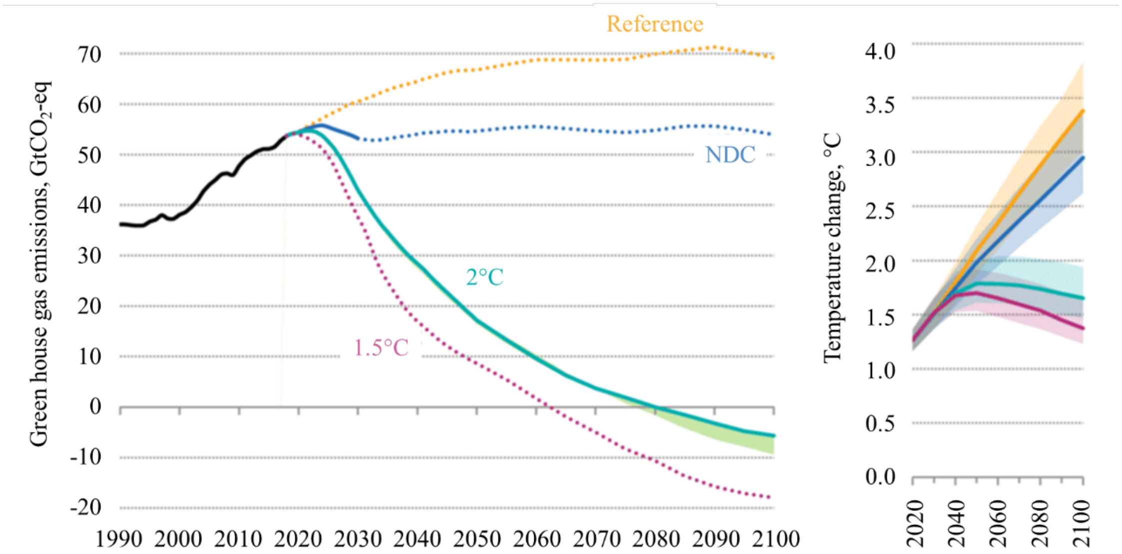


Fig. 1-3 Global greenhouse gas (GHG) emissions and global mean temperature change

(Note: Shaded area for the 2°C scenario emissions represent the2°C range of the sensitivities. Plain lines note medians. Shaded area for temperature 25%-75% probability. The 2°C and 15°C scenarios were designed with a probability not to exceed their temperature change at the end of the century of 75% and 66%, respectively.).

On the aspect of carbon dioxide emission (CO2), the COP 21 (the 21st conference of the parties to the framework Treaty on climate change) is held in December 2015 [2]. The Paris agreement was adopted a fair and effective international framework for the participation of all countries. Compared with before industrial revolution, the temperature rise was controlled below 2 degrees (as shown in Fig. 1-3). In addition, efforts to control within 1.5 degrees were pursued. After that, countries successfully ratified the Paris Agreement and entered into force in November 2016. The entry into force of the Paris Agreement and the adoption of the implementation policy are a landmark event that many countries in the world are actively committed to the response to the greenhouse effect.

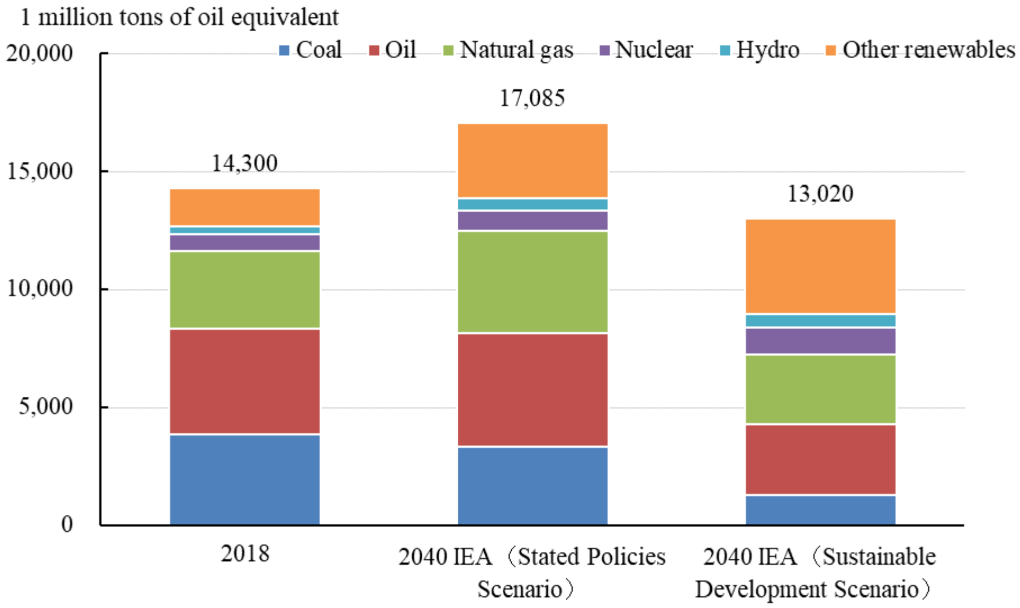


Fig. 1-4 Outlook for world energy demand [3]

The International Energy Agency (IEA) said that the future world energy demand forecast is based on several scenarios. Fig. 1-4 describes the comparison between the actual value in 2018 and the energy demand forecast of IEA in 2040. First, the policy plan means that the published policy objectives of various countries, such as the reduction target of greenhouse gas, which have been achieved, and the progress of existing technology continues. Then, sustainable development scenario refers to all the programs implemented in the sustainable recovery plan recommended by IEA, which is consistent with the objectives of the Paris Agreement. The stronger the measures to deal with climate change, the more low-carbon energy and technologies will be used. Under the sustainable development scenario, coal consumption is reduced to less than half, which is 0.34 times of the result in 2018. Oil has a similar tendency; it presents in the published policy scenario (1.07 times in 2018) and sustainable development scenario (0.67 times in 2018). The decline of consumption is slower than that of coal, due to coal and oil have different main uses. Coal is mainly used for power generation and industry, which can be relatively easily replaced by natural gas and renewable energy. Oil is mainly used as fuel for transportation. It is not easy to convert it into other energy sources. As a result, oil consumption fell more slowly. Compared with oil and coal energy, natural gas is the slowest changing fossil energy. It is cleaner than coal and oil and is expected to be used in various fields. Even under the sustainable development scenario, the estimated consumption of natural gas keeps 0.90 times that in 2018. Renewable energy and nuclear power, including hydropower with very low carbon emissions, are expected to increase. In particular, the growth prospect of renewable energy centered on wind and solar energy is significant. The published policy scenario is also expected to increase by 1.99 times compared with 2018, and the sustainable development scenario is expected to increase by 2.53 times. The future is uncertain, and these scenarios are only estimates based on certain assumptions. When conducting such scenario analysis, it is important to consider the future of better energy.

1.1.2 The significance of developing variable renewable energy

Since the industrial revolution, the energy structure of most countries in the world has been dominated by fossil fuels. This has a major impact on the global climate and human health. Three-quarters of global greenhouse gas emissions come from burning fossil fuels to obtain energy. Fossil fuels are responsible for a large amount of local air pollution-a health problem that causes at least 5 million premature deaths each year. To reduce CO_2 emissions and local air pollution, the world needs to quickly switch to low-carbon energy sources-nuclear energy and renewable technologies. In the coming decades, renewable energy will play a key role in the decarbonization of our energy system. The renewable energy is different from fossil fuels such as oil and coal, which will one day be depleted. For representative examples, there are renewable energy sources such as solar, wind power, and hydro power. The advantages of renewable energy development are mainly reflected in the following two aspects:

①. Does not cause (CO_2) and other greenhouse gases emissions

First, renewable energy does not emit greenhouse gases that are known as the cause of global warming. (Solar power generation and thermal power generation have less greenhouse gas emissions than thermal power generation.). Therefore, the movement to introduce renewable energy throughout the world is expanding. Currently, countries around the world have established reduction targets for greenhouse gases such as CO_2based on the Paris Agreement. Human beings are making reduction efforts for that target. At the same time, the popularization of renewable energy is indispensable for achieving this greenhouse gas reduction goal. Fig. 1-5 shown the historical CO_2

emissions from global fossil fuel combustion and industrial processes from 1750 to 2020. Since the birth of the Industrial Revolution, the amount of CO_2emissions released by global fossil fuel combustion and industrial processes has risen sharply. CO_2 emissions began to rise sharply in the 1950s and reached 25.23 billion metric tons of CO_2 by 2000. Emissions soared by 32% between 2000 and 2010, and total emissions in 2020 will reach 34.81 billion metric tons. That year, the COVID-19 outbreak caused emissions to drop by 5%.

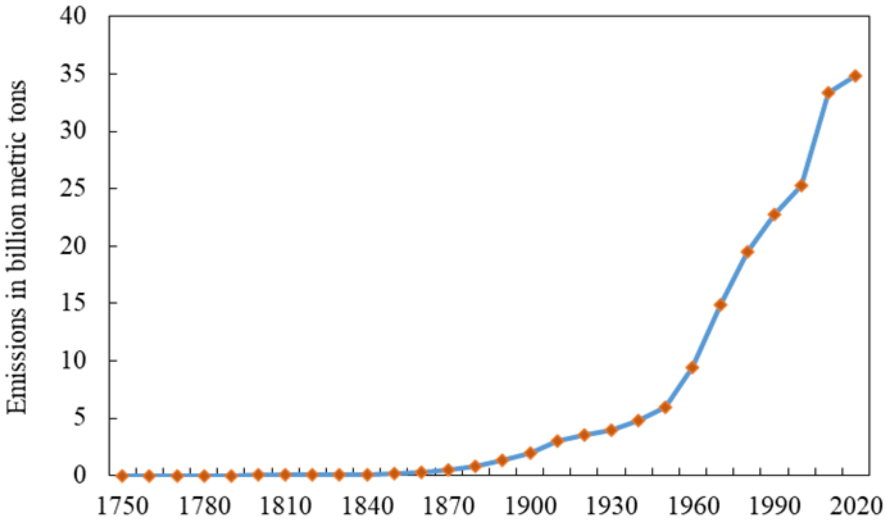


Fig. 1-5 CO_2 emissions from global fossil fuel combustion and industrial processes from 1750 to 2020 [4]

② Expected to improve the energy self-sufficiency rate

Renewable energy, which can produce energy anywhere on the planet, such as solar and wind power, may be the key to improving the energy self-sufficiency rate of resource poor countries, especially in Japan. According to the data published on the website of the Agency for Natural Resources and Energy, the energy self-sufficiency by countries is presented in Fig. 1-6, Japan's energy self-sufficiency rate was 9.6% as of 2017. The reason is that more than 80% of the energy sources used in Japan depend on foreign countries. As of 2017, the ratio of renewable energy in Japan is about 16%. In comparison, looking at the renewable energy ratio in the overseas power source mix, Canada 65.7%, Italy 35.6%, Germany 33.6%, Spain 32.4%, which greatly exceeds Japan's renewable energy ratio. Energy self-sufficiency in Japan It is no exaggeration to say that whether or not the rate can be increased depends on the spread of renewable energy.

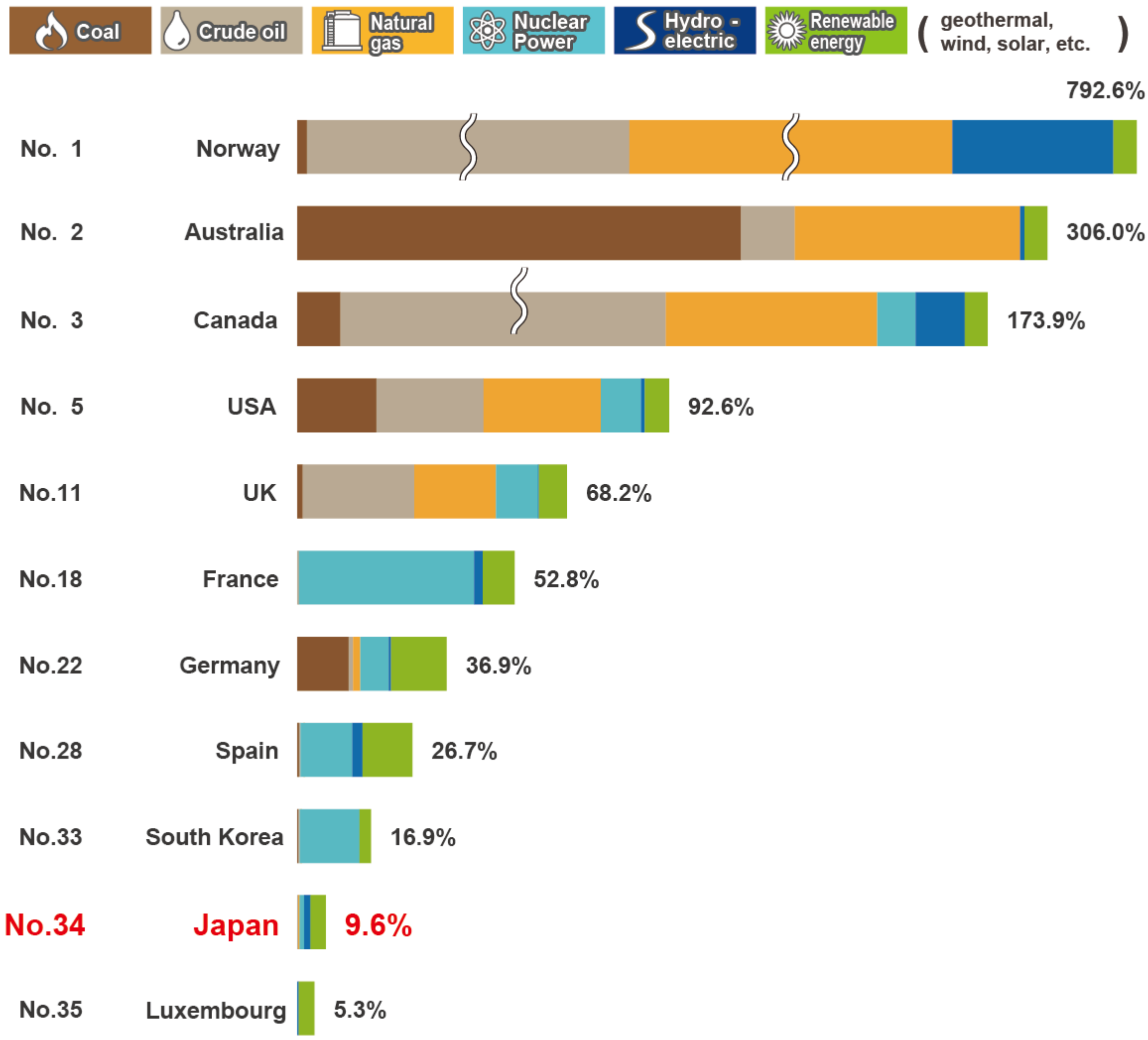


Fig.1-6 Comparison of primary energy self-sufficiency ratios of major countries (2017) [5]

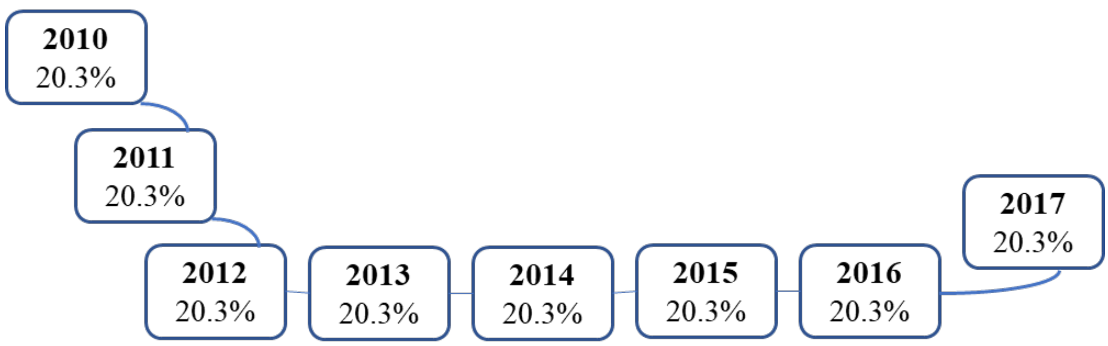


Fig. 1-7 Comprehensive energy self-efficiency statistics in Japan

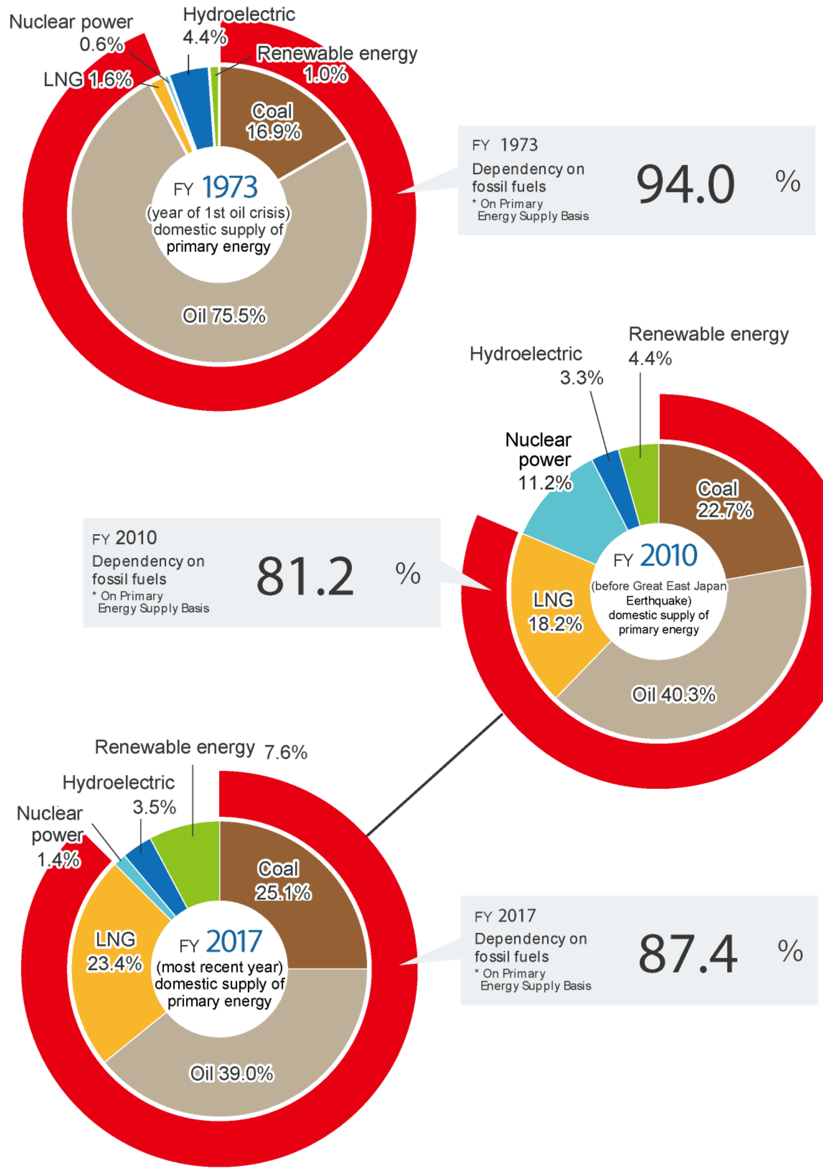


Fig. 1-8 Trends in the composition of primary energy supply of Japan [6]

As previously referred, Japan is largely dependent on traditional fossil fuels. For example, oil, coal, and liquefied natural gas (LNG). As shown in Fig. 1-7, one year before the Great East Japan Earthquake, 81.2% of Japan's total primary energy supply relied on fossil fuels. The dependence increased to 87.4% in 2017, mainly due to the increased use of thermal power to make up for the power shortage caused by the shutdown of nuclear power plants. Most of Japan's demand for fossil fuels has always been dependent on imports from abroad. In 2018, the dependence on fossil fuel imports was 99.7% of oil, 97.5% of LNG, and 99.3% of coal (as shown in Fig. 8).

As for the impot of energy resource for Japan, the proportion of fossil fuels that imported from the other countries is summarized as Table 1. Of the mentioned, about 88% of oil is imported from the Middle East. In terms of coal, Japan is highly dependent on Australia. In terms of LNG, it is purchasing from diversified regions such as Australia, Asia, Russia and the Middle East. The details are shown as Fig. 1-9.

Table 1-1 Japan's dependency on imports from overseas for fossil fuel resources

Oil	99.7%
LNG	97.5%
Coal	99.3%

1.2 Development status of renewable energy

1.2.1 The development and status of renewable energy in the world

① Current and forward energy structure, especially the situation of renewable energy

The discovery and use of fossil energy have brought a great leap in human history. In the nineteenth century, coal burned in the steam engine, igniting the flames of the industrial revolution, and illuminating the way forward for human civilization. However, with the continuous development of human society, the over-exploitation and use of fossil energy has also caused increasingly serious environmental problems. Since the industrial revolution, the total amount of CO_2 produced by the burning of fossil fuels has reached 2.2 trillion tons, and the average global surface temperature has risen by 1.1°C. According to this trend, it will exceed 2°C in the middle of this century. Climate change has become a global non-traditional security issue. Global air pollution endangers the basic living conditions of mankind. Under climate risks, the transformation of the global energy structure is imminent.

The first two energy structure transitions have gone through a long process. In this process, technological breakthroughs and institutional arrangements are key factors in the energy transition. A new energy revolution is emerging. It will be a high degree of integration of new energy technology, smart technology, information technology, network technology and smart grid. It will not only involve breakthroughs in multiple technical fields, but also involve the integration and coordination of many interest groups. Therefore, the orientation of development strategy and institutional arrangements will be the decisive factor of the new energy revolution. In different development periods, different countries have different strategic positioning for renewable energy. This strategic positioning determines the policy support orientation of renewable energy and determines its development process.

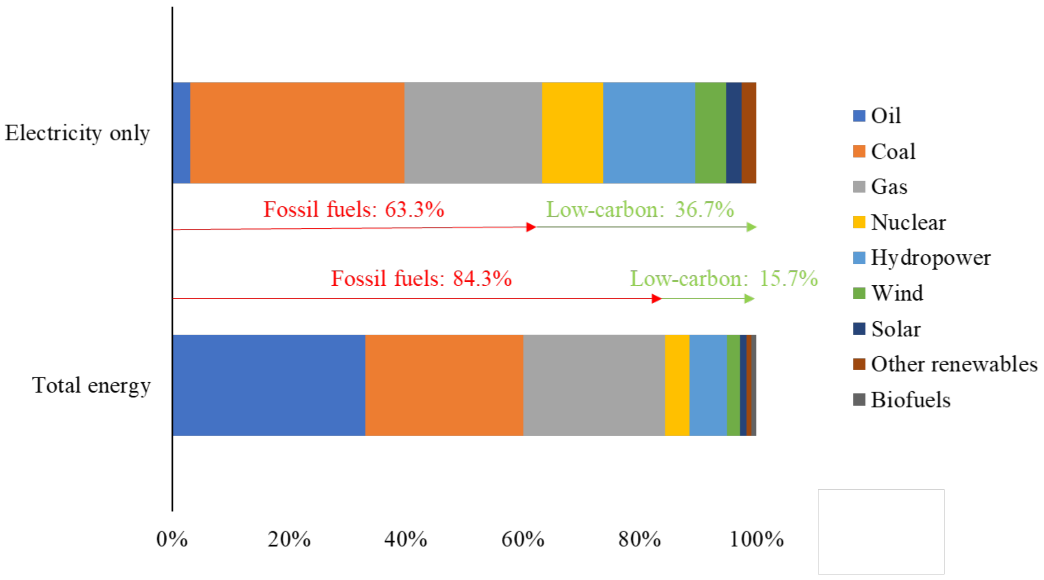


Fig. 1-9 Energy and electricity structures of worldwide [7]

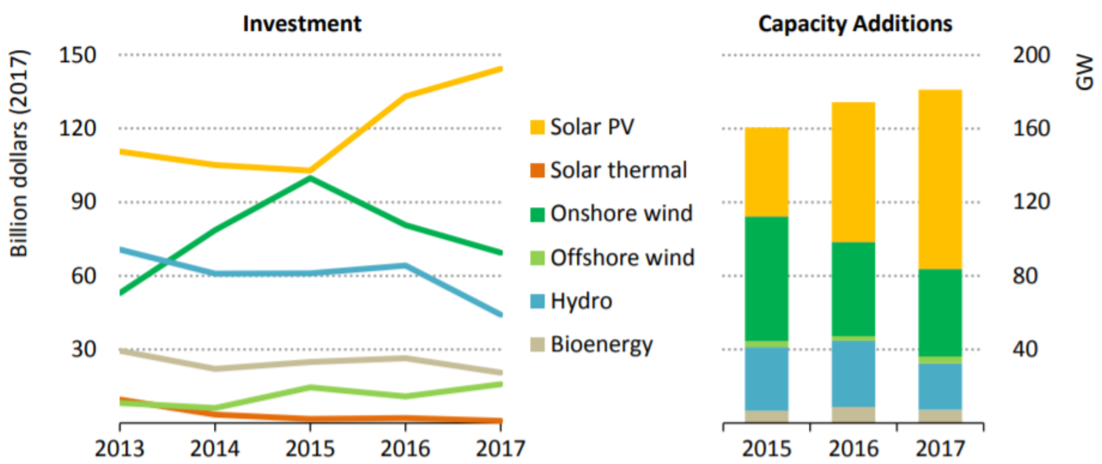


Fig. 1-10 Renewable electricity investment and capacity additions, 2013-2017 [8]

One of the reasons that the energy mix is so dominated by fossil fuels is that transport and heating are often harder to decarbonize that electricity. Transport relies heavily on oil, and heating on gas. There are fewer energy options available to substitute in these sectors. In the electricity system, however, we have more options: nuclear power, hydropower, wind, and solar. This means the electricity mix tends to have a higher share of low-carbon sources. This comparison is shown in the chart: in 2019, just over one-third of global electricity came from nuclear or renewables [more than double the share in the total energy mix, at 16%. This provides one important pathway for progress: if we can shift some activities towards electricity, we may see greater progress on decarbonization. One example of this is electric vehicles: if we can shift oil-dependent transport to electrification then we have more options for powering them in a low-carbon way. This will, however, require massive increases in nuclear and renewable generation to make up for rising demand for electricity.

The currently investment and installation changes of different types of renewable energy over time are shown in Fig. 1-10. As shown in the figure, the annual growth of photovoltaics by 18% is mainly due to the reduction of investment costs and policy support. The rapid growth of PV has offset for the decline in installed capacity of other renewable energy sources. The installed capacity of offshore wind was 18GW as of 2017, mainly driven by the public-private partnership initiative of European North Sea coastal countries. On the other hand, the investment cost of wind and hydropower on the road has shown a downward trend.

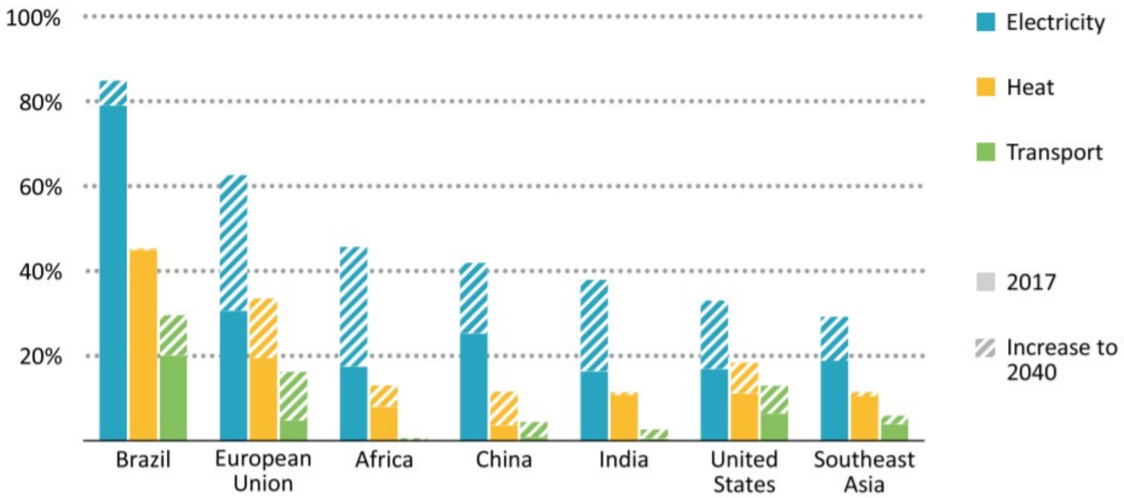


Fig. 1-11 Renewable share by category and country in the new policies scenario, 2017 and 2040 [8]

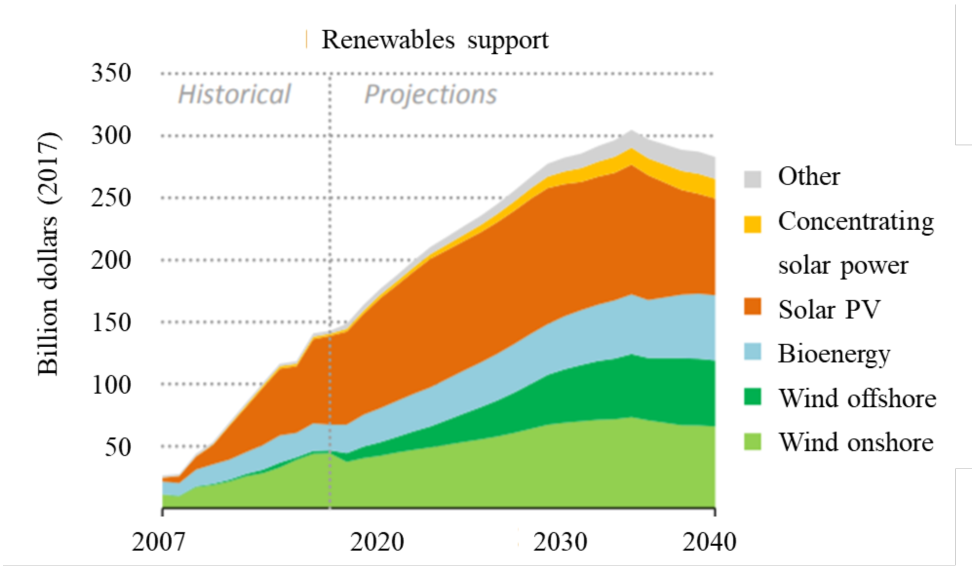


Fig. 1-12 Global renewables-based electricity support in the new policies scenario [9]

The forward renewable energy share by category and region is shown in Fig. 1-11. Under the new policy scenario of continuously eliminating fossil energy and developing renewable energy, renewable energy has been fully developed. The proportion of renewable energy in each country is mainly distributed in electricity, followed by heat and transportation sector. The forecast for each energy mode investment is shown in Fig. 1-12. The growth of investment mainly focusses on the solar PV and wind energy.

② The development and significance of renewable energy in different countries

Actually, the renewable energy will reshape the geopolitical landscape. A country's relative position in the international system is affected by a series of factors, including its gross domestic product (GDP), population, land size, natural resources, geostrategic location, military resources, and "soft power". Owning control and access to important energy resources and markets is an important asset because it can protect national interests and use foreign economic and political influence. In the past two centuries, the development of fossil energy has increased global energy use by 50 times, forming the geopolitical pattern of the modern world. IREAN evaluated the influence of some countries and groups based on the proportion of each country's oil, natural gas, and coal imports in the total primary energy consumption, as well as the cumulative number of patents for renewable energy technologies. The assessment found that the United States is close to energy self-sufficiency and is in a favorable position in the clean energy competition; China is leading the innovation and deployment of manufacturing and renewable energy technologies. Resource. Ecological environmental protection and mineral resource development coordinated development Natural Resource Economics of China 25 will benefit from the energy transition in terms of energy security; the European Union and Japan also occupy an important position in renewable energy technology, especially Germany has nearly 31,000 renewable energy patents, making it A leader in the deployment of renewable energy; Russia is the world's largest natural gas exporter and the second largest oil exporter, and may face challenges in adapting to the growing renewable energy sources. On this basis, IREAN calculated the proportion of net exports and imports of fossil energy in GDP in each region, analyzed the impact of the energy transition on the region; calculated the proportion of fossil energy rents in GDP, and analyzed the proportion of fossil energy exporting countries. Vulnerability: Analyzing the dependence of countries on fossil energy rents and economic elasticity, it is believed that in the context of energy transition, renewable energy has become the center of the global energy pattern. Renewable energy exists in a different form than fossil energy concentrated in a specific geographic location. Most renewable energy sources are energy streams that will not run out on their own and are more difficult to be destroyed. Renewable energy can be deployed at almost any scale and is better used in decentralized forms of energy production and consumption, which increases the democratization effect of renewable energy; the marginal cost of renewable energy is almost zero, such as solar and wind energy. Double the production capacity, and the cost will be reduced by nearly 20%. Therefore, the rapid growth of renewable energy makes it possible for countries that can use new renewable energy technologies to increase their global influence. Among them, countries with high-tech potential for renewable energy power generation are rich in mineral resources that may become necessary for renewable technologies. The three types of countries, including countries that lead to technological innovation, have the potential to become new leaders in renewable energy, take the initiative in the energy transition, and reshape the geopolitical landscape in the 21st century.

Therefore, the United States, Germany, Japan, and China are selected as typical countries for renewable energy policy research. On the one hand, because these four countries are in the forefront of the world's economic aggregates, they have an important influence on the world's economic and technological development. On the other hand, these four countries have led the development of renewable energy in different periods of time. Analyze the evolution of the renewable energy institutional arrangements, clarify the characteristics and context of renewable energy policies, and explore the ideological basis and changing trends of renewable energy policy formulation in these countries provide reference for fast renewable energy development.

i The united state

It is the main policy of the United States to promote renewable energy. Its overall policy framework is characterized by a combination of bottom-up state policies and top-down federal policies (as shown in Fig. 1-13) [10]. State policies mainly use market mechanisms to promote the development of renewable energy. In 1983, Iowa took the lead in implementing the renewable portfolio standard (RPS). As of 2015, 34 states have implemented RPS. The implementation of this policy with a market mechanism has provided the United States for the follow-up of renewable energy. The development of the company has laid a solid foundation. The federal policy system is mainly centered on fiscal and taxation policies, which can effectively reduce project costs, promote technological progress, and accelerate the process of industrialization. The main policy measures of the federal fiscal and taxation policy include the following aspects. First, long-term tax incentives based on investment tax credit (ITC) and production tax credit (PTC). Second, implement key plans and provide strong financial support to strengthen technology research and development and project promotion. Finally, in 2013, the United States proposed a government green purchase system. The proportion of renewable energy power consumption in the total power consumption of government agencies has gradually increased from 7% in 2013 to 10% in 2015 and will reach more than 20% in 2020.

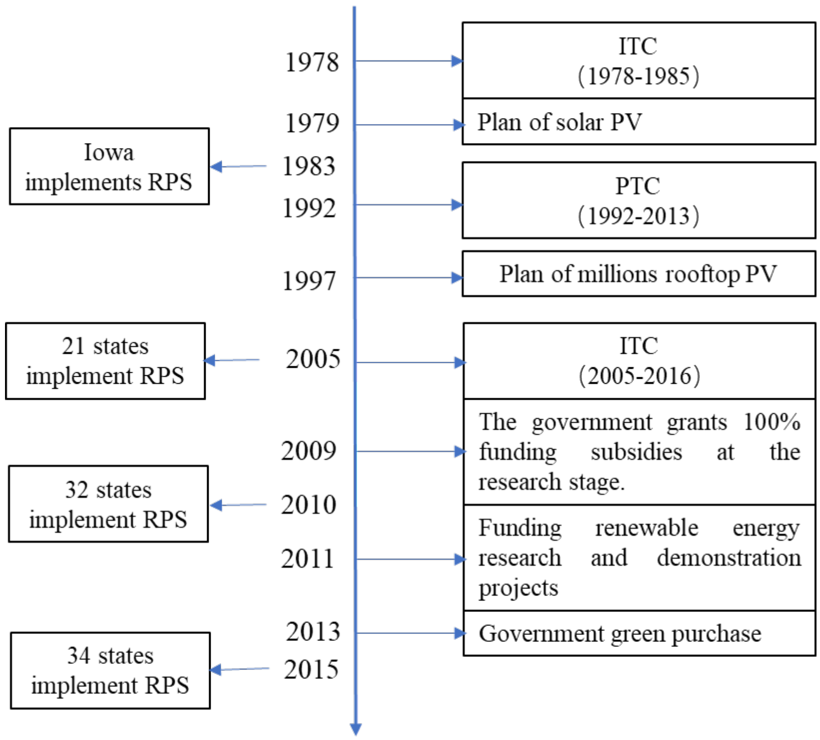


Fig. 1-13 The timeline of renewable energy policy implemented in the United States [10,11]

ii Germany

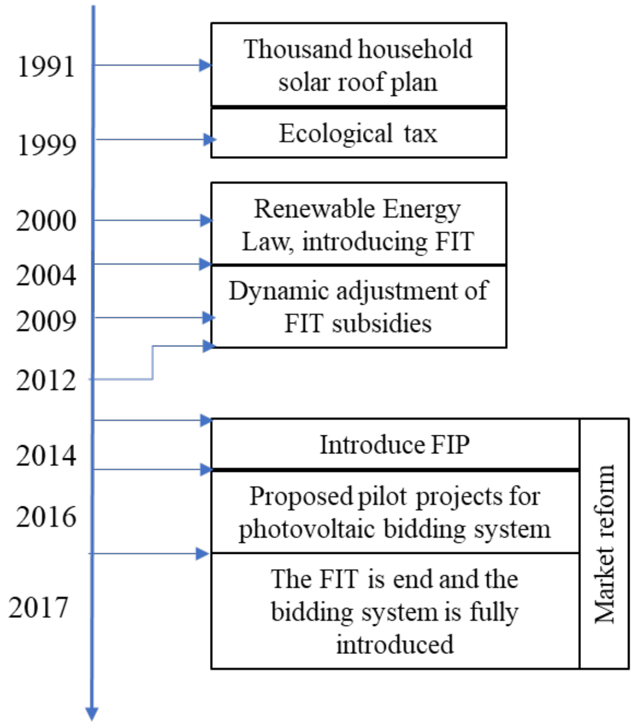


Fig. 1-14 The timeline of renewable energy policy implemented in Germany [10,12]

Fig.1-14 shows the evolution of Germany's renewable energy policy. From Fig.1-14, it can be seen that the German renewable energy policy system is divided into four typical parts, gradually changing from the government-oriented fiscal and taxation support policy

The transition to a market-based policy system is very clear. First, promote the basic installation capacity of renewable energy with key projects. Install rooftop PV for each household. Secondly, carry out ecological tax reform to enhance the competitiveness of renewable energy. This is reflected in the tax benefits for the electricity generated from wind, solar, and geothermal energy. Then promote the feed-in tariff subsidy system (FiT) and determine the solid electricity price in the form of loyalty. However, with the expansion of the scale of renewable energy, government subsidies have increased and the additional cost of renewable energy in the terminal electricity price. To solve this problem of the distortion of the electricity market and the rapid rise of terminal electricity prices, Germany reformed the "Renewable Energy Law" in 2014 and proposed a feed-in premium policy (FIP). Encourage the shift to renewable energy power generation to participate in the power market bidding for the Internet. The sales price is determined by the market supply and demand situation at the time. The government then grants premium subsidies to power generators based on the average of the electricity price level prescribed by various renewable energy sources and the monthly market price to promote renewable energy. Market competitiveness of energy power generation. New renewable energy generation must enter the power market and assume the power system balance obligation like the conventional power sources.

iii China

Fig.1-15 shows the evolution of China's renewable energy policy. Focus on planning projects first promote the start of renewable energy; secondly, fiscal and tax price policies are used to ensure the rapid development of renewable energy. Now the policy has begun to shift to a market-oriented policy system based on the quota system. Aiming at the multi-subject, multi-level quota system, the quota system is an internationally accepted effective measure to promote the development of renewable energy. Allocate the growth share of renewable energy in terms of installed capacity, power generation, and region of renewable energy. And on this basis, combined with the green certificate trading mechanism launched by the Energy Administration, it provides a solution for marketization [10].

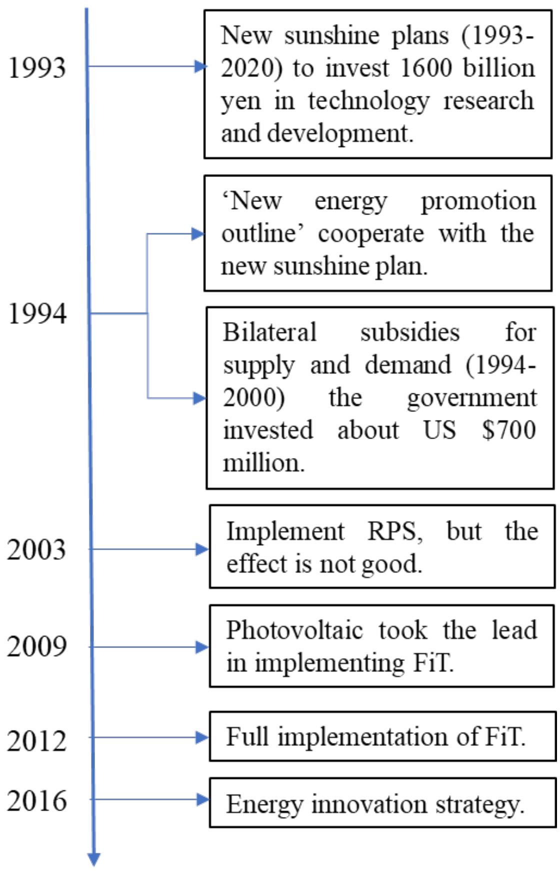


Fig. 1-15 The timeline of renewable energy policy implemented in China [13-15]

iv Japan

Figure 1-16 shows Japan's main renewable energy policies. The characteristics of Japan's policy system are mainly reflected in two aspects. In the first stage, Japan issued the "New Energy Promotion Outline" in 1994, officially announcing the development of new energy and renewable energy for the first time. It also proposed that by 2010, new energy and renewable energy will account for more than 3% of the country's energy supply, and subsidies will be provided to both sides of supply and demand. From 1994 to 2000, the subsidy reached approximately US$700 million. The Sunshine Project promotes the development of renewable energy in Japan. Solar thermal utilization and PV technologies are among the world's forefront, and geothermal power generation, wave power generation and fuel cells have entered the commercial development stage. In 1997, Japan passed the "Environmental Protection and Development of New Business Activities" plan and clearly listed the new energy and renewable energy industries as one of the 15 emerging industries. In June 2004, the Japanese government announced the "New Energy Industrialization Vision". The goal is to support new energy technologies such as solar and wind power generation into one of the pillar industries with an output value of 3 trillion yen by 2030. The second stage promotes renewable energy with a fixed electricity price system [10].

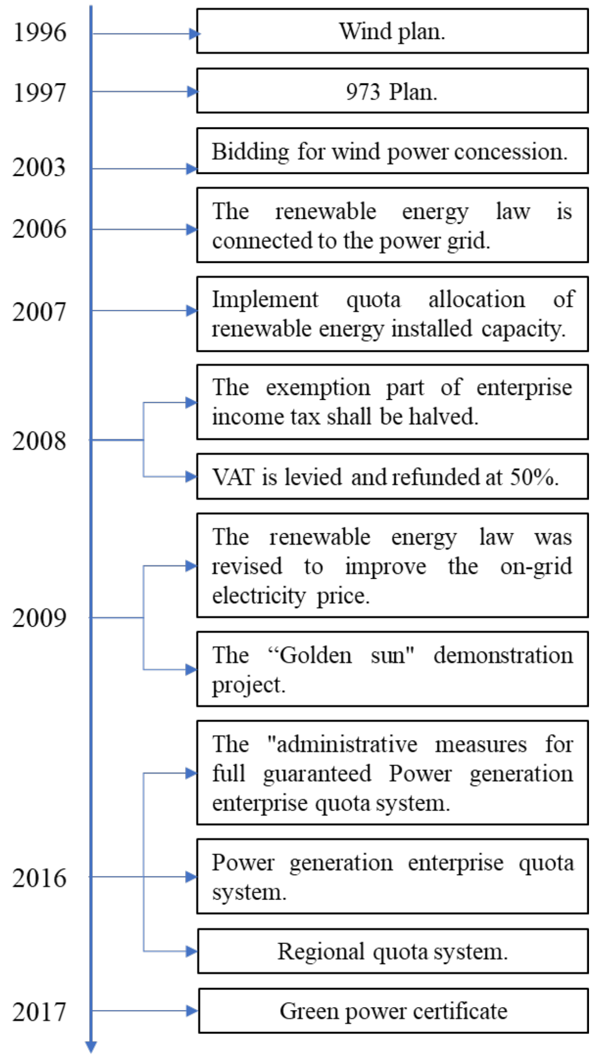


Fig. 1-16 The timeline of renewable energy policy implemented in Japan [10]

Energy development. In 2003, the renewable energy quota system was introduced, however, withdrew at the end due to the low degree of marketization and the insignificant policy effect. Beginning in 2009, a 10-year FIT system was introduced in PV power generation. In 2012, the renewable energy fixed electricity price system was fully implemented, and the fixed electricity price level and electricity surcharge were adjusted in 2015. The "Energy Innovation Strategy" released by Japan in 2016 has two main goals: one is to optimize the energy structure in 2030, and the target of renewable energy to account for 22% to 24%; the other is to achieve the goal of achieving greenhouse gas emissions and emissions in 2030. A decrease of 26% compared to 2013. The reform mainly revolves around the three themes of energy conservation, renewable energy, and energy supply systems.

Summarizing the development strategies of several countries, although the evolution of renewable energy systems in different periods of various countries has been continuously adjusted over time, however, they pretend similar tendency. Clarifying the development plan of renewable energy is the foundation of the policy. The development paths of several countries are basically the same. The policy system is all based on improving the creativity of renewable energy. At the initial stage, breakthroughs in renewable energy technology will be achieved, the industrialization process will improve power generation efficiency and initial investment costs. Besides, the large-scale grid-connected stage will seek grid absorption technology.

1.2.2 The development and status of renewable energy in Japan

① The history of renewable energy development in Japan power generation progress

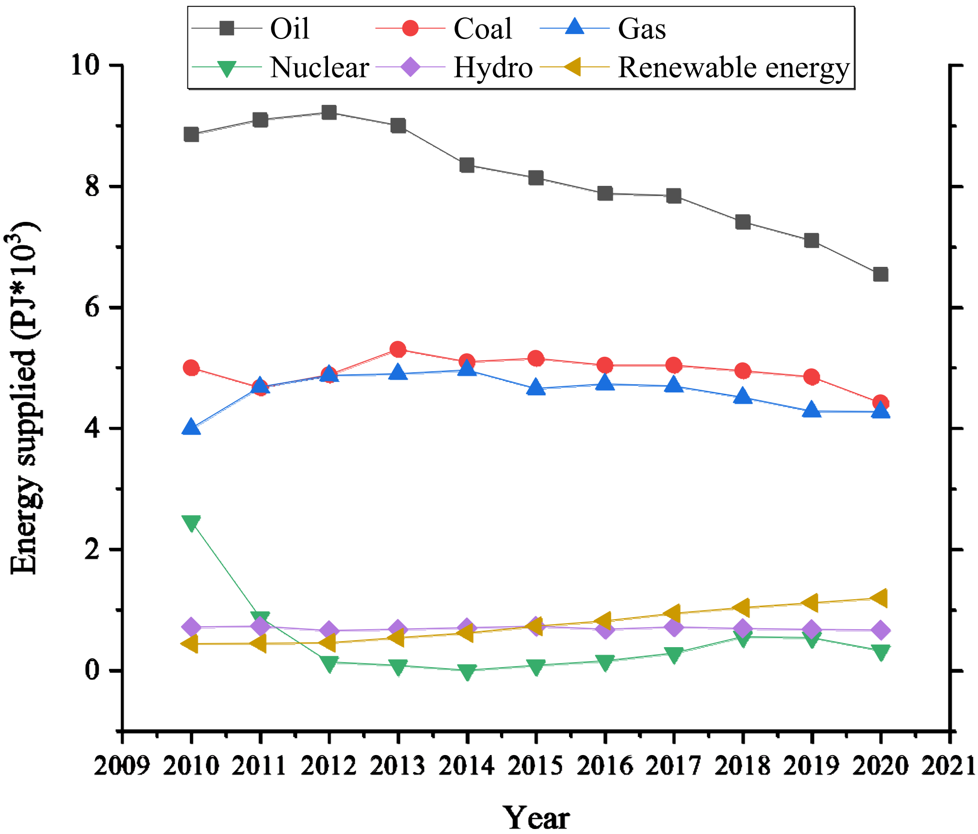
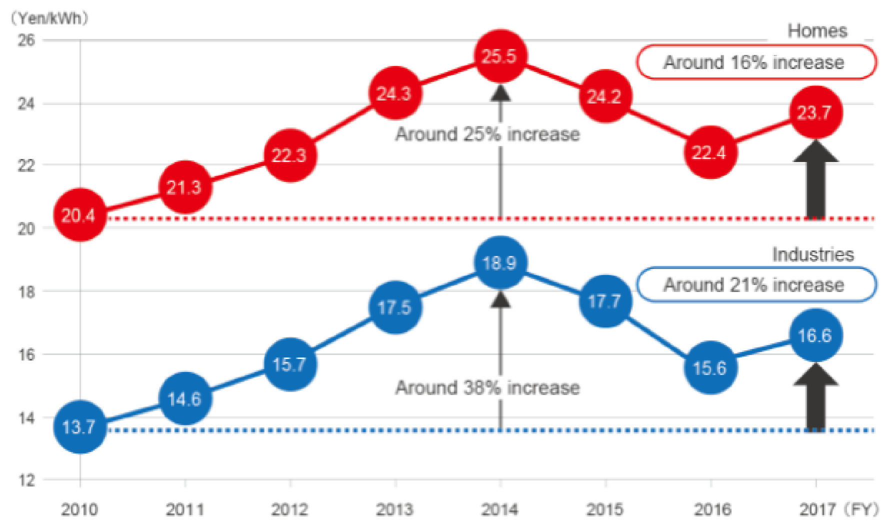


Fig. 1-17 Changes in the Japan composition of power sources (supply) (upper and lower) [6]

Fig. 1-17 shows the changes in power generation structure in Japan in recent years. Since the 2011 East Japan earthquake, nuclear power generation has plummeted. Compensate for closed nuclear power generation by increasing thermal power operation. As a result, fossil fuel power generation increased and peaked in 2014. Due to the shortage of resources in Japan, fossil fuels depend on overseas imports. Therefore, the power generation cost gradually increased after 2011 and reached 18.9yen/kwh (plant power) in 2014 (as shown in Fig. 1-18). However, due to the technological progress of renewable energy and FIT system subsidies, the power generation of renewable energy also showed an increasing trend after 2011 and reached 8.1% of the total power generation in 2017. At the same time, due to the lowest marginal cost of renewable energy and the reduction of initial investment, the electricity price began to decline again. In recent years, another factor affecting electricity price is the "surcharge" paid by power users. The surcharge increases year by year, which is one of the reasons why the electricity price increases again in 2017.

Changes in average electricity rates



Source: Created based on monthly reports of generated and received electric power, and financial materials of each electric power company

Fig. 1-18 Changes in average electricity price in residential and industrial aspect [16]

By analyzing the development of renewable energy from 2010 to 2017, it can be found that the average annual installed capacity increase rate from 2010 to 2012 is 9% (as shown in Fig. 1-19). After the implementation of FIT scheme in 2012, renewable energy showed a surge trend, with an annual increase rate of 22%. Among them, solar PV installation accounts for the main position of installation increment. By 2017, the installed capacity of renewable energy has exceeded 6000GW. The details of surcharge after introducing FIT scheme are depicted in Fig. 1-20. According to the unified national unit price, the expenses required for purchasing renewable energy shall be taken as the levy corresponding to the power consumption (renewable energy power generation surcharge price), which shall be borne by the guests using power. In addition, regarding multi energy consuming enterprises, there is a tax deduction system for promoting renewable energy power generation. Since the introduction speed of renewable energy may deviate between regions, an organization for adjusting its burden (cost burden adjustment organization) is set up. The cost burden adjustment organization temporarily recovers the collection amount collected by each power company according to the national unified unit price, and then pays subsidies to each power company according to the acquisition cost. The calculation of surcharge price is expressed as follows [17,18]:

$$surcharge\ price = \frac{the\ purchase\ cost\ in\ the\ relevant\ fiscal\ year}{the\ estimated\ power\ supply\ amount\ of\ the\ electric\ power\ company}$$

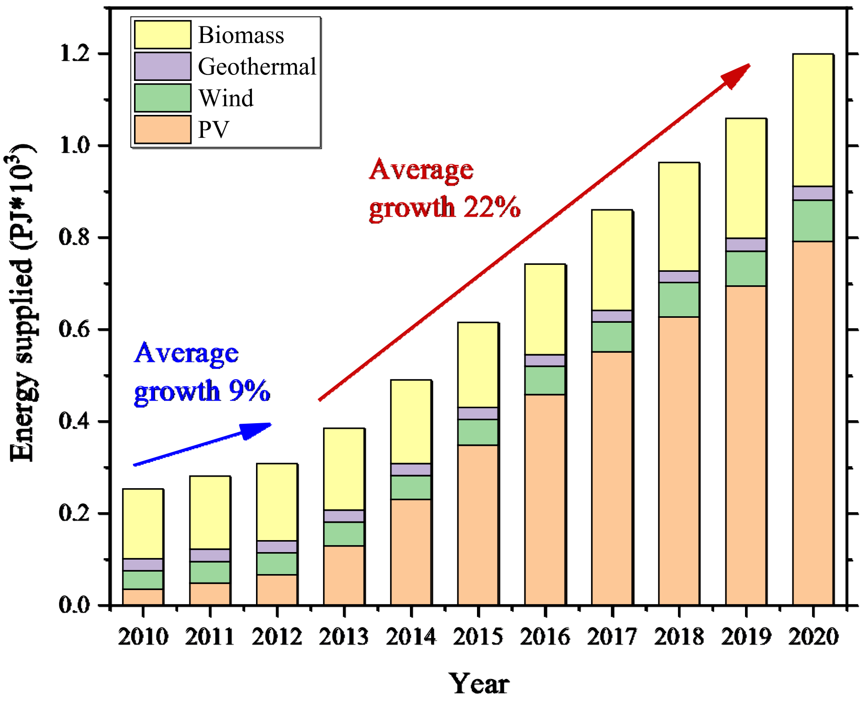


Fig. 1-19 Changes in the installed capacity resulting from renewable energy (except for large scale hydroelectric power) [19, 20]

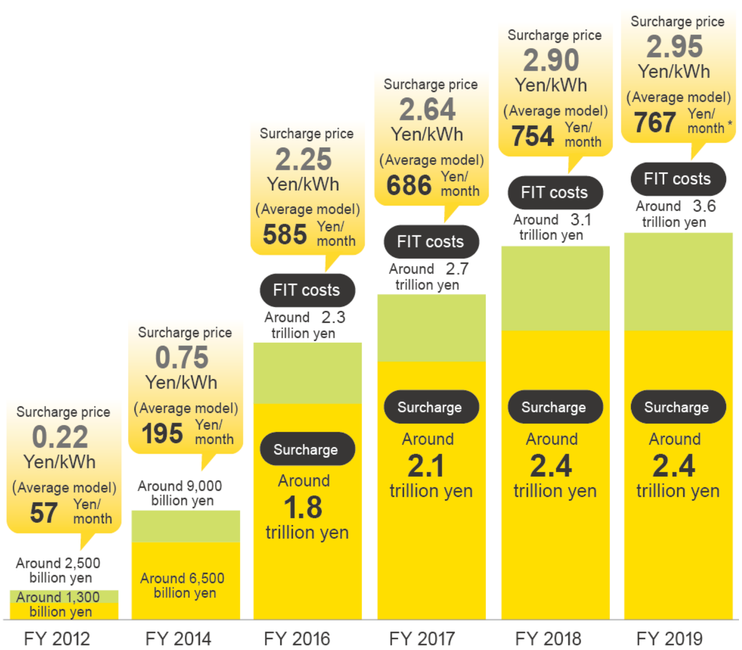


Fig. 1-20 Trends in surcharge after introducing FIT scheme [6]

② Summary of the characteristics and problems of Japan's renewable energy development

Combined with the changes in Japan's energy structure mentioned above, the characteristics of Japan's new energy market generally include the following aspects [21].

First, the overall scale of the new energy market is relatively small. As mentioned above, before 2000, the scale of renewable energy supply was always small, maintaining roughly at the level of 7 million kiloliters of crude oil equivalent, accounting for less than 2% of the primary energy supply. In the 21st century, the scale of renewable energy supply has increased significantly, especially after the implementation of the FIT system, the scale of new energy supply has increased significantly. However, the overall scale is still small. Taking 2017 as an example, the supply scale of renewable energy was 23.79 million liters of crude oil equivalent, accounting for less than 5% of the total primary energy supply, only 1/9 of the oil supply and 1/20 of the three major fossil energy sources.

Secondly, the market for renewable energy is growing with a faster rate. Although the overall market size of renewable energy in Japan is small, the market has grown rapidly, especially after the Fukushima nuclear accident. The implementation of the FIT system has greatly promoted the development and utilization of renewable energy. From the perspective of the primary energy supply of renewable energy, from 2013 to 2017, the scale of renewable energy supply increased by 17.9%, 16.2%, 19.2%, 10.8%, and 14.7% respectively, with an average annual growth rate of over 15%, far exceeding the overall growth level of primary energy supply. From the perspective of the energy structure of power generation, the power composition renewable energy such as PV power generation, wind power generation, geothermal power generation, and biomass power generation has increased to a certain extent in the proportion of total power generation. And the power generation has grown rapidly. The annual growth rates in 2017 were 11.0%, 9.7%, 25.6%, 27.6%, 24.8%, 19.9%, 15.4%, and the average annual growth rate reached more than 19%. Especially photovoltaic power generation has achieved rapid growth. The annual growth from 2011 to 2017 reached 36.6%, 36.7%, 98.7%, 78.1%, 48.7%, 31.5%, and 20.3%.

Thirdly, there have difference in the development of variable types of renewable energy. In recent years, to achieve energy security, stable supply, energy conservation, and emission reduction goals, Japan has launched many plans and policies to promote the development of the renewable energy industry. Especially after the introduction of the FIT system, the new energy industry has developed rapidly. However, from the perspective of the renewable energy industry and the market, there presents different in the development of renewable energy type. From the perspective of power generation scale, PV power generation plays the dominant position, followed by biomass energy utilization, wind and geothermal power generation. From the perspective of growth rate, PV power generation is the fastest, wind power generation is the second, and biomass power generation is third. The geothermal power generation basically did not increase or even showed negative growth.

Therefore, there are structural differences in the development and utilization of renewable energy, and the development of different energy fields is not balanced enough.

Fourthly, the renewable energy market has policy dependence. In recent years, Japan's renewable energy market has achieved rapid growth, the scale of energy development and utilization has been greatly increased. And the scope of applications has become more extensive. However, it can be seen from the development path that the expansion of the renewable energy market is strongly dependent on policies. Whether it is energy development or energy conversion and utilization, policy guidance and encouragement are very significant, including financial subsidies and tax incentives for energy companies to develop renewable energy. At the same time. the mandatory grid connection and price compensation in energy conversion and utilization is also included in the policy encourage. All have played a key role in promoting the development and utilization of renewable energy and expanding the scale of the new energy market [22].

In summary, under the vigorous promotion of the Japanese government, the scale of the renewable energy market has increased rapidly. However, there are still structural imbalances and high policy dependence. In the future, it is still necessary to continuously improve the market system to promote the sustainable and healthy development of the renewable energy industry.

③ The role of renewable energy in Japan's industrial structure

In the 1970s, Japan's energy consumption was higher than the growth rate of its gross domestic product (GDP). Taking the two oil crises as an opportunity, the energy-saving movement centered on the manufacturing industry, energy-saving technologies, and products continue to emerge. Under these conditions, while Japan has achieved economic growth, it has also improved energy efficiency. In the 1990s, international crude oil prices remained low, and energy consumption centered on the household sector and the tertiary industry continued to increase. After reaching a peak value in 2004, energy consumption gradually decreased. Since 2011, affected by the Great East Japan Earthquake, the awareness of energy saving in the whole Japanese society has been further improved, and energy consumption has been reduced accordingly.

From the perspective of various sectors, the energy consumption from 1973 to 2016 was increased by 1.0 times in the industrial sector (0.8 times in the industrial sector and 2.1 times in the tertiary industry), 1.7 times in the transportation sector, and 1.8 times in the household sector. The reasons are that, on the one hand, the development and application of energy-saving technologies and products in the industrial sector have reduced energy intensity; on the other hand, the continuous application and popularization of electrical equipment and automobiles in the household sector and transportation sector has led to an increase in energy consumption. As a result, the market shares of industry, households, and transportation have changed from 74.7%, 8.9%, and 16.4% in 1973 to 62.7%, 14.1%, and 23.2% in 2019 (as shown in Fig. 1-21).

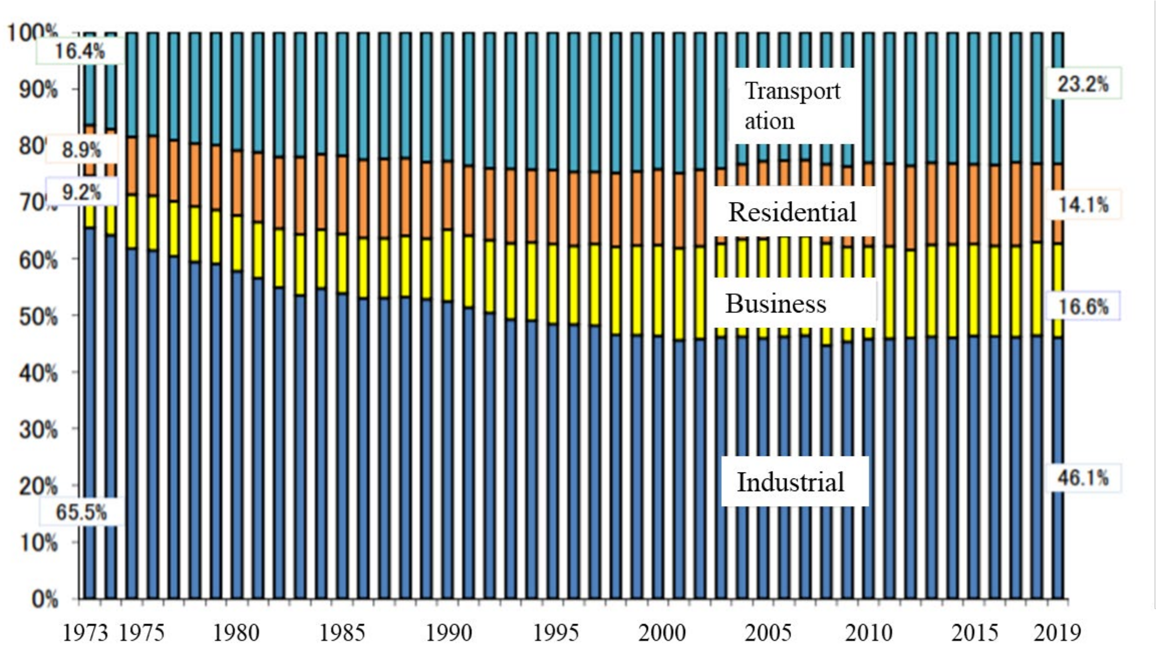


Fig. 1-21 The history of primary energy consumption sector [23]

i Trends in energy consumption in companies, business establishments, and other sectors

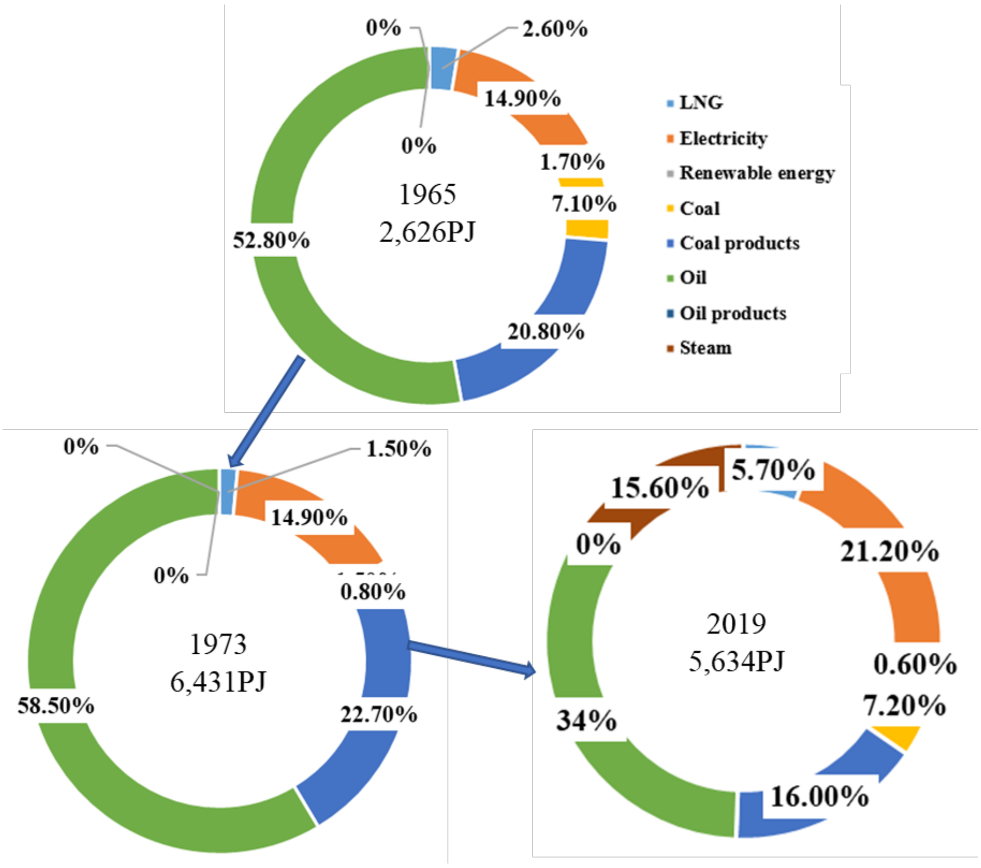


Fig. 1-22 The composition of industrial energy consumption [24]

Take manufacturing energy consumption as an example. From 1965 to 1973 before the first oil crisis, manufacturing energy consumption grew at an average annual rate of 11.8%, which exceeded the growth rate of real GDP. Since then, after the first oil crisis in 1973, there has been a downward trend. During the 10 years from 1973 to 1983, while real GDP has grown, energy consumption has fallen by an average of 2.5% per year. But it started to increase again in 1987, and it exceeded 1973 in 1994. Since 2008, due to the global economic recession caused by the global financial crisis and further progress in energy conservation since the Great East Japan Earthquake, the energy consumption of the manufacturing industry has been lower than the level of 1973. In 2019, it was 2.8% lower than the previous year. Compared with 1973 and 2019, the scale of the economy has increased by 2.6 times, the overall production of the manufacturing industry has increased by 1.6 times, but the energy consumption of the manufacturing industry has dropped by 0.9 times.

Secondly, from the perspective of energy types, the energy consumption of the manufacturing industry. The increase in oil consumption was significant before the first oil crisis in 1973, but after that, progress has been made in the conversion of fuels from the material industry to coal. And oil substitution has made progress (as shown in Fig. 1-22). In addition, since the second oil crisis, urban gas consumption has increased. In addition, due to the complexity of the industrial structure and the automation of manufacturing processes, power consumption has increased by 24.2% in the 46 years since the first oil crisis.

ii Trends in energy consumption in residential sector

Household energy consumption can be divided into five uses: refrigeration, heating, hot water supply, plumbing, power/lighting, etc. (using home appliances, etc.). The share in 1965 was hot water supply (33.8%), heating (30.7%), electricity/lighting, etc. (19.0%), kitchen Insurance (16.0%) and refrigeration (0.5%). With the diversification and diversification of lifestyles, the market share of electricity and lighting has increased. In addition, due to the popularity of air conditioners, the weather is cold. Refrigeration products increased, while heating, pipes, and hot water supply products decreased. Therefore, the market share in fiscal year 2019 will be electricity/lighting (33.9%), hot water supply (28.8%), heating (24.7%), kitchen Insurance (9.9%) and refrigeration (2.7%)). Until around 1965, when the Japanese economy began to grow rapidly, coal accounted for more than one-third of household energy consumption, but it was mainly replaced by kerosene, and coal appeared in 1973. About 6%. At this time, kerosene, electricity, and gas (city gas and liquefied petroleum gas) each accounted for about one-third, but due to the popularization of new home appliances and the increase in size and function, the share of electricity has increased. Significant increase. In addition, with the popularity of all-electric households, the proportion of electricity consumption exceeded 50% for the first time in 2013 and 49.8% in 2019.

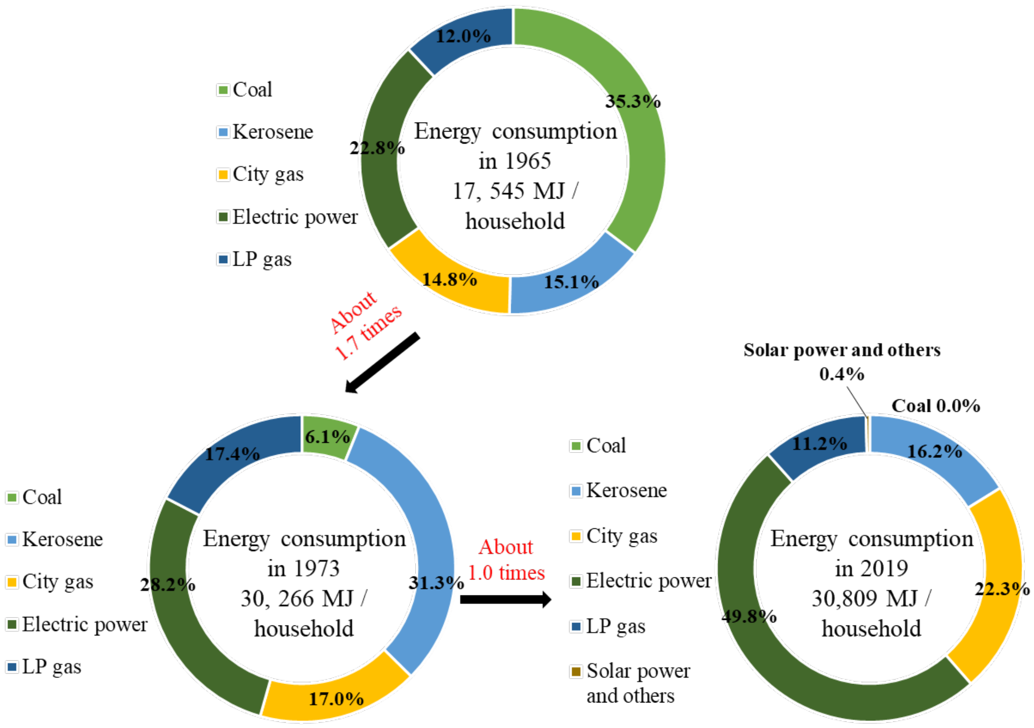


Fig. 1-23 The composition of residential energy consumption [23,24]

At home, a large amount of electricity is consumed by air conditioners such as air conditioners, the running power of refrigerators and washing machines, lighting equipment, and televisions. In addition, standby power consumption8 has been on a downward trend in recent years, but it accounted for more than 5% of total household electricity consumption in fiscal 2012, and there is still room for decline (as shown in Fig. 1-23).

iii Trends in energy consumption in transportation sector

The transportation sector is broadly divided into the passenger sector such as passenger cars and buses, and the freight sector such as land transportation, shipping, and air freight. The transport sector accounted for 23.2% of total final energy consumption in 2019 (passenger sector energy consumption accounted for 59.0% of total transport sector and freight sector accounted for 41.0%. The energy consumption of the transportation sector in 1965 was 798 PJ (18% of the total final energy consumption), and its composition was 41.5% in the passenger sector and 58.5% in the freight sector. 8 from 1965 to 1973. Annual energy consumption increased 2.3 times (10.8% annually) in the transportation sector as a whole, and although the growth rate slowed down after two oil crises, 28 from 1973 to 2001 (3,893PJ), which peaked. The annual increase was 2.1 times (annual increase of 2.8%). On the other hand, since the 2000s, the energy consumption of the transportation sector has started to decrease due to the decrease in transportation volume and the improvement of transportation efficiency. Assuming that the final energy consumption is 100, the consumption level as of 2019 is 195.3 in the passenger sector and 135.3 in the freight sector (as shown in Fig. 1-24).

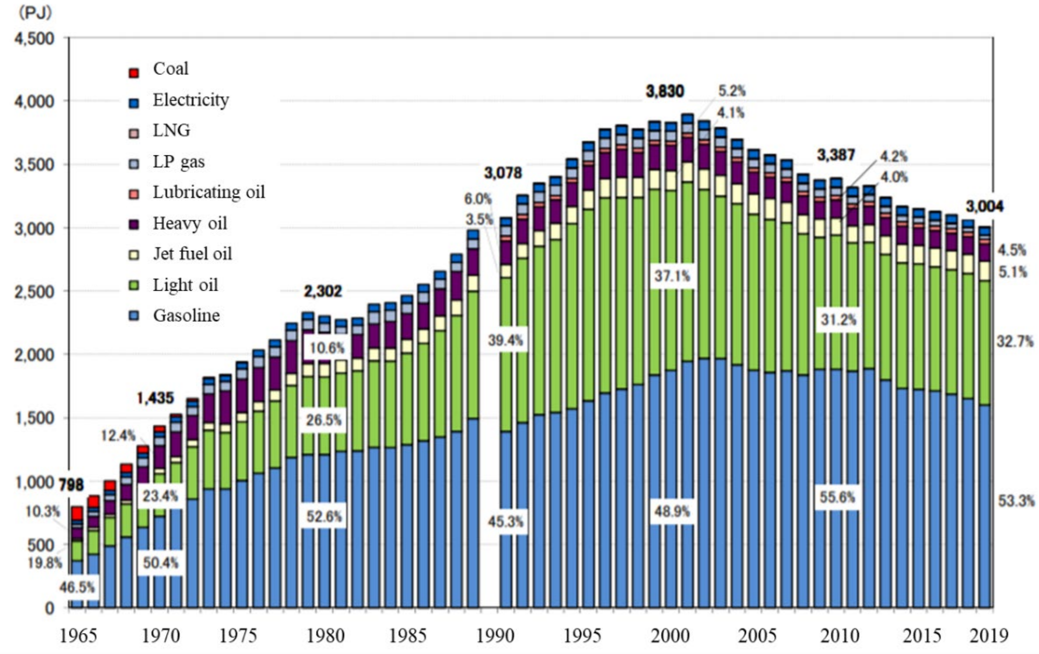


Fig. 1-24 The energy consumption in the passenger sector [23]

1.3 Research structure and logical framework

1.3.1 Research purpose and core content

In the background of safe energy use and the reduced of energy self-sufficiency, the development of renewable energy is imperative. At present, the proportion of the world's dependence on fossil energy still exceeds 50% of the total energy consumption, and it is also a general trend to strengthen the conversion of the power sector. Therefore, the power sector is responsible for energy conservation, emission reduction and energy supply. From a technical perspective, this paper comprehensively analyzes the maximum penetration of renewable energy in the Japanese power grid by combining power generation units on the supply side, load demand side, storage systems, and power grids, and analyzes the interaction between the units in the system.

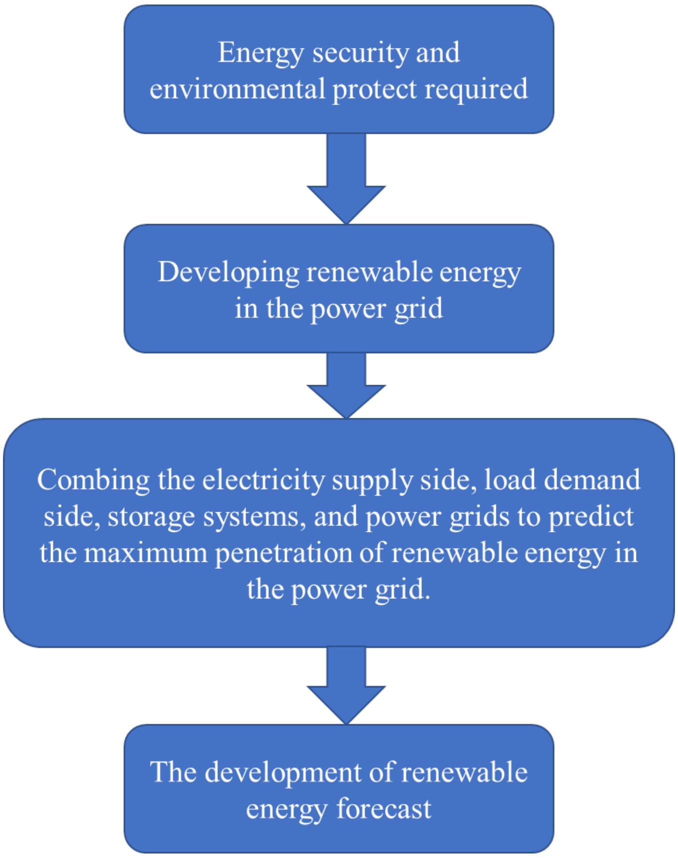


Fig 1-25 Research logic of the article

1.3.2 Chapter content overview and related instructions

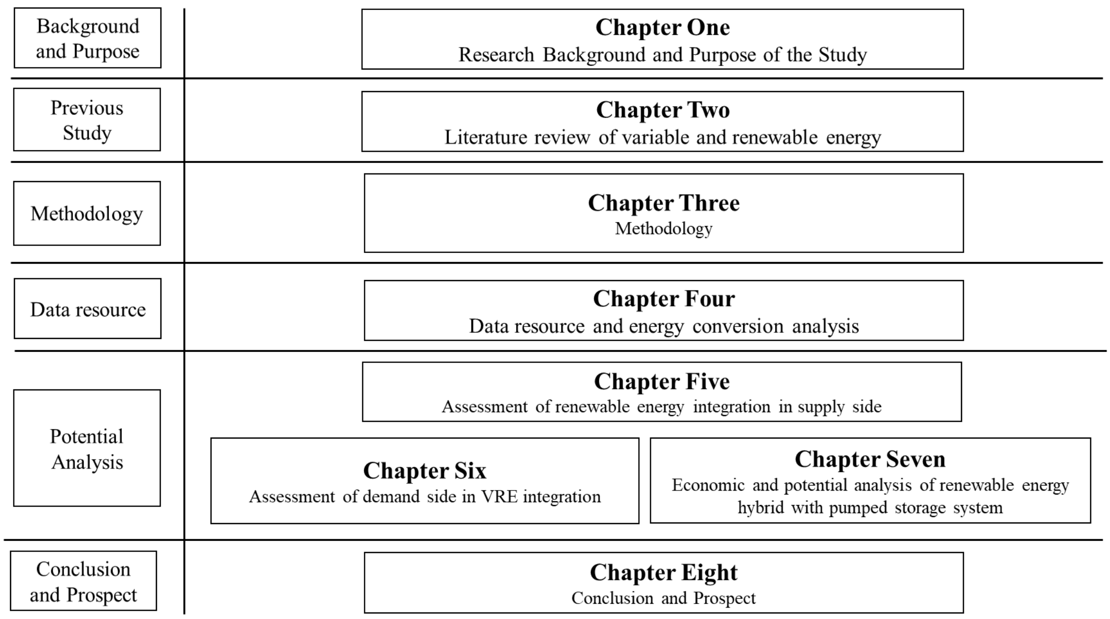


Fig 1-26 Chapter name and basic structure

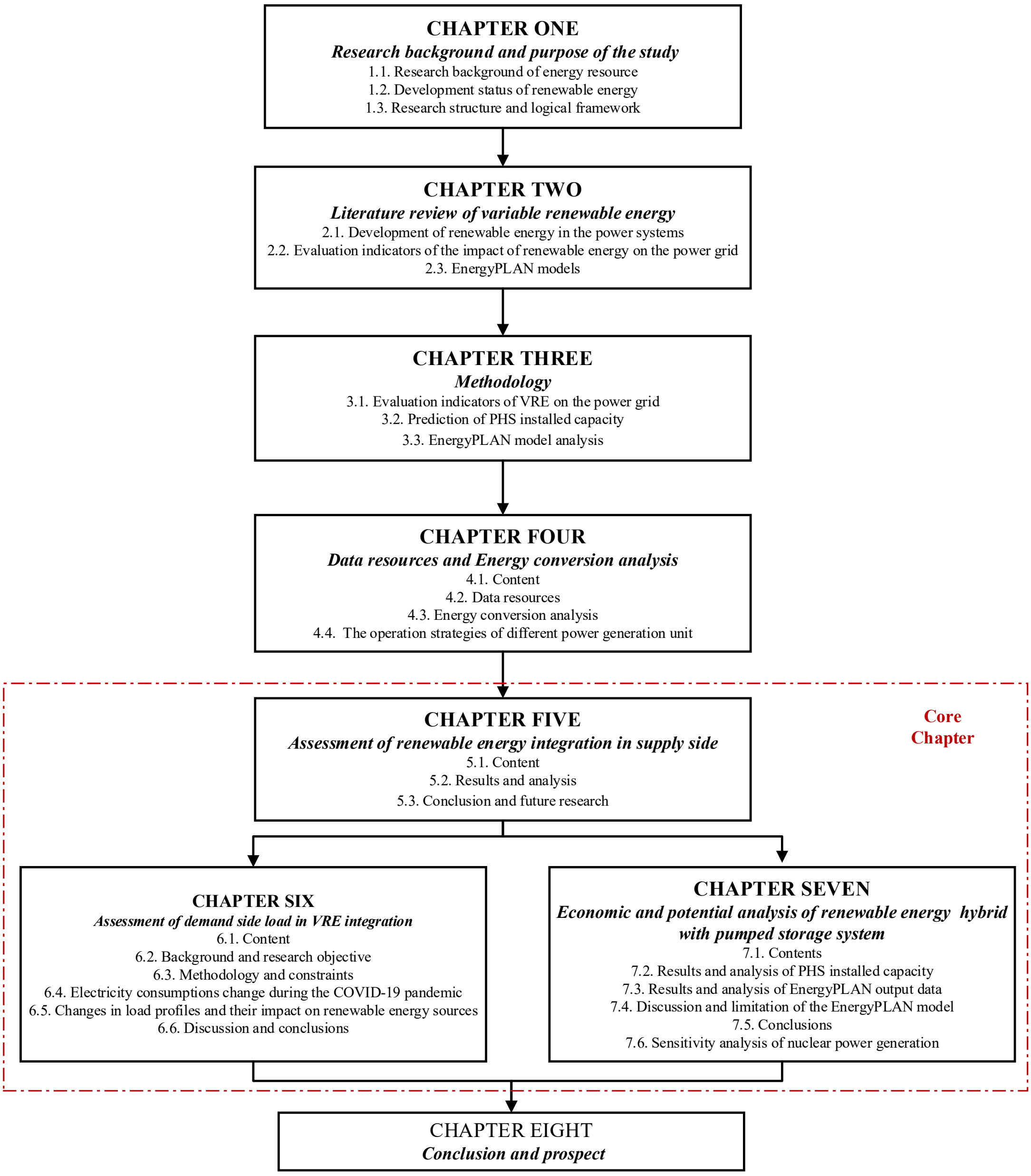


Fig 1-27 Brief chapter introduction

The chapter names and basic structure of this paper are shown in Fig 1-26. Besides, the brief introduction of chapters schematic is shown in Fig 1-27.

In Chapter 1, Research Background and Purpose of the Study:

Given the shortage of energy and the demand for safe supply, the development of renewable energy is imperative. This Chapter analyzes the international energy situation, bottlenecks, and historical evolution. In this way, the necessity of the development of renewable energy can be derived. Secondly, it summarizes the development trend of renewable energy in the international and Japanese regions. The international level combines the evolution of the energy structure and the renewable energy promotion strategies of typical countries, including the United States, Germany, Japan, and China. The region of Japan introduced in detail how renewable energy penetrated the grid and analyzed the evolution of the energy structure in detail in conjunction with the industrial sector, household sector, and transportation sector. This proves the importance of the power system in the stable supply of energy and the reduction of greenhouse gas emissions Finally, the context and chapter structure of this article are described for readers' reference.

In Chapter 2, Literature Review of Renewable Energy System:

This Chapter provides a detailed review of the application of renewable energy systems in this article. Section 2.1 reviews the application of renewable energy in power systems, and then summarizes the performance of renewable energy combined with energy storage units in power generation systems. Section 2.2. first reviews the indicators used to evaluate the impact of renewable energy on the grid, especially capacity credit, residual load curve, payback period, etc. Section 2.3 gives a detailed description and summary of the EnergyPLAN tools used in this article. In general, the review in this section focuses on the application of renewable energy in the power grid, the indicators for evaluating the impact of renewable energy on the power grid, and the methods of model building.

In Chapter 3, Methodology:

This Chapter describes the research methods used in this paper. Including the calculation of indicators to evaluate the impact of VRE penetration on the grid, the prediction method of pumped storage, and the establishment and use of the EnergyPLAN model. Section 3.1 shows the technical aspects of the impact of VRE penetration on the power grid. The credit evaluation of the available capacity is based on the concept of the residual load duration curve. In terms of economy, the dynamic payback period of PV is adopted. Compared with the static payback period, the dynamic investment payback period adds a time cost. The PHS prediction method is documented in detail in section 3.2. Section 3.3 shows the specific operating modes and limitations of EnergyPLAN in this paper.

In Chapter 4, Data Resource and Energy Conversion Analysis:

The data resource and energy conversion analysis in this paper is shown in Chapter 4. The power grids of Kyushu, Tokyo, Kansai, and Hokkaido power grid is selected, which is featured with different power generation compositions and load profiles. Besides, as the eliminating progress of fossil fuel energy to renewable energy, the energy conversion management is employed in this paper. For the energy management system, the operation strategies of power generation unit are also explained.

In Chapter 5, Assessment of Renewable Energy Integration in Supply Side:

The impact of massive integration of variable renewable energy on the power grid is well-established. This Chapter focus on the impact of electricity supply side on power grid. Two evaluation indicators are employed to limiting the continuous introduced of variable renewable energy. Based on the residual load duration curve method, the new method combines a renewables capacity credit analysis indicator and dynamic investment payback period (DIPP) to explain the impacts on the reduction of peak load and renewables curtailment. Real data were used from the power grids of Kyushu, Tokyo, Kansai, and Hokkaido in Japan. The results and analysis of variable renewable energy implementation limitation and its impact is well explained in this Chapter.

In Chapter 6, Assessment of Demand Side in variable renewable energy(VRE) Integration:

The COVID-19 pandemic has had a significant negative influence on energy consumption in 2020. On April 7, 2020, in response to the rapid spread of the infection, the Japanese government imposed a state of emergency. This action impacted energy consumption, energy production, and electricity prices. This Chapter compares the impact of a reduction in load demand on renewable energy in the Japan public power grid under a state of emergency declaration (April to May 2020). Using publicly available data, comparisons are made for Kyushu, Tokyo, Kansai, and Hokkaido and assessed in relation to epidemic severity and geographical distribution. Therefore, this Chapter mainly analysis the changes of load profiles on the power generators of supply side.

In Chapter 7, Economic and Potential Analysis of Renewable Energy Hybrid with Pumped Storage System:

This Chapter exploits the existing small and medium-sized dams in Japan to predict the possible installation capacity of PHS in the study area. Combining with the phase-out of thermal power, analyze the basic load power supply equipment contributes to regional VRE penetration. Kyushu and Hokkaido power grids with different power generation structure and electricity demand profiles as case study. Scenario settings are based on hourly power demand and supply curves using the EnergyPLAN tool. The results mainly concentrate on the prediction of pump storage system(PHS) installed capacity in research area, and its contribution to the balance of power grid as well as the continuous integration of variable renewable energy.

In Chapter 8, Conclusion and Prospect:

The conclusion of each Chapter is concluded.

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Chapter 2

LITERATURE REVIEW OF RENEWABLE ENERGY SYSTEM

CHAPTER TWO: LITERATURE REVIEW OF RENEWABLE ENERGY SYSTEM

2.1 Development of renewable energy in the power systems

2.1.1. Variable renewable energy (VRE) studies

Since the beginning of the Industrial Revolution in the 19th century, global warming has occurred. The inducement of global warming is the emission of greenhouse gases, especially carbon dioxide, which is mainly produced by human beings. As of 2021, 194 countries have signed the Paris Agreement with the European Union, including China, Japan, the United States, and so on. The agreement aims to respond to the threat of global climate change, limit the global temperature rise to well below the pre-industrial level 2 degrees Celsius, and strive to further limit the temperature rise to 1.5 degrees Celsius [1-3]. As the main energy consumption unit, power generation units are expected to reduce the utilization rate of fossil fuels to reduce carbon dioxide emissions [4]. On the other hand, limited by fossil fuel resources, the energy self-sufficiency rate in Japan does not exceed 8% [5]. Faced with the dual threats of the environment and energy supply security, it is imperative to develop renewable energy. Among them, renewable energy represented by PV and wind energy has developed rapidly in recent years. Since Japan implemented the FiT system in 2011, the installed capacity of PV has increased nearly 10-fold compared to 2011 [6,7]. However, with the massive integration of PV and wind into the grid, their periodicity and variability nature put pressure on the supply and demand balance of the power grid [8,9]. PV and wind energy are called VRE because of their variable power generation characteristics [10]. Based on the data from Japan's Electric Power Companies, the PV power suppression phenomenon occurred for the first time on October 13, 2018 [11], the utilization rate of renewable energy is reduced accordingly.

① PV integration

Limited by fossil fuel resources and environmental mitigation, the development of renewable energy is urgent [12,13]. Japan's PV installed capacity ranks third in the world [14], and the rapid deployment of PV has a major impact on the operation of the national power system. In the past, the overall renewable energy in Japan's power sector accounted for a relatively low proportion. Hydropower has always been the only major renewable energy source, and its resource endowment has almost been exploited and utilized. However, the FIT system has accelerated the installation of PV, and the overall proportion of renewable energy in the power generation structure has increased from 9% in fiscal year 2011 (FY) to 15% in fiscal year 2016. In particular, the ratio of renewable energy excluding hydropower increased significantly from 1.4% in FY2011 to 7.7% in FY2016. In FY2016, the proportion of solar photovoltaics increased to 4.7% [15]. In Japan, with the launch of the FiT system in 2012, PV power generation started developing nationwide, and the installed capacity of the PV system increased sharply from 100MW in 2011 to 10GW in 2019 [16,17]. The installed capacity distribution of PV in worldwide is expressed in Fig. 2-1. China accounts for the largest PV installed capacity in the worldwide, followed by US, Japan, Germany, India, Italy, Australia, South Korea, UK, and Spain. It have a rapid growth after a series of policies implemented.

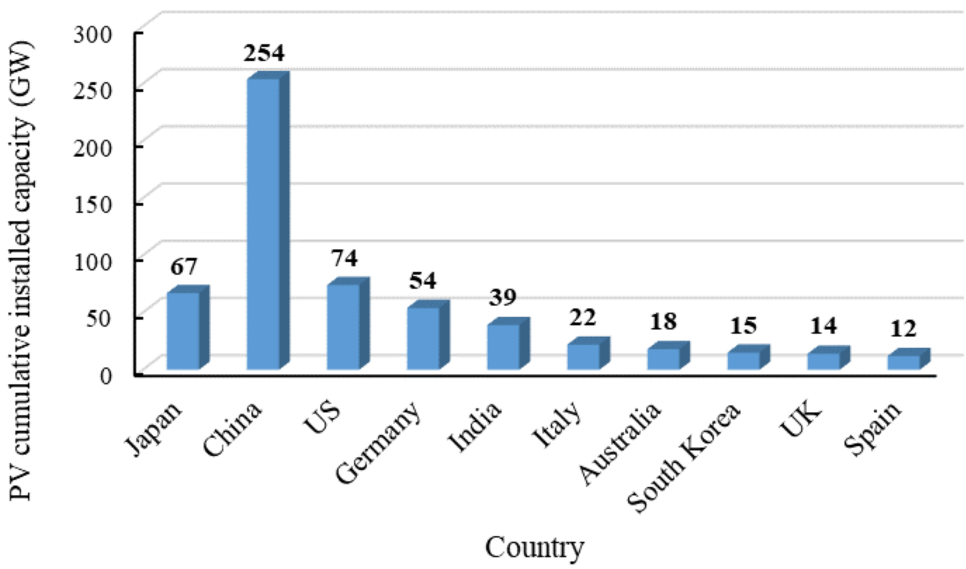

Fig. 2-1 Installed PV capacity in Japan on 2017 [15]

However, with the integration of massive accounts of PV power into the grid, it resulted in compression of base load generators [18]. When the electricity supply exceeds the demand, Japan's public power grid gives priority to the use of pumped storage and regional connecting lines for electricity dispatchment. Based on the current priority feeding rule, the power curtailment of PV power generation is then carried out to adjust the excess electricity [19]. In addition, to increase the penetration of PV, energy storage systems [20], regional transmission lines [21], hydrogen production [22], battery [23], and other flexible systems are used to power peak shaving and valley filling. These citied studies focus on analyzing the impact of variable PV penetration rates on the public grid, or how to increase the penetration rate of PV in the grid. The difficulty in accommodating a large number of PV power grids comes from the mismatch between the electricity demand curve and PV power generation. Fig. 2-2 describes the PV installation capacity of nine public grids in Japan, including the existing and planned PV capacity, together with the maximum and minimum power demand.

As shown in Fig. 2-2, in Kyushu, Tohoku, and Shikoku, the total scale of existing and planned PV capacity exceeds or is comparable to the maximum power demand. It is worth noting that in Kyushu and Shikoku regions, the existing PV capacity has exceeded the minimum power demand. PV output has significantly affected the existing grid operations in Kyushu and Shikoku regions, and PV grid-connected opportunities in these regions are on the verge of exhaustion. On the other hand, the PV capacity of the Kanto, Chubu and Kansai service areas is much lower than the grid scale, and it is technically feasible to further install PV installations in these areas. Therefore, there is a clear imbalance between the scale of Japan's power grid and the scale of PV. The government also recognizes these problems and predicts that there may be even greater annual PV curtailment rates in the future, such as 26.3% in Kyushu, 40.7% in Tohoku and 41.2% in Hokkaido [23]. Therefore, to effectively deploy large-scale PV, it is essential to more effectively operate the grid to solve the imbalance between the scale of PV and the grid by optimizing photovoltaic grid connection [15].

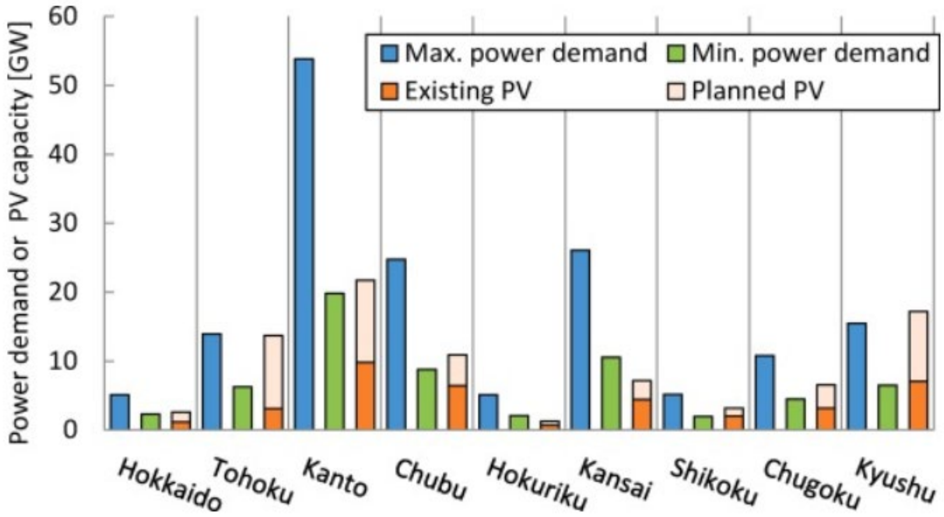

Fig. 2-2 Maximum and minimum power demands with existing and planned PV capacity in Japan in 2017

② Wind integration

The installed capacity possibilities of renewable energy resources in Japan are depicted in Fig. 2-3 [24,25]. Wind dominant the installed capacity potential, followed by PV, geothermal, and hydro (small-scale). The depletion of large-scale hydroelectric power stations in Japan resulted the potential capacity for hydro power keeps at small-scale. The situation of wind power and other renewable energy has changed drastically after the Great Eastern Earthquake and Tsunami in early 2011 and the subsequent Fukushima nuclear power plant accident. The FIT system is introduced, and the reform of the power sector is slowly advancing. Although wind energy has greater potential than other renewable energy sources in Japan (as shown in Fig. 2-3), so far, FIT has not increased the installed capacity of wind power. Besides, the number of bottlenecks has also hindered the large-scale market deployment of wind power. Limited grid capacity, the current power market structure, and the grid operation practices of existing power companies all restrict the grid access of wind power projects.

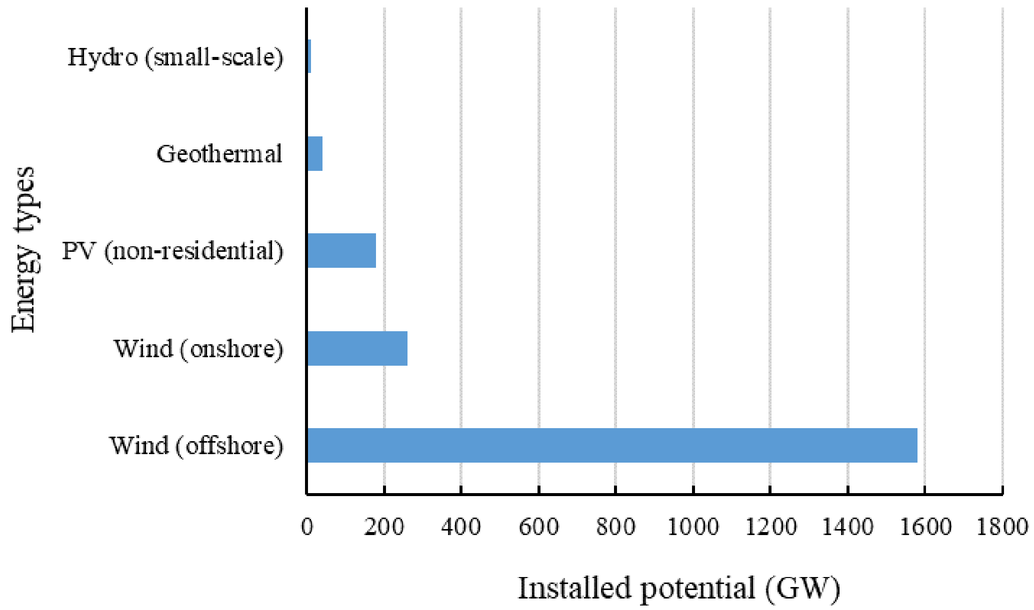

Fig. 2-3 Resource potential of renewable energy in Japan, compiled form (MOE 2011)

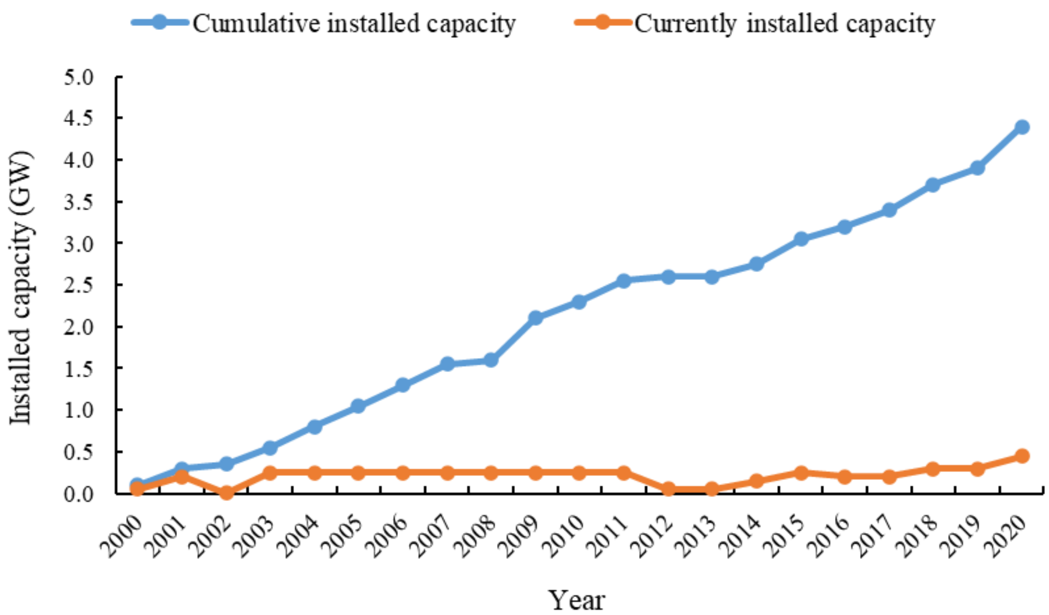

Fig. 2-4 Annual and cumulative wind energy installation in Japan (2000–2020)

The installed capacity of wind energy in Japan up to 2020 is shown in Fig. 2-4 [26]. The 2000 Green Certificate Program brought the first boost. Although installations in 2002 declined with the anticipated introduction of the RPS system in 2003, the combination of the Renewable Portfolio Standard (RPS) and capital subsidies supported an annual installation of approximately 250 MW between 2003 and 2010. However, Japan failed to achieve the 3 GW wind energy target in 2010.

Due to the anticipated FIT introduction that led to the cessation of NEDO's capital subsidies for wind energy projects in fiscal year 2010, wind energy installations fell by 20% between 2010 and 2011. In the past two years, due to the increasing difficulty in finding suitable land-based project sites, the application of the National Environmental Impact Assessment (EIA) to wind energy projects (from October 2012) and the end of capital subsidies, the number of installations has decreased, despite the introduction of FIT system took effect on July 1, 2012 [27].

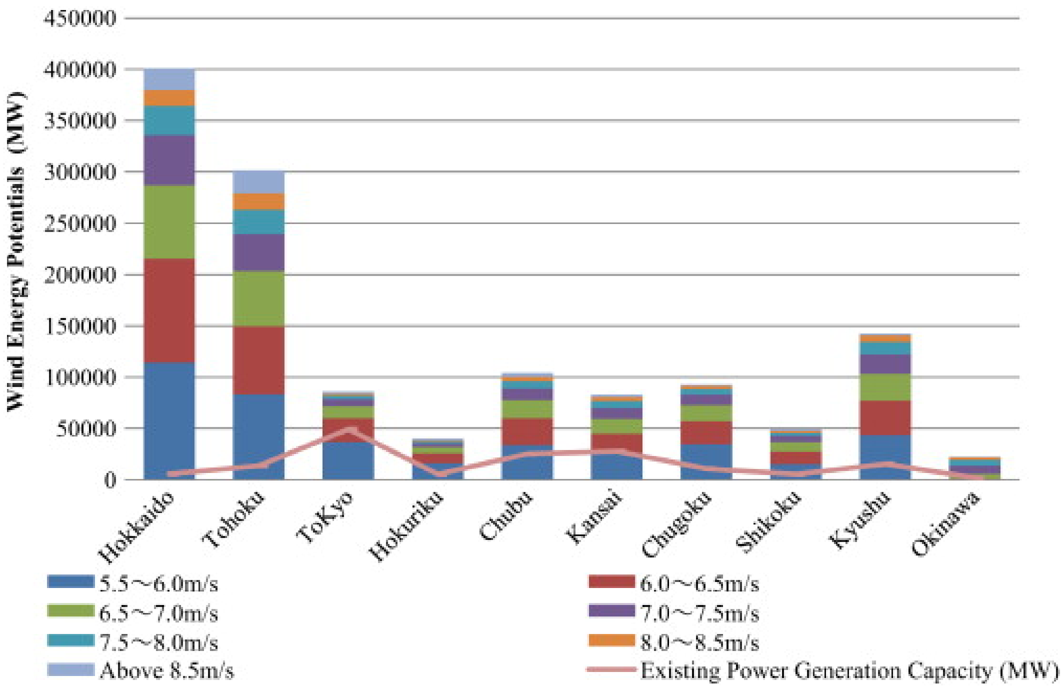

Fig. 2-5 Wind energy potentials and existing power generation capacity by Electricity Power Company

Geographical distribution of wind resources is quite uneven across Japan. Fig. 2-5 shows wind energy potentials examined by the MOE (2011) and the existing power generation capacity for each Electricity Power Company area, illustrating that wind energy resources are concentrated in Hokkaido, Tohoku, and Kyushu Electricity Power Company area regions, but the demand centers indicated by the existing power generation capacity are in the areas supplied by the Tokyo, Kansai, and Chubu area. Thus, the regions with good wind resources do not have strong demands. Also, good wind resources are remotely located areas with no transmission lines or very small capacity lines, making it very difficult to connect large-scale wind energy projects without fortification of transmission line capacity within each region. This regional discrepancy of market demand and wind energy supply also creates the necessity for a strong transmission grid between regions in order to transmit wind-generated electricity from Hokkaido, Tohoku, and Kyushu to the demand centers such as Tokyo, Kansai, and Chubu regions [27,28].

In the aspect of technical bottlenecks, power generation companies usually use possible voltage fluctuations, difficulty in maintaining an appropriate frequency, and handling of the surplus power generated intermittently by wind and photovoltaic power generation as reasons to justify the grid connection limit. Due to the isolation of regional markets, there is no strong regional interconnection. Each power generation company must strictly match the supply and demand in each region. The intermittent nature of wind will cause difficulties in balancing supply and demand. The actual problems of wind power grid integration vary from regional power company to regional power company. For example, the Tohoku, China, Shikoku, and Kyushu power companies lack flexible and controllable power generation capacity, and there is a problem of insufficient downstream reserves when demand is low and air volume is large. During periods of rapid demand changes, all public grids lack the ability to control long-term (20 minutes to 6 hours) fluctuations and steep slopes caused by wind power.

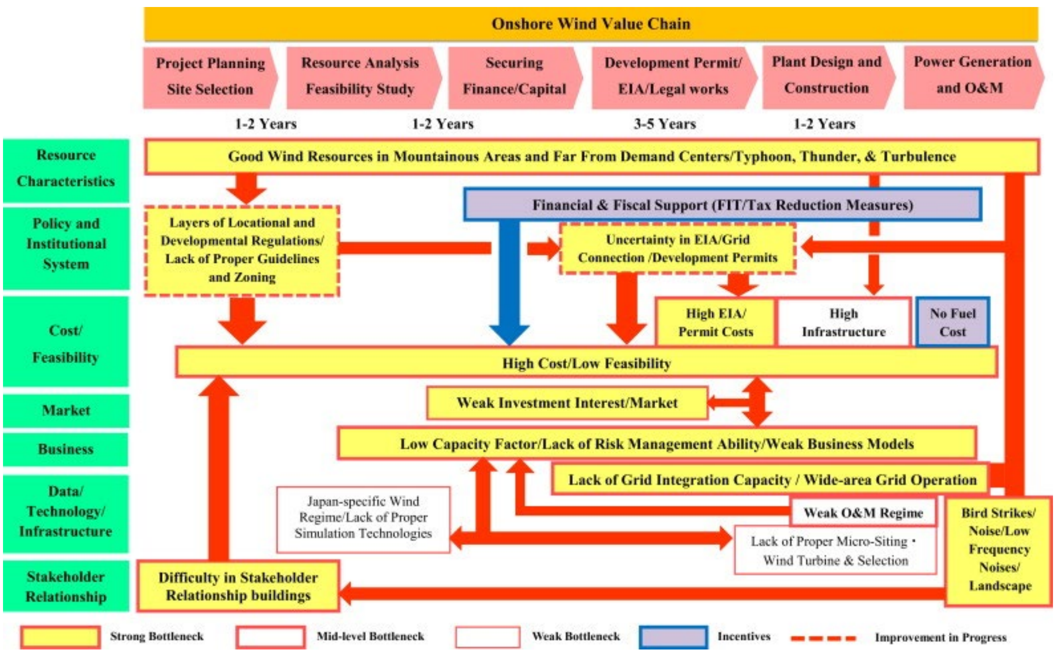

Fig. 2-6 Current bottlenecks and risks of onshore wind energy development in Japan [28].

Fig. 2-6 shows the risks and bottlenecks in typical wind power project process value chain, resource characteristics, policies, and regulations on the horizontal axis, illustrating the risks and bottlenecks, data/technologies, and data/technologies that hinder the large-scale deployment of onshore wind energy in Japan. Infrastructure, business practices, costs, markets, and stakeholder relationships on the vertical axis, as well as the relationships between them.

Each value chain activity has multiple bottlenecks, causing uncertainty and high risk, increasing the project lead time, and pushing up the risk premium and cost at all stages of the project. Although it is impossible to change the characteristics of natural wind resources, most of the bottlenecks are man-made. Insufficient grid capacity, unclear rules, and unclear operating procedures for wind power projects to connect to the existing grid are another major bottleneck. Although the integration of large amounts of wind and solar energy into the grid is currently a strong interest of countries wishing to add intermittent renewable energy to their energy mix, the scale of Japan’s problems is quite different from that of countries that already have strong winds. Energy deployment records in Germany and Spain. The current vertically integrated and regionally isolated small power market structure and the lack of transparent grid connection rules require major institutional changes. The issue of social acceptance is another very critical issue. These problems mean that the Japanese market is still small, depriving them of the opportunity to create economies of scale in cost reduction, wind turbine manufacturing, and operation and maintenance practices. In addition, the NEDO capital subsidy that lasted for more than 15 years before the introduction of FIT in 2012 resulted in a weak industry business model, lack of risk management capabilities and efforts to reduce costs.

In the face of these bottlenecks, from a technical perspective, strengthening the grid capacity and large-scale operation of the grid is the key to increasing the scale of wind power grid connection and solving the problem of regional wind energy supply and demand imbalance. This must be combined with power sector reform and long-term wind energy goal setting. Complete market opening will also promote the development of wind energy by realizing the hidden market demand for wind energy. In addition, reforms need to clarify the responsibilities of grid management and investment [28].

③ VRE integration

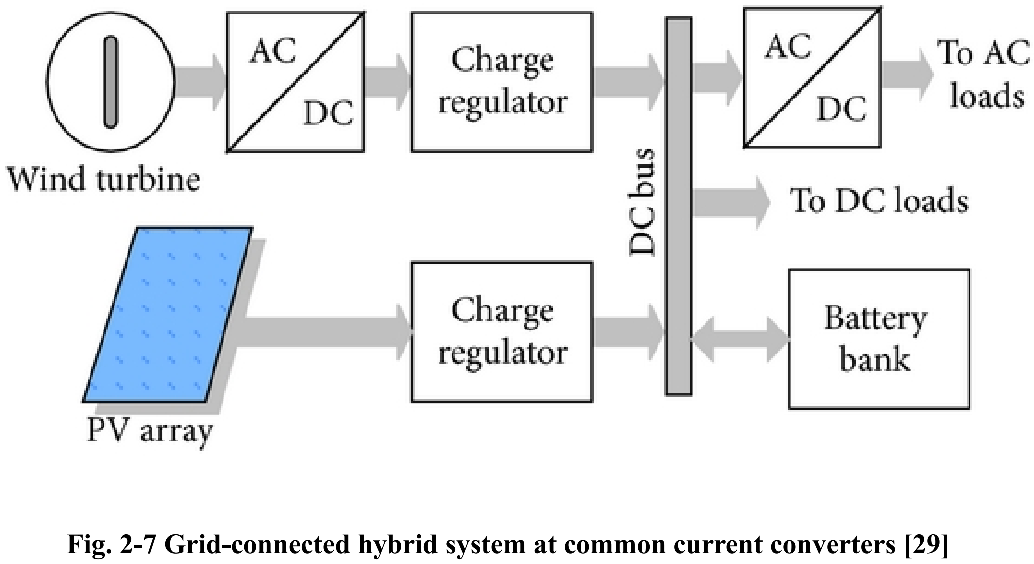

Fig. 2-7 Grid-connected hybrid system at common current converters [29]

The power generation characteristics of PV and wind energy are different. PV power generation affected by sunlight is mainly concentrated in the daytime and changes periodically over time. The wind speed is more unknown than PV and fluctuates at any time 24 hours a day. Therefore, both PV and wind energy are affected by geographical environment and climate environment. However, due to the cleanliness and low marginal cost of renewable energy, the comprehensive utilization of these renewable energy sources has become more and more attractive. And is widely used as a substitute for petroleum production energy. Renewable energy is also promising in terms of technology and economy. The renewable hybrid energy system consists of two or more energy sources, a power regulation device, a controller and an optional energy storage system. The grid-connected hybrid of PV and wind system is depicted in Fig. 2-7.

i Technical analysis

In terms of technical analysis, PV and wind energy systems cannot provide continuous power supply because these systems can only generate electricity on sunny and windy days. Therefore, the combination of these two sources can increase the overall penetration of electricity in the grid. Based on long-term weather data and power demand curves, an optimization model is established to find the optimal size and capacity of PV and wind energy. Artificial intelligence technologies such as fuzzy logic, genetic algorithms, and artificial neural networks are often used. In addition, optimization performance indicators such as net present value [30], energy index reliability, expected energy supply [31], energy cost [32], etc. are often used. These indicators can be used to determine the reliability of the project.

At the same time, the increase in the penetration rate of grid-connected renewable energy has an impact on the power quality of the grid, especially the weak grid. Voltage fluctuations, frequency fluctuations and harmonics are the main power quality issues. In addition, the intermittent energy of solar photovoltaic and wind energy has a huge impact on network reliability. However, accurate forecasting and scheduling systems can minimize the impact. Various statistical prediction and regression analysis methods and algorithms are used to predict weather patterns, solar radiation and wind speed [33-36]. System operators can adjust other flexible power generation units in the system to cope with any shortage or surplus of renewable energy power generation [37]. This will reduce the impact of renewable energy generation fluctuations. In addition, by distributing renewable energy in small units to a larger geographic area, instead of concentrating large units in one area, the intermittent effect of renewable energy power generation can be controlled [38]. Batteries or energy storage equipment can be used as a balancing device to provide electricity when renewable energy generation is insufficient, and to store excess energy when renewable energy generation has surplus power [39-41].

ii Economic analysis

In terms of economic analysis, for a long time, the economics of the power sector have been estimated based on the levelized cost of energy or electricity (LCOE) [42]. Using the cash flow method to calculate the total life cycle cost of a plant per unit of electricity output allows us to compare the relative competitiveness of various power generation technologies. However, in recent years, with the rapid decline of VRE's LCOE, system-level cost or integration cost, as an additional cost brought about by the high penetration rate of VRE, has also attracted considerable attention and has become the focus of attention [43,44]. In recent years, the cost estimation in the case of a high penetration rate where the VRE penetration rate is close to 100% has been noticed. Most of these studies focus on Europe [45-50] Europe-North Africa model [51], used in a subregion of Europe [52] or a single country, such as Scotland [53] and the United States [54-57]. But in recent years, some studies have also analyzed the situation in other regions, such as Canada [58, 59], Chile [60], Australia [61], China [62,63], India [64], Saudi Arabia [65], Africa [66] and Pakistan [67]. The results of these studies show that the integration cost depends largely on multiple regional specifications, such as the load factor of wind and solar photovoltaic power generation, the expected ratio of these two technologies, and other meteorological and geographic conditions. Therefore, when investigating the feasibility of global deep decarbonization, specific regional studies are considered essential.

In terms of data interval, although early research divided a year into dozens or hundreds of time slices to formulate optimization problems [68], recent research used more than 8,760 time slices (that is, they used a resolution of one Hours or higher). For this reason, it is necessary to estimate the hourly wind and solar photovoltaic power generation in a given area throughout the year, and some studies have attempted to build databases for this purpose (for example, wind energy [69] and solar PV [70]). At the same time, because these calculations consume a lot of machine time, simpler methods have been proposed, such as the use of residual load duration curves (RLDC) [71], with the purpose of incorporating system cost analysis into a comprehensive evaluation model, such as REMIND [72] And MESSAGE [73,74].

The cost of 100% renewable energy in Japan is higher than in other countries. It is estimated that Japan’s unit power generation cost in 2050 is 12.6 cents/kWh [75], which is higher than the world average. Given that more than 80% of Japan's energy supply is assumed to come from PV, the high cost seems to be related to Japan's high PV cost. In fact, the actual initial cost of PV in Japan in 2017 was much higher than that of other countries [76], with a residential cost of US$2.37/Watt and a large floor of US$1.89/Watt. In the installed system, not only the price of the module, but also other costs are higher. Therefore, even if module prices are expected to move closer to the international level, and BOS will decline rapidly based on the historical learning rate, it is expected that future PV costs will still be higher than other countries [77]. Another factor leading to high costs is isolated and stringed power grids and regional differences in renewable resources. Since Hokkaido, the largest producer of wind power, is far away from Tokyo, the largest energy consumer, Japan’s high wind power penetration rate will inevitably require power transmission. Major reinforcement of the line, including large-scale expansion of submarine DC cables. It is worth noting that Japan [78] has tried to use cumulative residual load (CRL) to estimate storage requirements, although it is not thorough enough and has obvious shortcomings. For example, it is used for calculation in ignoring the efficiency of the use cycle [79].

iii Combined energy storage system and data used

With the high penetration rate of VRE, energy storage capacity affects the economy of the power sector. Reducing surplus electricity [80] and strengthening the transmission grid [73] are effective means to solve the intermittent problem of VRE with a moderate penetration level. With the penetration rate of VRE exceeding 50%, power storage is essential [81,82]. Although storage in a relatively short period of time is sufficient, unless the VRE share is very high. Among the various types of storage systems proposed to solve the intermittentness of VRE [83,84] and provide flexibility options [85], batteries, such as lithium ion (Li-ion) and sodium sulfur (NaS) batteries, which helps short-term energy storage. However, when the share of VRE exceeds 80%, electricity-to-gas (PtG) technologies, such as hydrogen [86] and methane [87] storage, will play an important role [88,89].

Most studies use hourly VRE output curves to simulate power systems, usually based on a year's observations or estimates of VRE output. However, extreme weather conditions may have a significant impact on the economics of power systems with particularly high VRE penetration [90]. This requires trying to use multi-year data, which can span decades to obtain reliable conclusions.

2.1.2. Pumped storage systems (PHS) studies

① Prediction of PHS installed possibilities

In view of the surplus of renewable energy power, increasing the power generation proportion of dispatchable units [91], adding energy storage systems [92], and using inter regional transmission lines [93] are common solutions. Among them, energy storage system plays an important role in improving the stability and reliability of power grid, it has the ability to improve the rate of RES into grid by compensating for the mismatch between the power supply-side and demand-side [94]. In terms of energy storage technology, different energy storage systems have been compared comprehensively. For large-scale public power grid, the most common energy storage technology is PHS [95-97]. It has the advantages of large storage capacity and long-life. PHS has a history of more than 100 years, however it still widely used in the United States [98], Japan [99], China [100], Greece [101], and other countries [102]. Currently the installed capacity of PHS is 180GW in the worldwide, of which China (32.1GW), Japan (28.5 GW) and the United States (24.2 GW) account for 50% of the world's total installed capacity. Most of the operation strategies are absorbing thermal and nuclear power generation at night and compensating for the peak load demand during the daytime [103]. In addition, PHS is also applied to hybrid single PV or wind energy to increase capacity and address their suppression. In recent years, PHS hybrid PV and wind energy have received the attention of many researchers due to the complementary characteristics of their power generation nature [104,105]. The mature development of pumped storage is accompanied by challenges from the feasibility of site selection and the constraints of ecological environment [106]. Particularly in Japan, there is no place where large scale PHS can be constructed [107]. To overcome these shortcomings, we can consider pursuing small and medium-sized decentralized PHS plants to adjust the penetration of VRE, and increase the flexibility and stability of the power grid further.

Reviewing other references reveals that the installed capacity of PHS facilities can be expanded by using existing water resources. For example, seawater, river, lake and so on [108]. They are used as lower sinks for pumped storage. In Japan, there are more than 2,700 existing dams [109], which are employed to build small and medium-sized decentralized pumped storage equipment. Multifunctional reservoir dams in Japan are often applied to store water to reduce the seasonal variation of river flow, so as to ensure the supply of water source. It has the functions of flood control, irrigation, water conservancy and power generation, industrial water use, irregular water utilization and so on [110]. Therefore, in the process of using water dames as pumped storage, we need to pay attention to the basin area of the reservoir, whether there is a platform with a certain height difference beside the reservoir, the effective utilization of water storage and other factors. The maximum utilization of pumped storage in the study area is predicted to improve the permeability of renewable energy and reduce the vulnerability of power grid.

② VRE hybrid PHS studies

Renewable energy can be used alone or in combination, but it is generally believed that due to its inherent intermittency and variability, there is no single renewable energy source that can reliably supply electricity [111]. The idea of using renewable energy as the main energy source has become popular, especially solar-wind-hydropower, which complements each other's unpredictable nature due to their complementary characteristics [112]. The feasibility study [113,114] and the technical and economic optimization method of the hybrid solar wind-PHS system [115] have been developed in the literature, and some articles have analyzed and analyzed the best solution based on the defined configuration range [116-118] option. Case studies show that there is a trade-off between environmental impact and system cost [119]. In addition, it has been observed from the literature that the greenhouse gas emissions of PHS-based hybrid systems are 9.3 times lower than that of grid electricity [120]. Further research and analysis are needed to compare and analyze the environmental aspects of the proposed system and other configurations to verify the superiority of these hybrid systems and promote emission-free power systems [121]. The schematic of hybrid solar-wind system with PHS is shown in Fig. 2-8.

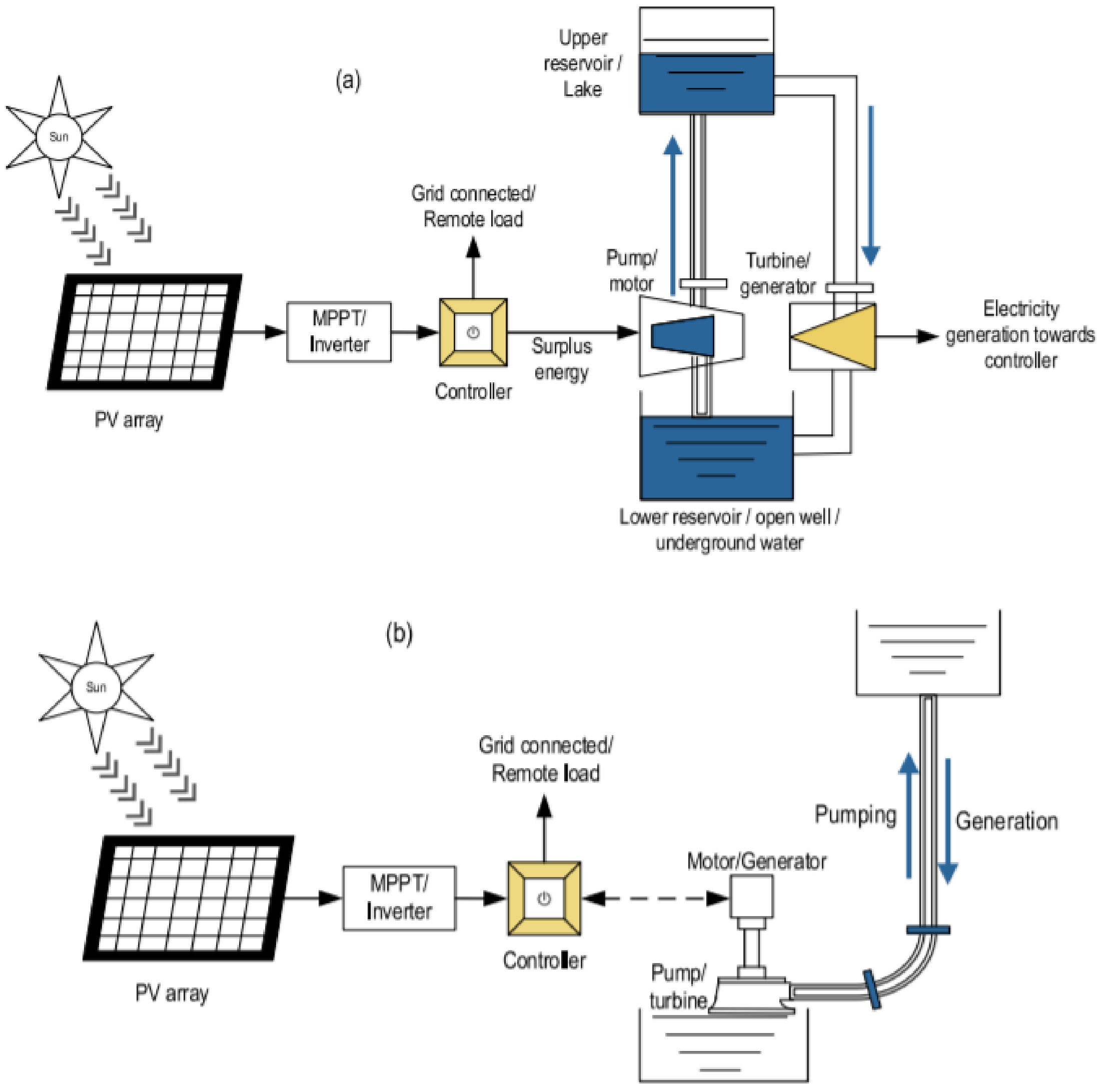

Fig. 2-8 A hybrid solar-wind system with PHS (a) with two penstocks (b) with single penstock [121]

2.2 Evaluation indicators of the impact of renewable energy on the power grid

Many studies have been devoted to analyzing the capacity credit of VRE in recent years. The commonly used method for calculating the capacity credit of VRE is covered in previous works [122,123], which refer to the effective load-carrying capability and the loss of load probabilities. In addition, a series of capacity methods for accurately and appropriately calculating PV or wind capacity credit are reviewed in the literature [124,125]. In actual cases, based on the characteristics of capacity credit evaluation, most of the research focuses on large regional power grid levels such as those of Japan [126], Spain [127], and Florida [128]. These studies are often combined with the power market [129], dispatching strategy [130], energy storage technology [131], etc., to evaluate the impact of the popularization of VRE on large regional power grids [132] and the adaptive effects of various solutions [133]. One previous study discussed the impact of misestimating the capacity credit of VRE generators on the U.S. power grid, presenting the system cost, emissions, and reliability of the power grid and emphasizing the importance of accurate capacity credit evaluation [134]. The calculated results revealed that capacity credit is affected by many factors, including sufficiently paired chronological load, VRE resource time series data, and the characteristics of the power system [135]. VRE power production depends on the sources of energy and geographic diversity. Wind energy can produce energy at any time of the day. PV power generation has a time periodicity, determined by the position of the sun. PV and wind thus exhibit different energy production performances. Therefore, it is essential to analyze and compare PV and wind resources from different areas that contribute to the capacity credit of the power grid.

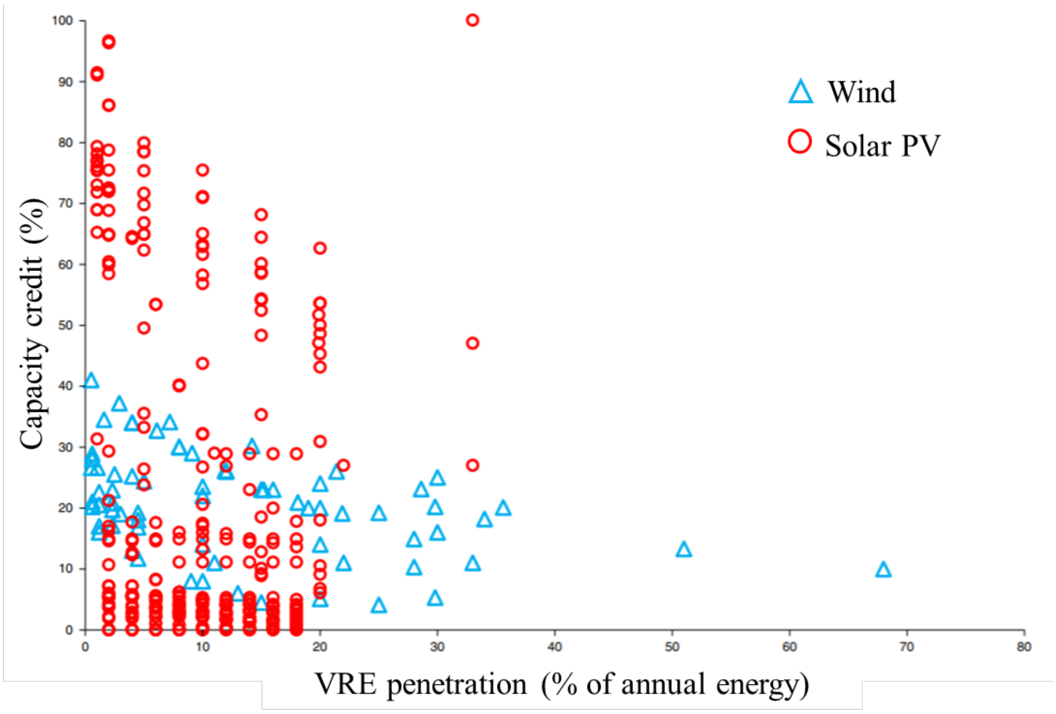

Fig. 2-9 Capacity credit data by VRE type [139]

Fig.2-9 shows VRE's capacity credits broken down by technology type in order to compare wind energy and solar energy. At lower penetration levels, some analyses have found that PV can have particularly high-capacity credits, and there is a very strong correlation between PV output and peak demand. However, generally speaking, the capacity credit value of PV is found to be wider than that of wind energy. Most PV values tend to be relatively low and a few (many) higher values. This illustrates the powerful technical geographic dimension of capacity costs—the capacity credits of wind energy are within a reasonable range of less than 10% to more than 40% of installed capacity. However, the PV data points [136, 137] account for a large part of the volume) are strongly clustered in the range of less than 10% and 50% to 80%. This is because in countries with peaks in winter, PV capacity credit may be zero (or close to) zero, while in countries with peaks during the daytime in summer, it may be very high. As the penetration rate increases, the reason for the decline in the capacity credits of wind energy and PV is the fixed capacity demand [138]. The data also shows that this effect of solar energy is more pronounced than wind energy, which may be a function of the day and night patterns of solar output.

The other indicators of VRE integration impact are summarized as three categories: VRE suppression, the effective of thermal power generation efficiency, and how technical characteristics of VRE impacts on frequency and voltage [139].

Adding VRE to a power system gives rise to a number of changes: some of them are related to the timing and unpredictability of output and technical characteristics of VRE, whereas others are related to the geographical location of wind or solar deployments. It is important that these costs are assessed holistically as there is some overlap and interaction between them. One way to characterize the costs imposed by VRE generators is to decompose them into three main categories17: costs imposed by unpredictability of output or forecasting errors (so-called balancing costs); costs imposed by the relatively uncontrollable nature of output and lack of correlation between output and demand, which affects the net load met by non-VRE generation (so-called profile costs); and a mix of factors related to geography and the unit size of VRE generators (so-called grid costs). Therefore, the breakdown of dataset by category of impact is depicted in Fig. 2-10 [139].

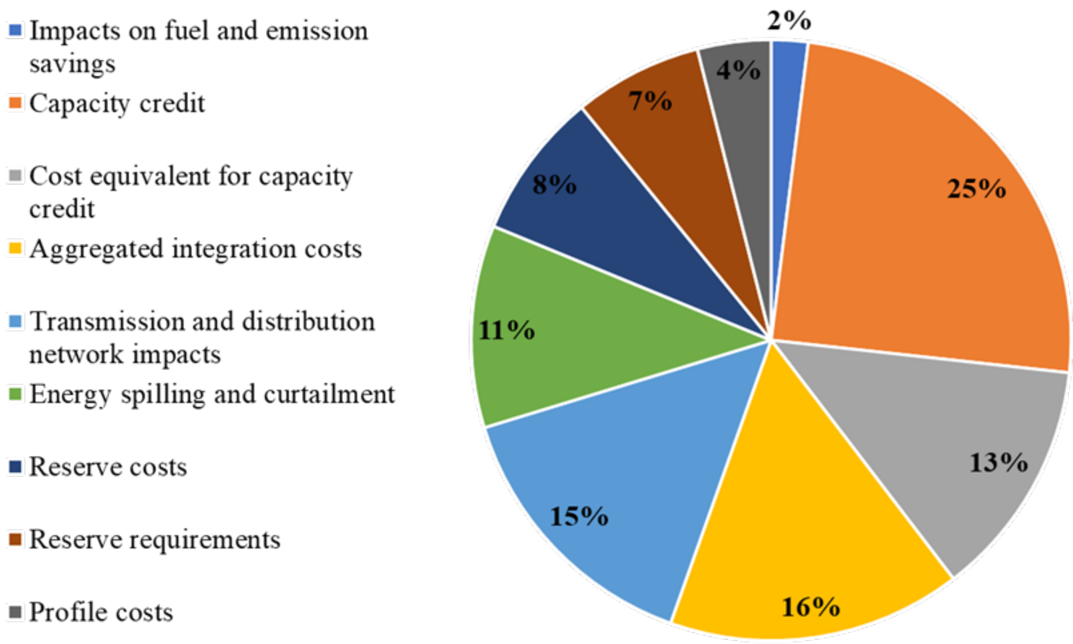

Fig. 2-10 Breakdown of dataset by category of impact

2.3 EnergyPLAN models

For achieving the goals of integrating massive RES hybrid PHS into grid, appropriate energy system management software is required. The energy system required to be modeled to provide the possibility of the impact of scenarios with different proportions of energy on the power system. And provide corresponding technical and economic evaluation indicators to analyze and compare the results under different scenarios. The type of each tool reviewed is summarized as Table 2-1. These tools mainly include, focusing on independent applications of renewable energy, such as individual buildings, local communities, or single project applications. Used in the power sector. Consider heating or transportation sectors other than the power sector. There is also the transportation field in the form of electric vehicles.

Table 2-1 Type of each tool reviewed [140]

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
energyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMax	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
Invert	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

After comparing many diverse energy planning tools, EnergyPLAN was selected [141,142]. This section comprehensively introduces the tool from the basic information, constituent units, scope of application, research fields and advantages of EnergyPLAN. It can be applied to analyze regional or national energy systems, which consistent with the research on public power grids in different regions of Japan in this paper. Variable energy power generation equipment, heating units, energy storage systems, load demand, electricity prices, energy consumption, carbon emissions and other elements are well mixed and used in this tool [143]. Applicable to Denmark [144], Germany [145], China [146], Spain [147], Japan [148] and other countries. A series of energy system optimization indicators is provided, the most of important of which are CEEP, cost, primary energy consumption, and carbon emissions [149]. Based on the technical and economic analysis of different energy systems, EnergyPLAN assist countries or researchers in the design of energy planning strategies. It is often used to infiltrate renewable energy into energy systems [140]. Its advantages are reflected in the rapid output of technical and economic results in different scenarios, omitting many iterative steps [150]. In terms of operation strategy management, it can realize the simultaneous application of pumped storage featured with double penstock to make full use of renewable energy.

The geographic scale of EnergyPLAN analysis from 2003 to 2015 is summarized in Fig.2-11. 76% of research scale is distributed in a country or state levels. As the model has several options, the majority employ a small range of criteria, while others employ a single criterion. The most frequently applied criterion is primary energy supply (PES); the sum of fuel usage and fuel equivalents for non-fuel energy sources as shown in Fig. 2-12. Some articles focus on specific primary energy sources whilst others address the sum of the entire range of the given energy system [140]. These main indicators are shown as follows:

① The most frequently applied criterion is primary energy supply (PES); the sum of fuel usage and fuel equivalents for non-fuel energy sources as shown in Fig. 2-12 [151].

② Greenhouse effect enhancing carbon dioxide emissions are assessed [152].

③ Excess power generation reveals the ability of a given energy system to properly integrate fluctuating power sources by showing the quantity which cannot be used in the system with the given configuration. The measure can be in terms of exportable excess – excess which may be exported from the given system constrained by interconnection capacity or critical excess – excess beyond the interconnection capacity [153].

④ Business economic costs are assessed in reference articles though in a variety of different shapes and forms depending on the particular focus of the authors – e.g., total annual costs, net present values, fuel costs, O&M costs [154].

⑤ Duration of various units either graphically as duration curves or quantitatively as operating hours of various units are investigated. This category also includes capacity factor – i.e., the ratio between actual production and production at full nominal load throughout the year [155].

⑥ The general system configuration is the main output. This is not so much a criterion as an output; typically used for further analyses of more specific topics in designated models [156].

⑦ RES share and production mix across all primary energy sources is assessed in reference papers [157,158].

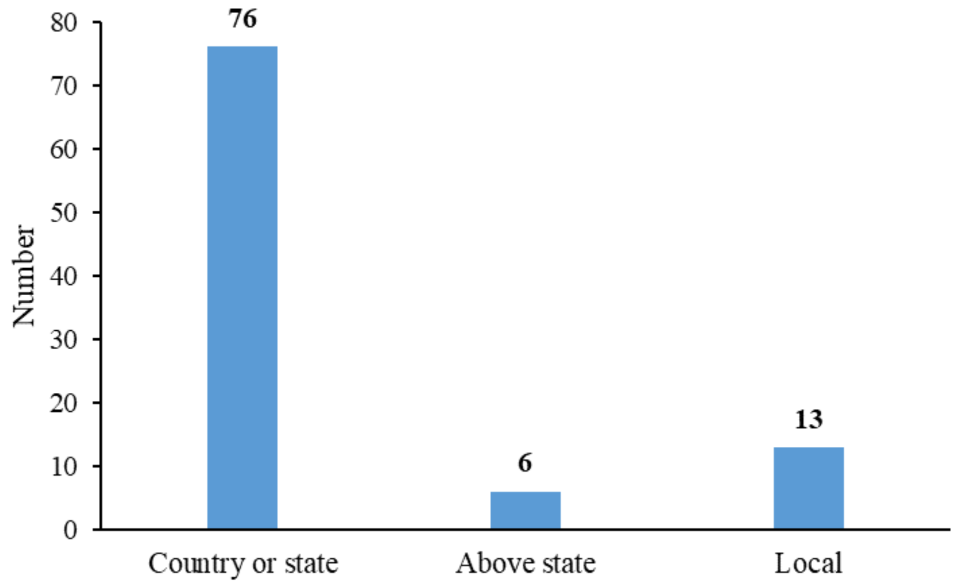

Fig. 2-11 Geographic scale of EnergyPLAN analyses 2003–2015 [41]

Application of different criteria in the reference that applying in EnergyPLAN model as of May 26th, 2015

Criteria	Number
PES	46
CO2	42
Costs	37
Excess	35
Duration	11
Configuration	11
RES share	11
Mix	11
Export	7
Import	7
COMP	6

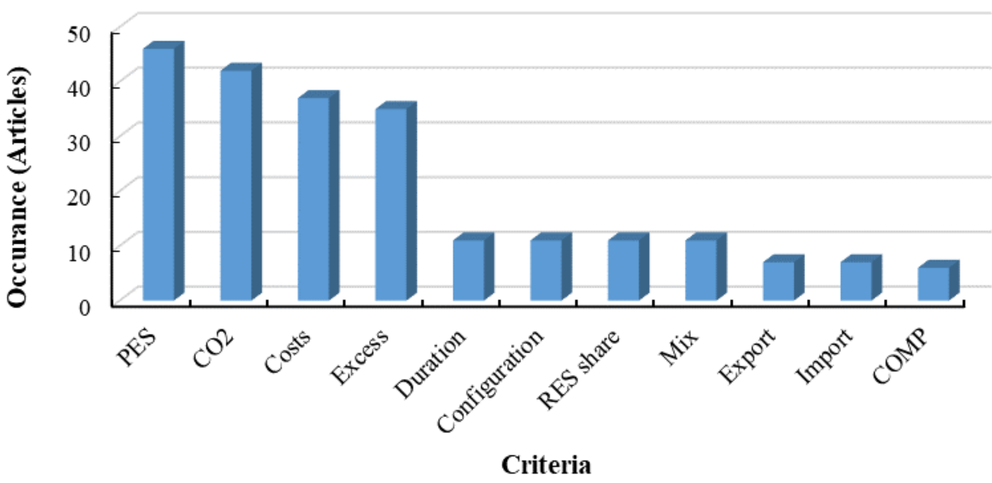

Fig. 2-12 Application of different criteria in the reference that applying in EnergyPLAN model as of May 26th, 2015 [41]

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Chapter 3

METHODOLOGY

CHAPTER THREE: METHODOLOGY

3.1. Evaluation indicators of VRE on the power grid

3.1.1. Capacity credit analysis

Capacity credit is an important indicator for evaluating the penetration of renewable energy into the grid. The PV and wind capacity value metrics and their associated calculation methodologies are summarized in Section 2. The capacity credit calculation method is based on the load curves. First, the LDC can be obtained by sorting the power demand per hour of the year, and the residual load is expressed by subtracting the corresponding PV or wind production capacity from the LDC. The residual load gradients are then sorted in descending order to derive the RLDC[1]. Hence, the RLDC is represented in terms of the change in the LDC induced by VRE. In the subsequent step, the application of RLDCs is presented as an evaluation tool for analyzing systems with arbitrary levels of penetration of both wind and PV. On the basis of the RLDC, one indicator is defined that represents the independent impacts of variability on the structure of the RLDC, namely, capacity credit. Capacity credit is an evaluation indicator that directly refers to the power grid. The capacity credit value quantifies the impact of PV and wind energy on the grid, which aids in analyzing and comparing their differences in variable grids.

① Residual load duration curve

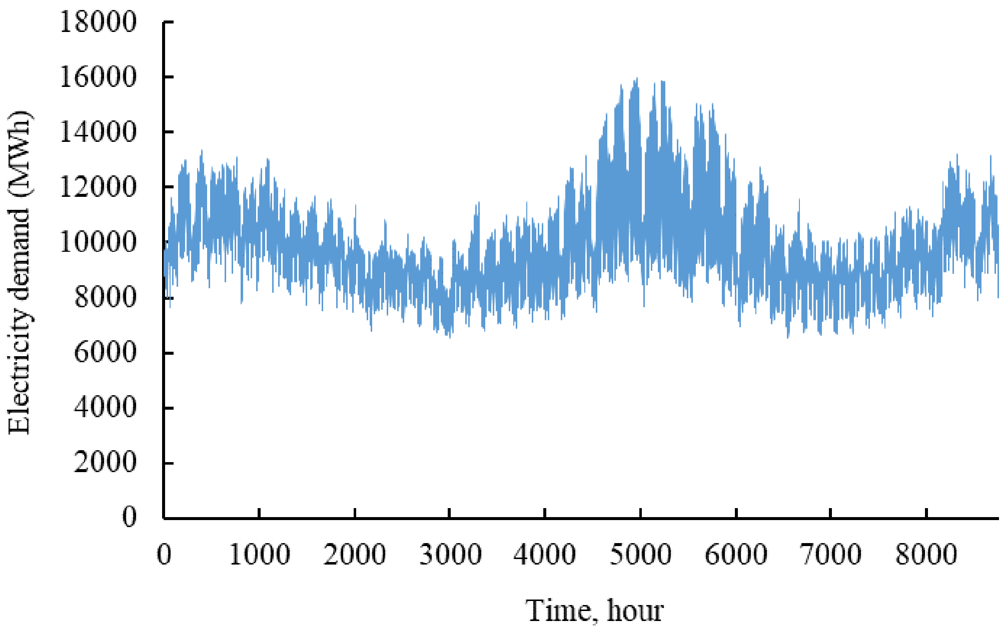


Fig. 3-1 Load curve at hourly interval for one-year

Fig.3-1 shows the annual power load curve, and the data adopts the power demand from April 2018 to March 2019 in Kyushu Electric Power Company. Then, the power load curve is arranged in descending order from large to small, and the load duration curve (LDC) in Fig. 3-2 is obtained.

Subtract the PV and wind power generation values in the same period from the LDC curve (as shown in Fig. 3-3) and arrange them in descending order to obtain Fig.3-4, which is named residual load duration curve (RLDC). Fig. 3-5 directly shows the difference between LDC and RLDC. Therefore, the RLDC refers to the residual load demand provided by other power generation units by subtracting the PV and wind power generation at the same time from the load curve.

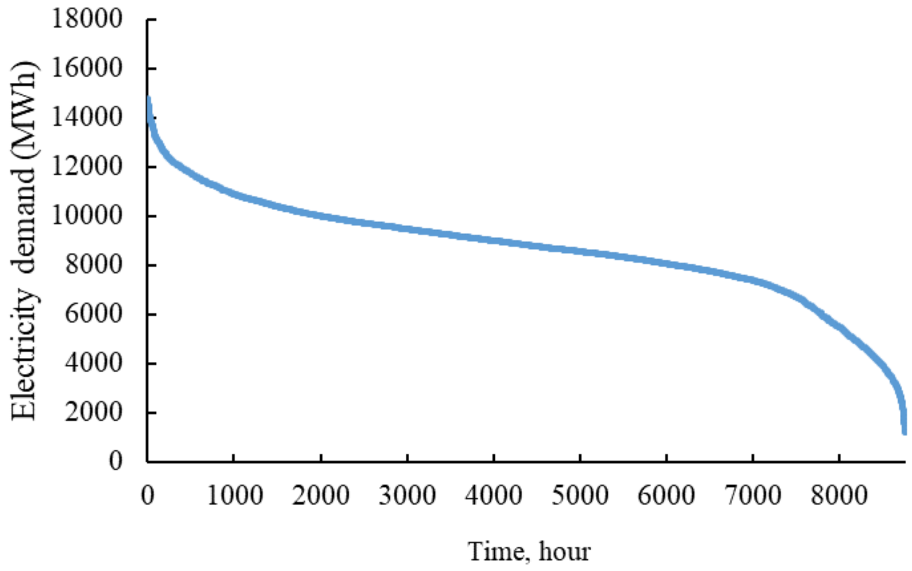


Fig. 3-2 LDC is derived by sorting the load curve (Fig. 3-1) in descending order

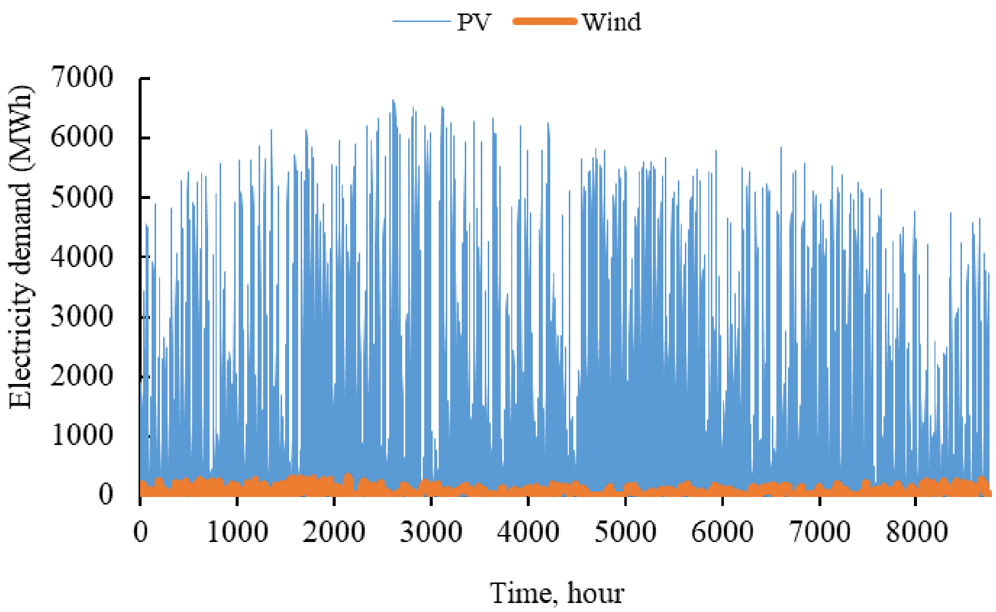


Fig. 3-3 VRE power generation profile

RLDC is a purely physical concept that only requires load demand and VRE supply data and does not use exogenous parameters. As the share of VRE increases, changes in RLDC will lead to potential changes in the non-VRE capacity mix. In addition, RLDC captures the so-called "configuration cost", which depends on the real-time matching of the VRE supply profile with the (surplus) power demand. References [2,3] indicate that RLDC captures the three main drivers of configuration costs: low-capacity credits, reduced utilization of dispatchable factories, and over-production VRE power generation. There are several integration options to reduce the cost of configuration files. In addition to shifting to dispatchable plants that are less capital intensive, the RLDC approach also includes endogenous investments in seasonal energy storage through hydrogen and methane (electricity to natural gas storage). This provides some flexibility to alleviate the challenges of variability in the power sector and the corresponding costs. Other integration options, such as short-term storage and demand-side management (DSM) are not easy to model Therefore, RLDC is widely used [4].

Based on the RLDC method, overproduction by VRE has been calculated and compared in many cases, including Indiana [5], New York [6], and Germany [7]. The RLDC method captures the challenges of increasing VRE share integration into the grid without significantly increasing the numerical complexity, the calculation of capacity credit and overproduction of VRE will be shown in the following part.

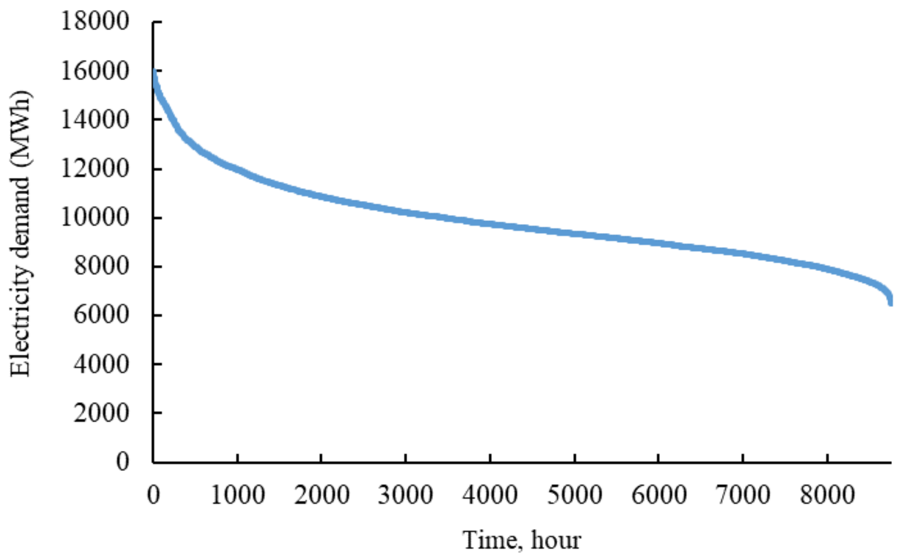


Fig. 3-4 RLDC is derived by subtracting the time series of VRE from the time series of power demand (Fig. 3-1)

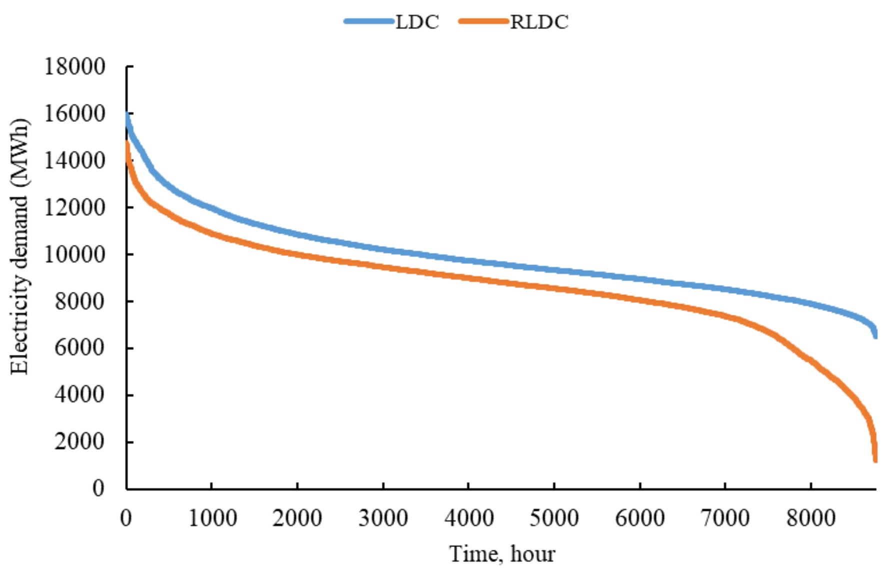


Fig. 3-5 LDC and RLDC

② Capacity credit calculate

Fig. 3-6 depicts the LDC and RLDC of Kyushu region. The lower shaded area represents a partial enlarged view of the top-left part in the upper area. Capacity credits are widely used to evaluate the contribution of renewable energy generators to power generation adequacy. This paper focus on analyzing the contribution of intermittent PV and wind power generation to peak load reduction. Accordingly, the calculation area of the capacity credit value is distributed in the peak electricity demand area of load curve. Capacity credit indicates, given a certain amount of demand (upper shade area in Fig. 3-6) response available to the utility, the extent of the possible guaranteed load reduction if VRE is deployed [8]. This metric is calculated based on RLDCs and accounts directly for grid penetration. The data used in Fig. 3-6 is for the Kyushu electricity power grid, with an 817 MW installed PV capacity from April 2018 to March 2019. The calculation of capacity credit can be expressed as follows:

$$\text{Capacity credit} = \frac{\mathrm{Y} - \mathrm{X}}{\mathrm{Y}} \tag{1}$$

where Y is the demand response needed to achieve total peak demand reduction, and X is obtained by subtracting the corresponding load value of 5% for 8760h.

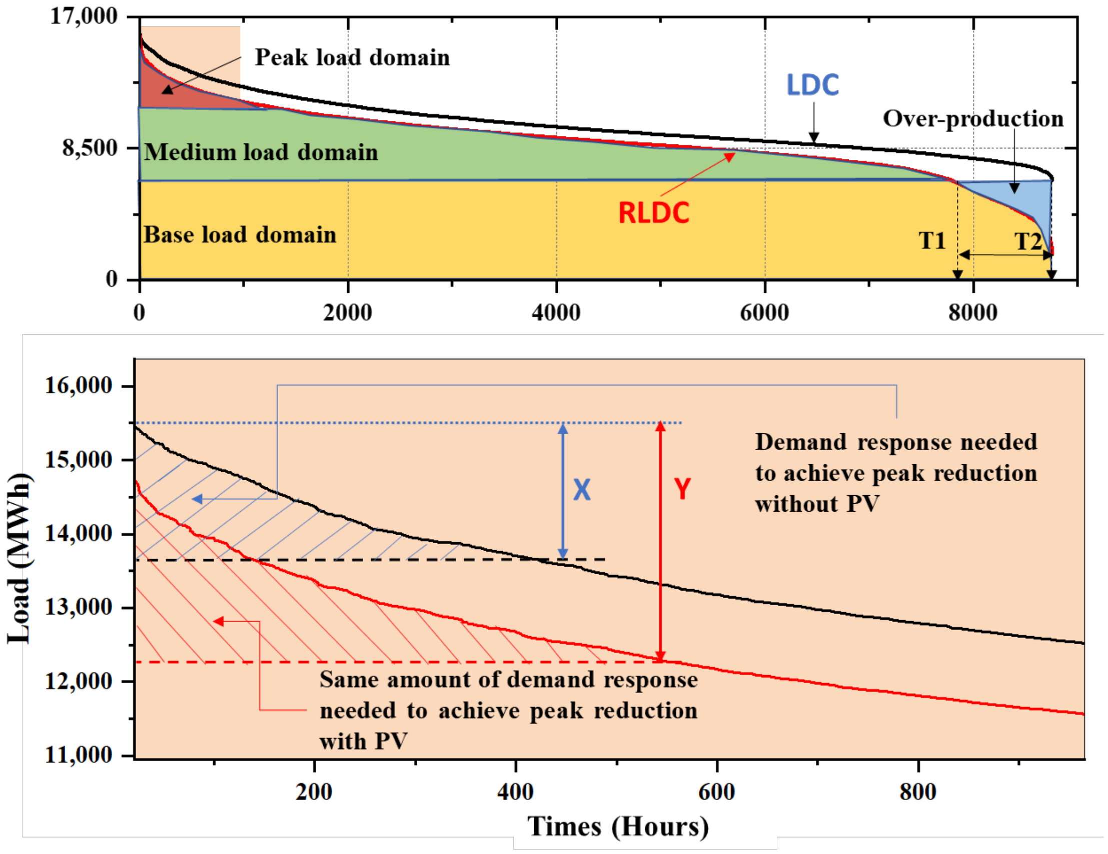


Fig. 3-6 Illustration of capacity credit metric

3.1.2. Evaluation indicators of VRE integration

According to the characteristics of power demand on the user side and the features of variable resource power generation, the load curve mainly consists of the basic load, medium load, and peak load, as shown in Fig. 3-6. For Japan's public grid, the maximum output from base-load plants and intermittent load plants equals 0.35 and 0.7 ratio of annual peak grid load, respectively (as shown in Fig.3-6). As the grid demand needs to be balanced at any point in time, the daily demand and supply balance are constrained as follows:

$$\mathrm{P_b^t} + \mathrm{P_m^t} + VRE_{direct} = \mathrm{load_{grid}^t} \tag{2}$$

where P_b^t and, P_m^t represent power flows from constant-output base-load plants and flexible plants, respectively, $load_{grid}^t$ refers to the total grid load, and VRE_{direct} is directly integrated VRE production. Annual electricity production was estimated on the basis of the utilization hours VRE. Here, "utilization hours" refers to the valid monthly number of hours for wind or PV power, which is equal to its generation divided by the system installed capacity. The formula for calculating the utilization hours is

$$\text{Utilization hour of VRE} = \frac{P_{VRE}^{t}}{\text{Installed capacity}} \quad (3)$$

$$\text{VRE}_{\text{direct}} = P_{VRE}^{t} - \text{overproduction(t)} \quad (4)$$

where P_{VRE}^{t} is the total VRE production, overproduction(t) refers to the curtailed VRE production.

The detailed calculation of electricity overproduction is dependent on the simultaneous base-load demand and available VRE generation. Finally, the overproduction potential is defined as follows:

$$\text{Overproduction} = \int_{T1}^{T2} \left(P_{b}^{t} - \text{RLDC(t)}\right) dt \quad (5)$$

where RLDC(t) refers to the residual load demand. By calculating the DIPP and overproduction rate, DIPP is not only used as an economic indicator to evaluate the feasibility of PV and wind energy investment, but also reflects the percentage of abandonment of PV and wind.

The key concept of DIPP is the period after which the capital invested has been recovered by the discounted net cash inflows from the investment perspective. The results of the economic analysis of the VRE systems show that the projects are profitable because the payback period is less than the lifespan of the system. This indicator can be used in this study to quantitatively limit the maximum penetration of VRE in the public grid, that is, the investment possibility. The DIPP is computed as:

$$\sum_{t=0}^{P_t} (C_1 - C_0)_t (1 + i_t)^{-t} = 0 \quad (6)$$

where P_t is the DIPP of PV or wind, i_t refers to the yearly interest rate, C_0 is the initial investment of PV and wind, C_1 represents the annual revenue of VRE power generation, which is the product of the annual utilization hours and electricity price per unit, and t is the time unit. The yearly interest rate, i_t, is set at 3.0% [36]. It is worth noting that the annual profit of VRE electricity production, C_1 is the product of the annual effective utilization hours and the electricity price. The initial investment in PV and wind has been declining year by year with improvements in technology, which has led to a decline in electricity prices generated by renewable energy. Therefore, this study assumes that the initial investment cost of VRE and the price of electricity sold are constant. The initial investment for PV and wind energies are 195,000 Yen/kW and 300,000 Yen/kW, respectively, while maintaining electricity prices P at 12.3 Yen/kWh and 16.1kWh, also respectively. Table 3-1 shows the technical parameters [9].

Table 3-1 Related parameters of DIPP

Energy	i_t	C_0 (Yen/kW)	P (Yen/kWh)	Lifetime (years)
PV	3%	195000	12.3	30
Wind	3%	300000	16.1	20

By calculating the DIPP and overproduction rate, DIPP is not only used as an economic indicator to evaluate the feasibility of PV and wind energy investment, but also reflects the percentage of abandonment of PV and wind.

3.2. Prediction of PHS installed capacity

3.2.1 The geographical position required of PHS constructions

Pumped-storage Hydroelectricity is a way of generating electricity. When the electricity is surplus, the surplus electricity is pumped from the lower reservoir (lower pond) to the upper reservoir (upper pond). When the demand for electricity increases, water is drawn from the upper pond dam to the upper pond dam. It is a way of generating electricity using the conversion of gravitational potential energy and electric energy. The utilization rate of existing pumped storage is low. There are the following requirements for the development potential of pumped storage in the future:

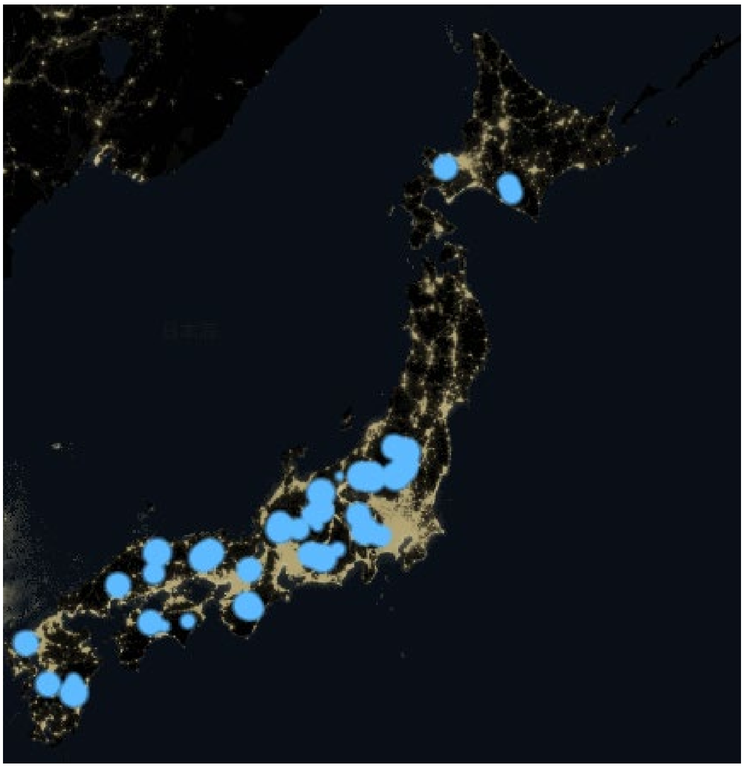


Fig.3-7 The existing PHS facilities in Japan [10]

i Decentralized demand for power supply.

ii The cost of batteries has dropped sharply, and the share of energy storage systems in the future will change. However, PHS has many advantages in terms of scale, responsiveness, and inertia, so it still occupies the mainstream position in pumping and storing energy.

iii Pursue small and medium-sized decentralized PHS construction sites. The currently installed situation of PHS is drawn in Fig. 3-7.

The aspects considered when planning a storage reservoir and topographical influence is summarized in the following aspect [11]:

i Storage Volume

The main objective of a storage reservoir is to store water and energy. The higher the usable storage volume the better.

ii Land Requirement

The are-a occupied by the reservoir. One of the main causes of environmental, social, and economic impact of reservoir dams. Should be minimized as much as possible.

iii Flooded Area Variation

The amount of reservoir area which changes with the tidal variation as the reservoir is utilized. Flooded area variation has social, environmental and economic impacts and should be reduced as much as possible.

iv Level Variation

The total variation of the reservoir level from full to empty. The higher the level variation, the higher the storage volume/ land use ratio.

v Evaporation

Evaporative losses that scale with the flooded area and reduce the overall stored volume [12]. A storage reservoir should have a high storage volume/ flooded area ratio to reduce evaporation.

Only a few aspects can be controlled when planning a storage reservoir. The main parameters are the location of the dam, dam height and length, and reservoir level variation. The resulting storage volume, land use, flooded area variation, evaporation, will depend on the topography, geology, and climate of the location.

3.2.2 The efficiency calculation of PHS power generation

The configuration of PHS is shown in Fig. 3-8. It contains the upper reservoir, lower reservoir, penstocks, converters, and reversible pump-turbine facility. Using the power required for pumping, the water in the lower reservoir is pumped into the upper reservoir, and while the water is used to generate electricity, there is energy lost due to equipment loss and friction loss in the waterway, so there has a difference in the power input and output. And the ratio is called pumping efficiency and is expressed by the following formula:

$$\eta = \eta_{TG} * \eta_{TP} \tag{7}$$

η is referred to the total efficiency of PHS power generation.

η_{TG} is referred to the efficiency of turbine generator.

η_{TP} is referred to the efficiency of pumping facility.

The pumping efficiency varies with the characteristics of the equipment type and channel length, but since the efficiency of the above-mentioned equipment is about 90%, the channel loss is about 5% of the total head, so it should be about 70%.

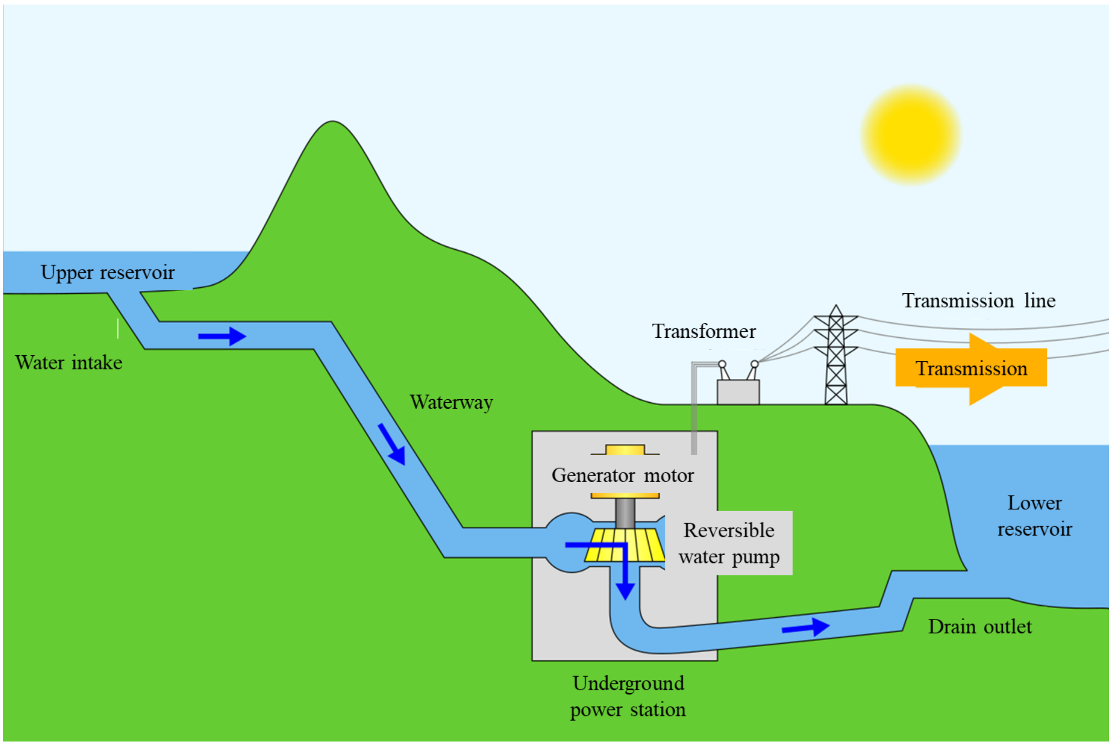


Fig. 3-8 The configuration of PHS interconnected [13]

3.2.3 The prediction of PHS in this paper

According to the composition of pumped storage, the predicted installation demand can be summarized as follows:

i The lower pool utilizes the existing multifunctional dam and seeks a high platform near the dam that can be used to build the upper reservoir (as shown in Fig. 3-9) [14].

ii Lift water from the upper reservoir to the lower reservoir to generate electricity, and then pump the water from the lower reservoir to the upper reservoir through hydraulic pipes to store electricity.

iii The lower pool is a multifunctional dam. Although the multifunctional dam is responsible for disaster prevention, irrigation, and power generation, the pumping power generation uses only part of the water to generate electricity and store electricity. Will not hinder the function of the multifunctional dam itself.

iv Japan now has more than 2,700 decentralized dams. According to Table 3-2, we seek the most suitable scale for PHS power generation [15,16].

Fig. 3-9 A pure pumped storage power plant with a dish-shaped artificial lake as an upper pond

It is possible that the water consumption of PHS power generation is part of the total water storage capacity of the multifunctional dam. This paper is set to 30%. Its definition is illustrated in Fig. 3-10.

The total water storage capacity is the sum of sand piling capacity, water conservation capacity, and flood regulation capacity.

Sand pile capacity is the hypothetical value of the sand body capacity accumulated in the dam in a certain year (100 years).

The effective water storage is the total water storage minus the sand pile capacity.

Conservation capacity is the effective water storage minus the flood regulation capacity. Although its water capacity varies with the seasons, it is calculated based on the amount of water in the normal season regardless of floods and droughts.

Water storage rate is the percentage of water storage capacity and water conservation capacity.

The possible water storage capacity is 20-30% of the effective water storage capacity

Table 3-2 Design requirements of new PHS Power Station

Research item	content
Dam number and function	Detail the characteristics of dams distributed in Kyushu (except the already resistance dam for power generation)
Effective water storage capacity, $V_0(*10^3\ m^3)$	According to the basic data of each dam
Potential pumped storage, $V_1(*10^3\ m^3)$	V_1=V_0*20%
Head conditions, H (m)	H≥ 200
Capacity of installed capacity, S (MW)	S=V_1/3600/5/9.8*200* η*0.001, head is defined as 200
Capacity of power generation, P (MWh)	P=S*5, assuming the discharge period is 5 hours, once a day
Total power generation for a year, P_y(MWh/y)	P_y=P*300

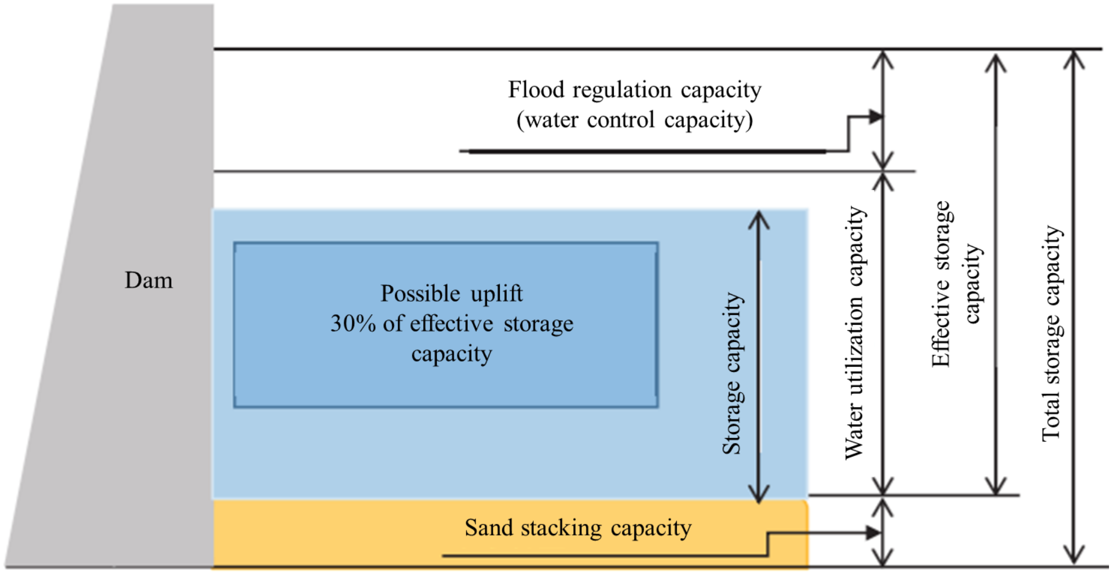


Fig. 3-10 The relationship between effective storage of water resource and possible utilized water resource of power generation [17]

④ The description of PHS construction in details

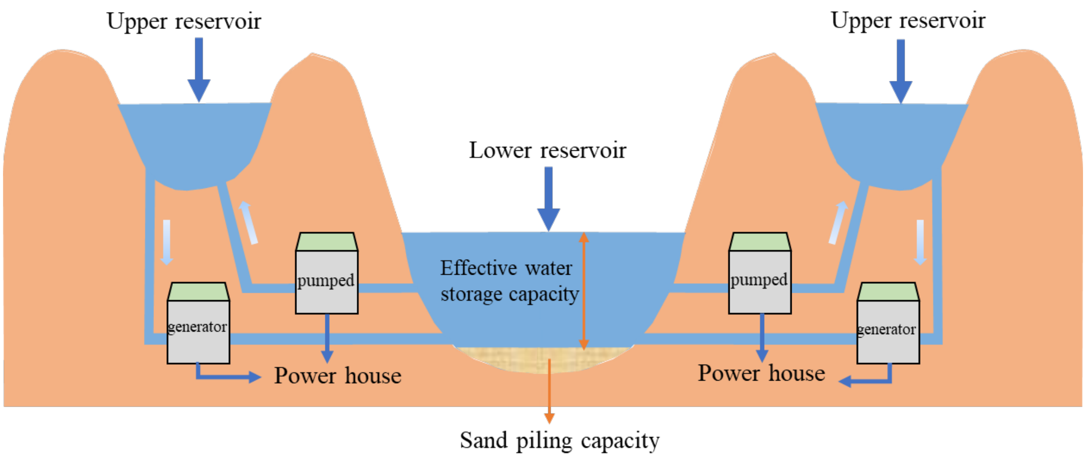


Fig. 3-11 Basic layout with main parameters of the PHS with dams

As shown in Fig.3-11, a pumped storage equipment consists of two reservoirs at different altitudes, and two penstocks are used to connect the pump and generator. According to the terrain and geological conditions of the site, the powerhouse includes electromechanical and control equipment such as pumps, turbines, valves, generators, and transformers. Energy conversion occurs when electrical energy is converted into water's gravitational potential energy during the pumping process, and vice versa. The charging process occurs when the RES power is surplus, result from the water from the lower reservoir is pumped to the upper reservoir. Power generation can be performed to compensate for insufficient power supply or reduce the use of thermal power generation whilst.

In terms of the possible pumping capacity of the dam, considering the flood control, irrigation, water conservancy and other factors of the dam itself, it is set to 30% of the effective water storage capacity of the dam (the total water storage capacity of the dam minus the sand piling capacity at the bottom of the reservoir). It is worth noting that huge dams with a water storage capacity of more than 100 million should be eliminated to protect the rare creatures in the reservoir and reduce the difficulty of development.

The head of upper and lower reservoirs shall be greater than or equal to 200m. A buffer zone with a radius of 1.5km shall be set around each reservoir to detect all upper reservoirs within the buffer zone that meet the marked distance. The upper reservoir is set to be 100 meters in length and width, and 10 meters in height, respectively.

The storage capacity of electricity power $PHS_{storage}$ can be calculated as follows:

$$PHS_{storage}\,(kWh) = \rho\left(\frac{kg}{m^3}\right) * V(m^3) * g * \left(\frac{m}{s^2}\right) * h\,(m) \tag{8}$$

where, V is represented the volume of upper reservoir, g is gravitational acceleration, h stands for the head between upper and lower reservoir. The storage capacity is the sum of the maximum power output for 5hours. Therefore, the rated power generation C is explained as:

$$C(kW) = {}^{S(kWh)}\!/_{5(h)} \tag{9}$$

3.3. EnergyPLAN model analysis

3.3.1. The basic introduction about EnergyPLAN model

This section introduces the EnergyPLAN software and its application in this paper. To predict the ability of the energy system to accommodate renewable energy in different scenarios. The model used in this paper is shown in Fig. 3-12. EnergyPLAN is an hourly input-output model, including input data, operating strategy constraints, and output results. The length of time analyzed by this tool is 8784 hours a year. It provides a detailed overview of the daily, weekly, and monthly time frame modeling system. Considering the renewal of existing power generation equipment, this paper analyzes the impact of PHS capacities development potential on VRE integration. Therefore, the required data input are power demand, production, and storage capacity. The output of the results is reflected in the power production by different power generators, import and export, fossil fuel consumption, and total cost per unit. This article focuses on the ability of EnergyPLAN to quickly simulate scenarios without excessive iterative algorithms.

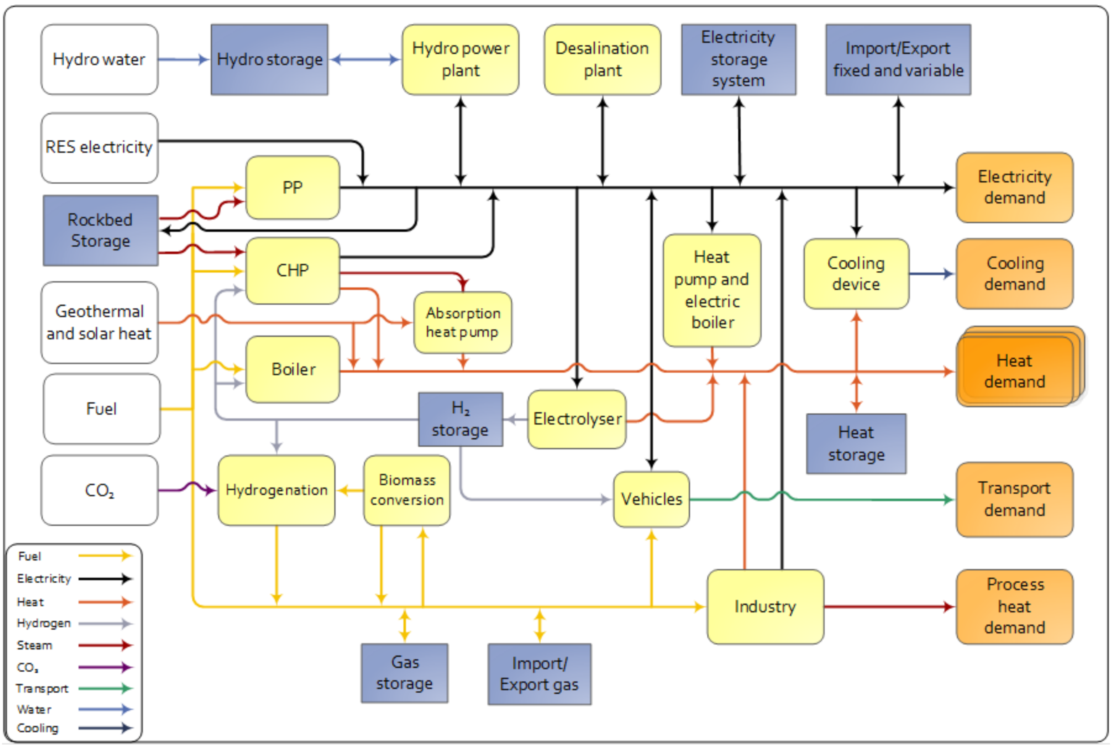


Fig. 3-12 Schematic diagram of the EnergyPLAN tool

The main goal of researchers using EnergyPLAN is to design regional or national energy planning systems based on technical and economic analysis, determined by different power generation composition and investment. Its main technical regulation strategy is to minimize the overproduction of electricity and the consumption of fossil energy power generation. Economic simulation requires a series of input data, including the investment and variable costs of different power generation units.

The approach presented in this paper requires the following assumptions, which we list hereafter:

i Possible renewable energy with high penetration rate requires the coordinated operation of power, heat, transportation, storage and other sectors. Considering the actual case of Japan's existing power grid, this paper focus on analyzing the impact of the power sector and the development potential of PHS on VRE.

ii This paper selects two independent public power grids of Kyushu and Hokkaido in Japan for case analysis, rather than the whole Japanese power grid. They are featured with different load profiles, power generation composition and PHS development potential.

iii EnergyPLAN is a future based energy planning model. In this paper, the possible penetration of RES in the future is analyzed by taking the renewal of thermal power generation operation life as the time axis. In addition, the maximum penetration of RES takes into account the limitation of the possibility of actual installation.

iv This tool requires minimum grid stability share (MGSS), which is the proportion of power (thermal power generation, nuclear power and energy storage system) supply of dispatchable units and is set to 30%. In addition, due to the limited start-up and shutdown of thermal power generation, 15% of the total installed capacity is set as the minimum output form electrical power plants. This value is calculated based on the actual power generation data of Kyushu and Hokkaido in 2019.

3.3.2. Finding and inputting data into EnergyPLAN

① Technical data

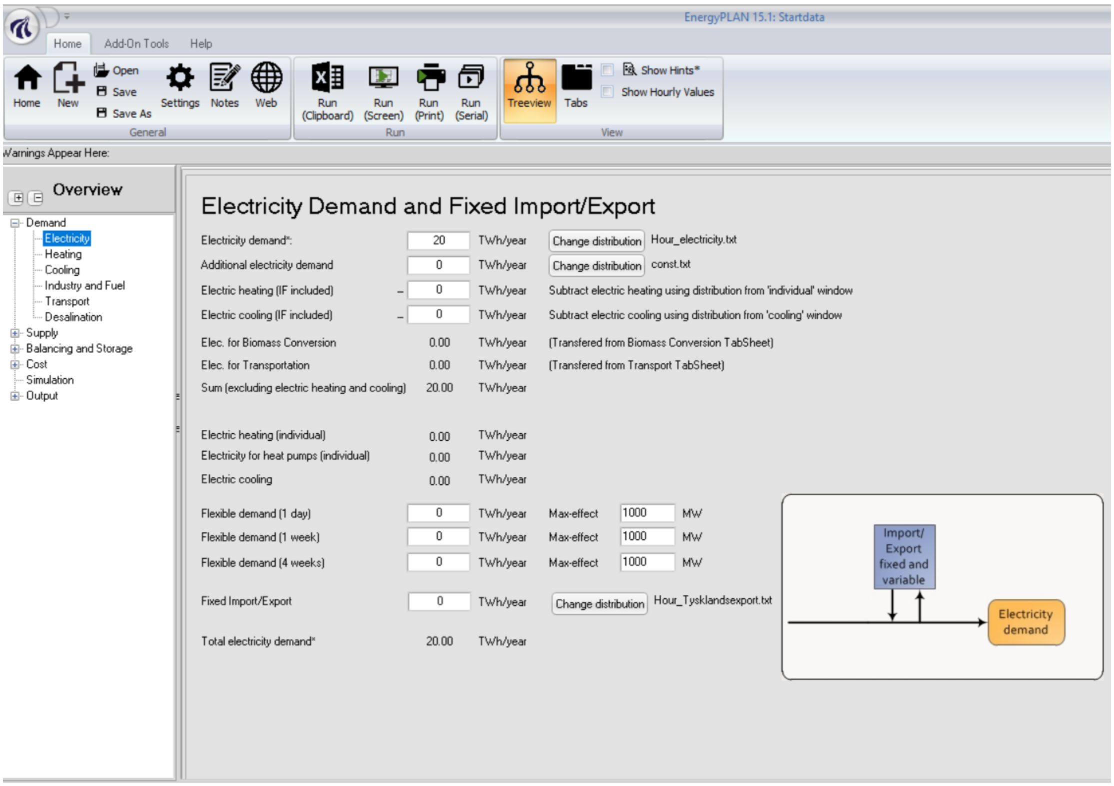


Fig. 3-13 The inputted data of electricity demand in EnergyPLAN

The data required about EnergyPLAN can be summarized as two parameters, including of Annual power demand of electricity and distribution of hourly load demand. The distributed data showed be 8784 hours, one for each hour. The distributed is inputted as a text and stored in the 'Distributions' folder [18,19].

i Electricity demand

The electricity demand is referred to the total load of user-side. It includes the following aspect (as shown in Fig. 3-13):

·Total power demand (TWh/year).

·Distribution of hourly electricity demand.

ii Renewable energy

The electricity supplied data required by renewable energy is summarized as follows (as shown in Fig. 3-14):

·The type of renewable energy, which is referred to PV, wind, hydro energy in this paper.

·The installed capacity of the renewable type.

·The distribution profile for one year.

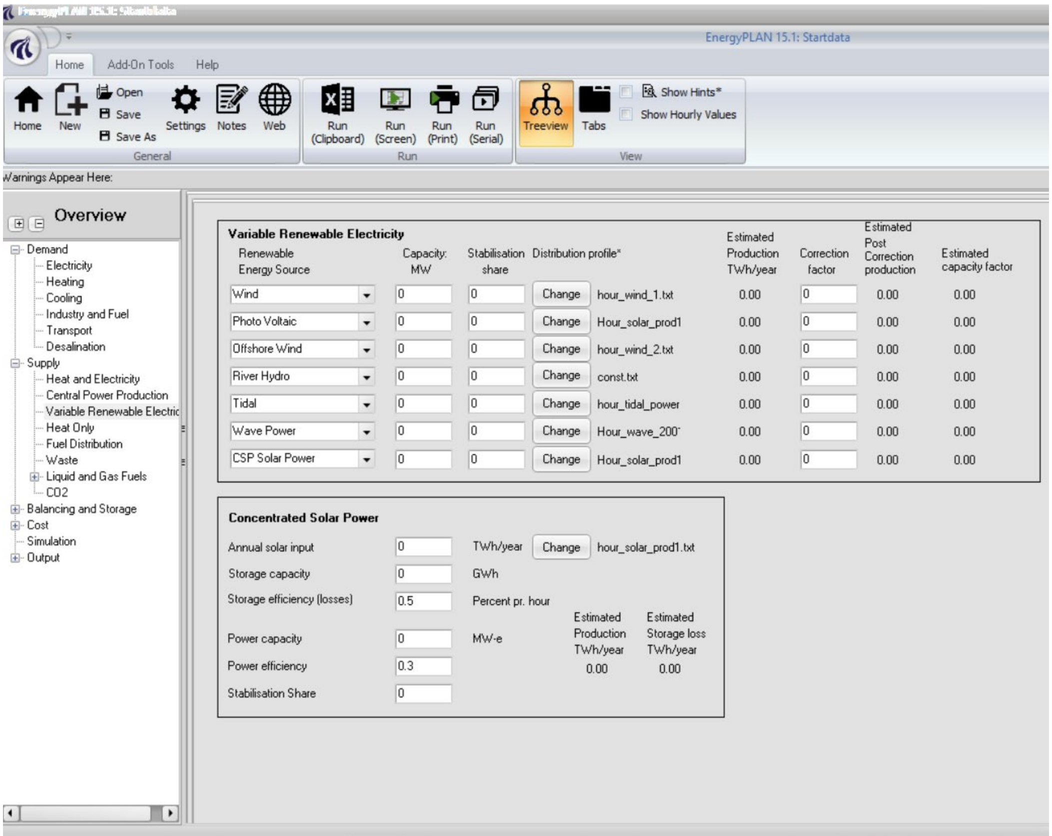


Fig. 3-14 The inputted data of renewable energy in EnergyPLAN

iii Central power production

The central power production refers to the thermal power generation and nuclear power generation in this paper. These two parameters can be used as load regulation unit as their flexible characteristics of power generation. The inputted data of central power production is summarized as follows (as shown in Fig. 3-15):

·The installed capacity of the energy type.

·The distribution profile for one year.

·The efficiency of power generation

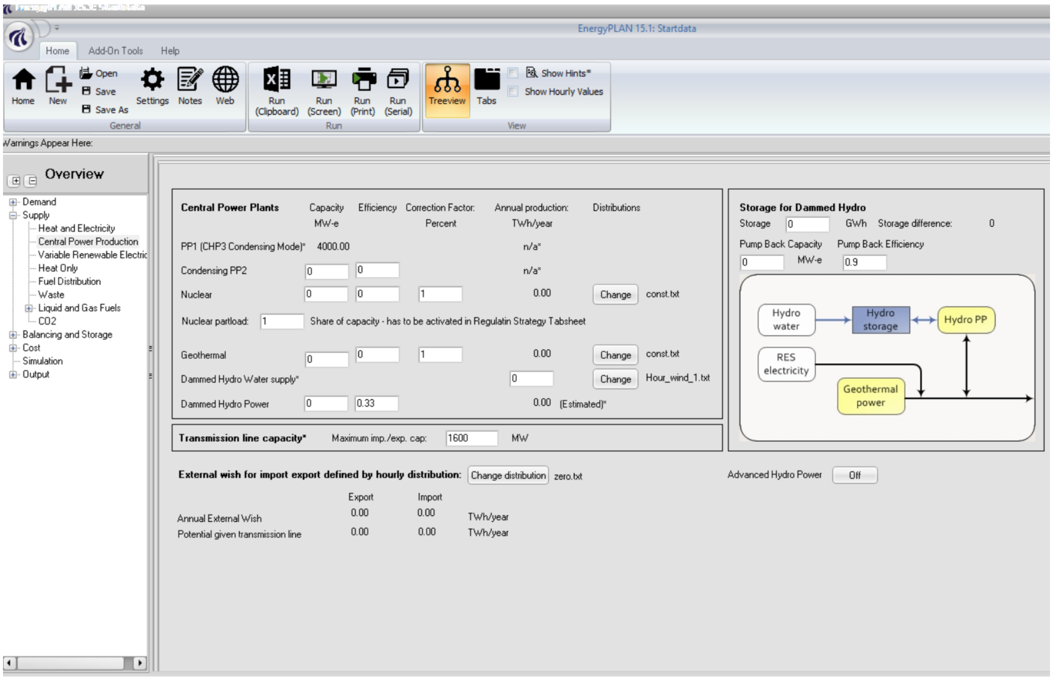


Fig. 3-15 The inputted data of central power plants in EnergyPLAN

iv Storage system and operation strategies

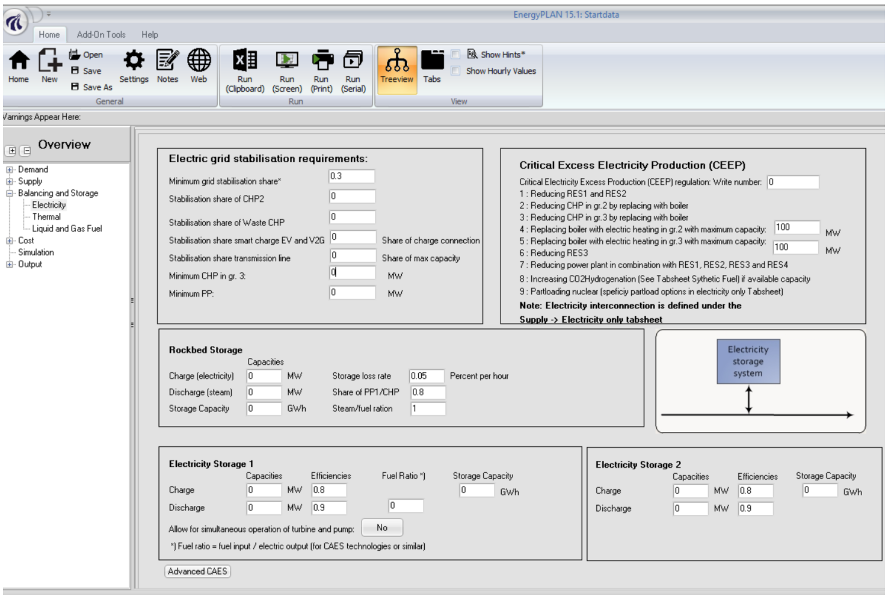


Fig. 3-16 The inputted data of electricity storage system and operation strategies in EnergyPLAN

Only electricity storage of PHS is used in this paper, we did not consider the utilization of thermal storage or the other electricity storage types. For the PHS parameters, the pump and turbine storage information and operation efficiency are required for the inputted data. The overall efficiency using in this paper is shown as follows:

$$\eta = {}^{E_{out}}/_{E_{in}} \tag{8}$$

where, E_{out} was the total electricity produced from the research objective and E_{in} is the total electricity consumed. Note that the same efficiency was usually used for the pump and turbine as this is typically the situation within a PHS facility.

As for the operation strategy for electricity storage, the question asked in EnergyPLAN when defining an operation strategy is "Allow for simultaneous operation of turbine and pump: YES/NO", which is displayed in Fig.3-16. This paper used two penstocks in the PHS facilities, we therefore chosen YES in the energy system set. The one PHS facility with h (A) a single penstock system and (B) a double penstock system is shown in Fig. 3-17.

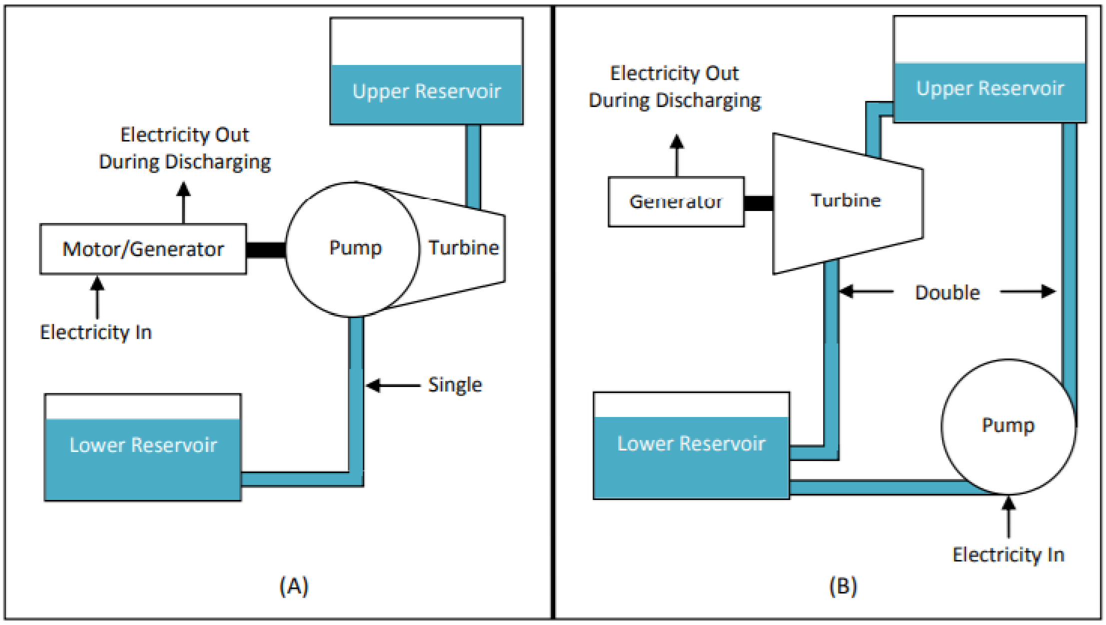


Fig. 3-17 One PHS facility with (A) a single penstock system and (B) a double penstock system [18]

In terms of the description of 'stabilization load' from EnergyPLAN results window as displayed in Fig. 3-16, there are a number of grid stabilization regulations that can be specified under the Regulation tab. This includes that "Minimum grid stabilization production share" (MGSPS), which specifies the percentage of production that must be from grid stabilizing units (i.e., power plants, hydro, nuclear, etc.). It is important to remember that this is a percentage of total production and not total demand. The calculation of grid stabilization is shown as follows:

$$Grid\ stabilization = \frac{e_{stab}}{d_{stab}} * 100 \tag{9}$$

$$stabilization\ load = \frac{Grid\ stabilization}{MGSPS}$$

where, e_{stab} is the total electricity production from grid stabilising units and d_{stab} is the minimum grid stabilisation production share that was specified in EnergyPLAN, the stabilization load required is then calculated.

② Economic data

EnergyPLAN simulates the costs of an energy system in four primary categories:

·Fuel costs: purchasing, handling, and taxes in relation to each fuel as well as their CO2 costs.

·Investment costs: capital required, the lifetime of each unit, and the interest rate on repayments.

·Operation costs: the variable and fixed operation and maintenance costs for each production unit.

·Additional costs: any extra costs not accounted for in the program by default e.g., the cost of insulating houses for increased energy efficiency. We do not consider this cost in this paper.

·Fuel costs (as shown in Fig. 3-18)

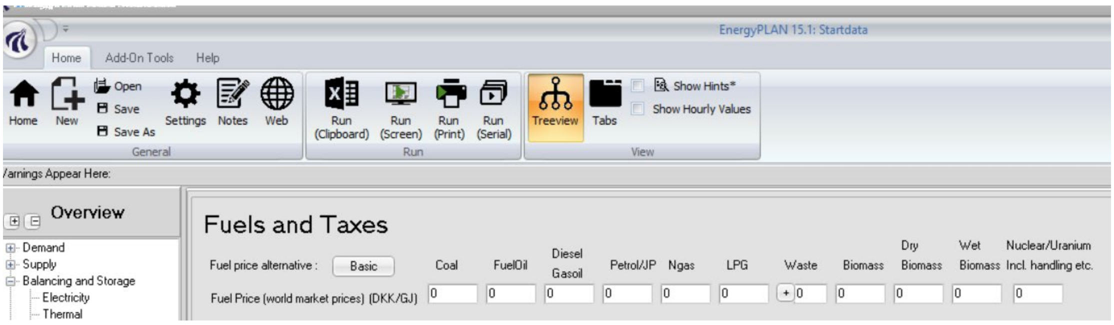
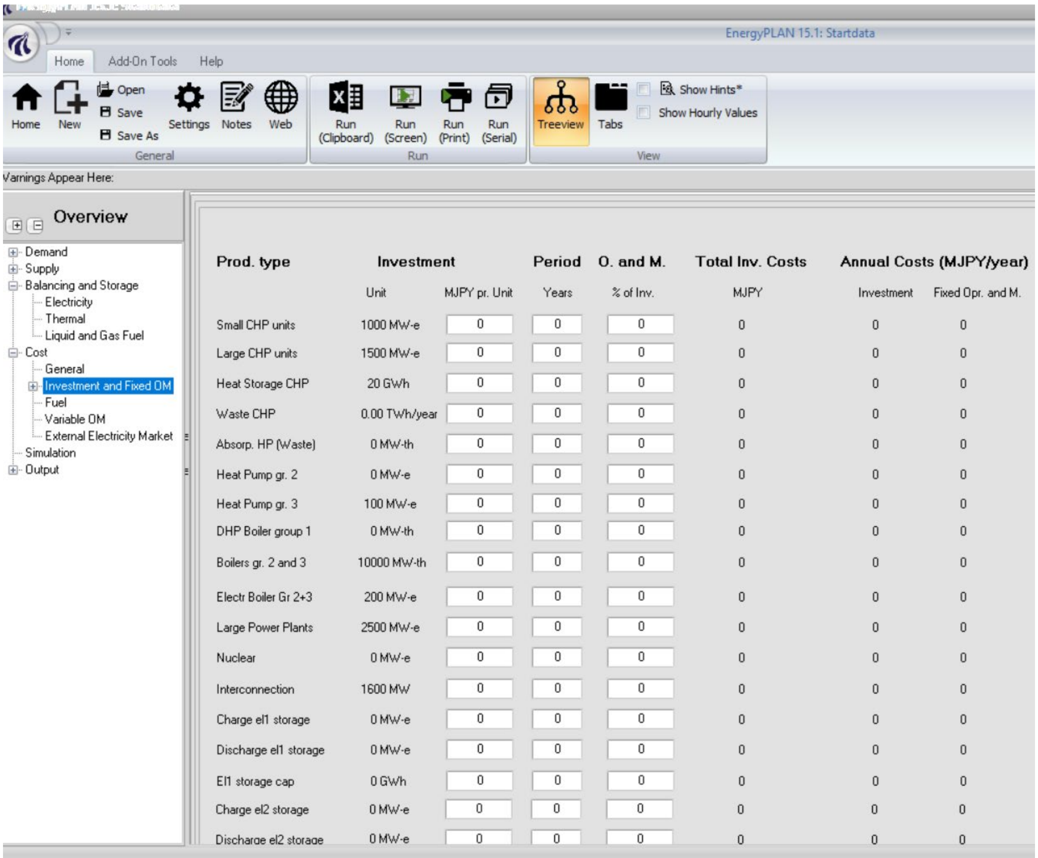


Fig. 3-18 The inputted data of fuel cost in EnergyPLAN

The fuel cost including the types of energy used, including coal, oil, and LNG. The details of fuel price will be introduced in Section 4.

·Investment and operation costs



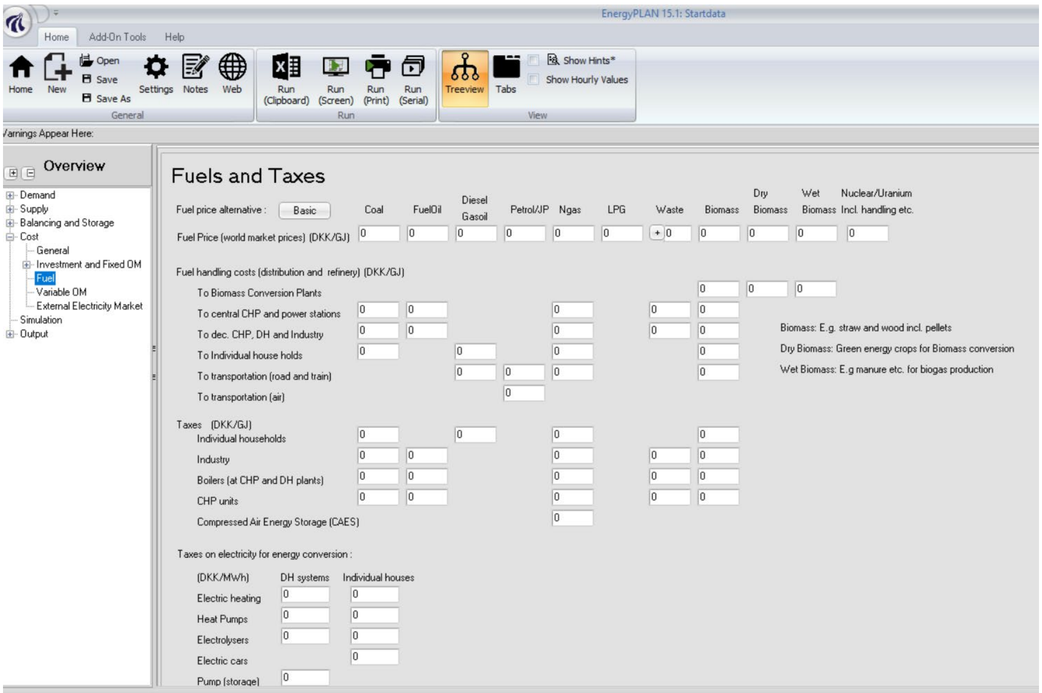


Fig. 3-19 The inputted data of investment, operation (upper), and fuel cost (bottom) for power generators in EnergyPLAN

Under this tab the investment, lifetime, and fixed operation and maintenance costs must be entered (as shown in Fig. 3-19). These costs are used for to calculate the annual costs of each component based on a fixed rate repayment loan.

③ Optimization criteria for an Energy System

It is very important to know how EnergyPLAN identifies that one energy system is better than an alternative energy system. There are primary variables that are recorded when doing this are:

·CEEP (Critical Excess Electricity Production): This is the amount of electricity that had to be exported from the energy system BUT COULD NOT be exported because the required transmission was not available.

·RES & Import: this is referred to the energy generation by renewable energy and imported electricity, respectively.

·Total cost: this is standard for the total cost of different power generators. The cost per unit can be calculated further.

3.3.3. The utilization of EnergyPLAN model with PHS facilities

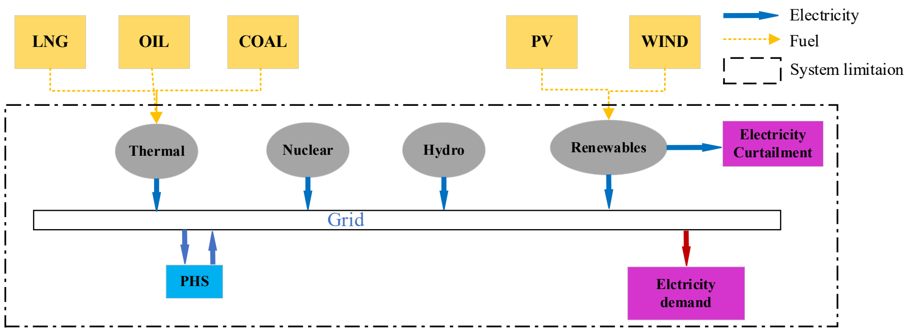


Fig. 3-20 Facility composition of the electricity co-ordination of supply and demand

When considering the application of PHS in EnergyPLAN, PHS converts renewable electrical energy into mechanical energy, and vice versa. It plays a major role in reducing power surplus caused by the volatility of renewable energy, reducing the use of fossil fuel energy, and balancing power supply and demand. Because the single pump turbine configuration must be switched during braking and reversing to reach the charge and discharge mode, it increases the response time. However, the double penstock configuration can reduce demand response time by pumping and generating power at the same time. In this paper, the double penstock PHS configuration is selected to cater to the main purpose of maximizing the penetration of RES and reducing thermal power generation. The schematic diagram of PHS mixed renewable energy, nuclear power and thermal power generation is shown in Fig. 3-20, these sectors are used for power supply. And the energy management flowchart with the strategies of PHS operation is shown in Fig. 3-21.

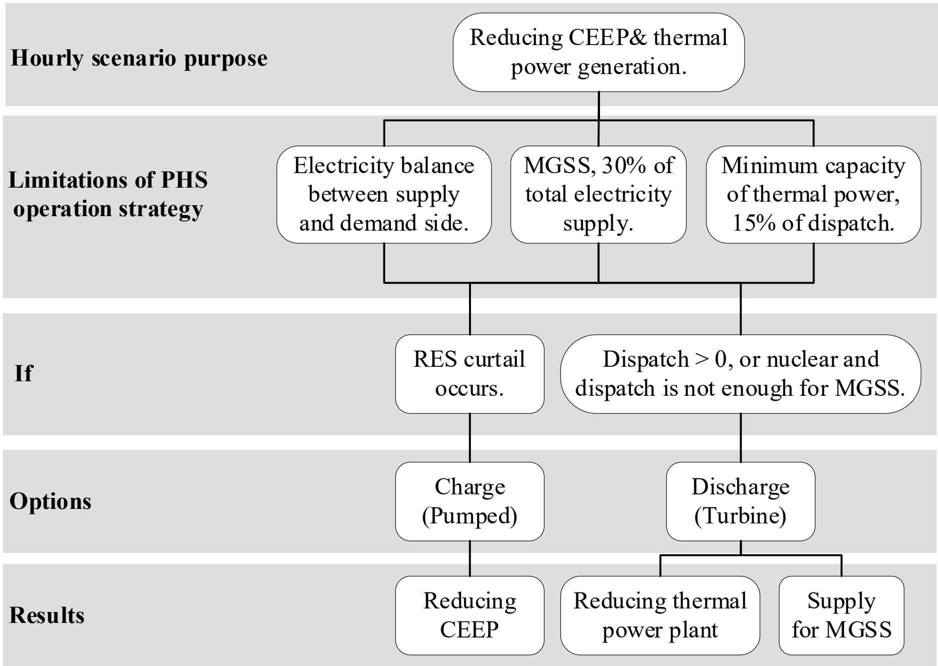


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Fig. 3-21 Energy management flowchart with the strategies of PHS operation

The supply and demand of electricity must be maintained in a real-time balance. According to the power generators referred in Fig. 2, the details of electricity balance is explained in Eq. (10).

$$dispatch^i + discharge^i - charge^i + RES^i + nuclear^i + hydro^i - curtail^i = Demand^i \quad (10)$$

where, i is the time unit. $dispatch^i$ refers to the flexible thermal power generators, which can regulate their output. $discharge^i$ and $charge^i$ standard the amount of electricity pumped and generating by PHS, respectively. To reduce the CEEP from RES, the pump will be operated when the electricity curtail occurs. While generating electricity by turbine to reduce thermal power generation or supply for the MGSS. The $discharge^i$ and $charge^i$ is calculated by:

$$charge^i = \min[curtail^i, \frac{PHS^i_{storage}}{\eta_{pump}}, C_{pump}] \quad (11)$$

$$discharge^i = \min\left[[curtail^i, \frac{PHS^i_{storage}}{\eta_{pump}}, C_{pump}\right] \quad (12)$$

where, η_{pump} and $\eta_{turbine}$ is the water pump and turbine efficiency, respectively. The maximum capacity of pump and turbine is explained as C_{pump} and $C_{turbine}$. The pumping capacity is limited by the amount of power curtailment, the current storage capacity, and the rated capacity of the pump. PHS discharge is not only used to reduce fossil fuel energy power generation, but also provide

MGSS for power grid as basic energy. In terms of MGSS, it can be calculated is as follows:

$$30\% * supply^i \leq nuclear^i + dispatch^i + discharge^i = MGSS^i \tag{13}$$

$$supply^i = dispatch^i + discharge^i + RES^i + nuclear^i + hydro^i \tag{14}$$

where, $supply^i$ is the total electricity generation by all power sectors.

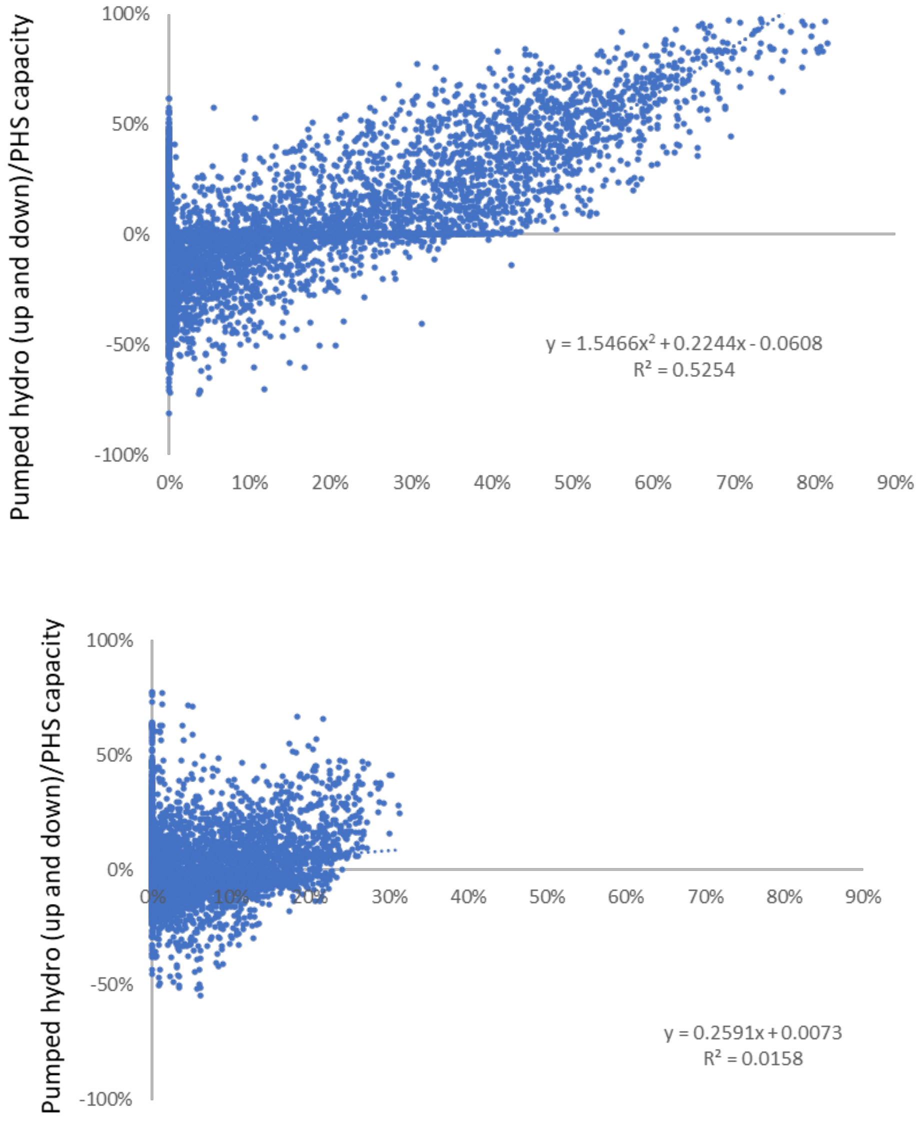

Fig. 3-22 Hourly basis on pumped hydro ratio and VRE ratio in Kyushu (upper) and Kansai (bottom) area [20]

From this, in Kyushu area, the ratio of VRE increases and the pumping operations of pumped hydro are actively performed. On the other hand, in Kansai area, even if the VRE ratio increases, the pumped hydro ratio does not increase at the same rate. However, in most cases where the VRE ratio is close to zero, the pumped hydro ratio is about 50%, and it is presumed that the combined operation with conventional nuclear power plants is still performed (as shown in Fig. 3-22).

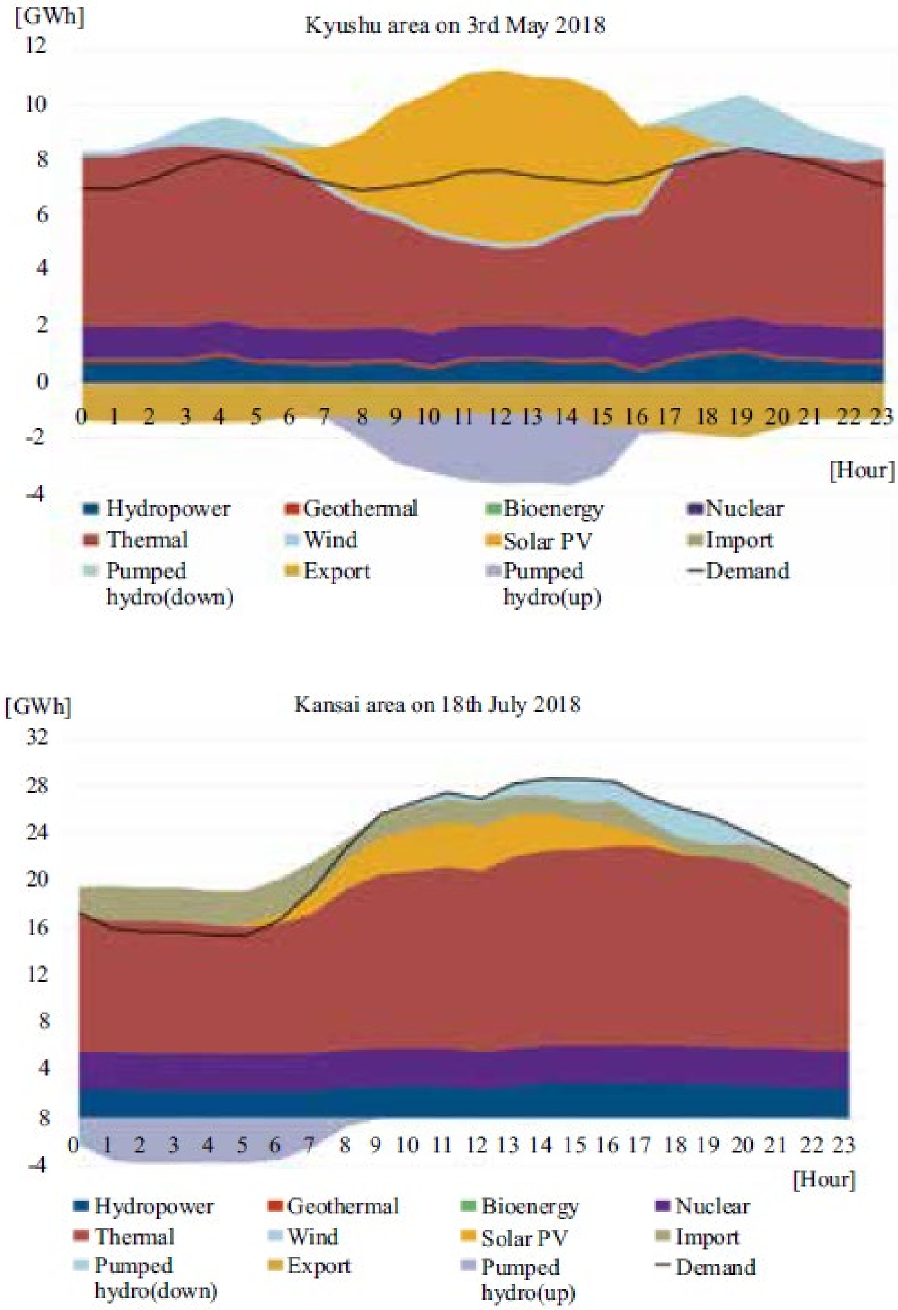

Fig. 3-23 Demand and supply balance in Kyushu and Kansai area [20]

In Kyushu area, pump up operation of pumped hydro takes place during the day almost mirroring electricity generation from PV, and electricity is generated from pumped hydro power plants during the time zones when the electricity generation from PV is small or zero in the morning, evening, and at night (as shown in Fig. 3-23). It is very efficient operations to compensate for the fluctuations.

In Kansai area, unlike operations in Kyushu area, pumping up of pumped hydro is performed at night when demand is low, and power generation is being performed during the daytime. This may be due to the conventional operations of keeping the output of nuclear power generation constant and absorbing fluctuations by pumped storage power generation although the ratio of VRE may be small compared to Kyushu area.

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Chapter 4

DATA RESOURCES AND ENERGY CONVERSION ANALYSIS

CHAPTER FOUR: DATA RESOURCES AND ENERGY CONVERSION ANALYSIS

4.1. Content

Japan's public grid is divided into ten grids by region, with electricity supplied separately by a fixed power company [1]. Each grid has different load requirements, power generation compositions, and energy resource distribution. Because PV and wind energy are seriously affected by the geographical and meteorological environment, in this study, we chose four regions Kyushu, Tokyo, Kansai, and Hokkaido that are spread across Japan. These sites were selected to represent a mix of summer and winter peaking loads and different levels of PV and wind resources, but also for the availability of actual and predicted energy data. In the current study, the available hourly time series of wind power, solar power, and load from April 2018 to March 2019 were collected and prepared for later analysis from the electricity power companies of Kyushu, Tokyo, Kansai, and Hokkaido. The collected data are available via the corresponding webpage of the Institute for Energy Systems at these locations [2]. Therefore, this Section will introduce the data resources from the location distributed, supply and demand profiles, composition of installed capacity, and economic data.

Besides, as the share of VRE penetration in the power grid, we hypothesis the continuing eliminates fossil fuel energy to developing cleaning energy used. Therefore, an approach of convert thermal power to VRE power will be introduced in Section 4.3.

4.2. Data resources

4.2.1. Distribution of research area

As seen in Fig. 4-1, the geographical distribution of installed wind and PV power, shows that Tokyo dominates in PV, followed by Kyushu, Kansai, and Hokkaido, and that Kyushu dominates in the wind, followed by Tokyo, Hokkaido, and Kansai.

① Kyushu Electric Power

Due to economic growth and the advancement of electrification, the demand for electricity in Kyushu has increased year by year. From the time when the company was founded (1951), the energy structure was hydropower and coal power, and then to oil power. Since the oil crisis in the 1970s, nuclear power and other energy sources, coal, LNG, oil power, and hydropower have developed in a balanced manner. Starting in 2011, fossil fuel consumption, fuel costs, and CO2 emissions will increase due to the increase in thermal power generation due to the closure of nuclear power plants (as shown in Fig. 4-2 and Fig.4-3), the installed capacity of power generation is also increased with the time. Since the oil crisis, the policymakers have been aiming for the best mix of power sources that combines various power sources in a well-balanced manner from the perspectives of fuel procurement stability, power generation costs, and the impact on the global environment.

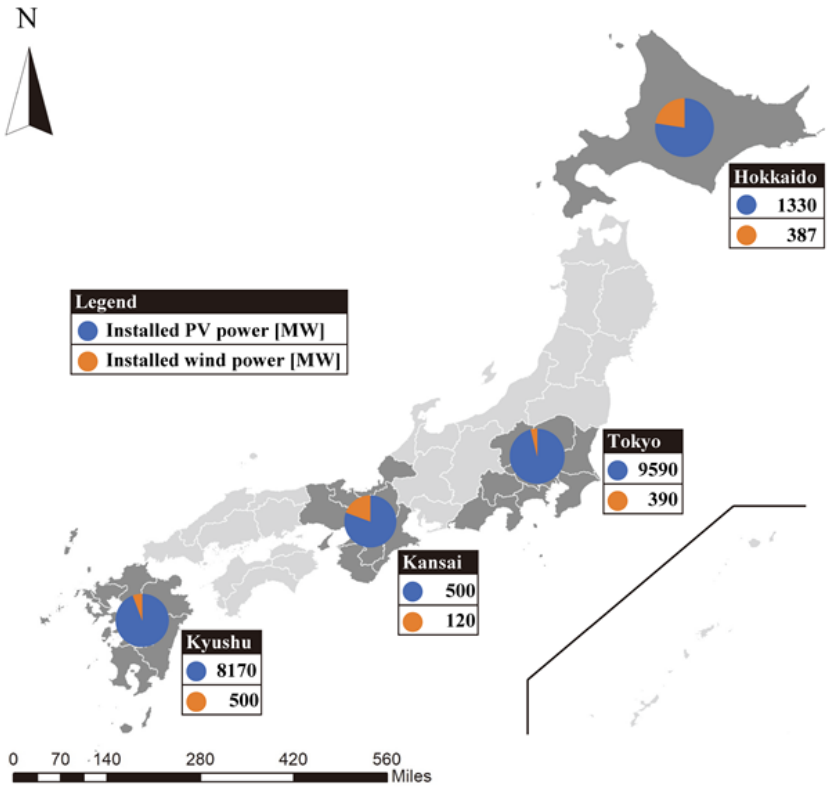
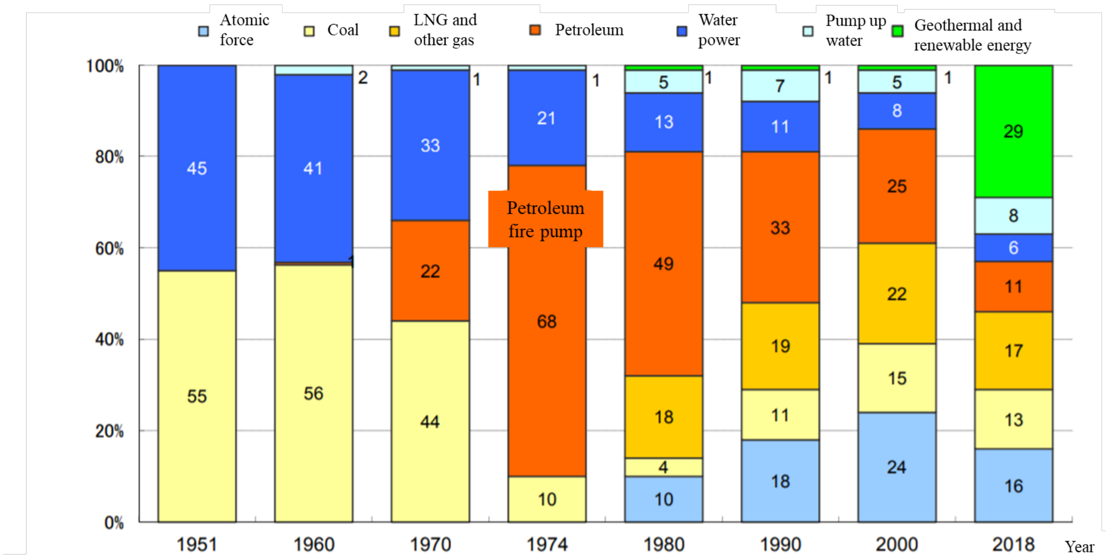


Fig. 4-1 Installed capacity of PV and wind power and its regional distribution for Kyushu, Tokyo, Kansai, and Hokkaido electricity companies



Capacity of power generation equipment(Million kW)	115	228	403	680	1, 132	1, 583	2, 181	2, 982

Fig. 4-2 The progress of the composition of power generations and installed capacity in Kyushu [3]

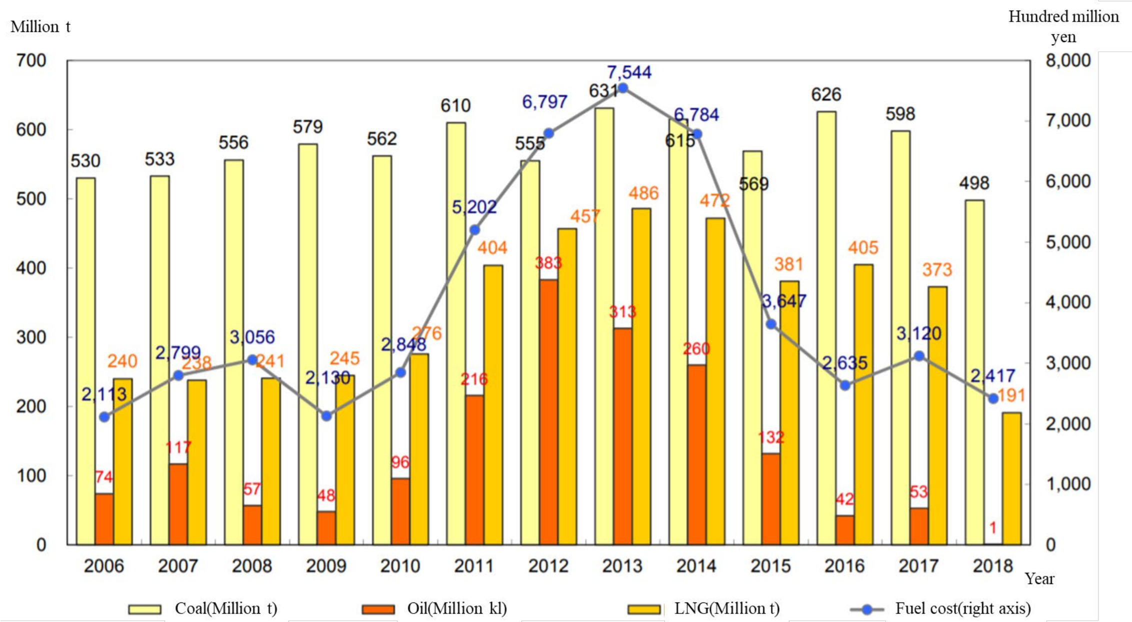


Fig. 4-3 The progress of fossil fuel energy consumption and cost [3]

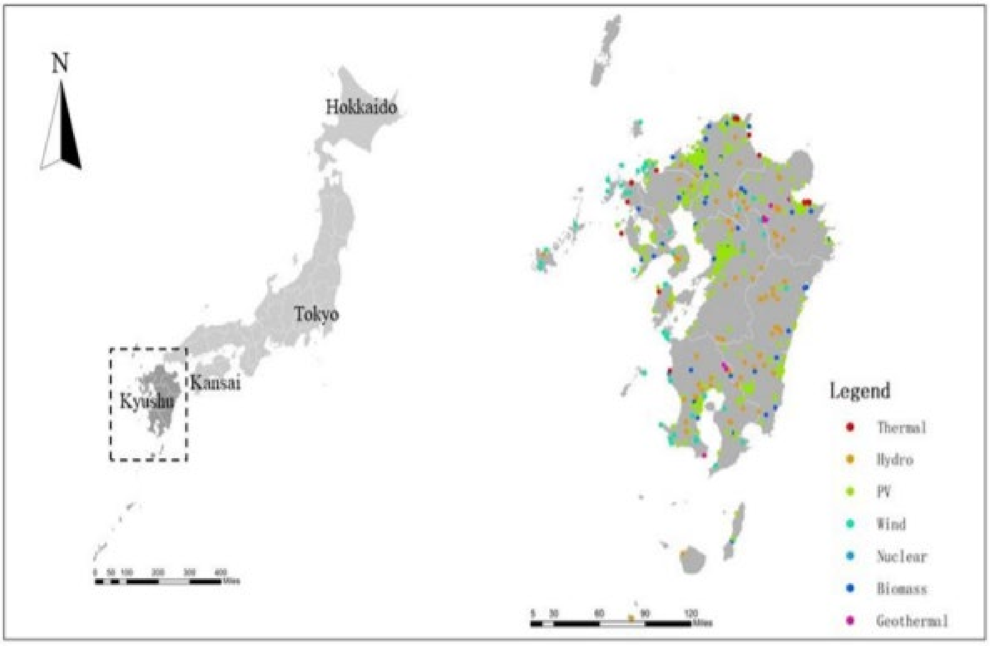
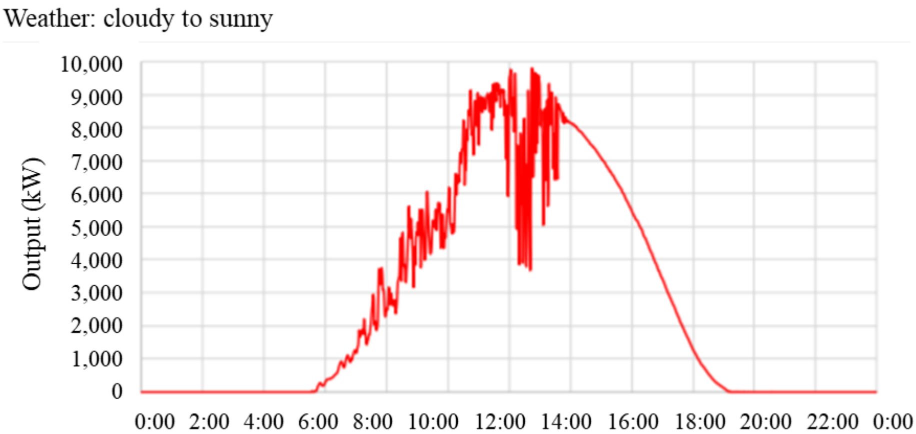


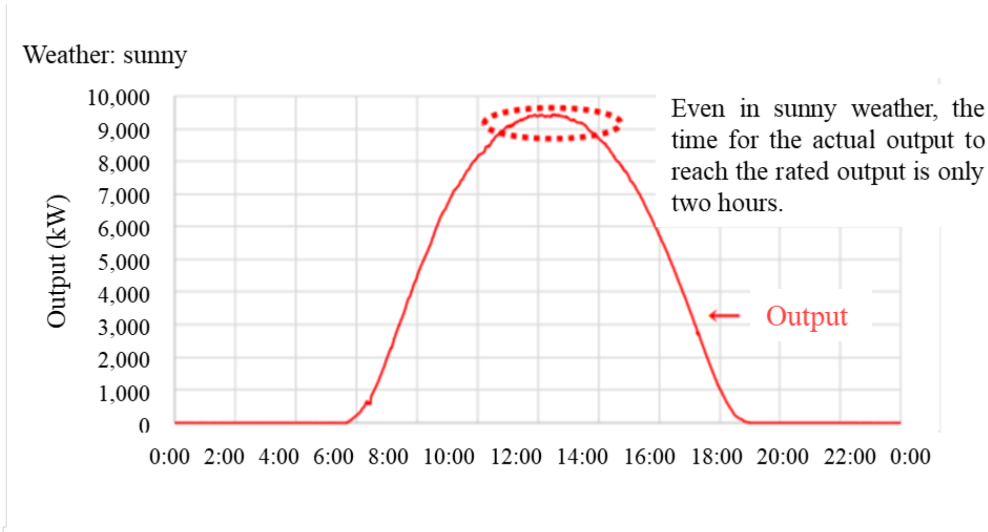
Fig. 4-4 The energy distribution in Kyushu

According to the existing data of energy production, the energy distribution in Kyushu is shown in Fig. 4-4. The development centered on group companies is promoted, such as solar power generation (mega solar) utilizing the site of a thermal power plant and wind power generation in consideration of harmony with the surrounding environment. Such as the construction of Sasebo Mega Solar Power

Plant and Nagashima Wind Power Plant (as shown in Fig.4-5). The power generation of PV in Sasebo Mega Solar Power Plant is shown in Fig. 4-6. The PV power generation is changed with meteorological conditions. We can conclude that even on a clear day, it took about 2 hours to reach the rated output. As the power generation output of PV power generation changes greatly depending on the time and weather. In order to supply electricity in a stable manner, we are dealing with output fluctuations due to solar and wind power generation by adjusting the output by thermal power generation.

Fig. 4-5 The live photo of Sasebo Mega Solar Power Plant (upper), and Nagashima Wind Power Plant (bottom)





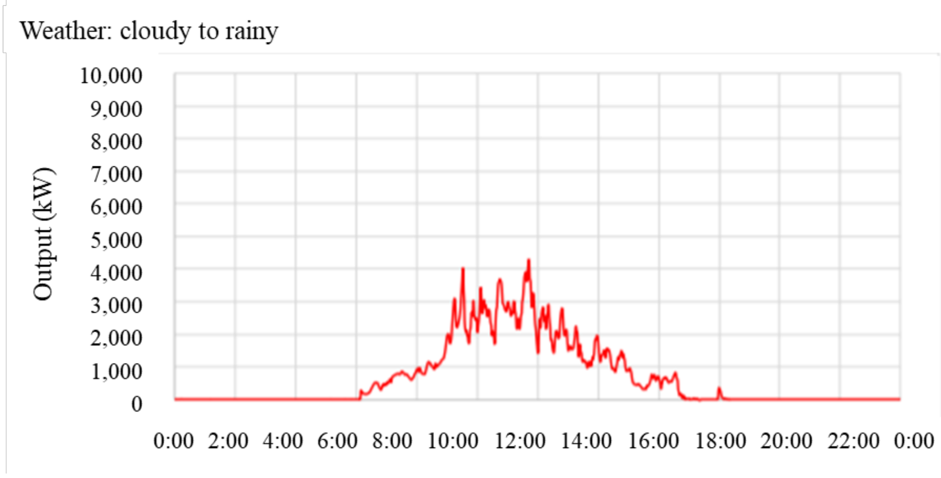
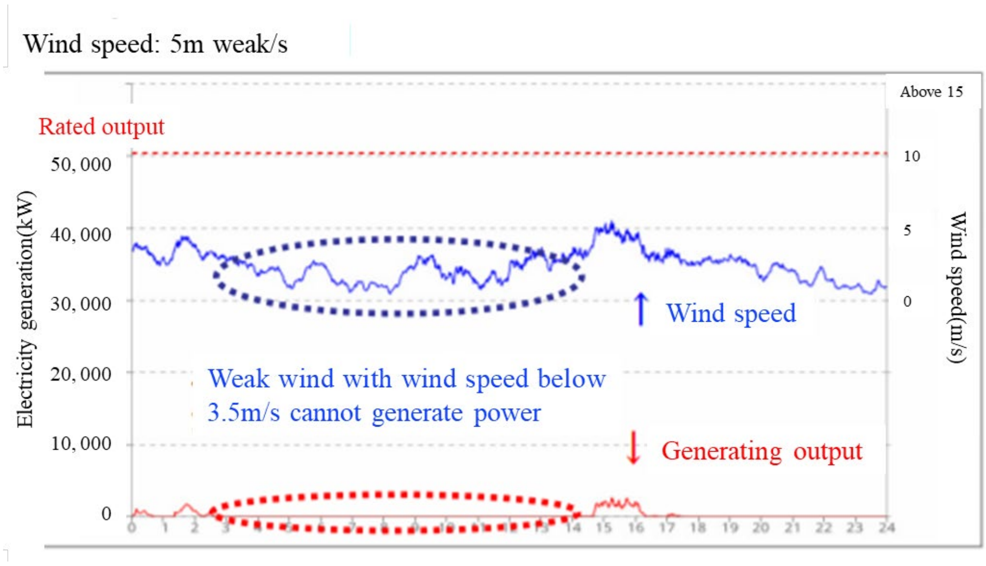
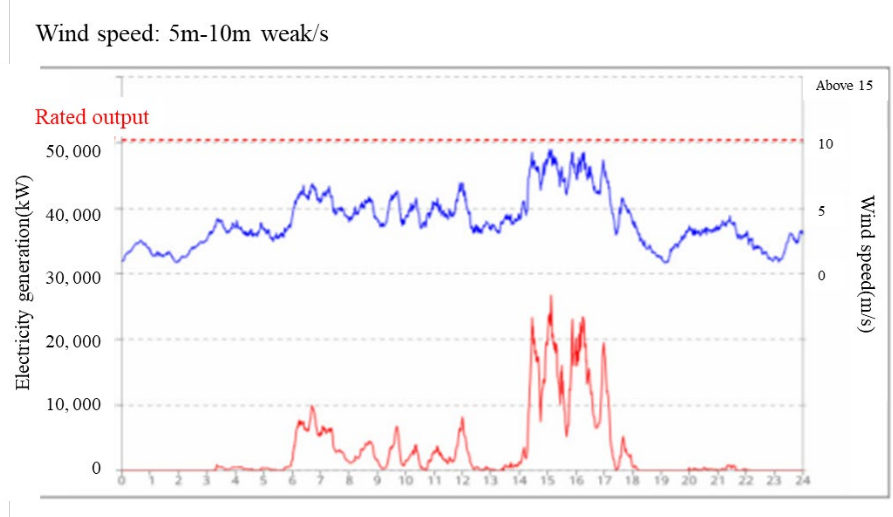


Fig. 4-6 The PV power generation profiles in terms of me meteorological conditions, which is located in Sasebo Mega Solar Power Plant [3]





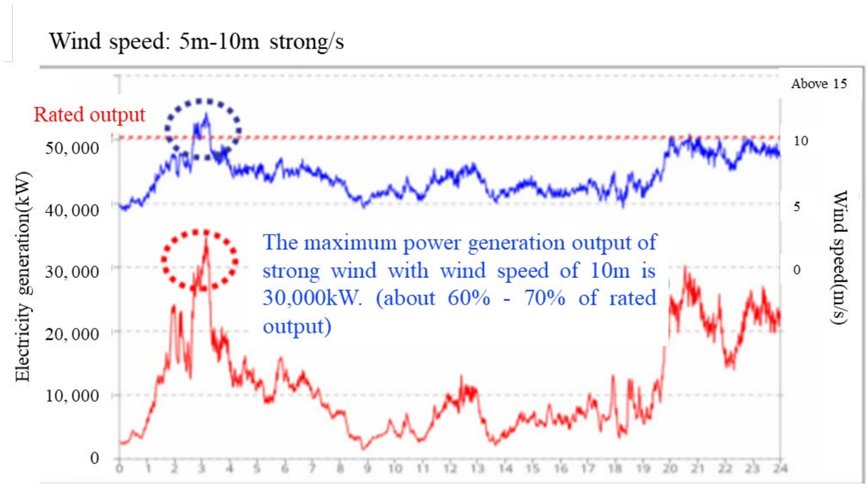


Fig. 4-7 The wind power generation profiles in terms of me meteorological conditions, which is located in Nagashima Wind Power Plant [3]

In wind power generation, the power generation output changes greatly depending on the wind speed. To supply electricity in a stable manner, we also deal with output fluctuations due to wind power generation by adjusting the output of thermal power generators.

② Hokkaido Electric Power

Hokkaido is located in the Northernmost of Kyushu, which is depicted in Fig. 4-8. The progress of the electricity power generation in Hokkaido is depicted in Fig. 4-9 and Table 4-1. Although the thermal power is deceased compared to 2015 year, it still accounts for 74% in the total amount of the power generation. The lower heating efficiency of the thermal power generation in Hokkaido is 39.7% (in 2019).

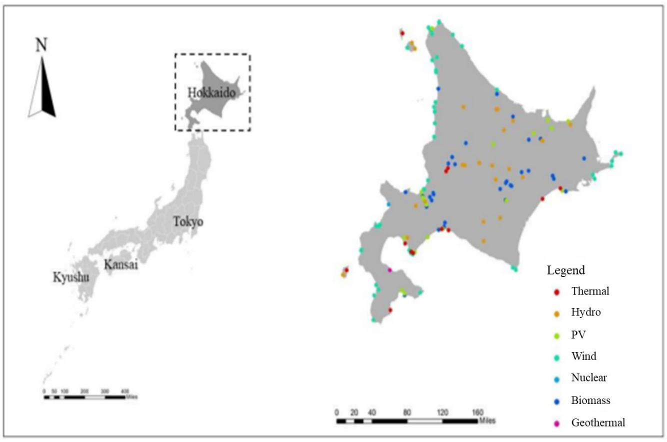


Fig 4-8 Energy distribution in Hokkaido

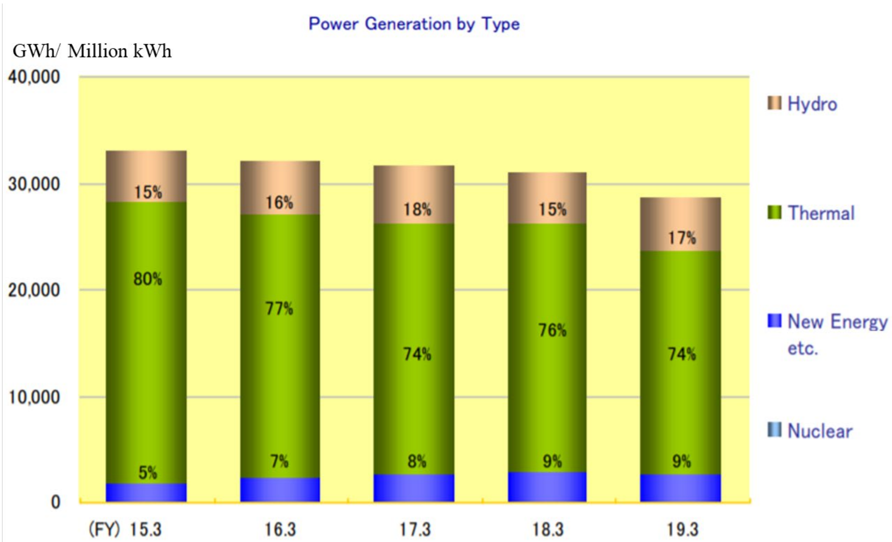


Fig. 4-9 The progress of variable power generation shares in Hokkaido power grid [4]

③ Kansai Electric Power

The electricity generation shares of power generation in Kansai are shown in Fig. 4-10. The thermal power plant with LNG energy supplied accounts for 48% shares in Kansai power grid. In contrast to the Japan power composition, coal energy pretends smaller percentages in Kansai power grid. Besides, very small proportion of renewable energy is shown. In addition, the lower heating value of thermal power efficiency is shown in Fig. 4-11.

Table 4-1 The summarized amount of electricity power generation

FY (Year)	15.3	16.3	17.3	18.3	19.3
Hydro	15.3	5,067	5,559	4,744	4,873
Thermal	26,463	24,866	23,569	23,373	21,027
Renewable energy	1709	2,148	2,556	2,814	2,573
Nuclear	-	-	-	-	-
Total	33,028	32,041	31,684	30,931	28,473

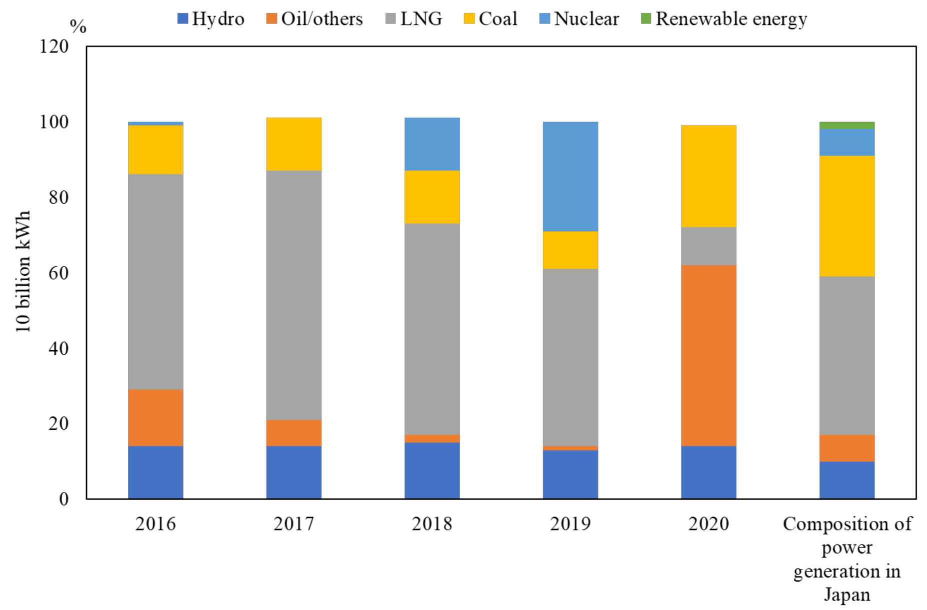


Fig. 4-10 The total power generation by energy resource in Kansai power grid [5]

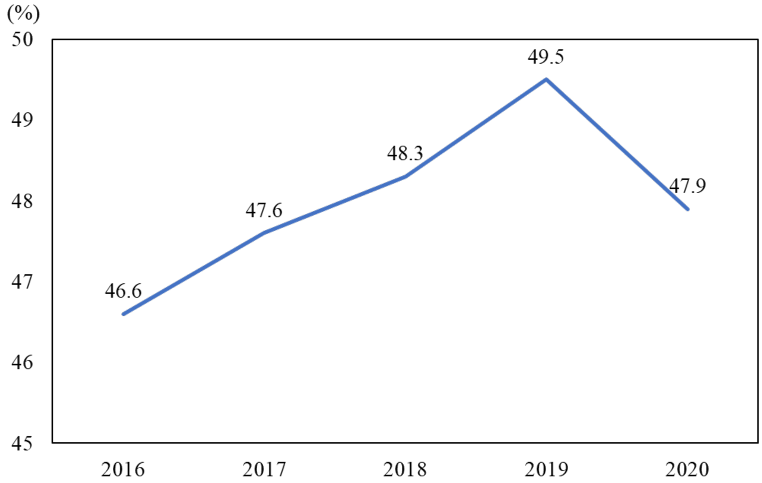


Fig. 4-11 The thermal efficiency of thermal power plant in Kansai power grid

④ Tokyo Electric Power

The energy distribution and location are shown in Fig. 4-12. The hydro electricity generation accounts for large parts at first before 1965, the oil power generation reduced the hydro energy after then. Since the oil crisis in the 1970s, nuclear power and other energy sources, coal, LNG, oil power, and hydropower have developed in a balanced manner (as shown in Fig. 4-13). The lower heating value of thermal power plant is shown in Fig.4-14, which is higher than that in Kansai power grid due to the lower coal energy utilization.

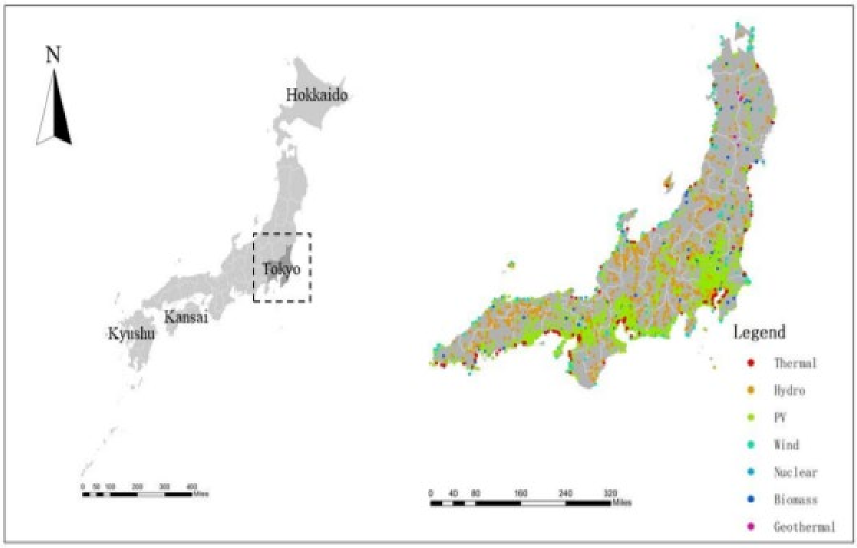


Fig. 4-12 Energy distribution in Tokyo

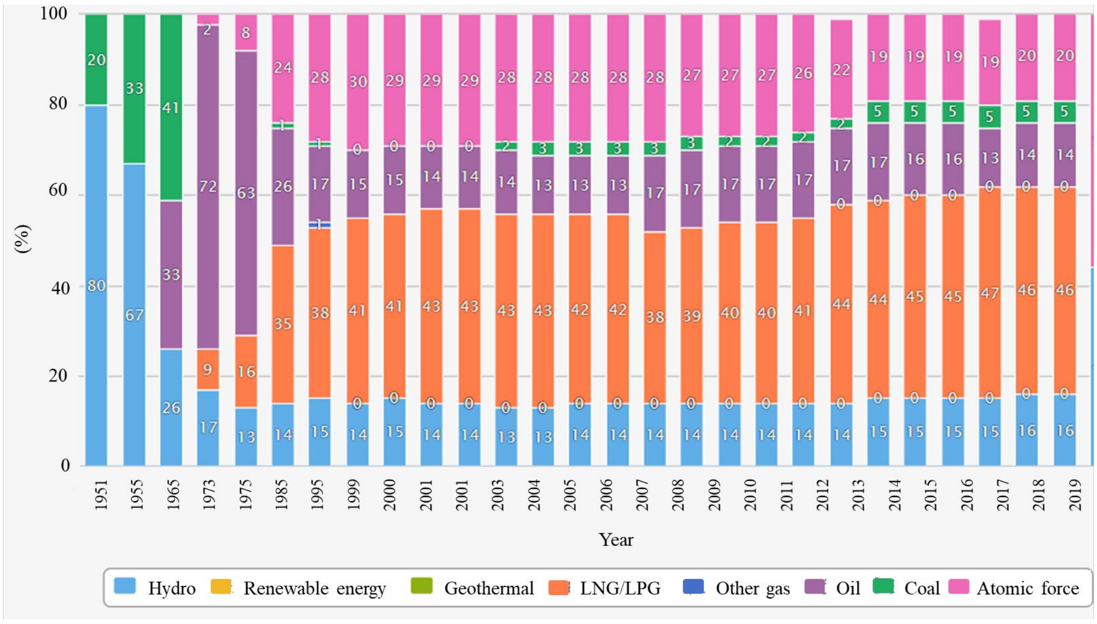


Fig. 4-13 The progress of power generation proportions by different energy types in Tokyo power grid [6]

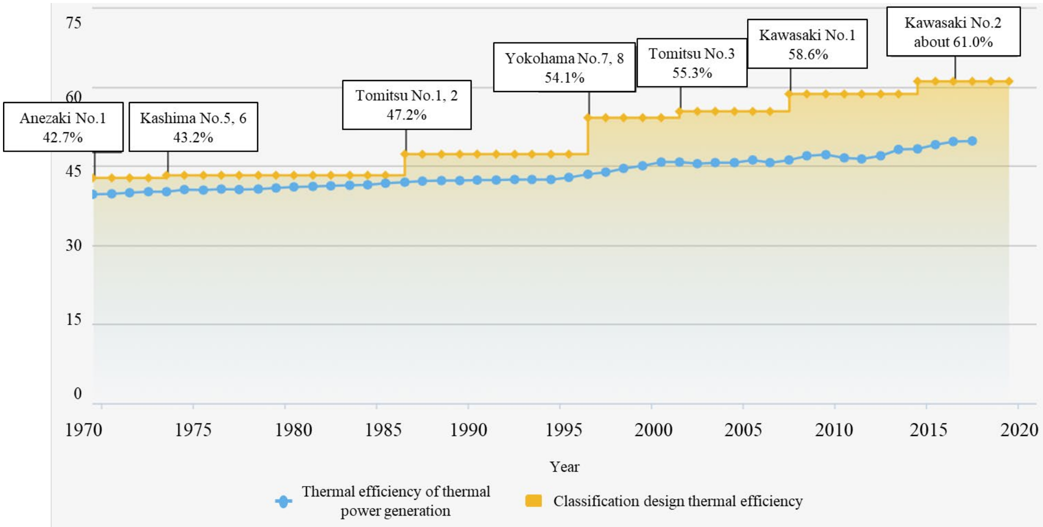


Fig. 4-14 The thermal efficiency of thermal power plant in Tokyo power grid

4.2.2. Comparison of the power generation composition

The current structure of the power supply in the four regions in terms of energy composition of power generation is illustrated in Fig. 4-15. Conventional thermal energy is the dominant energy supply. The proportion of VRE is no more than 10% of the total load demand. However, there is more potential for renewables than currently generated. Renewable energy includes biomass energy, geothermal energy, PV energy, and wind energy. These data resources are combined with hourly load demand from different sectors downloaded from the websites maintained by Japan electricity power companies. Beyond power generation data on both the supply and on the demand sides, the storage capacity and transmission lines between regions also play a significant role in real-time power balancing in different public grids.

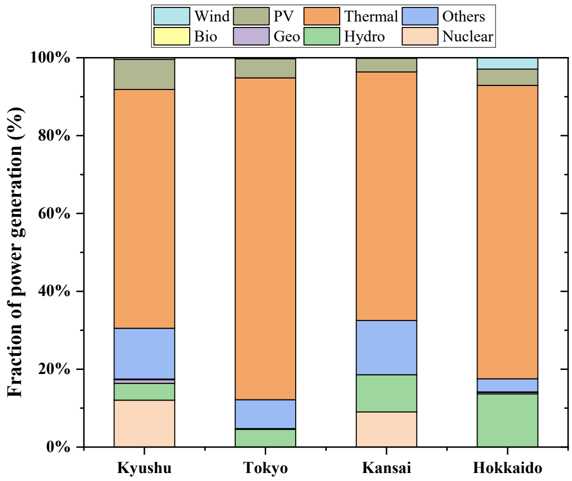


Fig. 4-15 Configuration of power generation in Kyushu, Tokyo, Kansai, and Hokkaido (in 2019) [11]

The correlations of PV, wind energy with demand, the share of PV and wind power production, and the utilization ratio of VRE facilities is summarized in Table 4-2. In terms of correlation between PV or wind with demand, Kyushu, Tokyo, and Kansai plays positive correlation with load demand, while Hokkaido without correlation with electricity demand. While the correlation between Hokkaido's load demand and wind energy is 0.348. No obvious correlation between wind and demand in the other regions. This is resulted from the correlation between demand profile and VRE power generations (shown in Section4.2.3). PV shares shows dominant in Kyushu, followed by Tokyo, Hokkaido, and Kansai. Wind shows dominant in Hokkaido area. In terms of utilization ratio of PV and wind energy, Kyushu is lower than the other area, which is already have VRE curtailment.

Table 4-2 Summarized data of VRE in different power grid

Item	Correlation		Shares of power generation		Utilization ratio	
Energy type	PV/Demand	Wind/Demand	PV	Wind	PV	Wind
Kyushu	0.23	-0.013	11.45%	0.69%	11.97%	11.72%
Tokyo	0.314	-0.008	5.3%	0.37%	13.26%	30.20%
Kansai	0.365	0.057	4.46%	0.24%	14.18%	33.60%
Hokkaido	-0.110	0.348	5.13%	3.08%	11.64%	24.47%

4.2.3. Load profiles and VRE generation profiles

① Load profiles

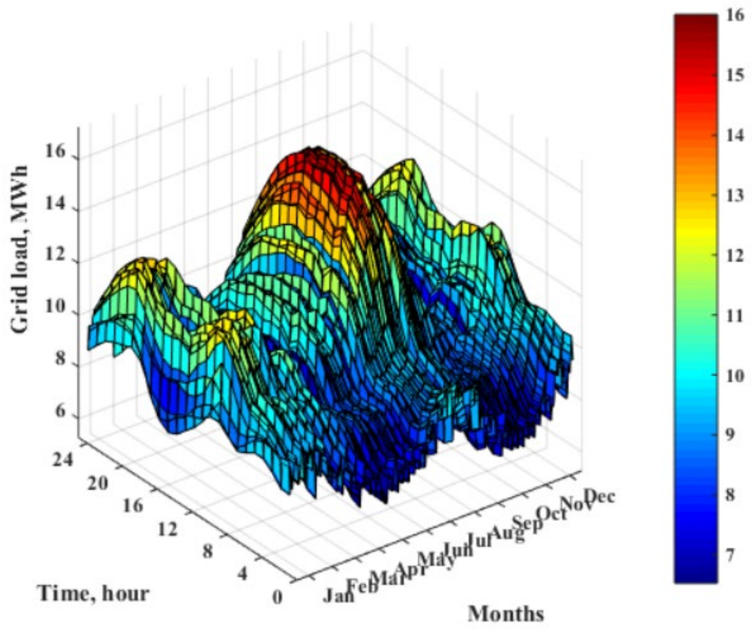


Fig. 4-16 Load profiles in Kyushu power grid

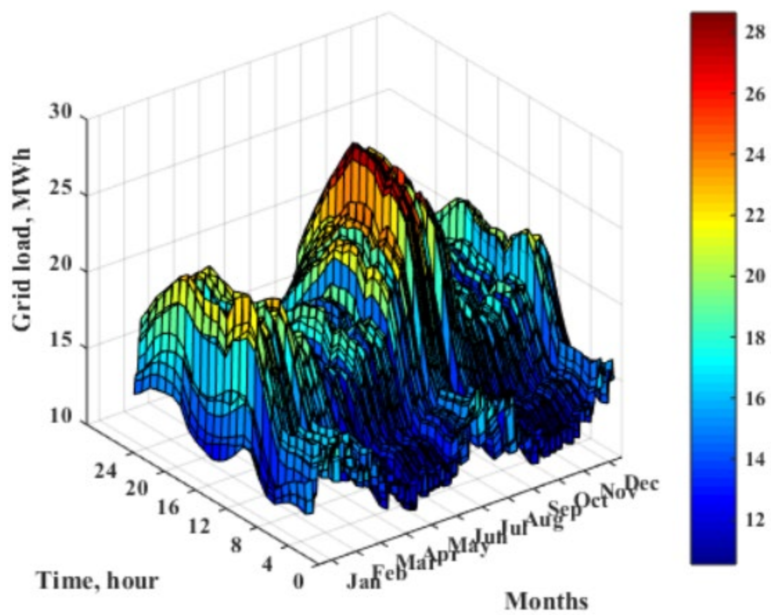


Fig. 4-17 Load profiles in Tokyo power grid

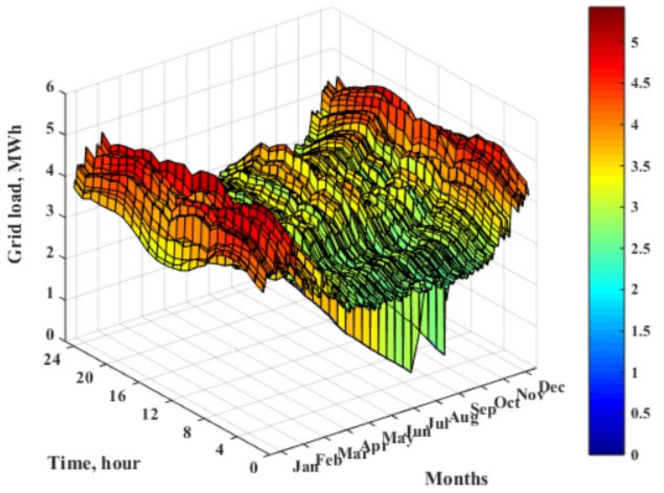


Fig. 4-18 Load profiles in Hokkaido power grid

The load profiles pretend the hourly electricity demand for one year. The electricity demand of Kyushu, Tokyo, and Hokkaido are shown in Fig. 4-16, Fig.4-17, and Fig.4-18, respectively. The Kansai area is similar to Tokyo, and the Kansai load curve is not reflected here. Kyushu is in the southern part of Japan, and its peak load demand appears during the summer day. The load demand in the transition season is low. The Tokyo area is well-developed industry with extra high voltage used, and the peak load occurs during the daytime working hours. And the total load demand is greater than the Kyushu region. The Hokkaido area is in the northernmost part of Japan, and the temperature is relatively low. Therefore, the load presents the peak value in winter. The transition season and summer load are lower than winner.

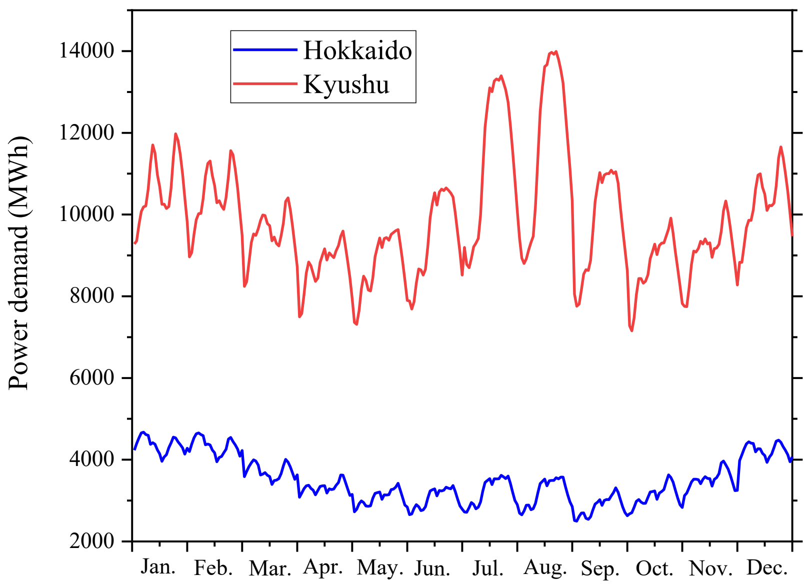
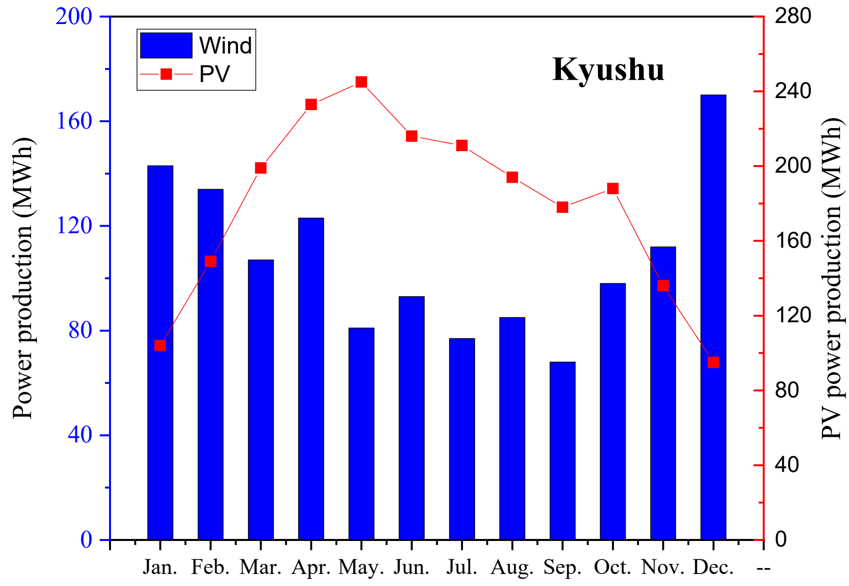
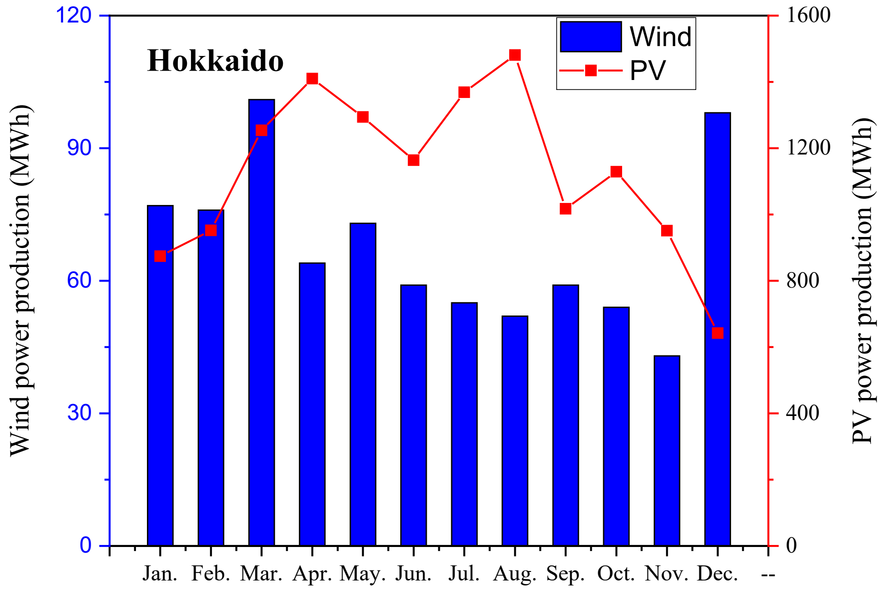


Fig. 4-19 Monthly-averaged hourly data of load profile over one-year in Kyushu and Hokkaido

Compared with the load distribution in Kyushu and Hokkaido in details, the monthly-average hourly data of load profile over one-year in Kyushu and Hokkaido is depicted in Fig. 4-19. This paper used the power generation data form April 2018 to March 2019. As shown in Fig. 4-19, the electricity demand in Hokkaido shows a peak load in the daytime of July and August, resulted from the refrigeration required in summer period. The heating demand in winter nighttime leads to the distribution of peak load from December to February in Hokkaido. In addition, the annual load demand in Kyushu is much higher than that in Hokkaido.

②PV and wind production





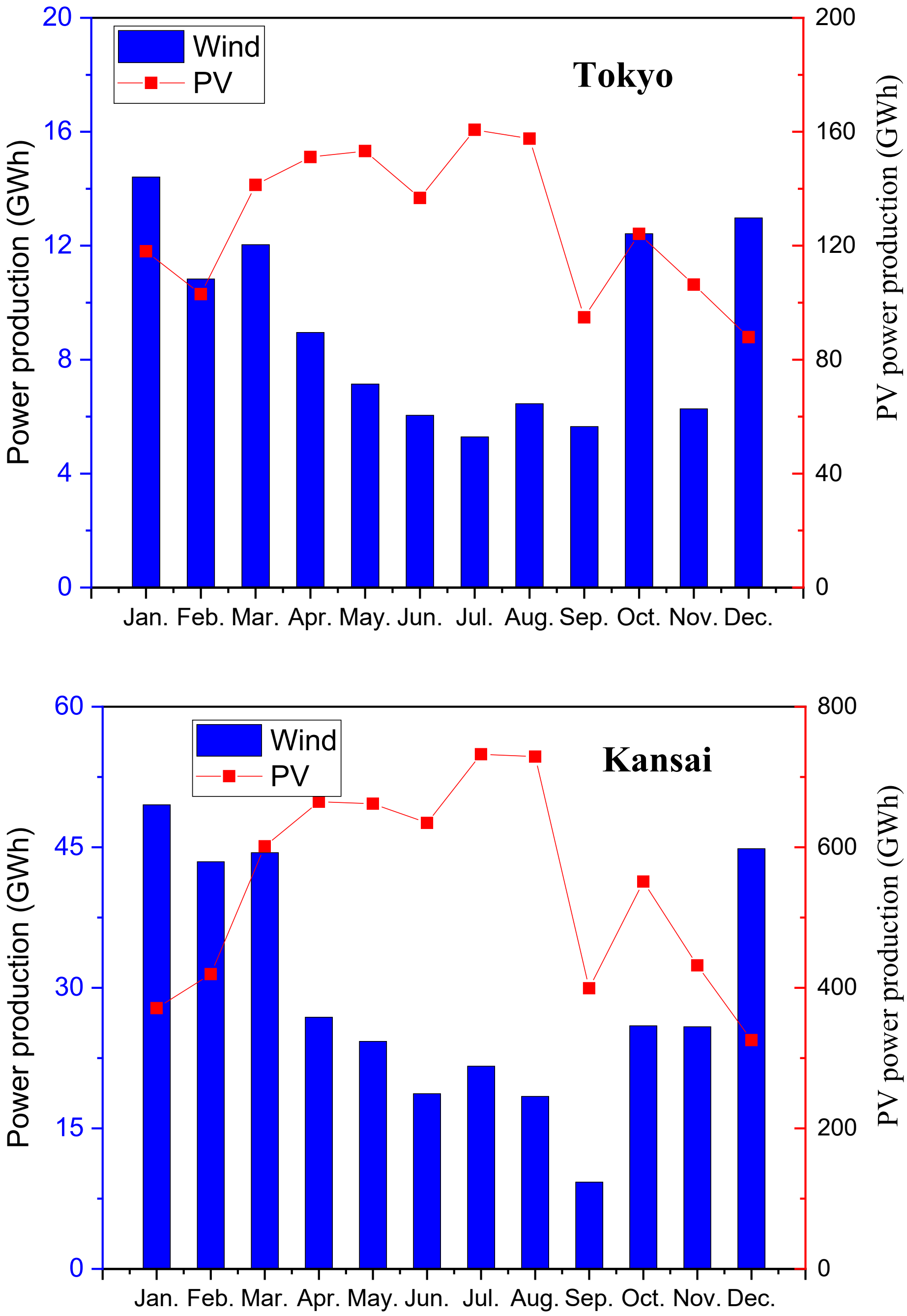
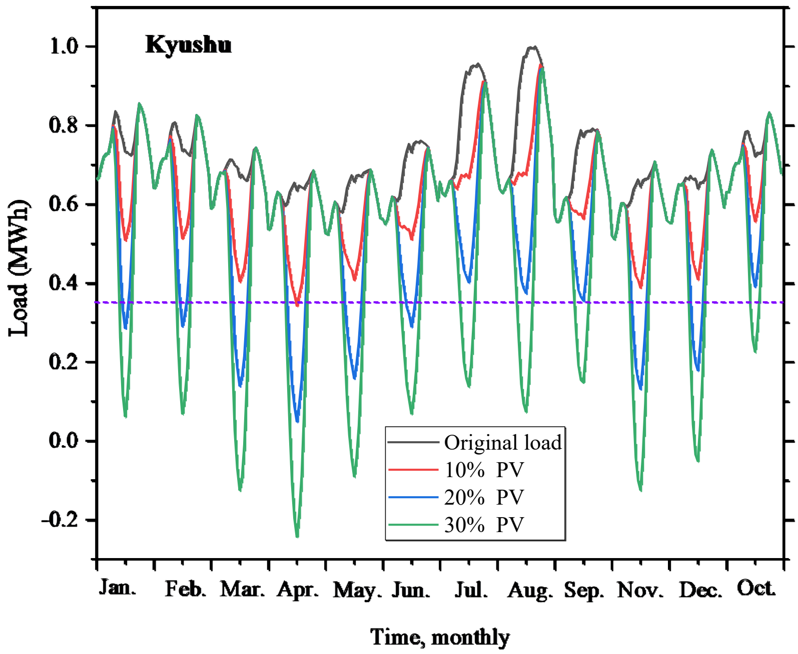


Fig. 4-20 The Monthly-averaged daily net power production from PV module and wind turbine in Kyushu, Hokkaido, Tokyo, and Kansai power grid, respectively

Fig. 4-20 depicts the current annual power generation distribution of PV and wind power in Kyushu, Hokkaido, Tokyo, and Kansai. PV power generation in four regions is significantly lower in winter than in other seasons. Wind power does not show obvious seasonality in Kyushu, while wind power in Hokkaido, Tokyo, and Kansai peaks in winter. Besides, the total power generation in Tokyo and Kansai is larger than that in Kyushu and Hokkaido. Therefore, PV and wind pretends different power generation characteristics.

③ Residual load reduced by VRE production



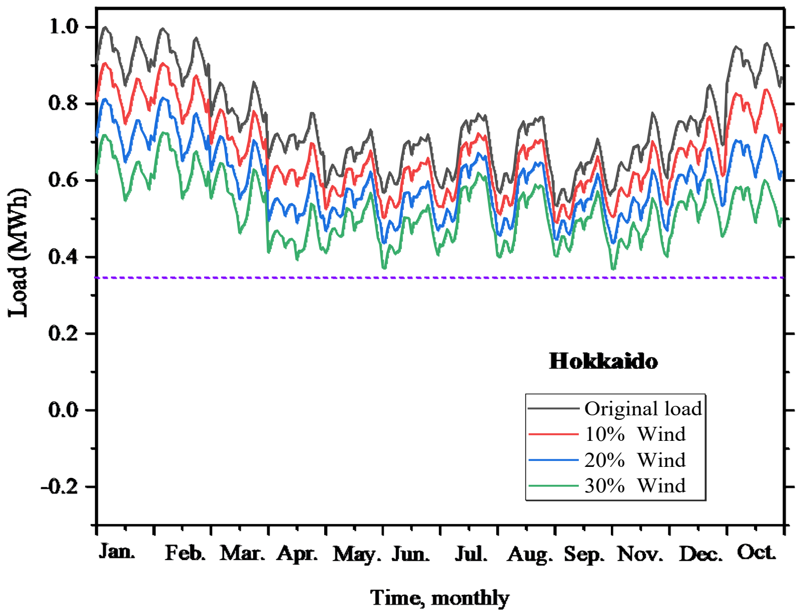
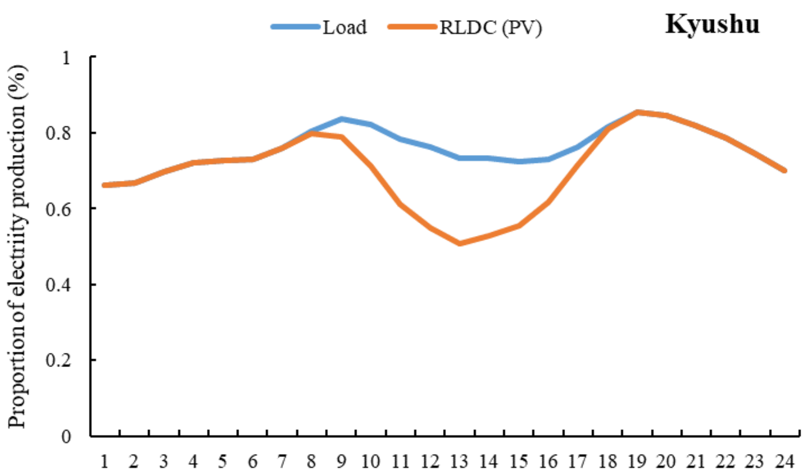


Fig. 4-21 Hourly residual load for days of different months with PV or wind production to grid load ratios of 0%-30% for Kyushu and Hokkaido

Because PV and wind energy are seriously affected by the geographical and meteorological environment, in this study, we chose four regions Kyushu, Tokyo, Kansai, and Hokkaido that are spread across Japan. These sites were selected to represent a mix of summer and winter peaking loads and different levels of PV and wind resources, but also for the availability of actual and predicted energy data. The average monthly load demand and residual load profiles with different integrated PV and wind capacities are shown in Fig. 4-21. Both PV and wind power generation significantly reduce the output of flexible power plants, and PV power generation causes the RLDC to be lower than the base load, which is equal to 0.35 peak load. Wind energy in Kansai and Hokkaido is continue tilt the load profiles during all days, it is resulted from the nature of wind production. In the current study, the available hourly time series of wind power, solar power, and load from April 2018 to March 2019 were collected and prepared for later analysis from the electricity power companies of Kyushu, Tokyo, Kansai, and Hokkaido. The collected data are available via the corresponding webpage of the Institute for Energy Systems at these locations [7-10].

Wind power is more unpredictable than PV power generation. PV is mainly affected by sunlight and has a periodicity, and the wind speed can change continuously throughout the day. Therefore, wind power can continuously reduce the residual load curve. As shown in Fig. 4-21. It is worthy noticing that the reason of choosing 10%, 20%, and 30% of PV and wind penetration in power grid (as shown in Fig. 4-21). RLDCs are used to compare the impact of PV and wind on the power grid. Although the residual load curve of PV and wind energy under different permeability is similar, the higher the permeability is, the more obvious the trend is. Meanwhile, in order to ensure the fairness of the comparison between regions, Fig.4-21 selects three cases with 10%, 20% and 30% penetration level of VRE for analysis. The details of daily load profile and residual load profile reduced by PV and wind production is shown in Fig. 4-22. It clearly shows the difference in the impact of PV and wind energy on load demand.



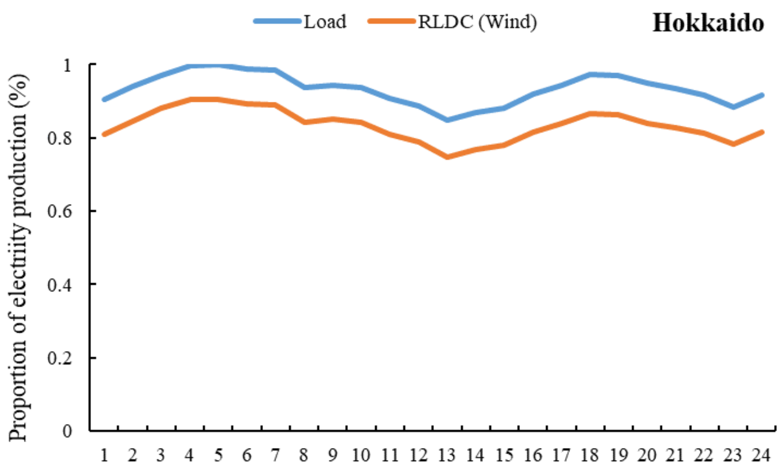


Fig.4-22 Load duration curve with one daily data in Kyushu and Hokkaido

4.2.4. Economic cost of power generators

The cost of power generation per unit can be calculated by the summarized of investment cost, operating cost, and fuel cost. In this paper, the fuel cost only comes from the fossil fuels, including the oil, coal, and LNG.

$$\frac{Yen}{kWh} = \frac{Capital\ cost + Operation\ cost + Fuel\ cost}{Capacity\ of\ power\ genration} \tag{1}$$

$$Thermal\ fuel\ cost = \frac{1kWh}{\theta * LHV} * Price \tag{2}$$

where, price is the average price of fuel at per unit, LHV stands for the lower heating value of coal, oil, and LNG. θ represents the efficiency of thermal power plant electricity generation. The data of LHV is introduced in Section 4.2.2 in details.

In terms of the thermal power efficiency, it is the amount of power generation accounts for the total energy consumed. We hypothesis the efficiency from the shares of fossil fuel types and utilization rate of power generation facilities. The schematic of thermal power efficiency is shown in Fig. 4-23 and formula (3), as follows:

$$\theta = \frac{Amount\ of\ power\ generation}{Calorific\ value\ of\ fuel} \tag{3}$$

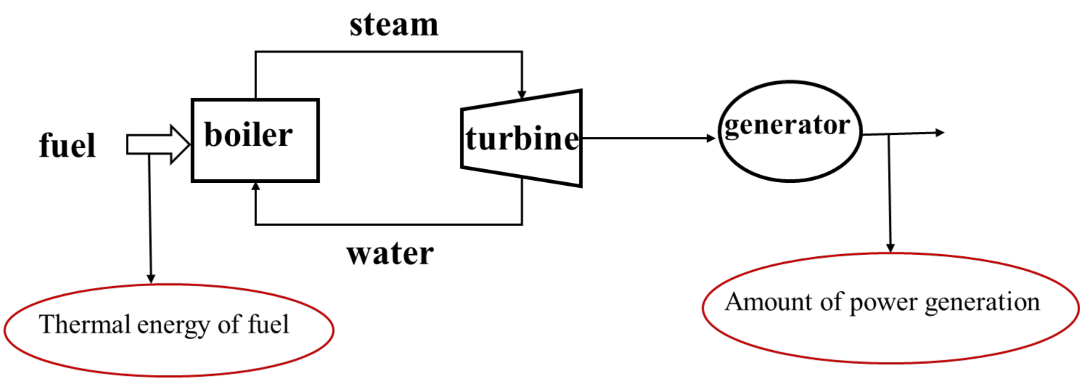


Fig. 4-23 Flowchart of thermal electricity generation

We set the power generation cost according to the statistics of the Japanese government. Based on the literature for PHS, fossil fuel cost, and other technologies, the cost assumptions are summarized in Table 4-3.

Table 4-3 Summarized of cost assumption [12]

Energy source	Coal	LNG	Oil	PV	Wind	Hydro	Nuclear
Unit construction cost (JPY thousand/kW)	250	120	200	169	212	640	370
Lifetime (year)	40	40	40	30	20	40	40
Annual O&M cost rate (%)	0.03	0.02	0.03	0.01	0.02	0.011	0.052
Fuel cost (Yen/kWh)	14.36	10.52	25.96	-	-	-	-
CO2 emission coefficient (t-CO2/t)	2.3	2.7	3.4	-	-	-	-
Fuel heat (MJ/kg)	24.66	50.06	39.05	-	-	-	-
Thermal efficiency (%)	42%	52%	39%	-	-	-	-

4.3. Energy conversion analysis

Energy demand is affected by many factors, including changes in population, socio-economic status, natural disasters, and unknown technological bottlenecks [39,40]. The population of Japan has been in the stage of slight negative growth in recent years [41]. According to the data of Tokyo Electricity Powe, the demand for electricity has not changed significantly [42]. Therefore, we use the data of electricity demand in 2019 for this study. On the supply side, after the Fukushima earthquake in 2012, the development of nuclear energy declined rapidly, and fossil fuels and renewables serve as primary alternative energy substitutes for nuclear power. PV and wind energy have played a significant role in power generation in the process of eliminating traditional energy sources to renewable energy sources. Hence, in the present study, we assume that renewable energy values except for wind and PV remain constant, as they were in 2018, and we hypothesize that all thermal power plants (coal, LNG, and oil) are stipulated to have 45-year lifetimes [43]. There will be no new construction of thermal plants till 2040, so the conventional thermal generation capacity is mostly substituted by VRE according to the historical installed capacity data from the Kyushu, Tokyo, Kansai, and Hokkaido electric power companies. The changes in the ratio of PV or wind electricity generation until 2040 are shown in Fig. 4-24. Based on the current installed capacity and penetration in four areas (as shown in Fig. 4-4), the specific PV penetration rates for different years are summarized in Table 4-5.

As for the energy conversion progress in details, the operation time, installed capacity, and predicted repeal time of thermal power plants in Hokkaido region are described in Table 4-6. It can be seen that there is no abandonment of power plants from 1985 to 1995. The penetration rate of renewable energy

among the period of 2030-2040 remains at the same level. Accordingly, the description of power generation structures is changed in Fig. 4-24, Fig. 4-25, Fig.4-26, and Fig.4-27, respectively. As shown in follows:

Table 4-4 Current installed capacity and penetration in four areas, as for 2019

Item	Installed capacity (MW)		Penetration (%)	
Energy type	PV	Wind	PV	Wind
Kyushu	9440	580	11.45%	0.69%
Tokyo	1502	430	5.3%	0.37%
Kansai	5750	120	4.46%	0.24%
Hokkaido	1880	480	5.13%	3.08%

Table 4-5 Predicted ratios of PV and wind energy under different years

Year	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040
Kyushu (PV)	21.3 %	28.9 %	40.9 %	40.9 %	45.4 %	49.2 %	49.2 %	54.5 %	59.8 %	59.8 %	69.0 %
Tokyo (PV)	21.4 %	27.6 %	33.9 %	38.6 %	38.6 %	38.6 %	42.5 %	54.7 %	58.7 %	62.6 %	62.6 %
Kansai (Wind)	11.0 %	15.0 %	15.0 %	15.0 %	18.7 %	24.6 %	28.5 %	31.1 %	32.9 %	36.9 %	39.3 %
Hokkaido (Wind)	24.7 %	39.0 %	41.5 %	48.4 %	67.1 %	80.9 %	80.9 %	80.9 %	80.9 %	80.9 %	80.9 %

Table 4-6 Descriptive summarized of thermal power plant in Hokkaido

Name of power plant	Unit	Capacity (MW)	Fuel	Operation time	Potential outdated time
Sunagawa power plant	3	125	Coal	1977	2022
Date power plant	1	350	Oil	1978	2023
Onbetsu power plant	1	148	Oil	1978	2023
Date power plant	2	350	Oil	1980	2025
Tomatouatsuhatsuma power plant	1	350	Coal	1980	2025
Sunagawa power plant	4	125	Coal	1982	2027
Shiriuchi power plant	1	350	Oil	1983	2028
Tomatouatsuhatsuma power plant	2	600	Coal	**1985**	**2030**
Shiriuchi power plant	2	350	Oil	**1998**	**2043**
Tomatouatsuhatsuma power plant	4	700	Coal	2002	2047
IshiKariwanshinkou power plant	1	569.4	LNG	2019	2064

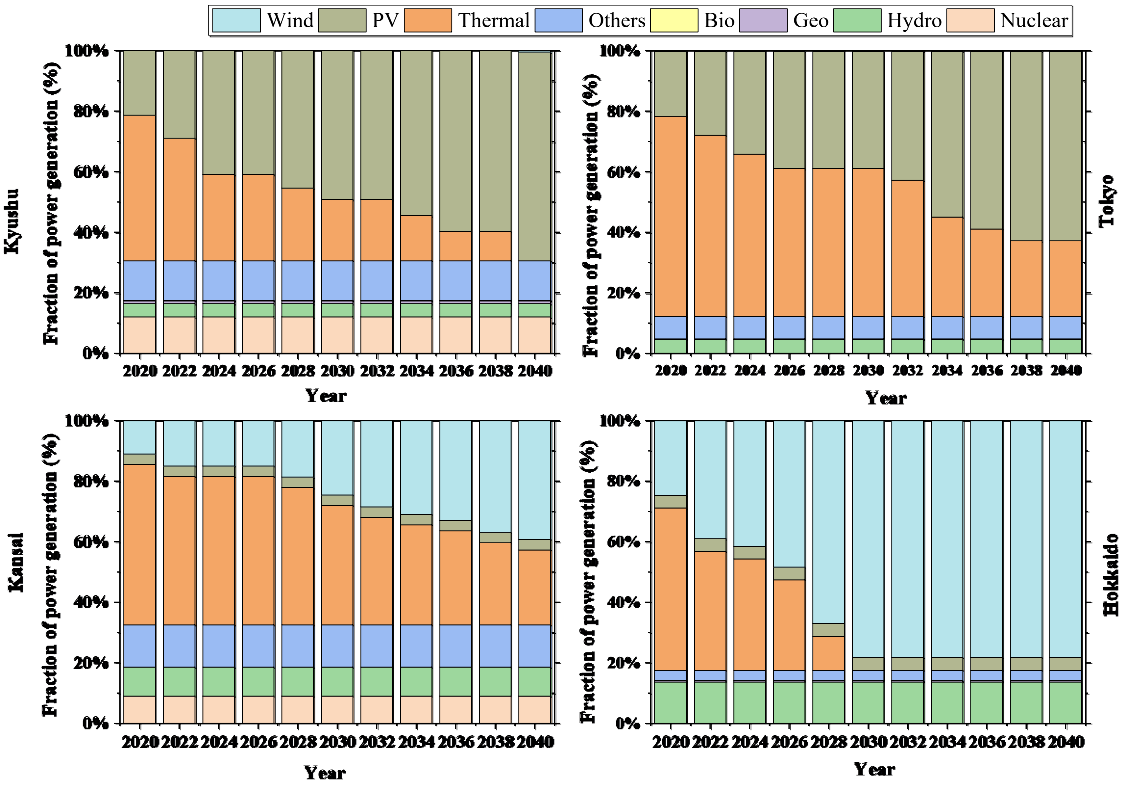


Fig. 4-24 Electricity consumption shares at demand side in Kyushu, Tokyo, Kansai, and Hokkaido

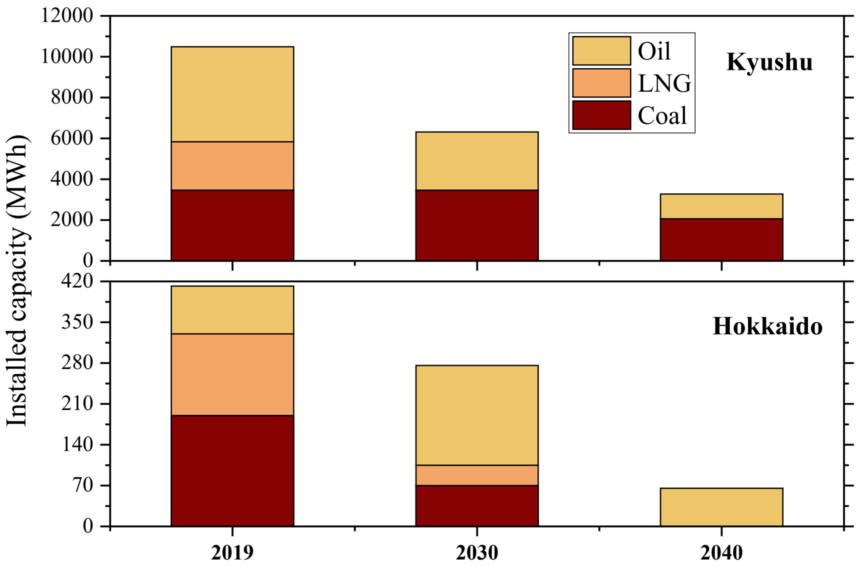


Fig.4-25 Prediction of thermal power capacities in Kyushu and Hokkaido until 2040. (Mistake of legend, order of LNG and Oil)

Regarding the difference in base load composition, the composition of thermal power generation and the starting operation time of each power station in 2019 can be obtained by referring to the public data of Kyushu and Hokkaido power plant. The predicted thermal power generation installed capacity is shown in Fig. 4-25.

4.4. The operation strategies of different power generation unit

Curtailment of cheap and clean electricity generation from renewable energy (RE), essentially solar, is now a reality in Kyushu, the most southwesterly of Japan's four main islands.

Based on data made available by Kyushu Electric Power Company (up to February 28, 2019), first curtailment of solar took place on October 13, 2018. Since then – in just about four and a half months, electricity generation from solar has been curtailed in 22 days, roughly 16% of days in the period considered. And a maximum of 925 megawatts (MW) of solar power – more than the installed capacity of operational nuclear reactors Sendai 1 or 2 in Kyushu – were curtailed at noon on November 4, 2018 (Fig. 4-26).

It is clearly observable that output of nuclear power plants is very stable throughout the day, and that fossil-fired power plants (coal, oil, and gas) as well as pumped hydro provide some flexibility; first by ramping down output and charging reservoirs, respectively, in the morning as electricity generation from solar increases, and then by ramping up output and discharging reservoirs, respectively, in late afternoon when electricity generation from solar decreases. These actions, still, did not prevent solar power curtailment.

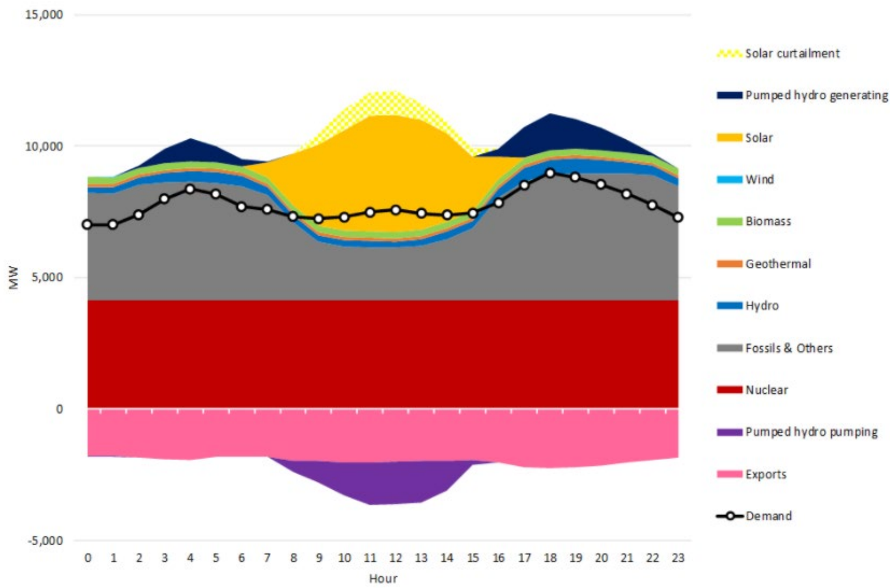


Fig. 4-26 Kyushu power system operations November 4, 2018 [13]

From an economic and environmental point of view, this system is inefficient. In the case of excessive renewable energy generation, low-carbon solar and wind power generating units are voluntarily reduced to support more expensive and high marginal cost power generation methods. However, renewable energy curtailments may be triggered by unrelated curtailment rules for the development of nuclear power. In fact, although Japan is at a disadvantage in terms of marginal cost economic competitiveness, after cutting solar and wind energy output, nuclear power output will also be further reduced (Figure 4-27). This is because in Japan, adjusting the output of nuclear reactors is considered more difficult. This technical argument is at least controversial overseas. *Électricité de France* (EDF) has promoted flexible nuclear power generation to promote the development of renewable energy.

The curtailment of renewable energy is already a very important topic in Japan. On the basis of encouraging nuclear and fossil power plants to become more flexible, encourage the development of innovative and inherently more flexible technologies, such as storage or demand response. As shown in Figure 4-28, when the PV or wind power is surplus, the water is raised to store electricity, and the electricity is discharged at the peak value of the electricity demand to balance the grid demand. At the same time, the battery can be used to increase the ability of power peak shaving and valley filling. This shift will lower electricity prices, reduce greenhouse gas emissions, and strengthen Japan's energy independence, making its economy and society more efficient, sustainable, and resilient.

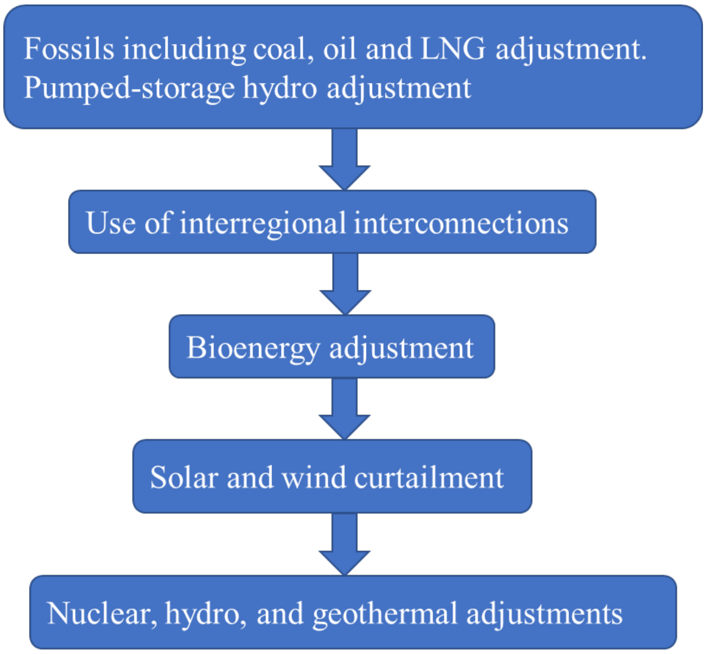


Fig. 4-27 Simplified presentation of curtailment rule of power plants in Japan [13]

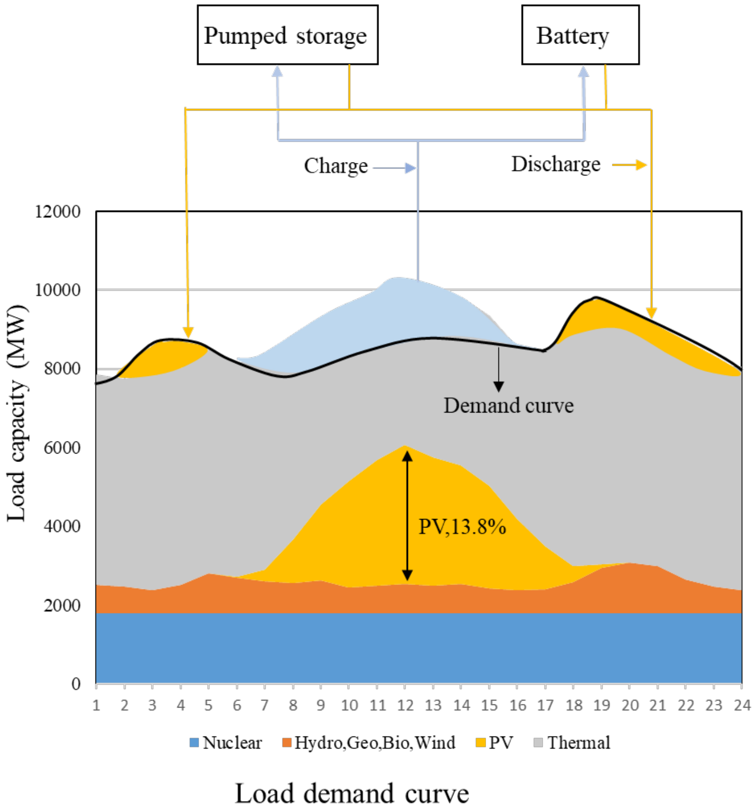


Fig. 4-28 The daily operation of different power generators hybrid PHS and battery facilities

According to the characteristics of each power generation unit in Figure 4-31, summarize the basic load unit during the peak period of power demand in summer, flexibly adjust the power generation unit, and adjust the peak load supply unit to maximize the introduction of VRE.

① Nuclear power and geothermal power are power generating units that provide base load, with 100% output during the day and night.

② The coal firepower is also used to provide the base load due to the difficulty of starting and stopping.

③ Oil thermal and LNG thermal adjust the power generation capacity according to load demand, and can be turned off when the load demand is low at night.

④ The pumping type is used to adjust the balance of power supply and demand.

⑤ PV power generates the highest amount of electricity during the day when the sun's intensity is high, and there is no electricity at night.

⑥ The wind power generation is constantly changing according to the wind speed and direction. The grid imbalance caused by VRE can be adjusted by thermal power or pumping water to generate electricity.

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Chapter 5

ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE

CHAPTER FIVE: ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE

5.1 Contents

With the increasing proportion of renewable energy represented by photovoltaic (PV) and wind power in the grid, the existing grid has faced some new challenges owing to is intermittent and uncontrollable characteristics. It is important to evaluate the impact of PV and wind on the public electricity supply system when they are introduced into the grid. We present a new method to predict the maximum penetration of renewable energy and its impact on the public electricity supply system from both qualitative and quantitative perspectives. Based on the residual load duration curve method, the new method combines a renewables capacity credit analysis indicator and dynamic investment payback period (DIPP) to explain the impacts on the reduction of peak load and renewables curtailment. Real data were used from the power grids of Kyushu, Tokyo, Kansai, and Hokkaido in Japan (as shown in Fig. 5-1) [1-4]. The results indicate that the capacity credit increases with an increase in PV and wind shares in the grid. However, it seems to be saturated when the share of PV and wind power in the grid reaches 25% and 60%, respectively. Compared with the wind integration in Kansai and Hokkaido, the PV penetration in Kyushu and Tokyo reaches saturation more rapidly. In addition, PV shows more power suppression, which prolongs its payback period compared to wind energy. The significant difference in the results of capacity credit and DIPP is limited by the characteristics of power demand in mixed regions and the relevance of renewables distribution.

The Section contributes to understanding the impact of intermittent power generation of PV and wind energy changes on public power systems, especially the impact of time matching between VRE power supply and load demand profile. Specifically, this impact occurs in the form of peak load reduction and electricity overproduction caused by the integration of VRE. Based on RLDC method, the capacity credit and DIPP are used at the same time to support the research objectives [5,6]. We aim to conduct a comprehensive analysis of the different shares of PV and wind energy and different public power grids. The degree of matching of these variables was used to analyze and compare the challenges of VRE integration. In addition, the method used in this study to enhance the penetration of VRE is to replace thermal power generation with wind or solar energy, which helps to understand the characteristics of the power generation structure in different regions. The framework of this study is illustrated in Fig. 5-2.

Nomenclature

Label	Unit	Description
PV	-	Photovoltaic
VRE	-	Variable renewable energy
FiT	-	Feed-in tariff
RLDC	-	Residual load duration curve
DIPP	-	Dynamic investment payback period
LDC	-	Load duration curve
X	-	Guaranteed load reduction without PV integration
Y	-	Guaranteed load reduction with PV integration
P	Yen/kWh	Electricity price
$\mathrm{P}_{\mathrm{b}}^{\mathrm{t}}$	MWh	Power flow from base-load plants
$\mathrm{P}_{\mathrm{m}}^{\mathrm{t}}$	MWh	Power flow from flexible plants
VRE_{direct}	MWh	Directly integrated VRE power generation
$\mathrm{load}_{\mathrm{grid}}^{\mathrm{t}}$	MWh	Total grid load
$\mathrm{P}_{\mathrm{VRE}}^{\mathrm{t}}$	MWh	Total VRE production
$\mathrm{overproduction(t)}$	MWh	Curtailed VRE production
T_1	h	Finishing hours of excess electricity
T_2	h	Starting hours of excess electricity
$\mathrm{RLDC(t)}$	MWh	Residual load demand
P_t	Year	Dynamic investment payback period of PV or wind
C_1	Yen/kWh	Annual revenue
C_0	Yen/kWh	Initial investment
i_t	%	Annual interest rate
t	h	Time units

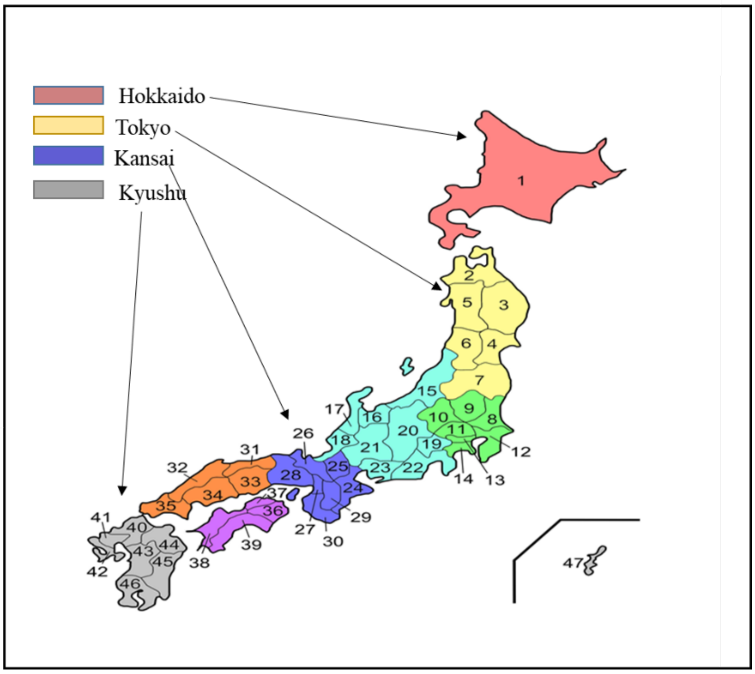


Fig. 5-1 The distribution of research area in Japan

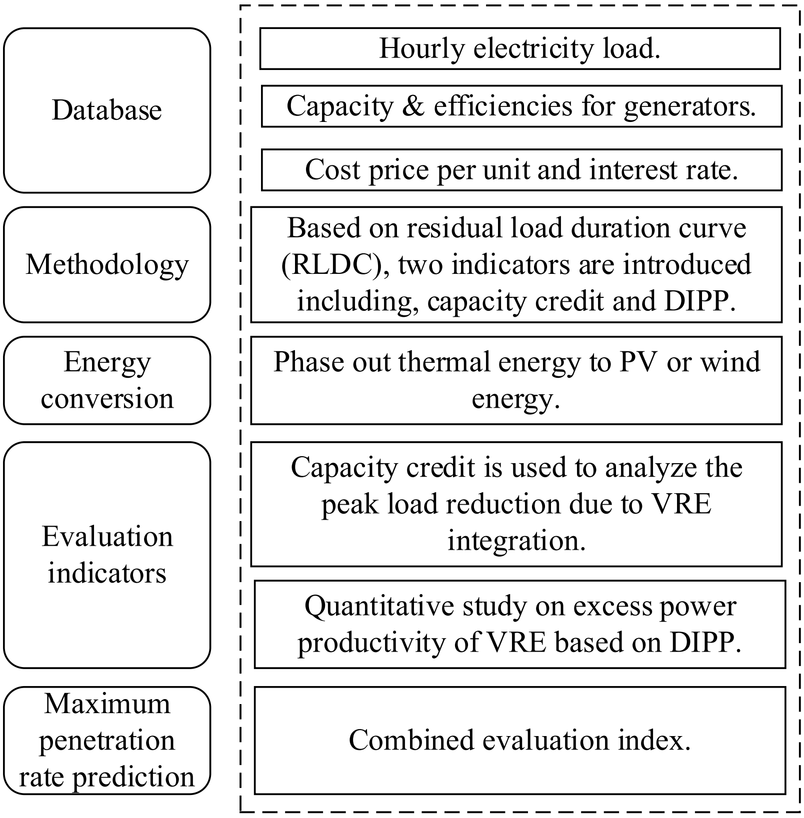


Fig. 5-2 Research framework

5.2. Results and analysis

This section discussed the integration of VRE energy impact on the power grid and predicted its maximum penetration. The limitation of VRE penetration is determined by the capacity credit indicator from the technical perspective and the DIPP indicator from the economic perspective. Therefore, the results will be split to three aspects including, the results of RLDCs, which is the basis of capacity credit, the results of capacity credit, and the results of DIPP.

5.2.1. Results and analysis of RLDCs

① Results of RLDC values

The results of a detailed analysis of the evaluation indicators are presented in this section. We start with an overview of the results of the analysis and then continue to discuss each variable. While the RLDCs of PV and wind energy under different permeabilities are connected, the higher the permeability, the more noticeable the trend. Meanwhile, to ensure the independence of the comparisons between research regions, Fig. 5-2 selects three cases for analysis with 10%, 20%, and 30% penetration levels of VRE (normalized to peak demand). The normalized (in terms of annual peak capacity) LDC and RLDC with 10%, 20%, and 30% penetration of PV energy for Kyushu and Tokyo, and the wind energy for Kansai and Hokkaido are depicted, respectively, in Fig. 5-3. The black line in Fig. 5-3 denotes the assumed base load (the base load is 35% of the annual peak) [7]. As the penetration rate of VRE increases, both PV and wind energy lead to a decrease in the residual load. With increasing VRE shares, the peak load and medium load are reduced, as shown in Fig 5-3. In addition, the overproduction of electricity generation occurs as a result of limitations in grid flexibility. To maintain the electricity dynamics of the supply and demand sides, production by VRE must be partially curtailed if the overproduced electricity cannot be stored or transmitted. However, the impact of PV and wind energy on the residual load shows different trends (as illustrated in Fig. 5-3). Both the Kyushu and Tokyo regions show that infeed PV production mainly decreases the annual operation period in base plants. The impacts on the peak load and intermediate load are relatively small. The specific reasons can be analyzed from the correlation between the characteristics of electricity demand and PV power generation. Peak loads in Kyushu and Tokyo are mainly concentrated in the morning and evening in the winter and daytime in the summer. Meanwhile, PV is affected by the periodic movement and radiation intensity of the sun. PV power generation is concentrated in the daylight. Therefore, PV has a lower impact on peak load reduction, except during summer daytime. However, in the period of larger PV power generation with a lower electricity demand, the increases in PV penetration compresses the residual load, especially in the transition seasons. Japan's public power grid gives priority to the protection of nuclear energy and coal power generation when electricity is overproduced. The ratio of PV overproduction reveals a significant increase with an increase in PV penetration.

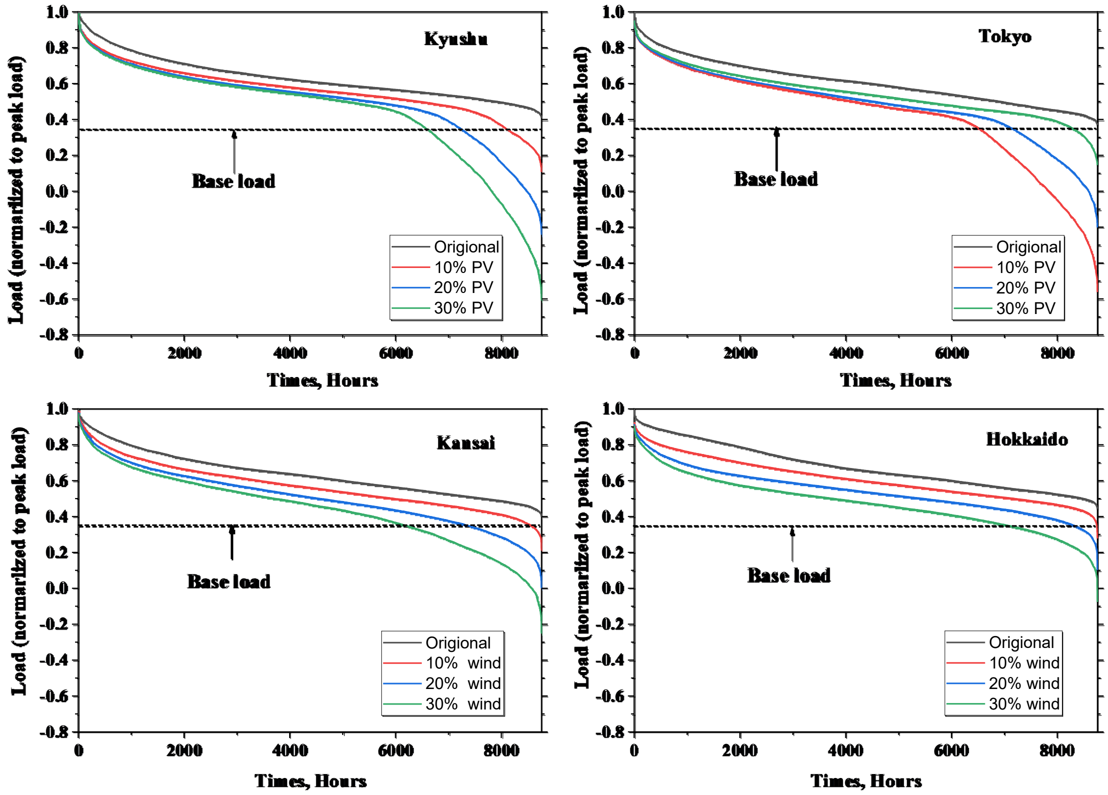


Fig. 5-3 RLDCs of PV and wind production to grid load ratios 0%-30% for Kyushu, Tokyo, Kansai, and Hokkaido

Comparing the impact of PV and wind energy between power grids, the RLDC caused by wind power production show flatter behavior ranges than those caused by PV power. As the wind continuously tilts the RLDC, PV creates a kink in the RLDC at the same time, so that at a high share, most of the generation is overproduction. Wind power generation is intermittent and random, and it lacks the periodicity of PV power generation. Therefore, compared with PV, RLDC for wind can be reduced evenly.

The impact of VRE on the different power grids will be quantified and compared by capacity credit and payback period in the following analysis.

② Results of VRE curtailment

For the contrast of PV and wind curtailment in the power grid, we chose Hokkaido as a case study. The results of VRE curtailment and VRE into Hokkaido grid is depicted in Fig. 5-4 and Fig. 5-5. As the VRE shares increasing in the power grid, the wind into grid is increasing and tend to saturation state. PV shows the increasing trends of PV into grid first and then decreasing with the PV shares over 30%. Besides, the monthly distribution of PV and wind curtailment in Hokkaido is shown in Fig. 5-6 and Fig. 5-7, respectively. Under the same penetration rate of VRE, wind energy shows lower electricity production curtailment than PV energy. The curtailment in Hokkaido peaks in winter time due to the strong wind speed distribution in winter period whilst. On the contrary, Hokkaido mainly focuses the electricity curtailment of PV on transsision season, especiallly Apri and May. This is resulted from the lower electricity demand and higher PV power generation. Therefore, the relavent of VRE power genration profile and electricity demand is essential for the analysis of VRE development in one region.

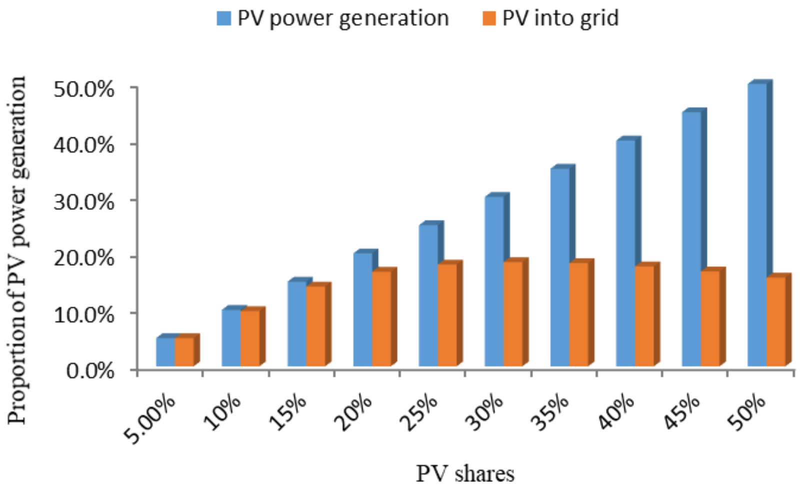


Fig. 5-4 The PV into grid with the PV power gernation shares increasing

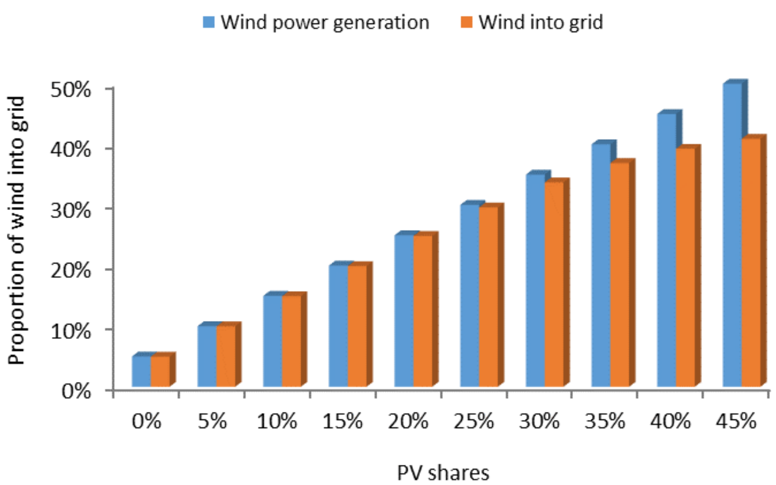


Fig. 5-5 The wind into grid with the wind power gernation shares increasing

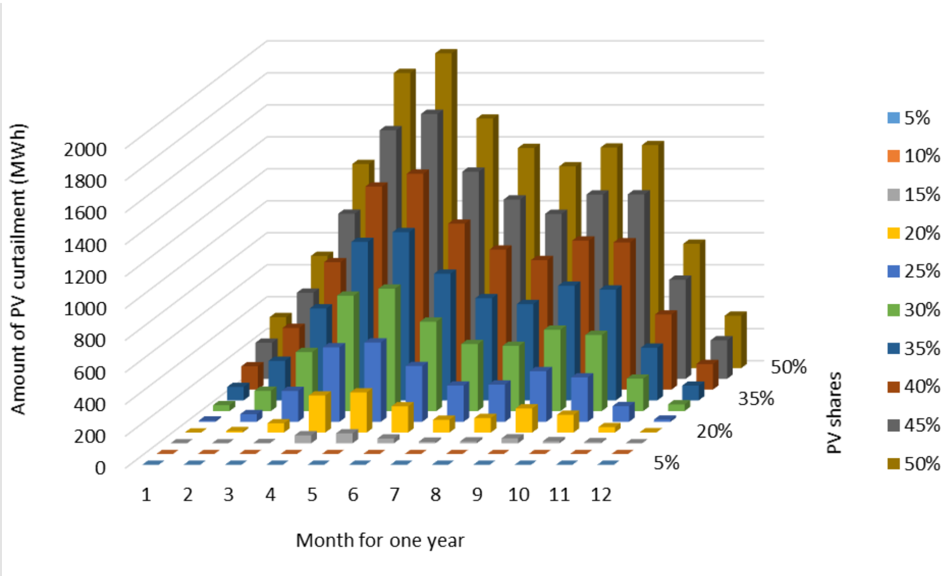


Fig. 5-6 The monthly curtailment distribution of PV power generation in Hokkaido

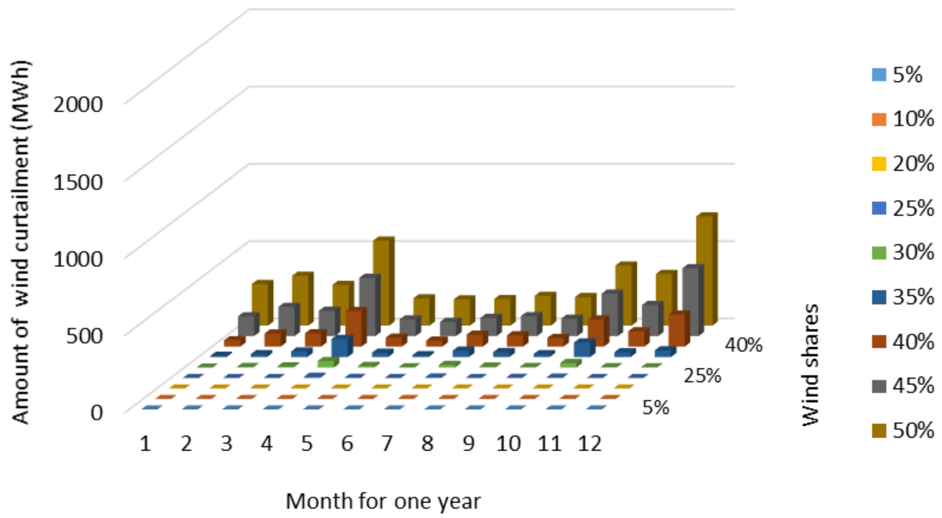


Fig. 5-7 The monthly curtailment distribution of PV power generation in Hokkaido

5.2.2. Results and analysis of capacity credits

Capacity credit refers to the potential of how much capacity of a conventional power plant can be avoided or replaced by an integrated renewable energy plant. The renewable capacity credit value could be calculated as the ratio of the differences of capacity reduction to maximum grid load L_{max}, and can be defined as follows:

$$Credit = \frac{Y - X}{L_{max}} \tag{1}$$

Fig. 5-8 clearly shows how to calculate the value factor of renewable capacity credit in a load duration curve (LDC). load management is expected to mitigate peak load in the absence of PV power. X, Y refer to how much more guaranteed load reduction could be achieved with the same amount of resource by demand response or ancillary service to the utility.

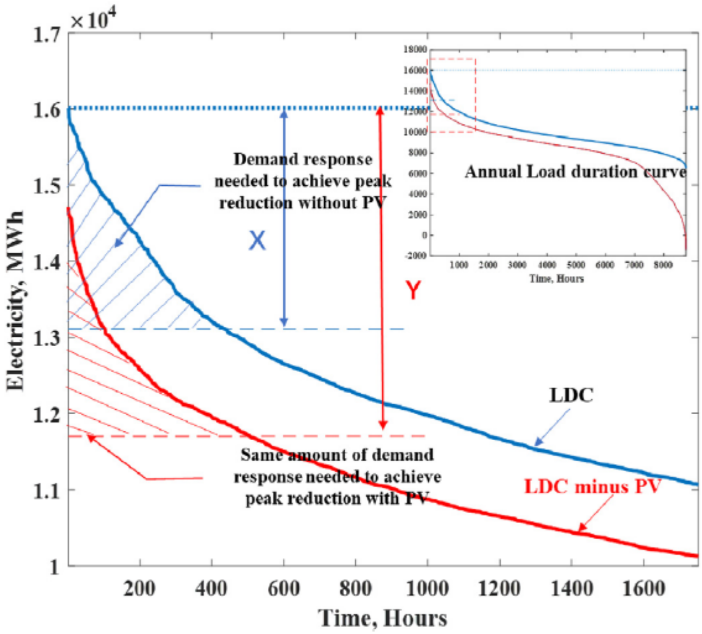


Fig. 5-8 Graphical illustration of PV power capacity credit calculation process

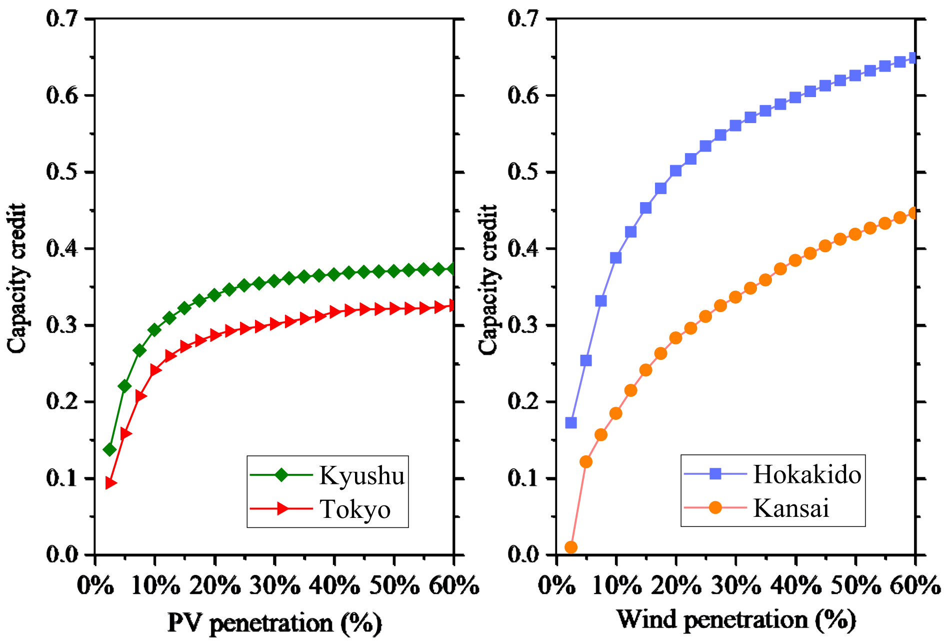


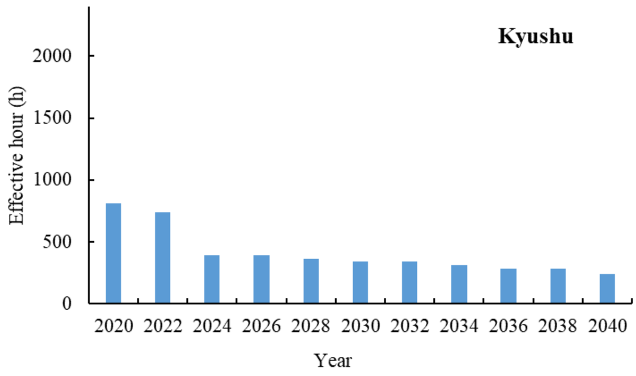
Fig. 5-9 Relationship between capacity credit and ratio of PV power production for Kyushu and Tokyo, and wind power production for Kansai and Hokkaido

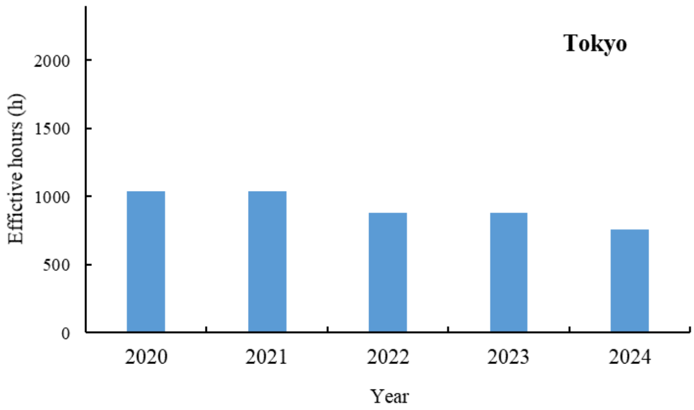
The RLDC results show that owing to the limited correlation between fluctuating VRE power generation and hourly demand, increasing the capacity of PV and wind technologies does not cause a linear decrease in the residual load. We use the metric of capacity credit to quantify the impact of VRE penetration on the peak load reduction of the power grid. A comparison can be obtained between PV and wind regarding how they affect the grid by applying this value. Fig. 5-4 shows the results for capacity credit in the Kyushu, Tokyo, Kansai, and Hokkaido regions with the consistent growth of wind and PV penetration. First, in terms of overall trend changes, with an increase in PV and wind energy penetration, the capacity credit value increases sharply at the beginning. It tends to be flat after reaching a specific value. This shows that the influence of VRE on the peak load is not linear, saturation is achieved. Secondly, it is worth noting the comparison of capacity credits for the continued integration of PV and wind on the power grids. PV reaches its saturation value earlier than wind energy, which confirms the results of the residual load curve in Fig. 5-9. Thus, owing to the different correlations between power load characteristics and VRE power generation characteristics, wind energy has greater potential than PV energy for improving its peak load reduction. In Hokkaido, power demand is highest during winter daytime due to the heating demand. Wind supply is affected by the seasons, and is mainly concentrated in winter. Therefore, the wind power supply is well correlated with power demand. It is obvious that the capacity credit value of Hokkaido is higher than that of Kansai under the same permeability. The abundant potential for wind power generation in the Hokkaido area can be seen.

5.2.3. Results and analysis of DIPP

① Utilization hours

The results of utilization hours of PV and wind in research area is shown in Fig. 5-10. The utilization hours are decreasing with the years, as the PV and wind share increasing could resulted in the electricity curtailment of VRE. The utilization hours of VRE by the power grid is therefore decreased. The progress of VRE curtailment is shown in Fig. 5-4, Fig. 5-5, Fig. 5-6, Fig. 5-7, respectively. The DIPP is calculated based on the effective hours of VRE and its overproduction rate. The results of constraints factor of DIPP are shown in Section 5.2.4.


Kyushu
Effective hour (h)
2000
1500
1000
500
0
2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040
Year


Tokyo
Effective hours (h)
2000
1500
1000
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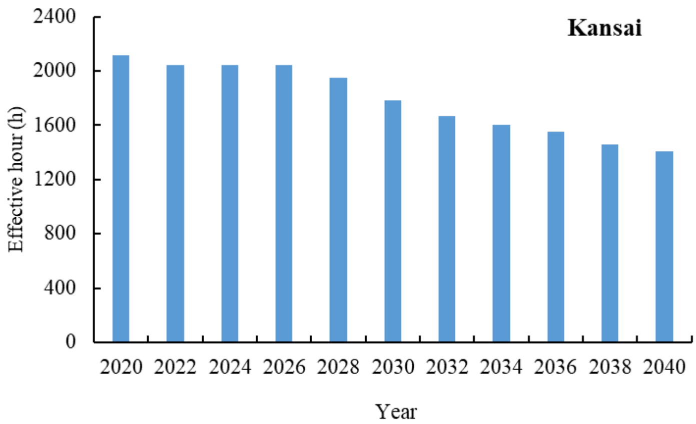
0
2020 2021 2022 2023 2024
Year


Kansai
Effective hour (h)
2400
2000
1600
1200
800
400
0
2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040
Year

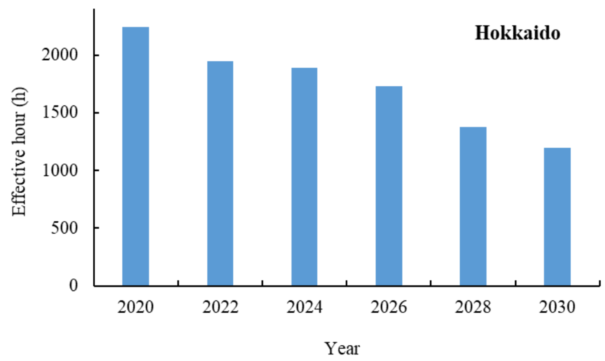


Fig. 5-10 Effective hours of PV power generation in Kyushu and Tokyo, and wind power generation in Kansai and Hokkaido, respectively

② DIPP

VRE's DIPP, as an economic evaluation indicator, is mainly related to its investment cost, operation and maintenance costs, capacity of power generation, government subsidies, and electricity prices. This study mainly analyzes the impact of the utilization of VRE power generation by the grid on the quickness of the recovery period. Taking the lifetime of PV and wind energy as the limiting condition, the possibility of continuous penetration of the power grid is restricted. Thus, the maximum penetration of VRE into the existing power generation structure of the study area was quantitatively analyzed.

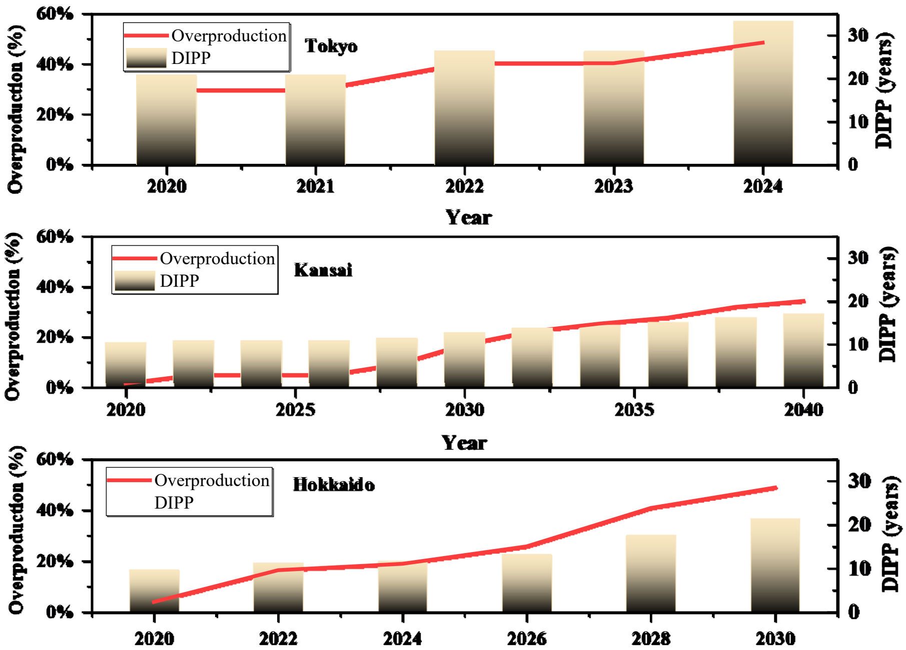


Fig. 5-11 DIPP of PV and wind and its overproduction rate in Tokyo, Kansai, and Hokkaido

The massive integration of VRE into the grid leads to the compression of the base load. Japan's public power grid gives priority to the protection of nuclear energy and coal power generation when electricity is overproduced in order to restrain the use of VRE power generation. Thus, light and wind are reduced, and the effective utilization hours of VRE are further decreased. Because of the strong correlation between the DIPP and excess power generation of VRE, the preparatory step for the analysis of DIPP illustrates the ratio of excess PV or wind power generation (normalized to peak load demand) for one year at an hourly time resolution. The DIPP of PV and wind penetration in different years and their corresponding excess power production rates are shown in Fig. 5-11 and Table 5-1. The changes in the PV and wind penetration rates corresponding to these years are summarized in Table 5-1. As depicted in Fig. 5-11, the overproduction rate of PV and wind power increases over time. At the same time, the DIPP is extended. For example, in Kyushu, the penetration rate of photovoltaics in the grid is 21.3% by 2020. However, 27.6% of the PV power generation is discarded. This phenomenon significantly increases the cost of PV power generation, which severely prolongs the payback period of PV investment to 29.9 years. Limited to the 30-year operating life of PV, the maximum penetration of PV in Kyushu under the existing constraints is 21.3%. Similarly, the maximum penetration of PV or wind energy into the power grid is obtained by applying it to the other three regions, as shown in Table 5-2. At the same time, the effective utilization hours of VRE are also indicated. For the comparison of PV penetration in Kyushu and Tokyo, Table 5-2 shows that Kyushu reaches the recovery limit faster than Tokyo, and the calculated maximum penetration is lower than in Tokyo. The main reason for this is that the effective utilization hours of PV in Kyushu are lower than those in Tokyo. The power demand curves for Kyushu and Tokyo are similar. The peak load is distributed between the heating demand in winter and cooling demand in summer. However, due to the extra-large factories in Tokyo, the peak valley difference between day and night is enormous. The utilization of PV power generation by power grid is higher in Tokyo. Furthermore, the power surplus caused by PV power generation is lower than that in Kyushu.

Table 5-1 DIPP and overproduction rate of PV in Kyushu

Year	2020	2021
Overproduction rate (%)	27.6%	33.8%
DIPP (years)	29.9	34.65

Table 5-2 Calculated maximum PV and wind penetration and its corresponding parameters

Region	Kyushu	Tokyo	Kansai	Hokkaido	Region
Year	2020	2023	2040	2028	Year
Maximum penetration (%)	PV	21.3%	27.6%	-	-
	Wind	-	-	39.3%	40.9%
Effective utilization hour (h)	PV	811.8	877.7	-	-
	Wind	-	-	1408	1380.3
Capacity credit			0.38	0.28	0.49
DIPP (years)			29.9	26.4	17.1

5.3. Conclusions and future research

5.3.1. Conclusions

The continuous introduction of VRE, with its inconstant characteristics, affects the supply-demand side power balance. Without considering adjustments to power storage equipment, the mismatch of load and VRE power generation, as well as the limits to grid flexibility, led to grid regulation pressure. Japan implements a strategy of prioritizing basic load demand sources, such as nuclear power and coal-fired power plants. Therefore, it is vital to consider the correlation between the regional load and equipment output to analyze whether a region develops PV or wind energy. In this study, four typical power grids in Japan were selected as examples to analyze the impact of increasing the penetration of PV or wind energy into the power grid, which could inspire other regions to increase their VRE penetration. Assessing the power grid's ability to accommodate VRE can help decision makers in energy planning.

On the basis of the research content, the obtained results can be summarized under three headings, namely, the RLDC, the capacity credit value, and the DIPP of VRE.

1) With regard to the RLDC, owing to the intermittence and uncertainty of VRE, the PV and wind production caused a non-linear drop in the residual load. As the wind continuously tilts the RLDC, PV creates a kink in the RLDC at the same time so that, at a high share, most generation is overproduction.

2) With regard to capacity credit, regardless of the region and energy supplied, the capacity

credit value increases with the increase in PV and wind penetration rate and tends to reach saturation. The capacity credit reaches a stable value when the PV and wind penetration rates are 30% and more than 60%, respectively. This means regional divergence; Hokkaido exhibits the highest capacity credit values, followed by Kansai, Kyushu, and Tokyo. This is because of the strong correlation between the load demand and wind power generation.

3) With regard to the DIPP, Kyushu and Tokyo reached their limits of the DIPP when the PV penetration rate was 21.3% and 27.6%, respectively, and the wind energy penetration rates in Hokkaido and Tokyo were 39.3% and 40.9%, respectively. The results show that the power generation characteristics of PV place great pressure on the power grid, which causes electricity oversupply and limits its own power generation, thus hindering the development of PV power. By contrast, wind power generates electricity at any time throughout the day, which places less pressure on the power grid.

Work in progress highlights the area-specific integrated capacity credit value as well as the economic mix in terms of PV and wind DIPP. The characteristics of the load profile and energy supplied affect the performance of VRE in different power grids.

5.3.2. Limitations and future research

On the basis of the RLDC, this study evaluates the impact of different shares of VRE integration on the power grid by combining capacity credit and the DIPP. This impact is not only reflected at the technical level, but also economically, directly reflecting the development potential of VRE in the research area. However, this study did not consider the reduction in VRE power generation suppression by storage devices. Future work will focus on analyzing the development of VRE in a region by combining the conversion of excess power into electricity storage, thermal storage, or gas storage.

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Appendix

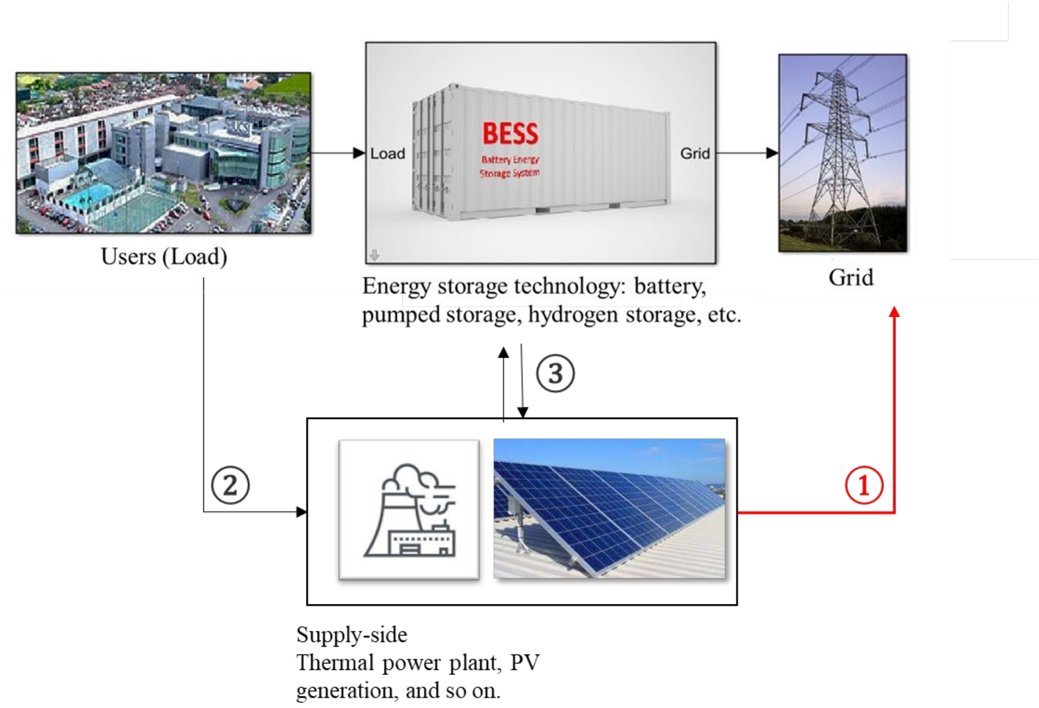


Fig. 5-12 Schematic diagram of research topics

This chapter discussed the VRE shares changing resulted in the imbalance of power grid and predicted the maximum VRE penetration without energy storage system. This Chapter is accepted by the Journal of Energy, which is entitled ‘The implementation limitation of variable renewable energies and its impacts on the public power grid’.

Chapter 6

ASSESSMENT OF DEMAND SIDE LOAD IN VRE INTEGRATION

CHAPTER SIX: ASSESSMENT OF DEMAND SIDE LOAD IN VRE INTEGRATION

6.1 Content

The COVID-19 pandemic has had a significant negative influence on energy consumption in 2020. On April 7, 2020, in response to the rapid spread of the infection, the Japanese government imposed a state of emergency. This action impacted energy consumption, energy production, and electricity prices. This study compares the impact of a reduction in load demand on renewable energy in the Japan public power grid under a state of emergency declaration (April to May 2020). Using publicly available data, comparisons are made for Kyushu, Tokyo, Kansai, and Hokkaido and assessed in relation to epidemic severity and geographical distribution. The results can be summarized as follows. (1) The consumption profiles and amounts of power consumption reduction are different in different areas. Tokyo shows the largest share of reduced load, followed by Kansai, Kyushu, and Hokkaido. The load reduction was mainly seen during the day, which reflects the differences in people's activities relative to the same period in 2019. (2) Different means of power dispatch, including power generators, energy storage systems, and transmission lines are used and compared in terms of responses to the changes in electricity consumption profile. (3) The overall fall in total load demand and the change in load sequence affected the integration and curtailment of photovoltaic (PV) power generation and consequentially caused the electricity price to drop. This paper clarifies the effects of COVID-19 on the public power grids of Japan. Further, it establishes the impact on policymakers in relation to the development of renewable energy.

6.2. Background and research objective

6.2.1. Background

According to Refs. [1,4], the outbreak of the novel coronavirus disease (COVID-19) has had a considerable impact on every sector of economic life. To prevent the spread of the disease, the Japanese government called a state of emergency on April 7, 2020, requiring 13 prefectures to shut down some public facilities and requiring that human contact be reduced by more than 70% by implementing telework. As described in Refs. [5,6], these restrictions were expanded to the national level on April 16. On May 25, the declaration of emergency, which had lasted nearly 2 months, was lifted. Under the declaration, public facilities were closed, and large industry and other businesses were also affected. The user-side structure of electricity distribution changed, and this affected the overall amount of electricity consumption and load demand distribution as well.

These circumstances can be expected to alter the supply of renewable energy and traditional fossil fuel energy with the load reduction. With declining energy demand due to the spread of COVID-19, it would be economically reasonable to give priority to renewable energy due to its low marginal cost. By contrast with traditional electricity generation methods, renewable energy does not require fuel. During the COVID-19 pandemic, it can be expected that the rate of transition from fossil fuels to renewables would consequently be maintained or strengthened further. However, unlike the conventional technologies of power supply, renewables with that have intermittency characteristics may pose challenges to the operational management of grids, such as power sector dispatch [7,8], renewable curtailment [9,10], and real-time spot-market prices [11,12]. Therefore, due to the intermittent characteristics of photovoltaic (PV) electricity output and seasonal patterns in relation to electricity demand (particularly in transition periods), this paper analyzes the impact of electricity load changes on PV power integration and its influence on the power grid during the epidemic period (April 7 to May 31). This paper studies 4 of Japan's electrical distribution areas, taking geographical distribution and the severity of the epidemic into account, to assess how power dispatch was affected by the load reduction caused by COVID-19.

① Worldwide studies of COVID-19 in the energy sector

The spread of COVID-19 has had a significant influence on economic activities worldwide, in addition to killing many people [13]. According to the COVID-19 tracking system developed by Johns Hopkins University (JHU), as of May 31, 2020, there had been more than 5 million cases of COVID-19 recorded around the world [14]. Many countries-imposed restrictions to slow the spread of the virus, including closing educational institutions, partial or full lockdowns, requiring employees to work from home where possible, and so on [15,16]. The energy sector, a pillar of the global economy, suffered a great deal. Because electricity is essential for most economic activities, we could use electricity demand to assess the impact of a change on the economy, as observed in Refs [17–19]. In Japan, hourly data for electricity demand in 10 regions are available on websites maintained by electricity transmission companies. Investigating decreases in electricity demand could provide an important and immediate understanding of how economic activities are affected by a pandemic or other occurrence. On April 7, 2020, the rapid spread of COVID-19 infection prompted the Japanese government to announce a state of emergency. The impact of the state of emergency on electricity demand in Japan has been empirically estimated [20]. Because the U.S. is among the most severely affected by COVID-19, a cross-domain approach to analyzing the short-run impact of COVID-19 on U.S. electricity sector is presented. The results indicate a significant reduction in electricity consumption that is strongly correlated with the number of COVID-19 cases, degree of social distancing, and level of commercial activity [21]. Because of the significant drift in electricity load consumption due to changes in human activity during the pandemic, it is essential to analyze the impact of COVID-19 on electricity.

The use of renewable energy reduces greenhouse gas emissions and ensures the continued energy supply. The capital cost of renewable energy has significantly dropped in recent years, and it is expected to fall still further. Depending on Refs. [22] and [23], renewable generation therefore may be more attractive on a cost basis than traditional fossil-fuel-based power technology. In Japan, the capacity of PV power generation has grown rapidly in recent years, particularly after the feed-in tariff (FiT) policy was launched by the Japanese government in 2012 [24].

② PV integration

Limited by fossil fuel resources and environmental mitigation, the development of renewable energy is urgent [25,26].] In Japan, with the launch of the FiT system in 2012, PV power generation started developing nationwide, and the installed capacity of the PV system increased sharply from 100MW in 2011 to 10GW in 2019 [27,28]. However, with integration of massive accounts of PV power into the grid, it resulted in compression of base load generators [29]. When the electricity supply exceeds the demand, Japan's public power grid gives priority to the use of pumped storage and regional connecting lines for electricity dispatchment. Based on the current priority feeding rule, the power curtailment of PV power generation is then carried out to adjust the excess electricity [30]. In addition, to increase the penetration of PV, energy storage systems [31] regional transmission line [7], hydrogen production [32], battery [23], and other flexible systems are used to power peak shaving and valley filling. These citied studies focus on analyzing the impact of variable PV penetration rates on the public grid, or how to increase the penetration rate of PV in the grid. However, this paper mainly analyzes the correlation between load and PV from the perspective of the impact of load characteristics on PV penetration. In addition, it analyzes the direct penetration and suppression of PV power generation considering the power generation composition of the study area. It provides new ideas for the development of PV in each region.

③ Electricity pricing

Electricity markets are becoming increasingly important for the global energy sector [33,34]. By adjusting the design of the electricity market, new challenges can be met, and renewable energy can be integrated into the power generation mix. However, the intermittent nature of the limited knowledge of future renewable energy power generation and the randomness of weather conditions has profound impacts on an integrated power system and constitute real challenges to grid operation and management, as well as to the operation management of real-time electricity spot market prices [35,36].

Due to the intermittent nature and non-dispatchability of PV and wind power generation, these sources of energy are classified as variable renewable energy (VRE). Aimed at assessing how intermittent renewable production depresses electricity prices, a previous study investigated the effects of intermittent VRE power generation on electricity price formation in Germany. And found that PV power generation reduces the volatility of electricity prices by scaling down the use of peak-load power plants [34]. Variable wind power reduced the electricity price [37], but at the same time increases their volatility [38]. The impact on prices has decreased over time in line with an increase in VRE electricity production [39]. These causes difficulties to managers in the choice of power generation units.

This paper analyzes not only the impact of changes in PV penetration on electricity prices, but also the comprehensive impact of power generation composition on electricity price. It complements previous studies on the influence of single energy and region on electricity prices. Moreover, this paper selects four Japanese public power grids with different power generation structures and load characteristics. A correlation between generation structure and electricity price is clearly indicated. This result provides a reference value for price makers to find the ideal generation portfolio. The results also help clarify the contribution of different energy sources to the electricity price, and could help inform the integration of renewable energy into the electricity market.

6.2.2. Research objective

The Japanese government's COVID-19 emergency program significantly altered people's habits and activities at the country level. These changes are reflected in the use of the electric power system, in particular with regard to electricity consumption curves. The integration of renewable energy changes with different match magnitudes between loads and the generation of power from renewable energy. However, due to the stochastic characteristics of the output of renewable energy, its integration into a power grid is attended with challenges to the management of power grid operation, and this can also affect price fluctuations in the real-time spot market.

Therefore, this manuscript evaluates the impacts of the state of emergency on electricity demand in the Japanese public electrical grid from April to May 2019 in two main aspects. These are the impact of the total load reduction on power generation structures and changes in load demand characteristics on renewable energy penetration. The real-time electricity market is also analyzed due to its strong relationship to renewable energy. The relevant framework for this research is given in Fig. 6-1.

The epidemic has caused changes in human activities, which affect power consumption and time. This changes the electricity demand curve accordingly. Power generators on the supply side are affected by the load characteristics on the demand side. This is especially true for PV power generation with intermittent characteristics. This paper focuses on the influence of load characteristics on power generation units, with a special focus on PV power generation. In addition, few studies have investigated the impact of different power generation structures on electricity prices. This paper analyzes four Japanese public power grids with different power demand characteristics and power supply ratios.

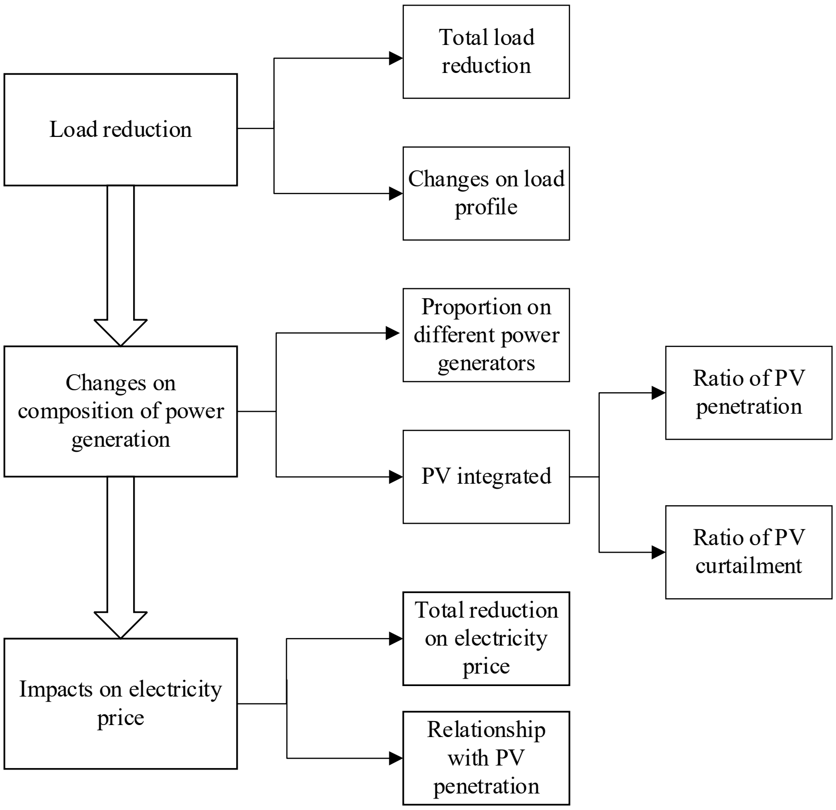


Fig. 6-1 Research framework

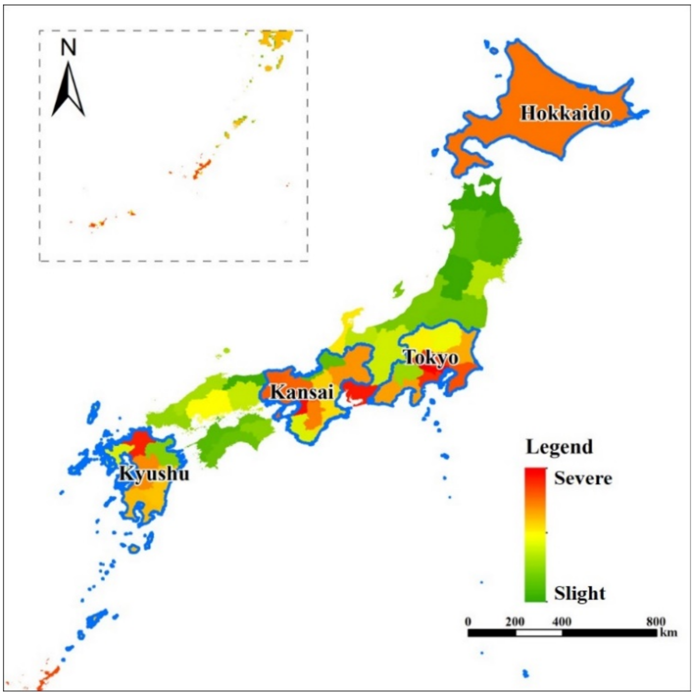


Fig. 6-2 Distribution of infected people and research areas (as of May 31, 2020)

6.2.3. Data sources

Japan reported its first coronavirus case on January 16, 2020. In response to the rapid spread of the infection, the Japanese government announced a state of emergency in seven prefectures in three areas on April 7. The state of emergency was extended to the entire country on April 16, and it was cancelled everywhere on May 26. During the emergency, the government restricted the use of public facilities, prohibiting restaurants, bars, stores, gyms, and other companies from normal operations as well as restricting people from moving, consequently reducing much economic activity. These changes are reflected in the electric power system, particularly in changes in electricity consumption. Therefore, we compare April and May 2020 to a reference period in 2019.

The Japanese public electric grid is divided into 10 areas. Different regions have different power generation compositions, show different load demand profiles, and experienced different levels of severity of the epidemic. Kyushu, Tokyo, Kansai, and Hokkaido were selected as the research objects by comparing the distribution of the severity of the pandemic, as indicated in Fig. 6-2, as these areas had the highest numbers of cases. According to the COVID-19 system developed by NHK, as of May 31, 2020, there were 21037 infections nationwide, affecting 28 of 46 prefectures.20

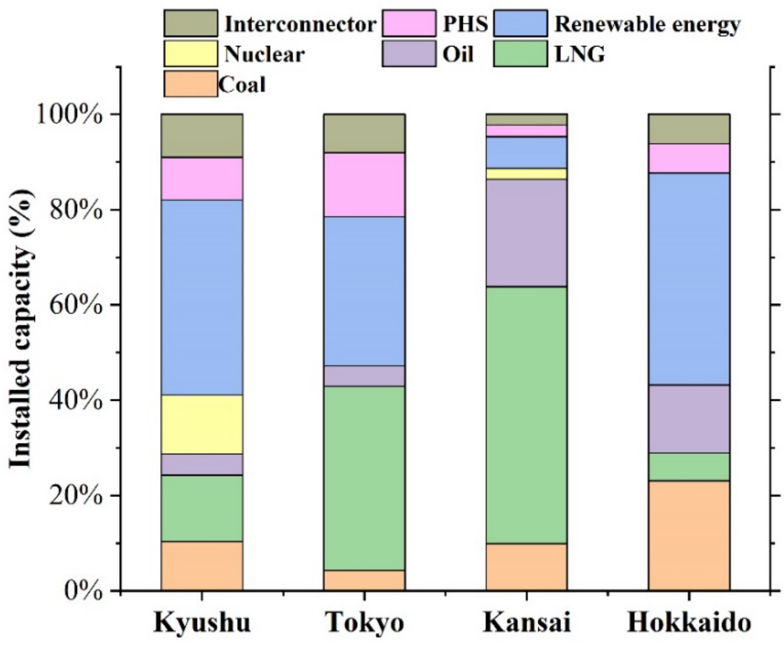


Fig. 6-3 Composition of power generation sectors in research areas (2019)

Fig. 6-3 depicts the installed capacity of power generators in the research areas according to Refs. [40-43]. Renewable energy includes biomass energy, geothermal energy, PV energy, and wind energy. These data resources are combined with hourly load demand from different sectors downloaded from the websites maintained by Japan electricity power companies.[44] Beyond power generation data on both the supply and on the demand sides, the storage capacity and transmission lines between regions also play a significant role in real-time power balancing in different public grids. Load demand in different areas and its influence on the penetration of renewable energy and consequent changes in real-time spot market price are also analyzed. For this purpose, we use hourly market spot trading prices in the research areas from the Japan Electric Power Exchange (JEPX) [44].

Data from April and May 2020 are compared to data from April and May 2019. Our final data set includes data on hourly load demand distribution, installed capacity of the power supply, and real-time spot market price distributions from Kyushu, Tokyo, Kansai, and Hokkaido, running from April to May for 2019 and 2020.

6.3. Methodology and constraints

6.3.1. Electricity load balance between supply and demand

The objective of this paper is to analyze the impact of changes in load characteristics on power generation, particularly the PV power penetration in different regions during the pandemic period and its further impact on electricity prices. The adaptability of the power grid to PV is closely related to the load shape, which determines the reliable operation of the dynamic balance between regional power generation and power consumption. Because the power grid needs to be balanced between the supply and the demand sides, daily supply and demand can be assessed as follows:

$$P_{cons} + P_{flex} + dis + PV_{direct} = Load_{grid}\,. \qquad (1)$$

where, P_{cons} presents the power generation from base-load plants, including nuclear power, hydropower, geothermal power, and coal power; P_{flex} is defined as flexible generators that can adjust their output to adapt to the situation of the PV and power grid, such as gas power; dis refers to the discharging power system, PV_{direct} is directly accommodated PV, integrated by power grid; and $Load_{grid}$ stands for total electricity demand.

The availability of PV power generation, the capacity of the pumped hydro storage system (PHS), and the flexibility of the power grid restrict the direct integration of the PV power generation. The load decreased during the epidemic period, but in cases of overproduction, it is difficult to reduce the constant output of nuclear power as a basic part of the load. Therefore, in this case, PV panels were controlled to reduce output. For this reason, excess power is generated by PV. In this study, two parameters are employed to evaluate PV penetration in the power grid. One is the PV_{direct} which is used to present the ratio of PV_{direct} in the power grid, as shown in Eq. (2). Then PV_{cur} is given as the ratio of PV production curtailment in Eq. (3).

$$PV_{direct} + PV_{cur} = P_{pv}. \quad (2)$$

$$PV_{cur} = \frac{(output - Load_{grid} - trans - dis)}{Load_{grid}}. \quad (3)$$

$$P_{pv} = {}^{PV}/_{Load_{grid}}. \quad (4)$$

where, P_{pv} represents total PV power generation, $output$ presents the total electricity generation on the supply side, and $trans$ is the flow of power transferred across regional transmission lines.

6.3.2. Impact of power generators on electricity price

Due to the low degree of correlation between PV power generation characteristics and load curve, the load distribution is reshaped to resemble a "duck curve" [45], thereby reducing residual load demand. In the peak load response, the low marginal cost of renewable power generation is generally given priority, which reduces the traditional thermal power generation. Japan's grid managers generally favor PV or wind power generation, fuel oil power generation, and PHS to meet peak load. However, limited by the capacity of pumped storage and constant output power generation, PV curtailment is increased when the penetration rate of PV power generation exceeds the basic load unit

Therefore, as the penetration rate of RES with lower marginal costs increases in the power generation structure, the overall price of the electricity market decreases, and grid operators, in response, lower the sale price of electricity. This paper considers the impact of PV on electricity price through a correlation between the distribution characteristics of price fluctuation and PV power generation. The interaction between PV and electricity price is analyzed by comparing the PV penetration-load histogram, price-distribution histogram, and daily-price fluctuation trend between the implementation period of emergency state and the same period in 2019.

6.4. Electricity consumptions change during the COVID-19 pandemic

6.4.1. Total load demand reduction

As seen in Fig. 6-4, electricity demand was reduced to varying degrees for all objective areas due to the COVID-19 pandemic. The drops in Tokyo and Kansai were more noticeable than those in Kyushu and Hokkaido. The reduction in electricity load caused by the gradual limitation of people's behavior and activities after the imposition of the state of emergency by the Japanese government during the epidemic period. The closure of public facilities and industrial centers had a particularly large effect on electricity consumption. However, differences in demand between research areas were also affected by the voltage composition of power consumption on the user side.

There are three major types of voltage produced by power utilities: including low voltage, high voltage, and ultra-high voltage (UHV). For UHV, the voltage supplied is more than 7,000 V. This is used for large-scale factories and facilities that use electricity on a large scale. High voltages are defined as alternating current voltages ranging from 600 to 7,000 V, and low voltages are below 600 V, respectively, for small and medium factory facilities and homes. In 2019, in Tokyo and Kansai, the main consumption came from the primary sector (34.85% and 34.85%, respectively), the secondary (industrial) sector had 31.25% and 29.02% of total load, and the residential sector accounted for 33.90% and 34.20% of total demand. In Kyushu and Hokkaido showed dominant consumption in the residential sector, at 49.74% and 40.79%, respectively. During the state of emergency, people's activities were limited, and they had increased demand for residential electricity as a result. However, the decline in commercial and industrial demand for electricity was far greater than the increase in residential demand. To sum up, the load reduction for Tokyo and Kansai was more noticeable than that for Kyushu and Hokkaido, as indicated by the differences in the composition of electricity consumption.

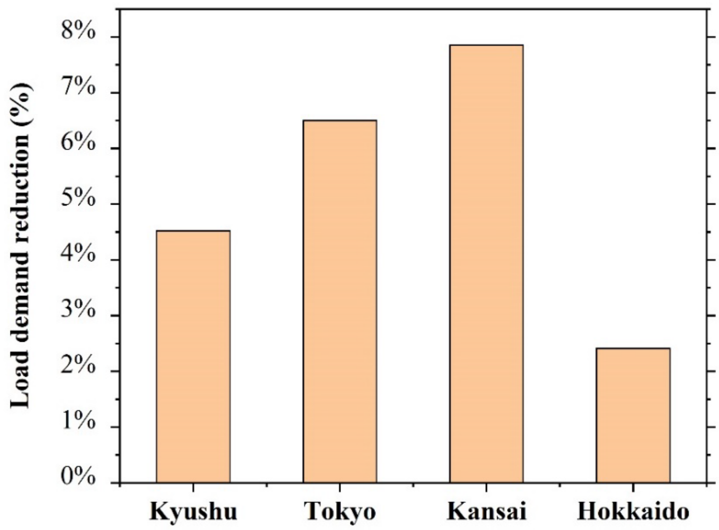


Fig. 6-4 Comparison of demand reduction for the month of April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido

6.4.2. Dispatch on power generation sectors

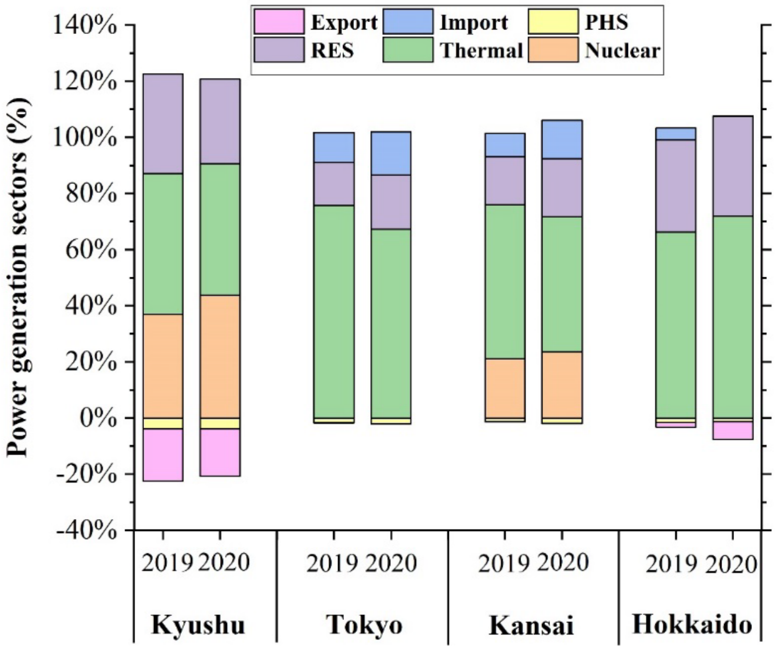


Fig. 6-5 Breakdown of power generation for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido

Due to the differences in infrastructure for regional and power generation, load demand reduction has different impacts on the different regions. The composition of power generation is divided into three parts for our analyses, namely, traditional thermal power generation, nuclear power generation, and renewable energy power generation, as well as and dispatching departments, including PHS and interconnection lines.

Fig. 6-5 shows the energy generation mix and percentage changes for the four areas most affected by COVID-19 pandemic. First, Kyushu Electric's rate of renewable energy power generation increased by 30.31% in April and May of 2019 to 35.38% in the same period of 2020. The total electricity demand for April and May of 2020 fell by 4.52% compared to the reference time of 2019, and for the real-time balance of power demand and supply, the constant output of nuclear plants was significantly reduced, from 43.67% to 36.90%. PV and wind power account for the largest proportion of renewable energy generation. However, the main obstacle to using PV and wind energy is its variability or intermittency, with power outputs fluctuating depending on unpredictable climate conditions. Therefore, increasing the percentage of thermal power generation can balance load demand at night or during periods of no wind or sunlight. In addition, discharged PHS power of can be used in conjunction with flexible thermal power plants to adapt to peak load at night, so PHS and interconnection line utilization therefore increase with increases in power generation percentage of VRE, as shown in Fig. 6-5.

Second, both Kansai and Tokyo Electric Power generated less than demand, with nearly 15% of the load demand coming from the neighboring regions through interconnection lines, unlike the case of Kyushu. In addition, renewable energy accounted for almost 20% of electricity generation in both areas, which is a lower rate than that in Kyushu. To balance between supply and demand on the grid, flexible thermal power generation in the Tokyo area fell to 67.29% from 75.75% in 2019, and that of Kansai Power fell to 48.08% from 54.77%. Due to the reduction in the baseload, the imbalance between supply and demand came at some moments when load demand is relatively high, which led to an increase in the power import capacity to compensate for the reduction in electricity due to partial closure of the thermal power system. Therefore, the proportion of power generation for the interconnection lines of both the Tokyo area and the Kansai area increased by about 5%, as shown in Fig. 6-5.

Finally, Hokkaido had the least reduction in total load affected by the epidemic. There was little change in renewable energy generation, and the increased thermal power generation resulted in a 4.02% reduction in electricity imports and a 5% increase in electricity exports.

This result indicates that grid operators made trade-offs between stability between power plants and VRE. At the same time, the power balance was also affected by the supply and demand of the power load as well as by the installed capacity of pumped storage and connection lines.

6.5. Changes in load profiles and their impact on renewable energy sources

6.5.1. Load-related statistics

① Load demand and profiles

Although Fig. 6-4 presents acceptable results for total load reduction, the performance can be evaluated more accurately through a histogram of electricity load and electricity consumption profiles, as shown in Fig. 6-6, for all possible 1 h intervals over 122 days of 2019 and 2020 (April to May). Compared to the same period in 2019, the fitted curve for 2020 shows a tendency to move toward the left, which can be attributed to reduction in electricity load due to the limitation of people's activities. The electricity load distributions exhibit short tails (see Fig. 6-6), which represented a noticeable reduction from peak load; however, this should also be understood in relation to the time distributions of the load. Fig. 6-7 illustrates the load distribution profiles aligned to the load histogram to comprehensively describe changes in load sequence due to COVID-19. The blue line in Fig. 6-7 represents trends in weekly electricity demand in April and May of 2020, and the red line shows the load for a reference week in 2019. Due to the high level of electricity consumption by large-scale factories during working hours, the peak load mainly occurs during the day, between 9:00 and 18:00, thus a significant peak load reduction was caused by the closure of factories and public facilities. To compare peak load reduction in research areas, Fig. 6 indicates a more noticeable kurtosis in Tokyo and Kansai than that in Kyushu and Hokkaido and decreases significantly for electricity loads higher than 34000 MW and 17000 MW, respectively. This is further evidence that peak load reduction is correlated with the composition of the electricity consumption voltage.

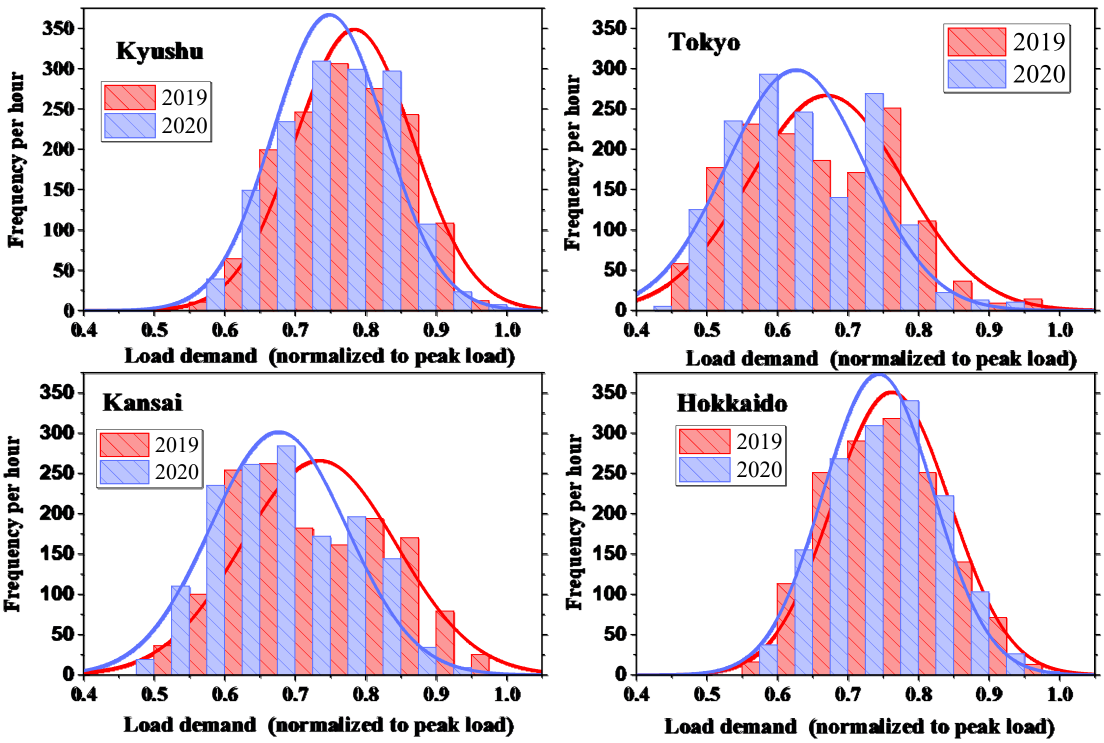


Fig. 6-6 Comparison of load histograms for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai

Fig. 6-7 presents a closer comparison, at the week level among the regions. It is obvious that electricity demand was reduced during daytime working hours from Tuesday to Saturday. However, the reduction in peak load reduction around 18:00 on Sunday nights showed a small downward trend, indicating that people were more restricted in their activities during working hours than in the reference times in 2019, and normal evening activities continued on Sunday night. In contrast with other weekdays, Monday mornings in 2020 showed a chaotic trend across all four regions. An important factor to consider is that Mondays mark the start of the work week, and in 2020, employees tended to work remotely, with more work being done than on the remaining weekdays. For Hokkaido, as seen in Fig. 6, the daily consumption profile during the pandemic is very similar to the profile of the pre-pandemic reference days in 2019. Therefore, the impact on Hokkaido power was appreciably smaller than that in Kyushu, Tokyo, and Kansai.

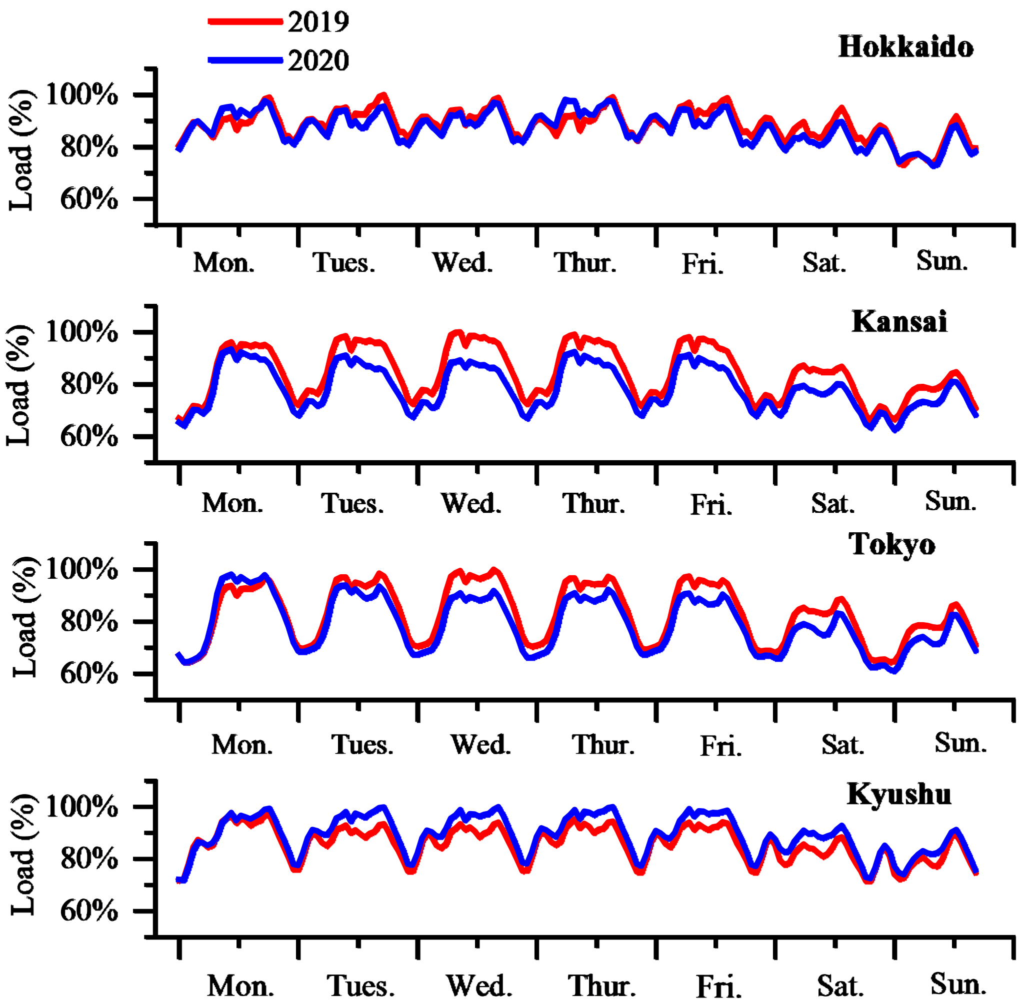
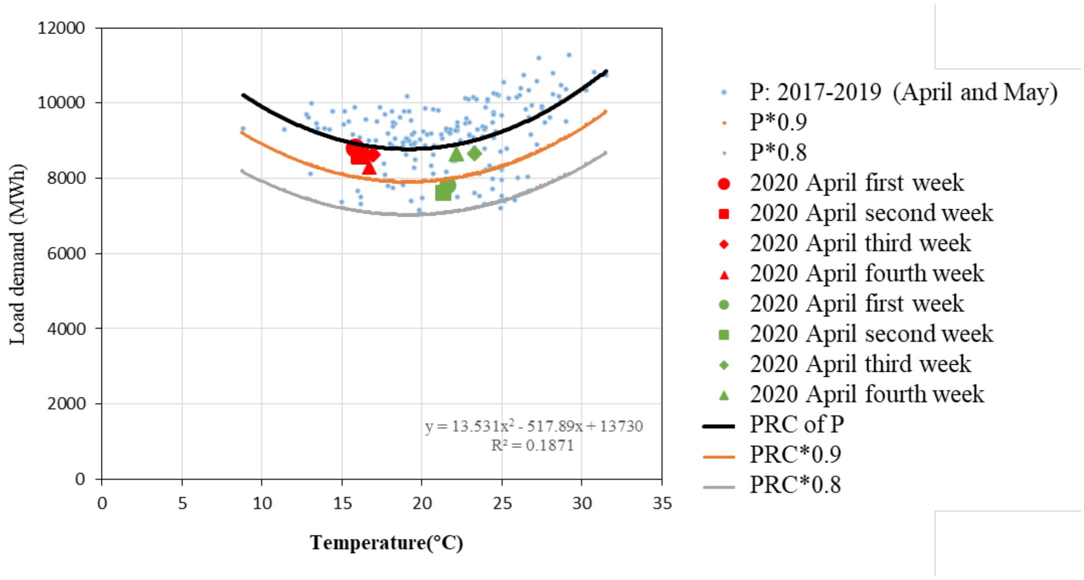


Fig. 6-7 Comparison of weekly load profiles for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido.

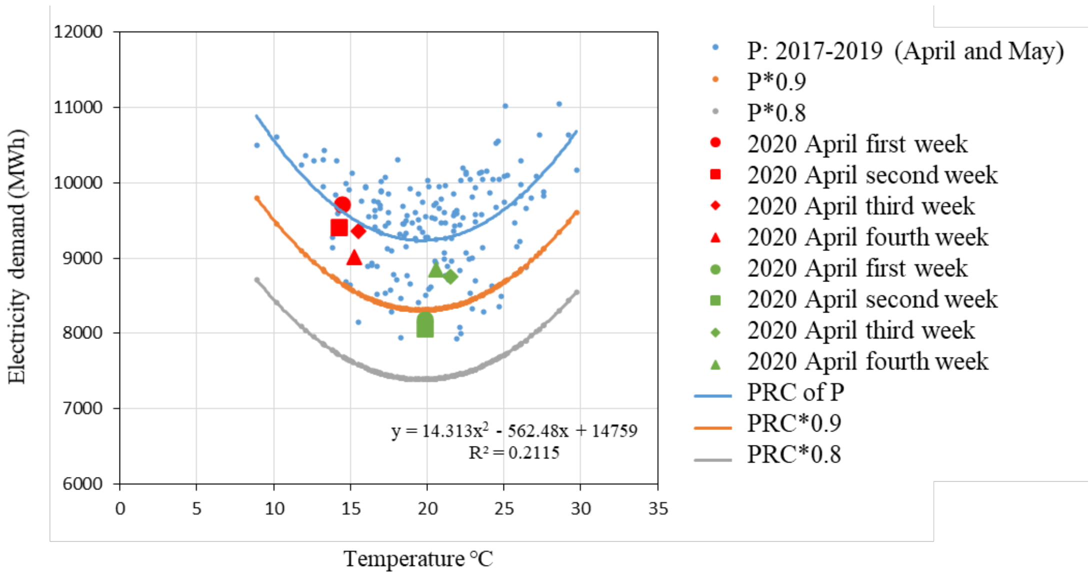
② Temperature factor

The electricity demand is affected by temperature deeply, it is therefore essential to eliminate the influence of temperature on load. Fig. 6-8, Fig. 6-9, Fig. 6-10, and Fig. 6-11 shown the reduction of load demand under the same temperature conditions. The data set selects the first 3 years of the same month as the emergency state implementation period. In terms of the demand of 2020, we have selected the average load value of one week to compare and analyze the changes in load more clearly. The polynomial regression curve (PRC) of the temperature set is employed to analyze the degree of load reduction. The time point is to select the working hours with high load demand value at 3:00 pm, 6:00 pm during off-duty period and 9:00 at night.

At: 15:00



At: 18:00



At: 21:00

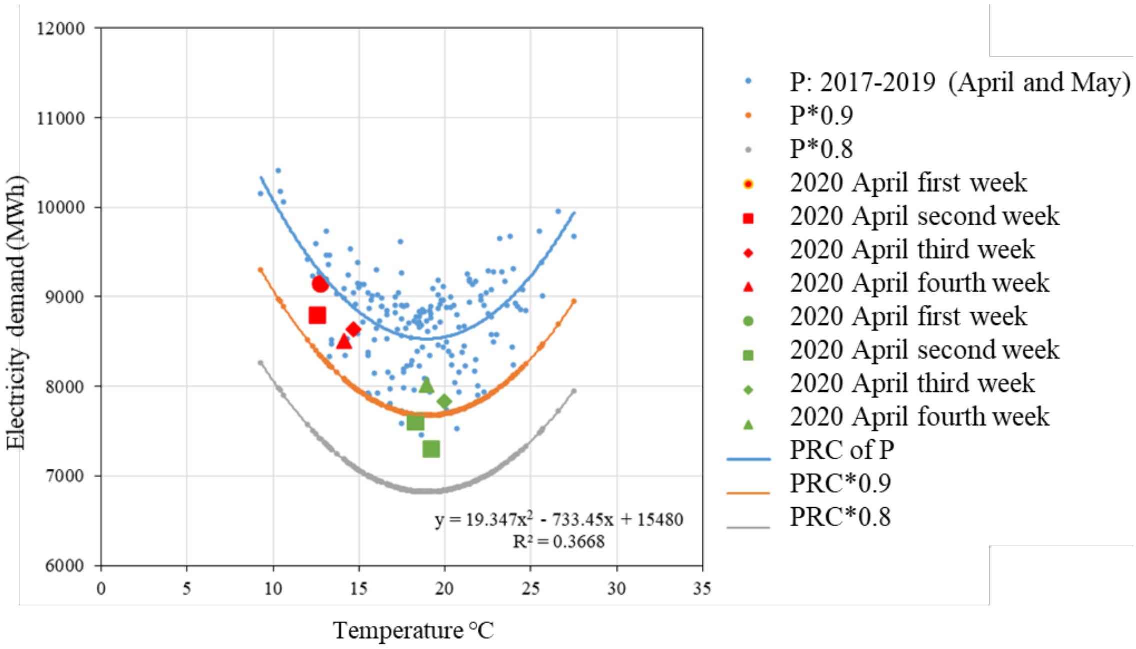
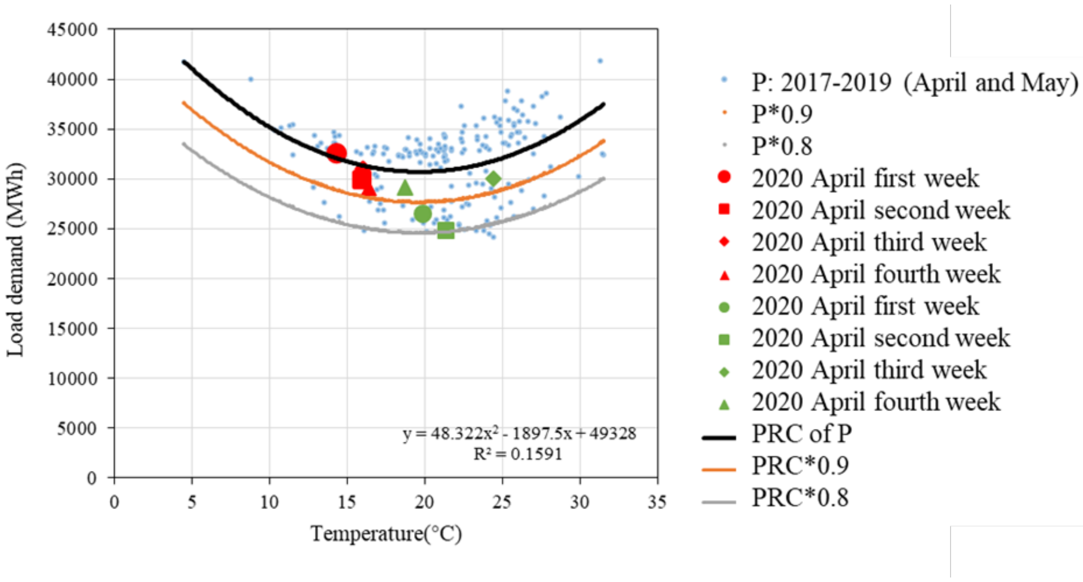


Fig. 6-8 The comparison of load changes in 2020 compared with previous years under the same temperature in Kyushu

The period of load drop in Kyushu is mainly reflected in May. The load reduction at 9:00 in the evening is about 10% larger than that at 3:00 and 6:00 in the afternoon (as shown in Fig. 6-8).

At: 15:00



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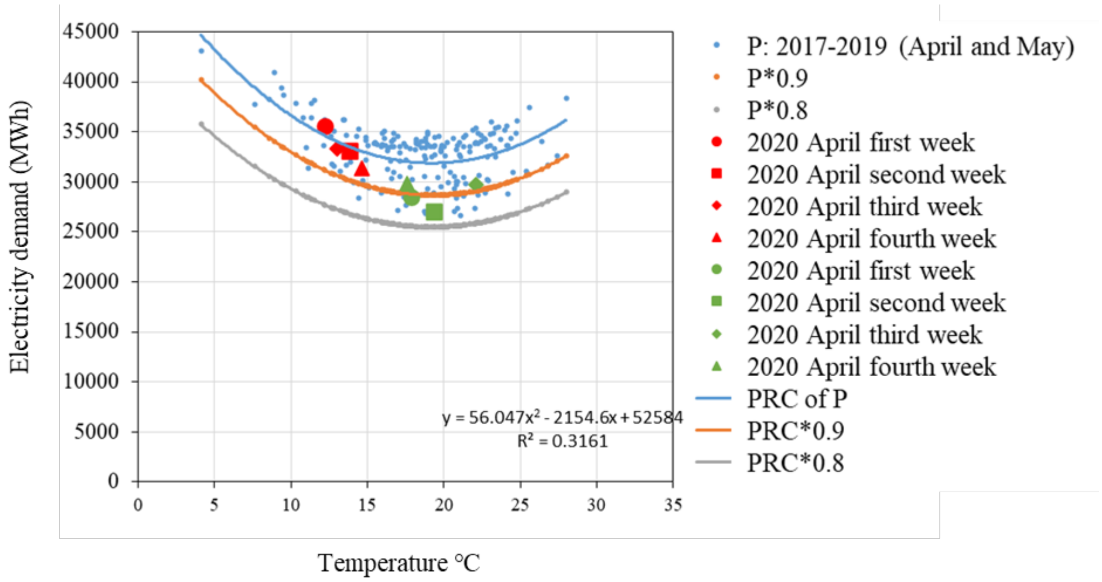

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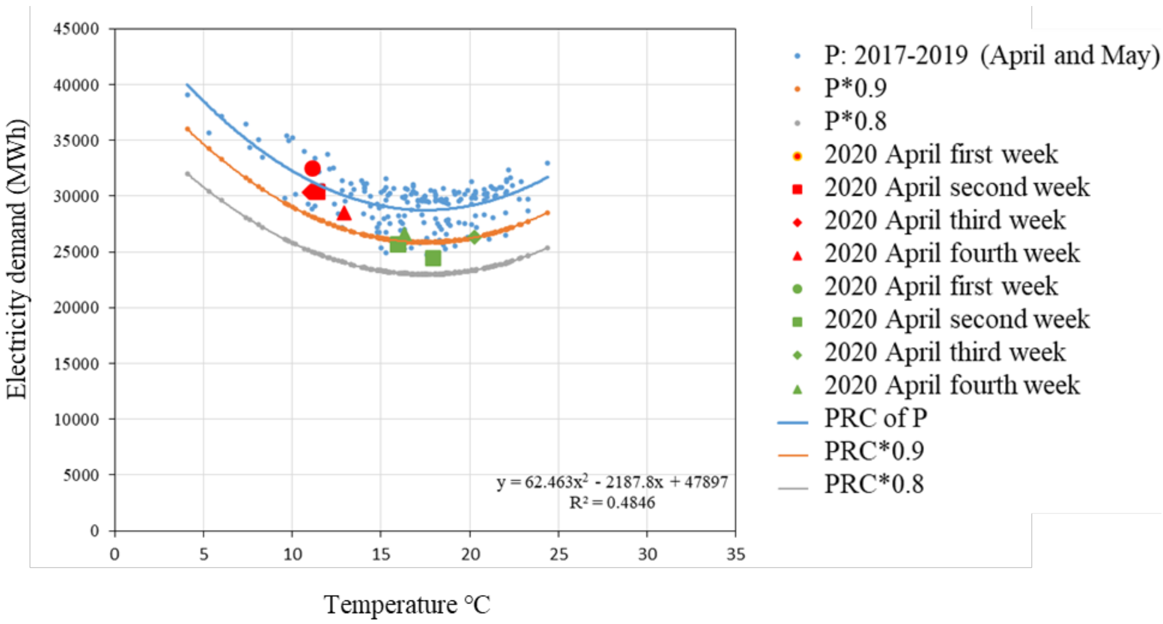
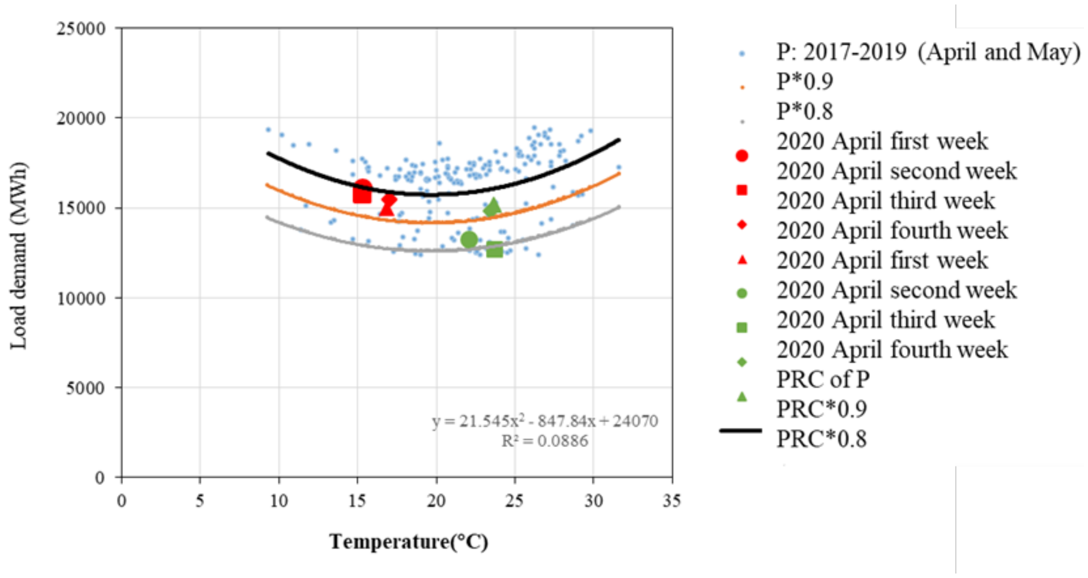


Fig. 6-9 The comparison of load changes in 2020 compared with previous years under the same temperature in Tokyo

Compared with the Kyushu area, the load reduction in the Tokyo area is more pronounced. The average load reduction in May even reached 20%. This is related to the closure of UHV factories in the Tokyo area due to the epidemic (as shown in Fig. 6-9).

The Kansai region is geographically close to the Tokyo region, and they are all industrially developed regions. In Section 6.4.1, it is described that the main consumption of Tokyo and Kansai comes from the first sector (34.85% and 34.85%, respectively), the second (industrial) sector accounts for 31.25% and 29.02% of the total load, and the residential sector accounts for 33.90%. Accounted for 34.20% of total demand. Housing consumption in Kyushu and Hokkaido dominates, accounting for 49.74% and 40.79%, respectively. Therefore, the load drop in Tokyo and Kansai is significantly higher than that in Kyushu (as shown in Fig. 6-10).

At: 15:00



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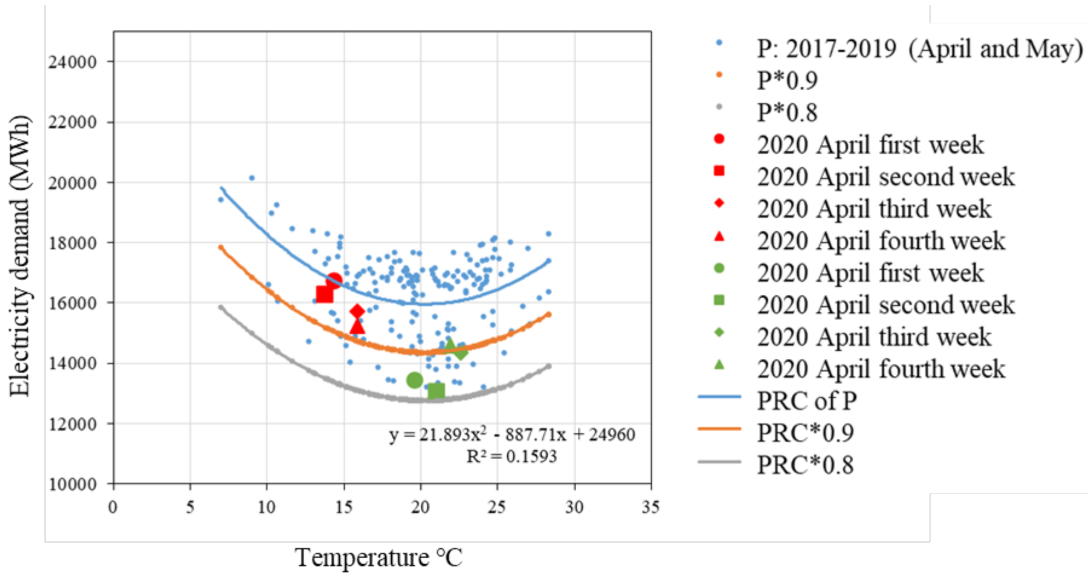


At: 21:00

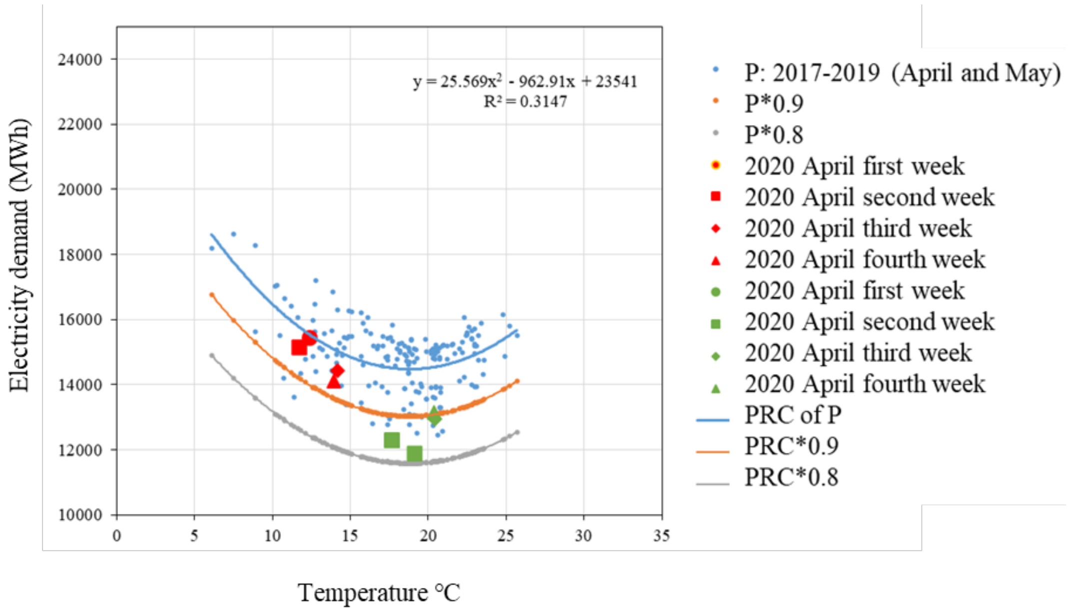
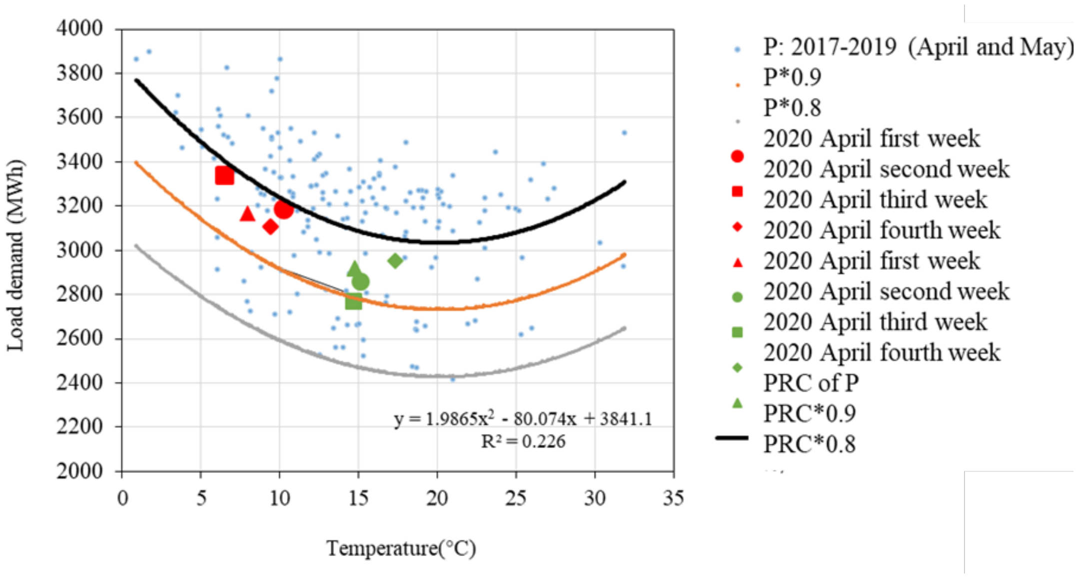
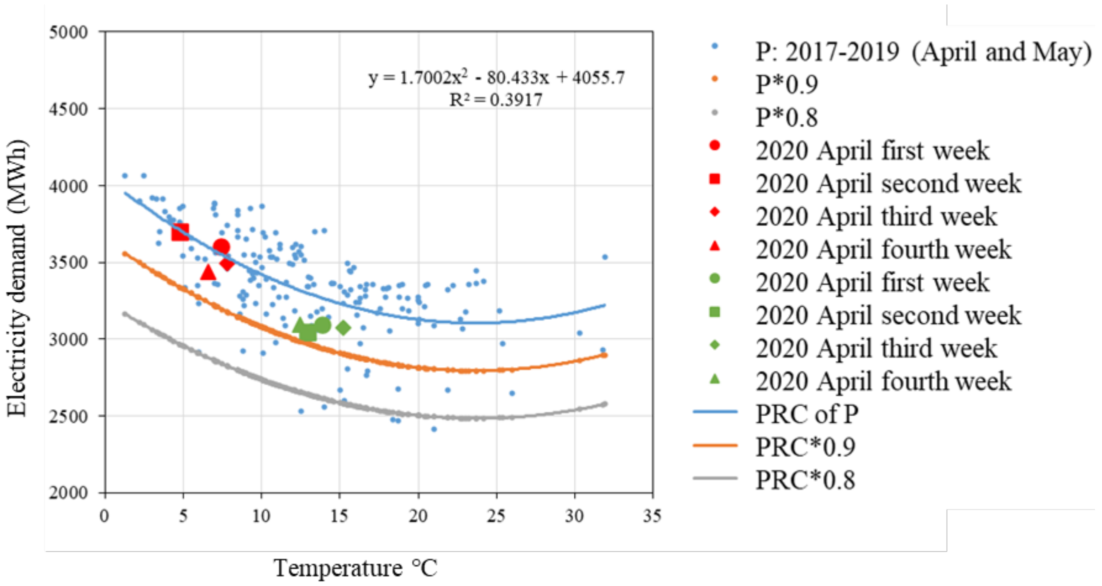


Fig. 6-10 The comparison of load changes in 2020 compared with previous years under the same temperature in Kansai

At: 15:00



At: 18:00



At: 21:00

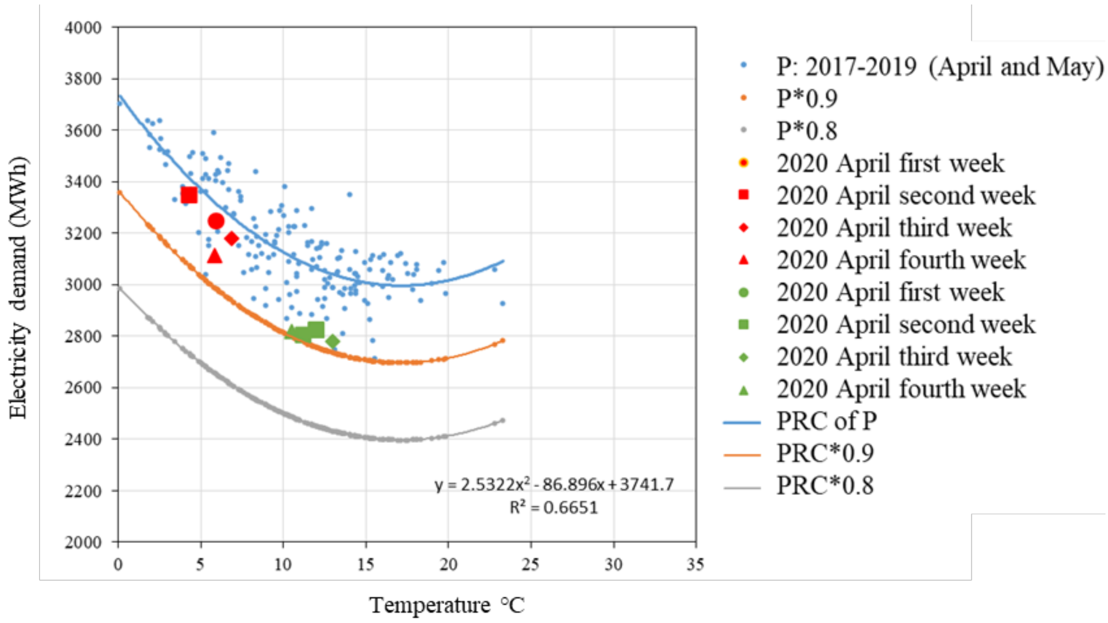


Fig. 6-11 The comparison of load changes in 2020 compared with previous years under the same temperature in Hokkaido

The overall load reduction period is still reflected in May. Analyzing the four regions, it can be found that the correlation between temperature and load demand at 9:00 pm is the highest. Especially in Hokkaido, the correlation at nine o'clock in the evening reaches 0.67. At the same time, the temperature is below 25 degrees Celsius (as shown in Fig. 6-11).

6.5.2. Impact on PV integration

Table 6-1 Descriptive statistics for PV power generation in 2019 and 2020 (April to May)

	PV penetration (%)		PV curtailment (%)	
Year	2019	2020	2019	2020
Kyushu	17.00%	20.68%	9.38%	10.72%
Tokyo	8.50%	9.29%	0.00%	0.00%
Kansai	7.45%	8.07%	0.00%	0.00%
Hokkaido	9.80%	11.62%	0.00%	0.00%

Due to the mismatch between real-time renewable energy generation and grid load, the changed load sequence affects the integration of PV power generation into the public grid. The descriptive statistics for total PV penetration and curtailment ratio in 2019 and 2020 are shown in Table 6-1. Kyushu had the dominant PV penetration, followed by Hokkaido, Tokyo, and Kansai. In the research areas, total PV penetration in 2020 was slightly higher than that in 2019, and PV curtailment only occurred in Kyushu and increased in 2020 compared to 2019. Fig. 6-11 depicts changes in PV penetration except for values lower than 10%. As can be observed, compared to the reference time, all regions showed the tendency to have a right-hand long tail, indicating an increasing penetration of PV, as seen in the larger values in 2020. Both the increased PV penetration and the curtailment relate to the flexibility of electricity generation and the implantation of dispatch storages. Taking Kyushu and Tokyo as examples, Fig. 6-12 depicts the daytime power balance schedule in Kyushu and Tokyo when PV accounts for the largest proportion of power generation, respectively. The day with the highest PV penetration is selected to illustrate the impact of increasing the PV integration ratio on different public grids, and the loads are normalized to peak value. However, the flexibility of available resources and the necessity of real-time balancing of the power system limits the integration of VRE penetration in the public grid. For Kyushu, PV penetration reached 69.61% in April and May 2020, and the limited available capacity of PHS and interconnector lines with the neighboring regions could not help releasing balance pressure under the overlarge integrated PV capacities. Thus, due to the operational constraints, approximately half of PV production needed to be reduced. In Tokyo, the maximum PV penetration in 2020 reached 41.92%, as flexible of thermal generators combined with PHS systems and regional interconnector lines absorbed PV production without causing any curtailment during the emergency. In both Kyushu and Tokyo, the results of the analyses indicated that flexible thermal generators and dispatch systems in PHS implantation and interconnector lines played an important role in reducing PV curtailment during the massive PV production periods. The utilization of PHS and interconnection lines were greater in 2020 than for the comparable day in 2019, as shown in Fig. 6-12.

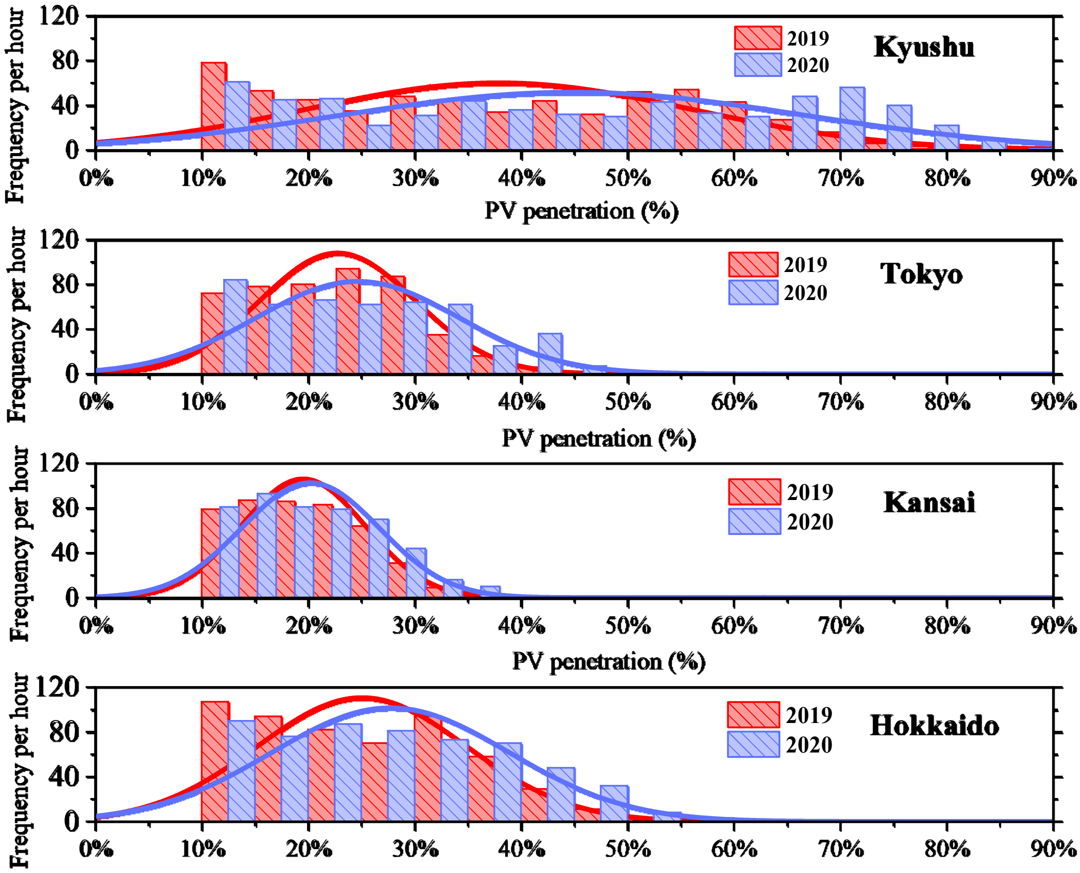
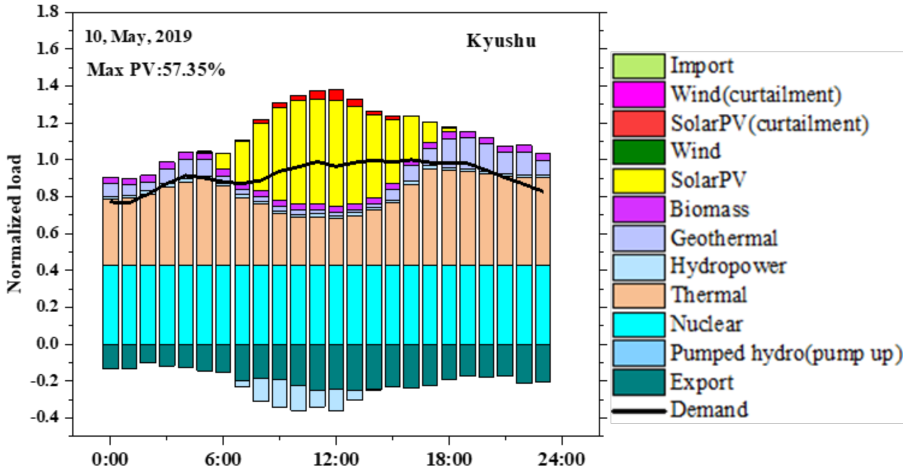
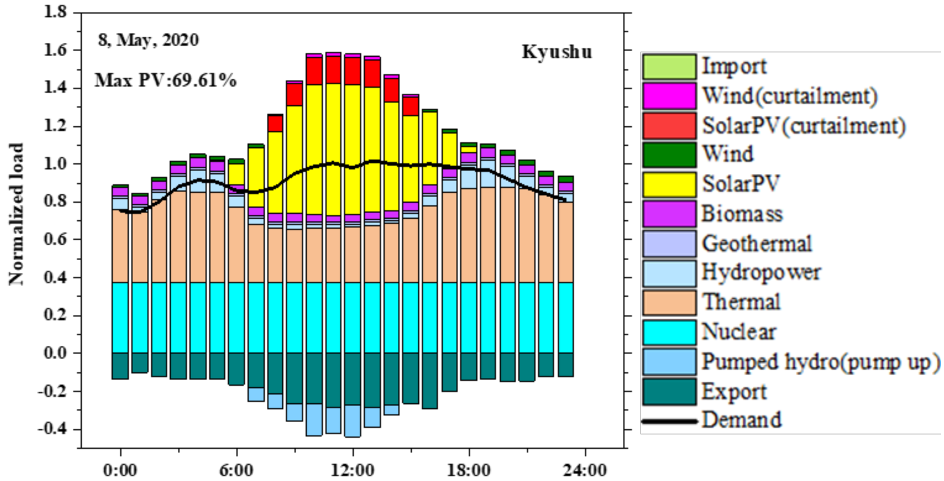
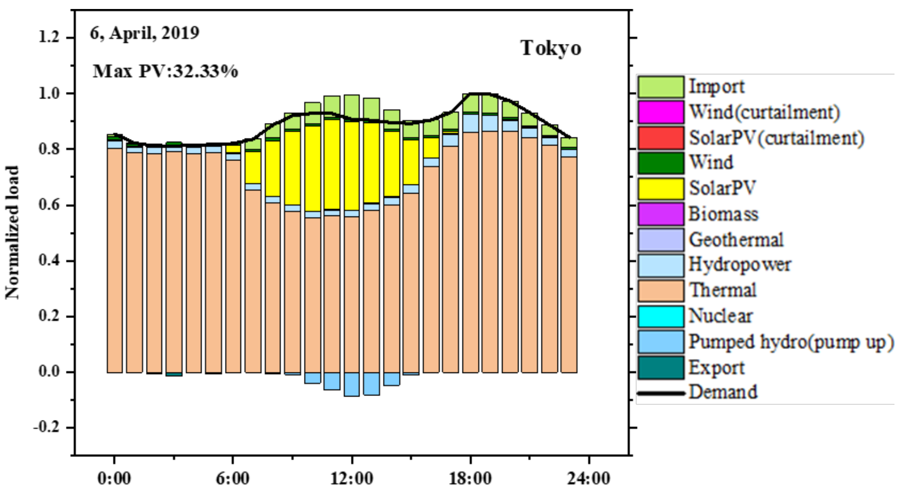


Fig. 6-12 PV penetration histograms for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido

At Kyushu:


10, May, 2019
Max PV:57.35%
Kyushu
Normalized load
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0:00
6:00
12:00
18:00
24:00
Import
Wind(curtailment)
SolarPV(curtailment)
Wind
SolarPV
Biomass
Geothermal
Hydropower
Thermal
Nuclear
Pumped hydro(pump up)
Export
Demand


8, May, 2020
Max PV:69.61%
Kyushu
Normalized load
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0:00
6:00
12:00
18:00
24:00
Import
Wind(curtailment)
SolarPV(curtailment)
Wind
SolarPV
Biomass
Geothermal
Hydropower
Thermal
Nuclear
Pumped hydro(pump up)
Export
Demand


6, April, 2019
Max PV:32.33%
Tokyo
Normalized load
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0:00
6:00
12:00
18:00
24:00
Import
Wind(curtailment)
SolarPV(curtailment)
Wind
SolarPV
Biomass
Geothermal
Hydropower
Thermal
Nuclear
Pumped hydro(pump up)
Export
Demand

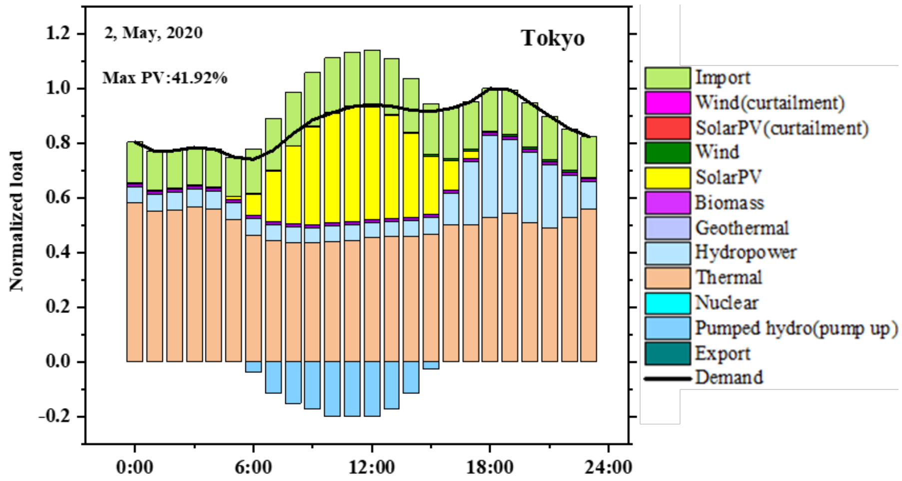


Fig. 6-13 Comparison of daily power balance for April and May 2019 and 2020 in Kyushu and Tokyo

6.5.3. Impact on electricity price

The increasing integration of renewable energy sources has a profound impact on power systems, as they are challenging for the operation and economy of real-time trading markets in their intermittency. Due to the changing daily pattern of electricity demand, the wholesale price of electricity fluctuates as real-time supply and demand change. To better understand the relation of real-time spot markets to demand, taking Kyushu as an example, Fig. 6-14 shows the color-scale distribution of real-time electricity trading markets in Kyushu at hourly intervals for April and May 2019 and 2020. First, compared with 2019, the real-time market prices for 2020 dropped significantly, especially in the early morning, noon, and evening. As previously discussed, the peak load reduction mainly occurred in the night and early morning affected by the epidemic limitation. Therefore, the load reduction interval and the electricity market price distribution in Fig. 6-14 feedback a good correlation between electricity demand and electricity price. In addition to the morning and evening, the data clearly indicate that the electricity price at noon was significantly reduced compared to 2019. This was caused by the increasing penetration of PV power generation. The share of PV power in the grid reshapes the price pattern and reduces the electricity price accordingly. The overall impact of electricity demand and PV integration rate on electricity prices are illustrated in Fig. 6-14. To accurately compare the impacts of the PV power integration changes on spot trading price within four research areas. Fig. 6-15 presents a histogram of the spot market prices for Kyushu, Tokyo, Kansai, and Hokkaido in April and May 2019 and 2020. The results indicate that in both 2019 or 2020, Kyushu and Kansai had similar spot trading distributions, as did Tokyo and Hokkaido. In addition, Kyushu and Kansai had a relatively leftward tendency, indicating a lower spot trading price than that in Tokyo and Hokkaido. To allow more detailed comparison of results, the statistics of the average real-time spot market price in research areas are presented in Table 6-2.

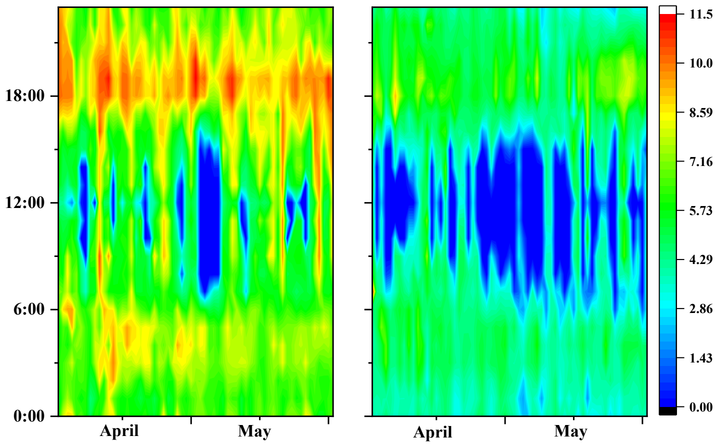


Fig. 6-14 Market spot trading prices in Kyushu during April and May 2019 (left) and April and May 2020 (right)

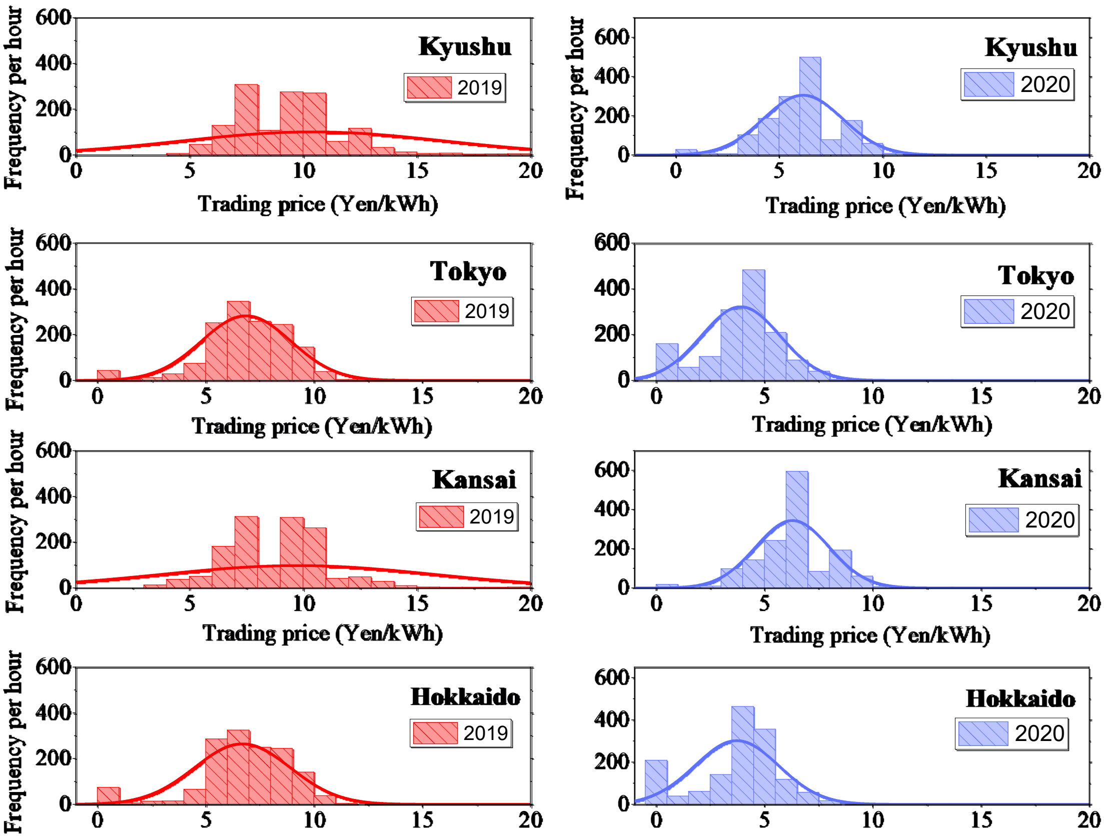


Fig. 6-15 Histogram of spot market prices in Kyushu, Tokyo, Kansai, and Hokkaido during April and May 2019 (left) and April and May 2020 (right)

6.6. Discussion and Conclusions

In this work, the impacts of COVID-19 on the public electrical grids of Kyushu, Tokyo, Kansai, and Hokkaido are analyzed through a comparison of data drawn from the declaration of emergency period and a reference period (April and May 2019 and 2020). The primary findings of this paper are as follows:

(i). COVID-19 caused reductions in load demand of varying magnitudes in 2020, with the reduction in Tokyo being the largest, followed by those in Kansai, Kyushu, and Hokkaido. The closure of large factories and the limitation of people's activity due to the emergency declaration resulted in a large reduction in working time.

(ii). Most electricity companies took countermeasures to respond to the load reduction due to the COVID-19 pandemic. These measures contained three main aspects, including the adjustment of the traditional generation of thermal nuclear power, the penetration of renewable energy power, and the utilization ratio of dispatch sectors, such as PHS and transmission lines between neighborhood regions.

First, the supply of renewable energy was not influenced by COVID-19. Because renewable energy has a lower marginal cost than thermal and nuclear power generation, the penetration of renewable power generation in the public grid increased with the decline of total load-demand reduction.

With the increasing penetration of renewable energy and decreased electricity demand, different degrees of compression for thermal power generation and nuclear power generation were obtained in the baseload composition. Pumped storage and transmission lines in Tokyo and Kansai directly consume the impact of the increased amount of renewable energy on the power grid without causing power suppression. Therefore, thermal power generation is mainly used to adjust load fluctuations, which decrease as load demand decreases. Maximum daily PV penetration reached 69.61% in the power grid of Kyushu, and the balance of supply and demand could not be maintained through power dispatch systems such as PHS and interconnectors. Consequently, the frequency and amount of curtailment of PV increases with decreases in demand and increases in supply. This caused the share of nuclear power generation to decrease from 40.12% in 2019 to 36% in 2020. The increasing penetration of PV power generation and the decreasing share of nuclear power generation are due to the intermittent characteristics of VRE, such that thermal power generation is increased to meet imbalances in power generation between the supply side and the demand side during the night or times of weak sunlight that reflect the low amount of PV power generation. Hokkaido exhibited the least impact from COVID-19 on load demand reduction, with an imported electricity amount that slightly decreased with the decreased total load-demand reduction.

In summary, the impact of COVID-19 on the power generation structure of the four research regions was thoroughly analyzed and compared. Once the load is reduced, the power company should immediately adjust the structure of the power generation and regulate the operation of the power grid, meanwhile ensuring the stability and reliability of the power grid. This reflects the importance of having a range of power generation structures to respond to natural disasters in a timely way.

(iii). Due to the closure of large-scale factories that consume UHV electricity, as well as the increased electricity consumption in the low-voltage residential areas, the load demand sequence was different during the study period. Therefore, the matching degree of PV power generation and load demand changed accordingly. PV penetration increased with the load demand reduction in the research areas, but PV curtailment ratio only increased in Kyushu due to the limitations of dispatch storage systems and almost 70% (normalized to peak demand) baseload operation demand. Hence, the overall load decline did not cause a decrease in PV power generation, and its penetration rate in the four regions increased, improving the utilization rate of PV.

(iv). Electricity spot trading prices decreased with the increased proportion of PV power generation. Because PV power generation reshapes the distribution pattern of the grid load, it can have a significant impact on the electricity trading price, particularly in the case of high PV penetration. It was further found that the trading price in Kyushu and Kansai had a lower value than that in the same period in Tokyo and Hokkaido, which indicates the need to explore the contribution of different power generators on prices more fully.

PV intermittent output has a significant impact on the balance between supply and demand on a power grid, particularly for a high penetration rate of renewable energy. This paper analyzes the interaction between load and renewable energy power generation, the composition of baseload units, and real-time spot market prices through total load demand reduction and changes in load demand characteristics during the pandemic period. A reduction in load demand leads to a partial outage of traditional thermal power generation based on fuel supply. On the other hand, considering economic constraints, it is necessary to maintain PV power generation with lower marginal costs. In this case, due to the increased penetration of PV power generation, technical and operational challenges such as intermittency and stability arose. However, these problems can be solved by adjusting the generation structure. Energy storage capacity and non-schedulable continuous generation units in this generation structure reveal the possibilities and limitations of future PV generation penetration. Moreover, correlations appeared between PV power generation and electricity price across regions of Japan, which shows that increased PV penetration can reduce the electricity market price to further strengthen national energy independence by increasing the PV penetration rate and reducing the electricity price. Overall, this paper presents a comprehensive understanding of the impact of COVID-19 on the public grid of Japan and allows the measures taken by different electricity companies faced with the sudden load change to be compared, to the benefit of the policymakers considering the future development of renewable energy.

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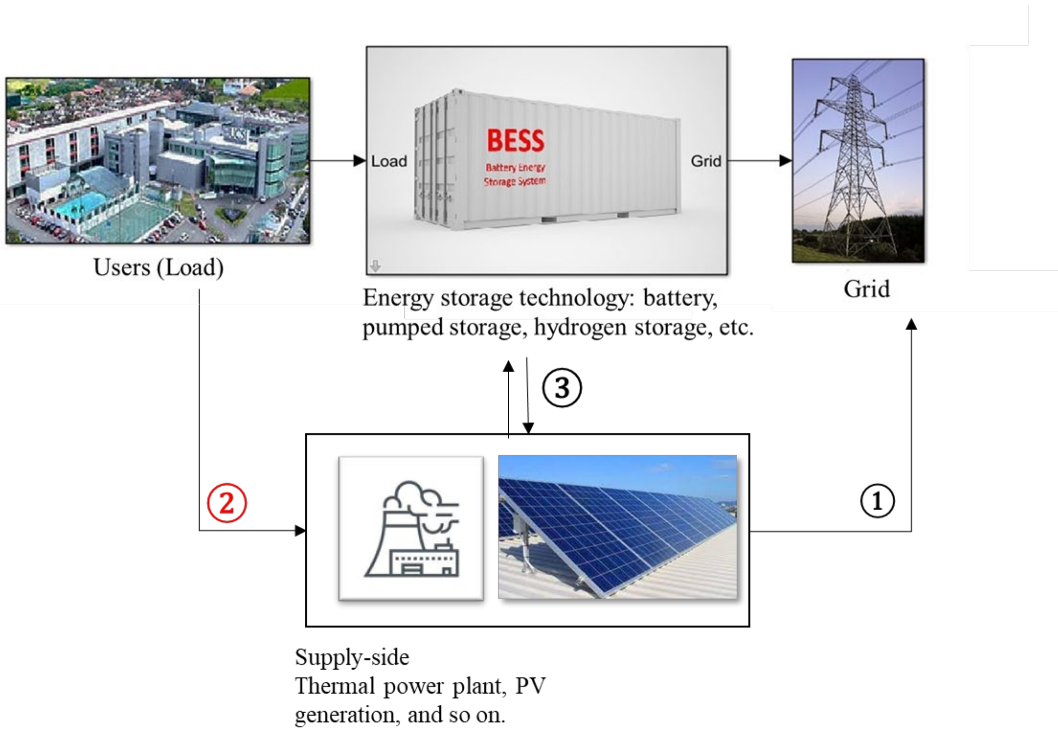
Appendix

① Timeline of pandemic period in Japan

January 6, 2020	Pneumonia of unknown cause in Wuhan, China Ministry of Health, Labor and Welfare calls attention.
January 16, 2020	Infection confirmed for the first time in Japan.
February 3	Cruise ship confirmed to be infected by passengers Entered Yokohama Port.
February 27	Announcement of the idea of requesting temporary closure to all elementary, junior high and high schools nationwide.
April 7	Declaration of emergency to 7 prefectures "Reduce human contact by at least 70% and as much as 80%".
April 16	The target is 7 prefectures of Tokyo, Kanagawa, Saitama, Chiba, Osaka, Hyogo, and Fukuoka, and 13 prefectures including 6 prefectures of Hokkaido, Ibaraki, Ishikawa, Gifu, Aichi, and Kyoto are particularly focused on preventing the spread of infection. We have positioned it as a "specific caution prefecture" because it is necessary to proceed with the efforts of.
May 14	The target has been expanded nationwide.
May 21	We have decided to cancel the emergency declaration in 39 prefectures, excluding the eight prefectures of Hokkaido, Tokyo, Saitama, Chiba, Kanagawa, Osaka, Kyoto and Hyogo.
May 25	We have decided to cancel the state of emergency for the three prefectures of Osaka, Kyoto and Hyogo. The state of emergency continues in the five prefectures of Tokyo, Kanagawa, Saitama, Chiba, and Hokkaido.

② Schematic of research content



This Chapter discussed the impact of load changes on supplied side. This paper is presented in the Journal of Renewable and Sustainable Energy, which is entitled 'Impact of COVID-19 Pandemic on the Reduction of Electricity Demand and the Integration of Renewable Energy in Power Grid'.

Chapter 7

ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM

CHAPTER 7: ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM

7.1 Research contents

This Chapter exploits the existing small and medium-sized dams in Japan to predict the possible installation capacity of PHS in the study area. Combining with the phase-out of thermal power, analyze the basic load power supply equipment contributes to regional VRE penetration. Kyushu and Hokkaido power grids with different power generation structure and electricity demand profiles as case study. Scenario settings are based on hourly power demand and supply curves using the EnergyPLAN tool. The results are summarized as follows:

1) the installed capacity potential of small and medium-sized pumped storage in Kyushu and Hokkaido is 18GW and 20GW, respectively.

2) PHS can reduce RES suppression and thermal power operation while providing a share of grid stability. The reduction of the initial installation of thermal power improves the penetration of RES and the operation rate of PHS.

3) the average power generation cost decreases with the reduction of thermal power installation capacity. Besides, the addition of PHS is first higher and then lower than the scenario without energy storage equipment. Under the same RES share, the maximum cost of Kyushu is 16yen / kWh and that of Hokkaido is 26yen / kWh. Attributed to the nuclear power in Kyushu, which accounts to 25% share of power generation. The penetration of VRE in the future public grid and its impact on other power generation units are covered.

4). For the utilization of EnergyPLAN in different scenario management, it is important to verify the accuracy of EnergyPLAN model in Japan power grid. Therefore, we present the accuracy experiment to show the feasibility and adaptability of EnergyPLAN in research regions.

The contribution of this section is summarized. In this section, Kyushu and Tokyo public power grids with different load curves and power generation structures are selected to analyze and compare the impact of the mixing of existing power generation units and PHS on the permeability of renewable energy. A research method for predicting the installed capacity of PHS is proposed. Results is concluded from the perspective of technology and economy of different scenarios. The operation strategy of pumped storage is limited by maximizing the penetration of renewable energy and reducing thermal power generation. In addition, two penstocks are adopted to shorten the demand response time. This paper seeks the development potential of renewable energy from three aspects: the basic composition of power supply side, the fluctuation difference of load demand side and energy storage system. The study content and results are useful to policy makers seeking better resource utilization and the development of pumped storage. The research flow is shown in Fig. 7-1.

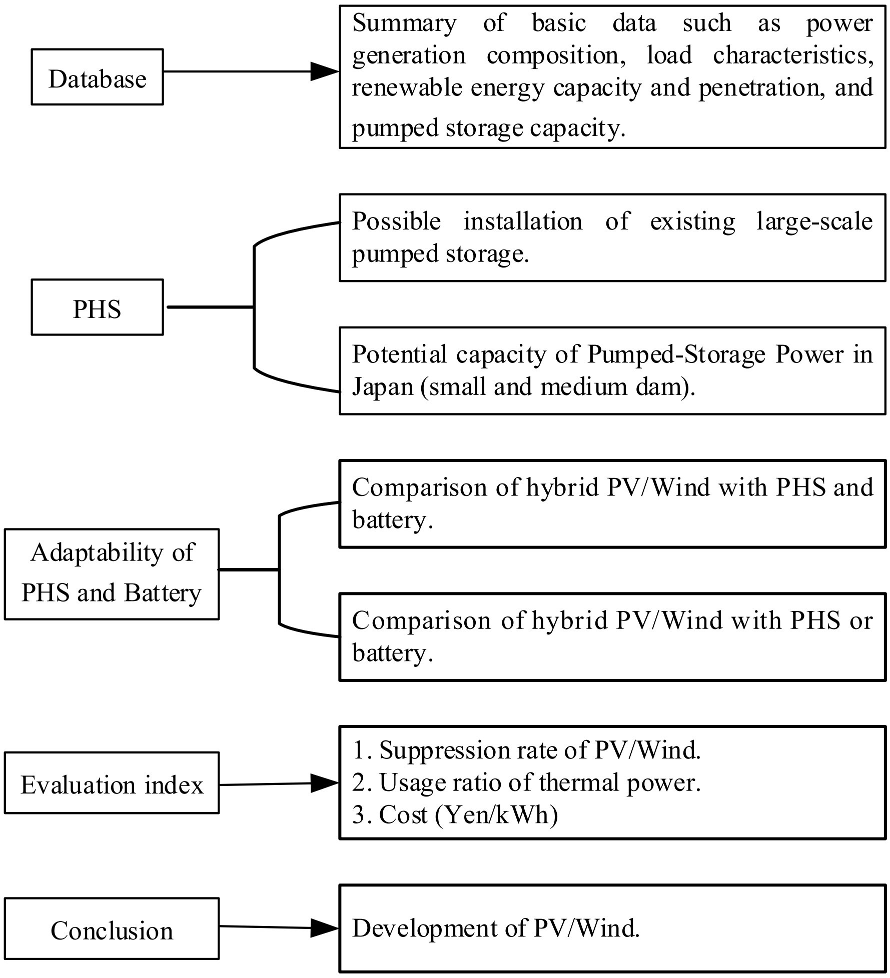


Fig. 7-1 Research flow

7.2. Accuracy of the EnergyPLAN model of Japan power grid

7.2.1. Background

With the shortage of fossil energy sources in worldwide and the increasement in greenhouse gas emissions, the development of renewable energy sources is imperative. Therefore, it is essential for future energy planning. This Section chooses EnergyPLAN tool to analyze its feasibility and applicability in the Japanese power grid. EnergyPLAN is a simulation software based on the future energy system, including economic, technical, and environmental analysis. This Section mainly focuses on the technical level. The data resource of Kyushu power grid, Japan is chosen for analysis, the data period distributed in the time of April 2018 to March 2019. The result shows that the monthly load difference is not higher than 1%, confirming the feasibility of calculating he electric load. Secondly, analyze the difference in the calculation of power generation for photovoltaic (PV) energy, wind energy, hydro power, geothermal power, and pumped storage, which does not exceed 5%. Therefore, we believe that EnergyPLAN can be used for technical research in Japan. It is the basement of energy management modeling in the future research. Besides, the basic information of EnergyPLAN also introduced in this study.

Since the energy consumption is proportional to the population, the intensify of energy competition can be seen in the forthcoming decades of years with the continuous increasing of population all over the world. For Japan, 92% of primary energy consumption relies on the import from other countries [1]. The reinforcement of energy security is considered as an important challenge. In global energy market, Japan is one of the largest energy consumers and importers, thus, nuclear, and renewable energy are expected to play an important role in ensuring domestic energy supply. However, Great East Japan Earthquake had resulted in intensive discussions for rethinking nuclear energy. After those different kinds of alternative energy sources which can compensate nuclear energy such as natural gas, coal, and solar PV as well as electricity saving have shown a dramatic increase.

For renewable energy, PV resources, and wind resources have the characteristics of short are non-dispatchable power generations. Because their electrical output is based on both technology design parameters (technology selection, installation characteristics, and site conditions). Therefore, solar and wind resource varies randomly over time, due to its variableness and randomness characteristics featured.

Therefore, the energy management in the future is important, appropriate energy system management software is required. The energy system required to be modeled to provide the possibility of the impact of scenarios with different proportions of energy on the power system. And provide corresponding technical and economic evaluation indicators to analyze and compare the results under different scenarios. After comparing many diverse energy planning tools, EnergyPLAN was selected [2-4].

Compared with other energy system analysis models, EnergyPLAN model has the following characteristics: (1) EnergyPLAN model can analyze the impact of different energy strategies or energy policies on the energy, environment and economy of a country or region. At the same time, on this basis, help design and optimize the energy development strategy and energy policy of the country or region. The model includes all sectors of a national or regional energy system, including power and heat supply, transportation, and industry. (2) The model is general when describing the system, rather than describing each component separately. For example, it does not input the installed capacity of each power plant separately, but the total installed capacity of a class of power plants, which can simplify the analysis of the problem. (3) The operation of the model is based on the analysis program, rather than iteration, dynamic programming, or advanced mathematical tools, which makes the model calculation direct and fast. The research framework is shown as Fig. 7-2.

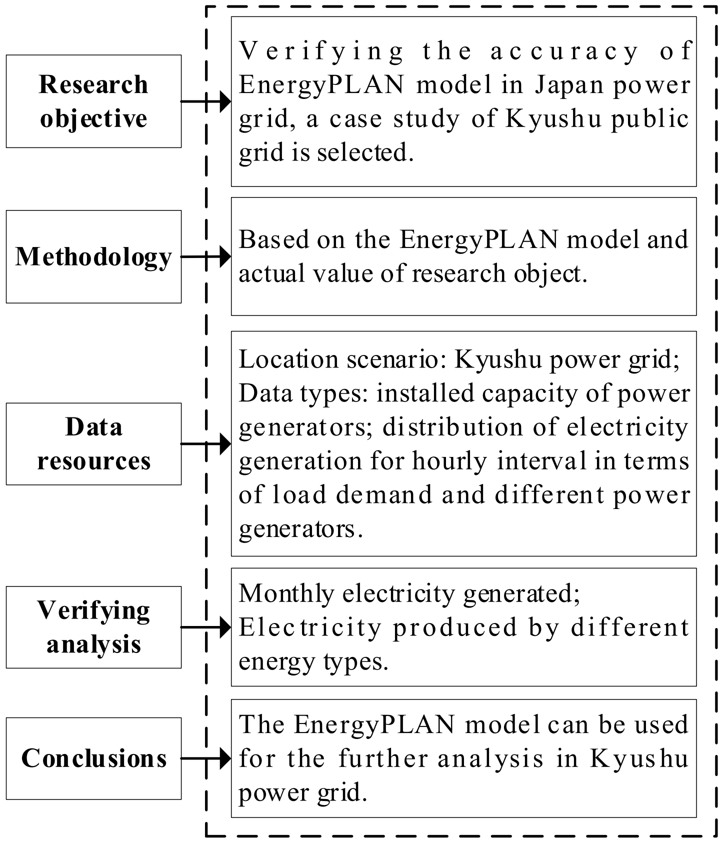


Fig. 7-2 Research framework

The basic configuration of EnergyPLAN is depicted in Fig. 7-3. It is an input and output model; the data period of research is 8784 hours for one year. The input data refers to the electricity demand, distribution of different power generators, installed capacities of different power plant, and the cost of different power generator types. The constraints of operation strategies mainly contain the shares of load unit operation, which is consisted of thermal power, pumped hydro storage (PHS) power, and nuclear power. Besides, the basic operation required for thermal power plant is the second power generation restraints. It is stetted by the specifical object. For the output results, it can be expressed as the weekly, monthly, and yearly electricity production of load or the variable power generators. The environmental indicators of CO_2 or the economical parameters of cost can also be summarized form this model.

EnergyPLAN has been continuously developed and expanded at Aalborg University in Denmark since 1999 [5]. It is a user-friendly tool designed in a series of tabs and programmed in Delphi Pascal. The main purpose of this tool is to assist in the design of national or regional energy planning strategies by simulating the entire energy system: this includes the heat and power supply, as well as the transportation and industrial sectors. Previously, EnergyPLAN has been used to analyze the large-scale integration of wind power [6] and the penetration and optimization of renewable energy [7], the management of surplus power [8], the use of wind power grid-connected electric vehicles

[9], small-scale thermal power The implementation of co-production [10], integrated systems and local energy markets [11], sustainable renewable energy strategies [12], the use of waste for energy [13], fuel cells and electrolyzes in the future energy system The potential of energy [14,15], the potential of thermoelectricity in thermal energy systems [16], and the impact of energy storage [17]. In addition, EnergyPLAN is also used to analyze the potential of combined heat and power and renewable energy in the country. Other relevant documents can be found on the EnergyPLAN website, and an overview of the work done with EnergyPLAN can be found. Finally, EnergyPLAN has been used to simulate 100% renewable energy systems in many countries [2] [18].

On the basis of model established, many scholars in the world have used EnergyPLAN model to analyze energy systems in different regions. With the help of EnergyPLAN, Ding analyze the operation of the energy system, pursue the highest energy efficiency while meeting the energy demand, and finally obtain the optimal wind power and photovoltaic penetration value in Beijing, Tianjin and Hebei [20]. Liu simulated China's energy system in 2007 and obtained the maximum wind power penetration under the conditions of minimum power surplus, minimum primary energy supply and total energy system operation cost, which is a relatively new aspect of the application of EnergyPLAN model [21]. G. De Luca combine EnergyPLAN and TRNSYS software to analyze the economy and feasibility of the renewable energy utilization system of Altavilla silentina, a small town in southern Italy, to achieve zero greenhouse gas emission in 2030[22]. Dejene Assefa Hagos use the EnergyPLAN model to analyze the inland energy system in Norway and propose two optimization scenarios for its strong dependence on hydropower. The basic purpose of optimization is to replace hydropower with other renewable energy such as solar energy, wind energy and biomass, to reduce its dependence on hydropower. At the same time, the heat pump technology is introduced to analyze the optimization effect of the optimization scene [23]. Géremi Gilson Dranka use EnergyPLAN model to simulate and establish the power part of Brazil's energy system, so as to provide feasible suggestions for the establishment of 100% renewable energy system in the future [24].

Above mentioned, EnergyPLAN is used for the continuous integration analysis of PV and wind energy in Japan power grid. However, before the utilized of this model for the potential research, it is essential for the verify of the adaptability in Japan power grid.

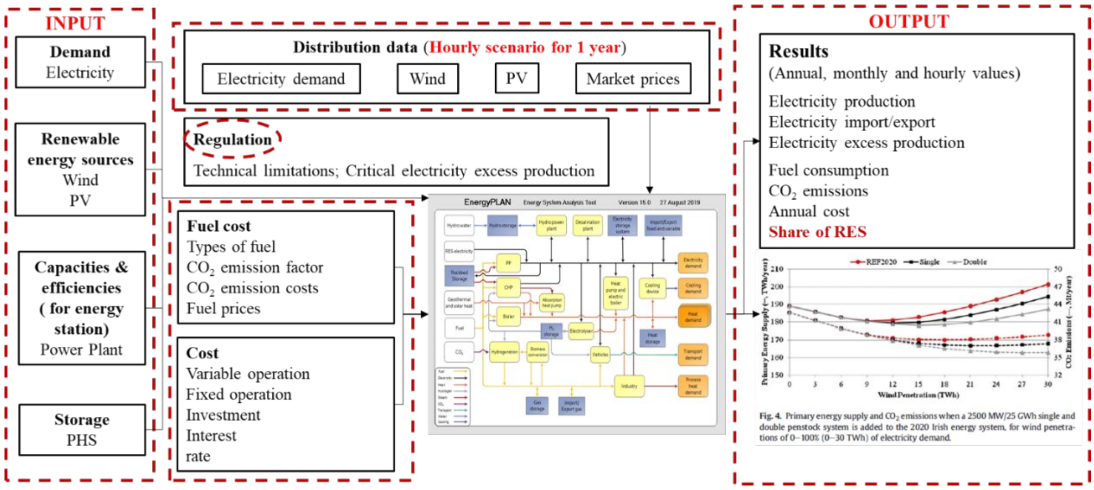


Fig. 7-3 The basic configuration of EnergyPLAN model

7.2.2. Data resource for the verify of EnergyPLAN model

① Location scenario

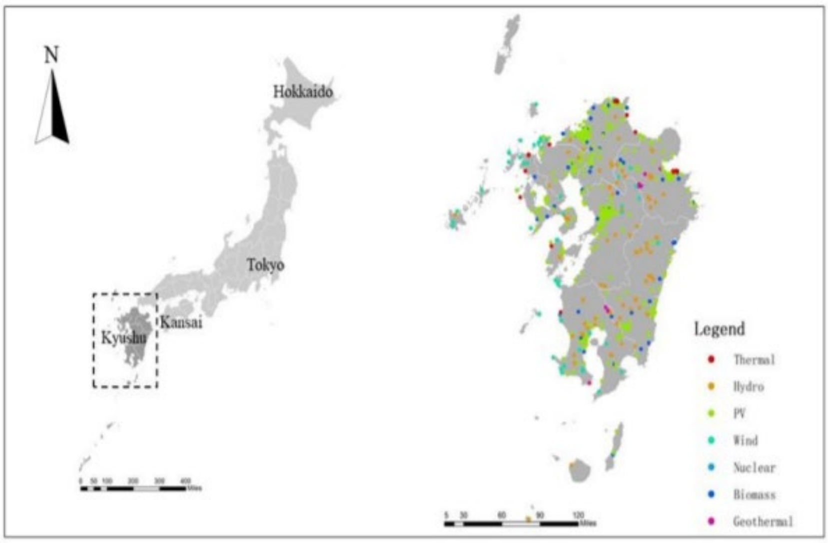


Fig. 7-4 The location scenario in Kyushu region

The research resource of this paper is located in Kyushu power grid, Japan. The location scenario of Kyushu area is shown in Fig. 7-4. Japan is divided into 10 power grids, which is featured with different power generation structures and load profiles. Kyushu is located in the southeast of Japan, which has sufficient lighting time. The data used of this paper is download from Kyushu Electric Power Company. The typical regions of Kyushu, Tokyo, Kansai, and Hokkaido are depicted in Fig. 7-4. We selected Kyushu power grid as a case study for the verify of EnergyPLAN model in this paper. The different power generators contained are shown in Fig. 7-4 as well. It consists of thermal power, hydro power, PV power, wind power, nuclear power, biomass power, and geothermal power, respectively.

② Capacity structure

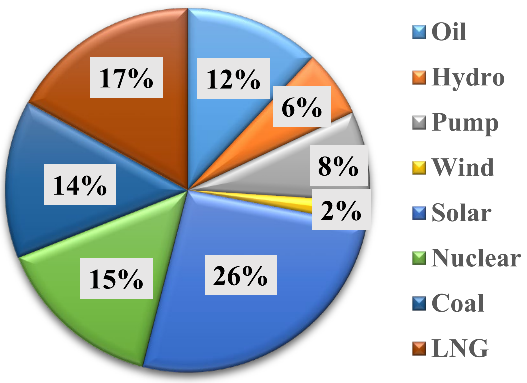


Fig. 7-5 The capacity structure of Kyushu power grid in 2018 [19]

The capacity structure of Kyushu power gid is shown in Fig. 7-5. It shows that nuclear accounts for 15% of installed capacity shares, thermal power have the proportion of 43% for the total capacity installed. There also have PHS power, wind power, PV power included in the Kyushu power generation structures. The geothermal power and biomass power is concluded as well. However, it can be omitted due to their small shares compared with the other power generators.

③ Load profiles

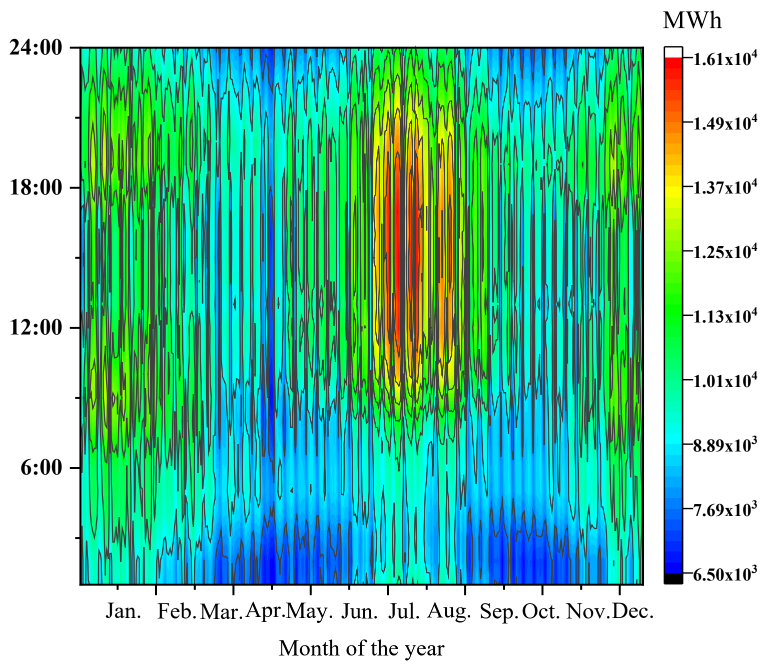


Fig. 7-6 Load profile of Kyushu electric power

The distribution of hourly electricity demand in Kyushu region is shown in Fig. 7-6. The electricity demand shows a peak load in summer daytime due to the requirement of cooling. A lower demand pretends in transition seasons, for example, March and October.

Generally speaking, the type of data required in the EnergyPLAN tools showed be aware of. Usually, the EnergyPLAN typical requires three of the following technical parameters: one is the total annual production or electricity demand in one year. For Kyushu is 84.63TWh/year form April 2018 to March 2019. The second parameter is the capacity of the unit installed (MW). This data resource is depicted in Fig. 7-4. The third parameter required for the EnergyPLAN analysis is the hourly distribution of the total annual electricity production/demand. The distribution data must consist of 8784 data points, one for each hour. Besides, the data points are usually between 0 and 1, representing 0-100% of production/demand. This is done by dividing each entry in the distribution by the maximum value.

④ Profiles of PV and wind power generation

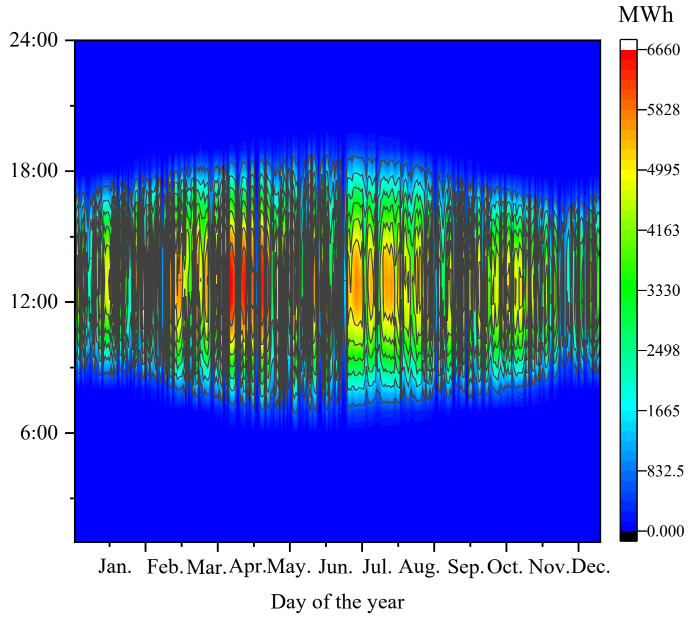


Fig. 7-7 The PV power generation in Kyushu

The distribution of PV and wind power generation in Kyushu is shown in Fig. 7-7 and Fig. 7-8, respectively. PV is more cyclical in terms of light radiation. The main power generation time is concentrated in the daytime. Wind energy is full of uncertainty due to the changes in wind speed, and its power generation is irregularly distributed over time. For the data resource required of EnergyPLAN, it must be distributed in hourly distribution, and contains 8784 hours. Compared with the power generation of PV and wind energy, the amount of PV power generation is larger than that of wind energy.

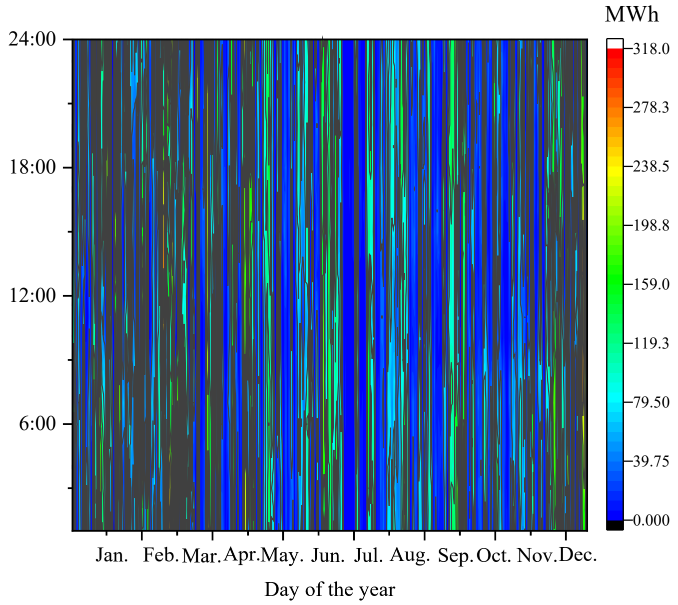


Fig. 7-8 The wind power generation in Kyushu in 2018 [19]

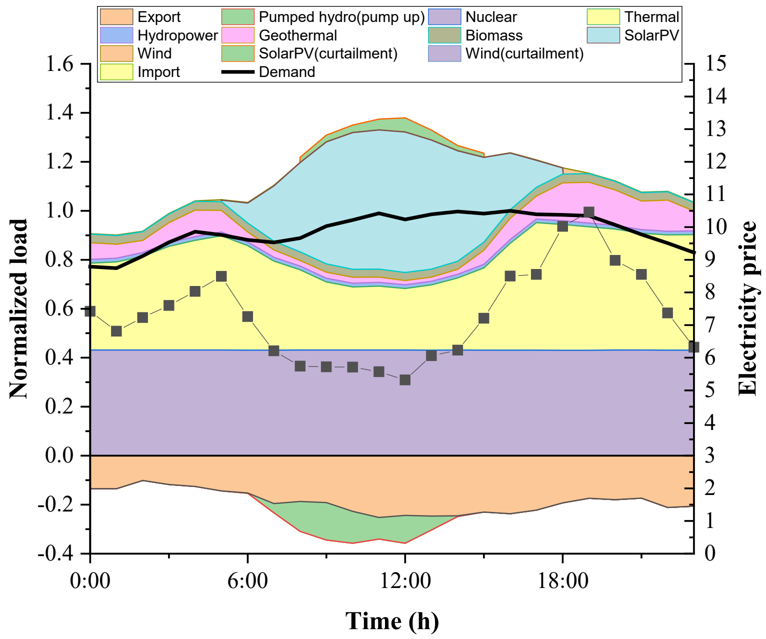


Fig. 7-9 Daily balance of power generation

In addition, the nuclear power keeps constant in power grid, due to the difficulties of start and up operations. Its generation profiles and daily power balance is illustrated in Fig. 7-9. It contains the daily power profiles of different power generators, the adjustment of PHS facilities is shown as well. It is used to eliminate the peak load and compensate the electricity when the power demand is low at nighttime.

7.2.3. Results and analysis on the outputs of EnergyPLAN

① Verifying on the electricity demand

The results and analysis of electricity load and energy generation by different types are shown in Table 7-1, and Table 7-2, respectively. As for the comparison of load demand in Kyushu regions, the output results from EnergyPLAN model are compared with actual monthly values. The difference between the model and actual results is relatively lower than the actual value of electricity production. The shares of the difference between model results and actual results are no more than 1%, as shown in Table 7-1. Besides, the data used is based on the hourly data distribution between the period of April 2018 and March 2019. There have 365 days of one year, however, the Energy PLAN model required 8784 hours for one year. Therefore, we added the average value of daily electricity demand to the February to calculate the results of monthly average electricity demand. For the details description of electricity generated by different power generators is summarized in the sub-Section 4.2. and 4.3.

② Verifying on the electricity generated by different power generators

In terms of the results of different power generators (as shown in Table 7-2.), PHS accounts for the largest different shares, followed by Thermal power. This is resulted from the operating strategies in Japan and the operation constraints in EnergyPLAN model. The PHS system in Japan is utilized to adjusting the curtailment of PV and wind energy and compensate its electricity on the peak load period. While the PHS system in the EnergyPLAN model mainly focus on the reduction of fossil fuel utilization and increasing the integration of PV and wind energy. The time of PHS operation time mainly occurs at the surplus of renewable energy production or the imbalance of power supply and demand. However, it promotes a new operation strategy for the PHS system. And the electricity generation difference between the actual value and EnergyPLAN molded value is no more than 5%. Therefore, we believe that the EnergyPLAN model can be used for scenario analysis.

③ PHS operation profile of EnergyPLAN model

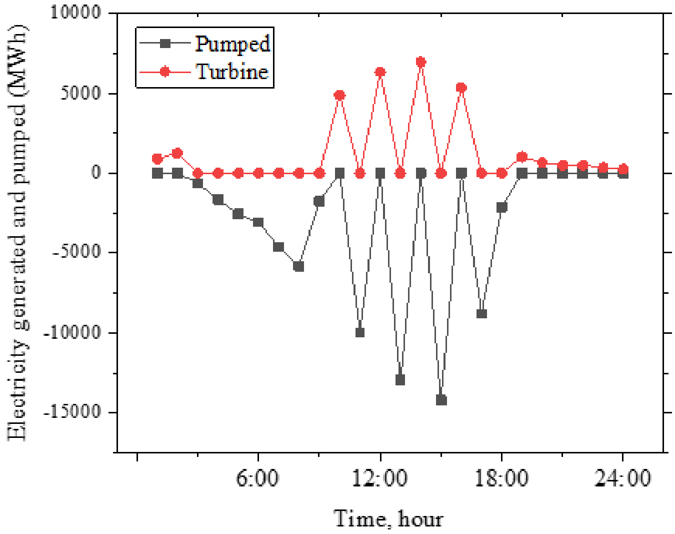


Fig. 7-10 Power generated of PHS in EnergyPLAN model

Fig. 7-9 depicts the operation results of pumped storage in EnergyPLAN. Its operating rules mainly include two aspects. (1) Balance the supply and demand of electricity. (2) On the premise of providing grid stability, reducing the critical excess electricity production (CEEP) caused by PV and wind energy, while reducing the use of fossil fuels. Therefore, the pumping process of PHS is mainly reflected in the daytime, that is, the time when PV power generation is concentrated. Its power generation period reflects the phased nature because it reduces the amount of thermal power operation. This operating rule is different from the current generation situation of Kyushu PHS, but EnergyPLAN is software based on future scenarios, so it is friendly to low-carbon design scenarios.

7.2.4. Conclusions of the verify results

The main goal of researchers using EnergyPLAN is to design regional or national energy planning systems based on technical and economic analysis, determined by different power generation composition and investment. Its main technical regulation strategy is to minimize the overproduction of electricity and the consumption of fossil energy power generation. Economic simulation requires a series of input data, including the investment and variable costs of different power generation units. This paper mainly carried out the verify of technical results from the EnergyPLAN model. It consists of the calculation on the electricity demand, and the electricity generation by different power generators. The approach presented in this paper requires the following assumptions, which we list here:

Firstly, this paper selects independent public power grids of Kyushu in Japan for case analysis, rather than the whole Japanese power grid. They are featured with different load profiles, power generation composition with Japan power grid. Secondly, EnergyPLAN is a future based energy planning model. This paper is the verify text of EnergyPLAN model in Japan power grid, not for the energy management modeling. The combining analysis of different energy system scenarios will be analyzed in the other research. Finally, this tool requires minimum grid stability share, which is the proportion of power (thermal power generation, nuclear power and energy storage system) supply of dispatchable units and is set to 30%. In addition, due to the limited start-up and shutdown of thermal power generation, 15% of the total installed capacity is set as the minimum output form electrical power plants. This value is calculated based on the actual power generation data of Kyushu.

For the results of the difference between EnergyPLAN outputs and actual value, the monthly electricity load is no more than 1%. In addition, the electricity generated by the other power generators are no more than 5%. We should notice the differences of PHS power generation. It pretends the largest deviation between EnergyPLAN model and actual value. It can be summarized as the operation strategy of PHS facility. The PHS is operating at electricity curtailment occurs and thermal power generating. This operating strategy is suitable for the low carbon design of the scenario analysis in the future. However, the operating strategies of PHS cannot be changed with EnergyPLAN model separately. It is required to combined EnergyPLAN with MATLAB software to seek the ideal operation strategy of power generation.

Therefore, for the prospect of the future research, it will be concentrating on the different scenarios with variable power generators and storage systems. And combined the EnergyPLAN model with the other programming software. This paper is the basement of the future research.

7.3. Result and analysis of EnergyPLAN output data

The results of the development potential of small and medium-size PHS in Kyushu and Hokkaido are presented in the following sections. In addition, the output data from EnergyPLAN are also compared and discussed. The results are divided into three parts, including the RES into grid under different scenarios, the compression on traditional thermal power generation, and the total power generation cost, respectively. The methodology used is shown in Fig. 7-2, which is the explain of input data and output results in details. The data resource and research background are introduced in Chapter 4. The following part of this Chapter will be introducing the results of VRE hybrid with pumped storage system on the power grid and its own power production.

7.3.1. Result and analysis of potential PHS installed capacity

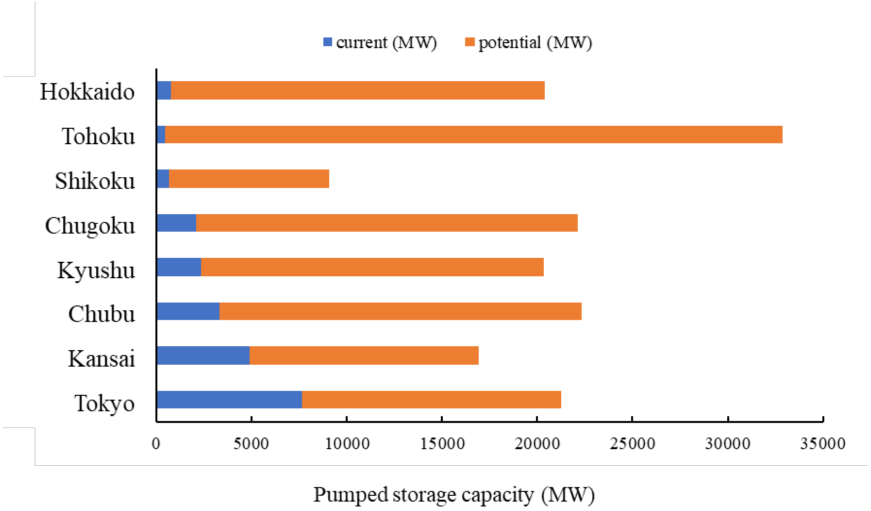


Fig. 7-11 Comparison of current and potential PHS power generation capacity in different electricity power companies

Fig. 7-11 depicted the distribution of pumped storage capacity potential within the control of electric power companies (except Okinawa). In addition, the huge dams with an effective water storage capacity of more than 100 million is eliminated. The current installed capacity of PHS in Japan is 28.5GW, which have 40 pumped power plants. Hokkaido and Kyushu accounts for 800MW and 2300MW installed capacity of PHS, respectively. While the potential for PHS development of medium and small size promote its possibility further.

7.3.2. CEEP of RES

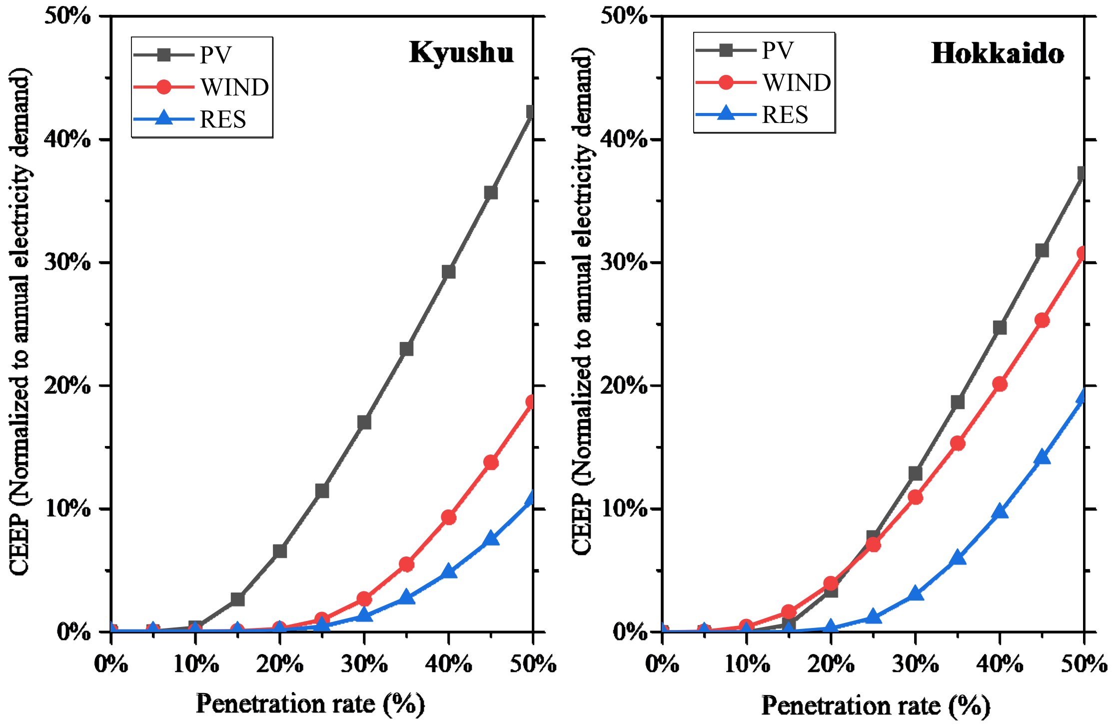


Fig. 7-12 CEEP of PV, wind, and RES in Kyushu and Hokkaido (database: 2019, PHS=0)

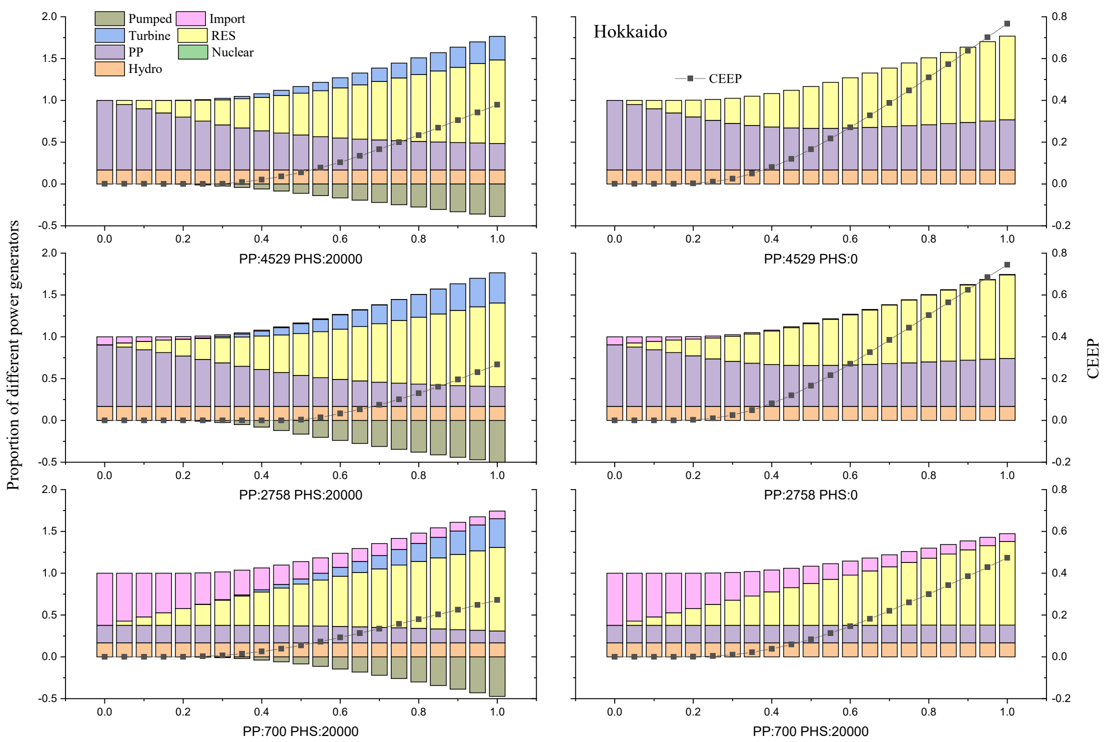


Fig. 7-13 Proportion of power generation mix under variable scenarios in Hokkaido

Fig. 7-12 depicts the CEEP curves of PV, wind energy and hybrid PV and wind energy as their permeability increases. It is based on the scenario without pumped storage in 2019. Both Kyushu and Hokkaido have surged with the growth of renewable energy, however, the CEEP of VRE is less than that of separately PV or wind energy under the same penetration rate (as shown in Fig. 7-12.). Therefore, this paper takes PV and wind energy as a whole into EnergyPLAN for analysis. It is worth noting that the realistic installation potential of PV and wind energy in Kyushu and Hokkaido is considered. The upper limits of solar and wind energy (onshore wind) introduction in Hokkaido are 15GWand 146GW respectively, and that in Kyushu are 37GW and 16GW whilst. it can be seen that the wind resources in Hokkaido are far greater than solar energy. Therefore, in the subsequent scenario analysis, when the PV capacity reaches the limited installation capacity, wind energy will be separately increased to increase the ratio of renewable energy installations.

Fig. 7-13 and Fig. 7-14 describes the composition of the power generation structure under different shares of VRE. Regardless of Hokkaido or Kyushu, the addition of PHS causes a reduction in RES suppression and compresses thermal power generation. By comparing the scenarios of different thermal installation capacity horizontally, it can be found that the reduction of thermal installation capacity not only directly reduces its own power generation, but also increases the import power due to the imbalance between supply and demand side, especially in the scenario with the lowest thermal installation capacity. However, it decreases with the share of VRE power generation growth. As mentioned above, the details can be shown as follows:

For the proportion of power generation mix under variable scenarios in Hokkaido:

Upper: At scenario PP:4529, PHS:2000 (right) and PHS:0 (left):

Medium: At scenario PP:2758, 2000 (right) and PHS:0 (left):

Bottom: At scenario PP:700, 2000 (right) and PHS:0 (left):

For the proportion of power generation mix under variable scenarios in Kyushu:

Upper: At scenario PP:6315 (Upper), PP 3275 (Bottom) and PHS:2000

Medium: At scenario PP:10490 (Upper), PP 6315(Medium), PP 3275(Bottom), and PHS:0

Bottom: At scenario PP:10490 and PHS:2000

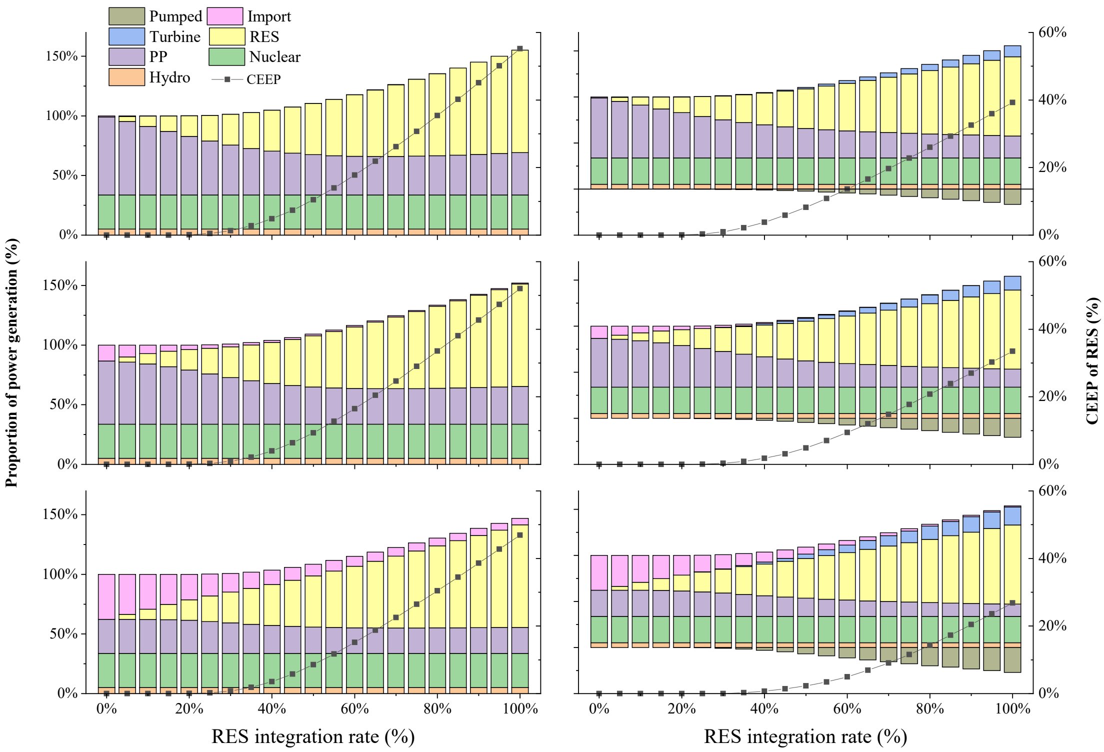


Fig. 7-14 Proportion of power generation mix under variable scenarios in Kyushu

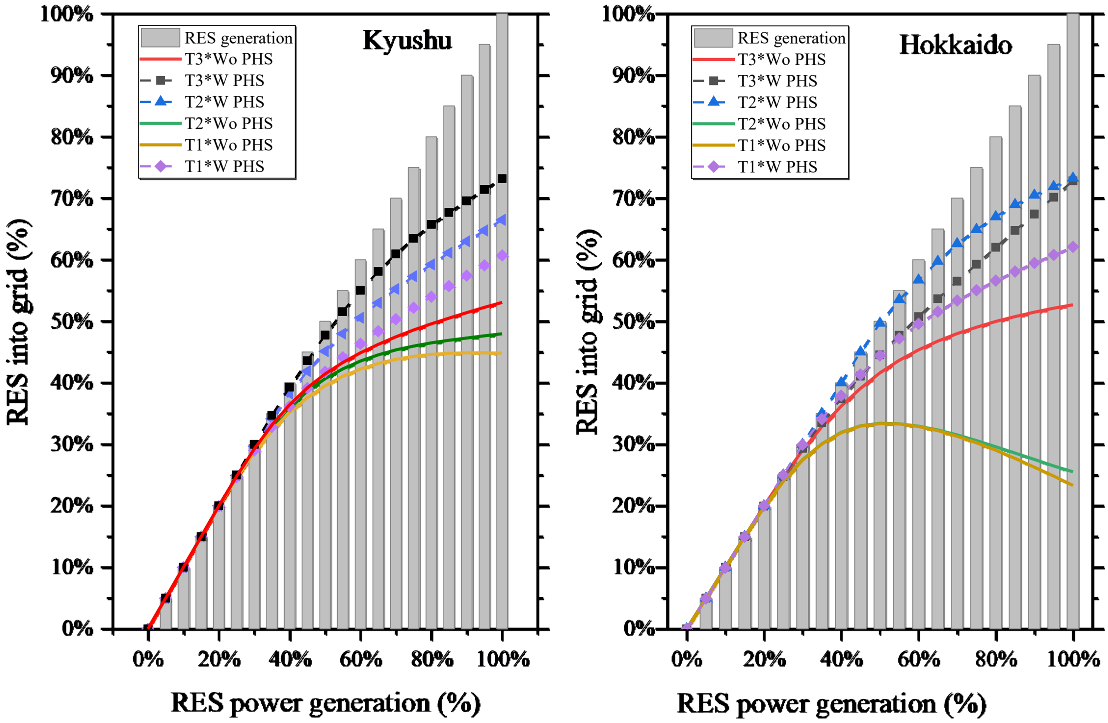


Fig. 7-15 RES output integrated into the Kyushu and Hokkaido grid

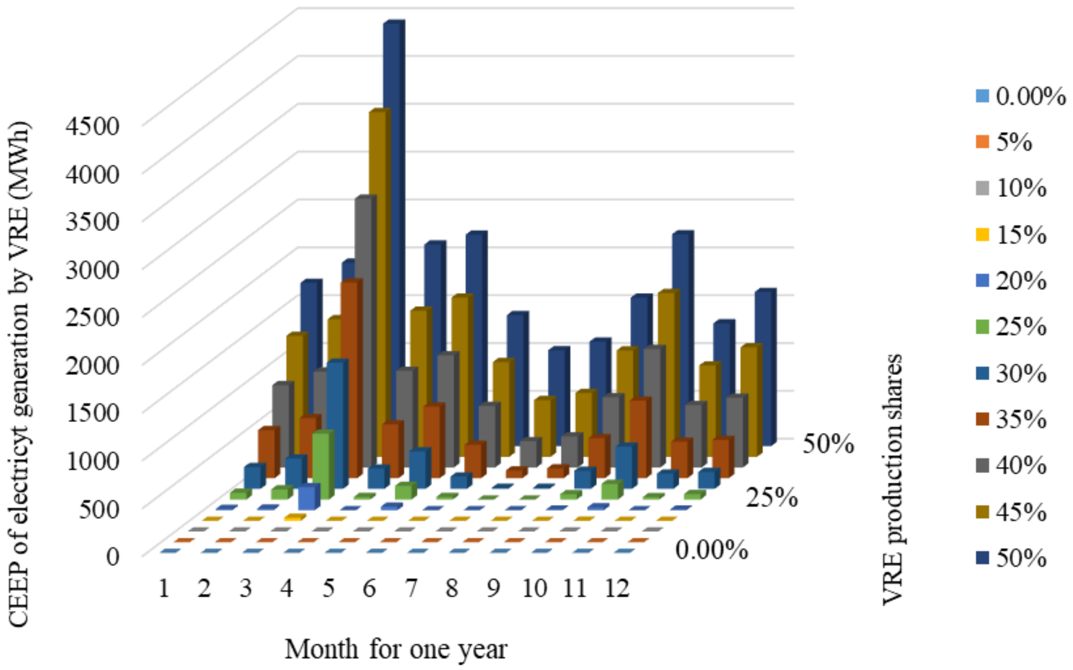


Fig. 7-16 The surplus electricity of VRE production in Kyushu

On the one hand, the penetration of RES into the grid in different scenarios is shown in Fig.7-15. It supports the conclusion that PHS can increase the penetration rate of RES into grid in Fig. 7-16. However, as the share of RES increases, the actual RES into grid tends to be saturated. PHS plays a significant role when the RES penetration share is greater than 30% in Kyushu and 25% in Hokkaido, respectively. Comparing Kyushu and Hokkaido, when the penetration of RES is greater than 50% without PHS facilities, the RES into grid incline whilst. It is resulted from the constraints of the operating strategy. 30% of the total power generation must come from the basic power generation unit, which is including, nuclear power, thermal power, and turbine. Nuclear power in the Kyushu region accounts for 25% of the total power generation, which can stably provide the supply of basic load. The only unit that can provide basic load in Hokkaido area is thermal power generation. Once the RES penetration rate exceeds 50%, the total power generation will increase sharply, and the required base load unit will increase accordingly. Thereby increasing the thermal power generation to compensate the basic electricity demand and reducing the RES into grid.

Fig. 7-16 shown the monthly CEEP of VRE production. The data resource is 10490 installed capacity of thermal power plant. The surplus electricity mainly focuses on the transition seasons in April and November.

7.3.3. Compression on thermal power generation

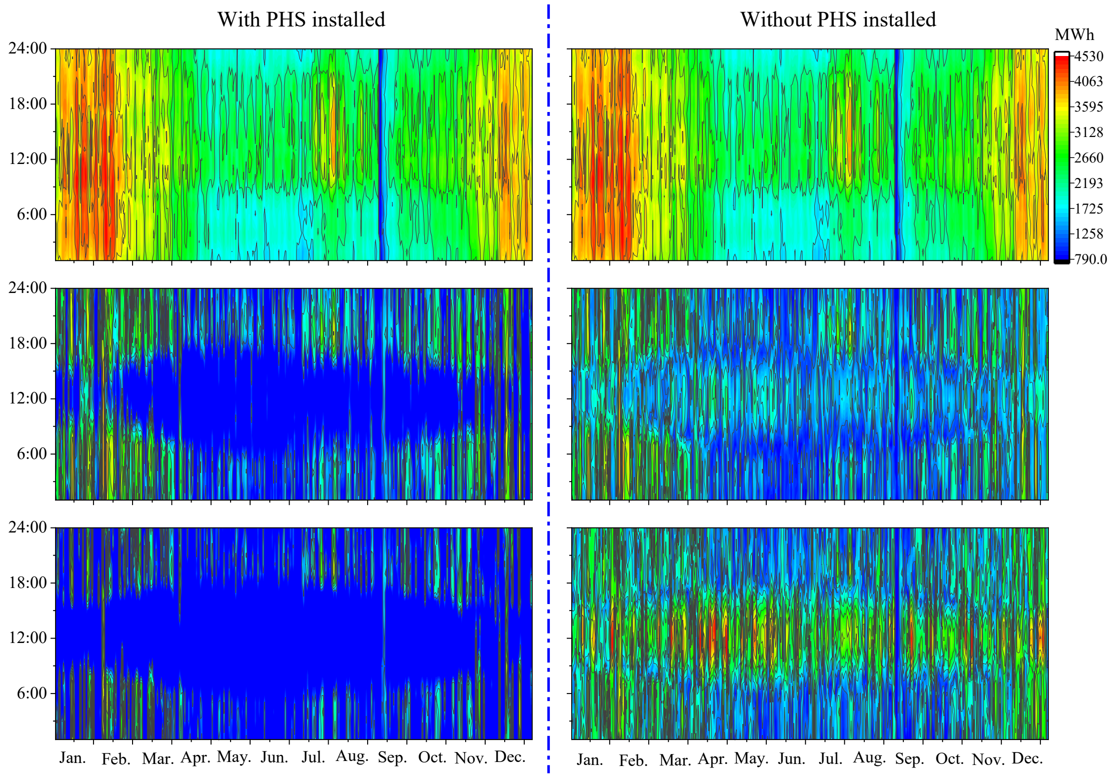


Fig. 7-17 Operation of thermal power plant in monthly inteval on Hokkaido power grid

On the other hand, to reflect the influence of the share of RES and the existence of PHS facilities, taking scenario 1 in the Hokkaido region as an example, the chromaticity diagram of thermal power generation is shown in Fig. 7-17, when the RES share is 0%, 50%, and 100%, respectively. Horizontally comparing the impact of PHS on the operation of thermal power generation, when the penetration of RES is 0%, thermal power generation does not show obvious difference due to the addition of PHS unit. When the penetration of RES is 50% and 100%, the usage rate of thermal power generation is reduced by PHS, especially during the daytime. These conditions are resulted from the operation strategy of PHS, which is mainly used to increase the penetration rate of RES and reduce the operation of thermal power generation. In case of RES excess occurs, the pump operates to reduce power suppression. At the same time, PHS generates power to mitigate thermal power generation or to improve power grid stability due to the penstock in PHS equipment. Longitudinal comparison of the impact of thermal power generation installed capacity on its own power generation. When PHS equipment is available, the higher the penetration of RES, the lower the utilization rate of thermal power generation. When there is no PHS equipment, the utilization rate of thermal power generation with 50% RES penetration is lower than that without RES, however, in case of the RES penetration is 100%, the amount of thermal power generation is greater than 50% RES production, which is due to the limitation of basic load operating conditions. 30% of the total power generation capacity must come from basic load supply units, such as thermal power generation, PHS facility and thermal power plant. Once the PHS capacity is utilized to the maximum, the stability of the power grid can only be provided by increasing thermal power generation. This phenomenon can be used to evidence that the permeability of RES in Fig. 7-15 increases first and then decreases with the increase of RES.

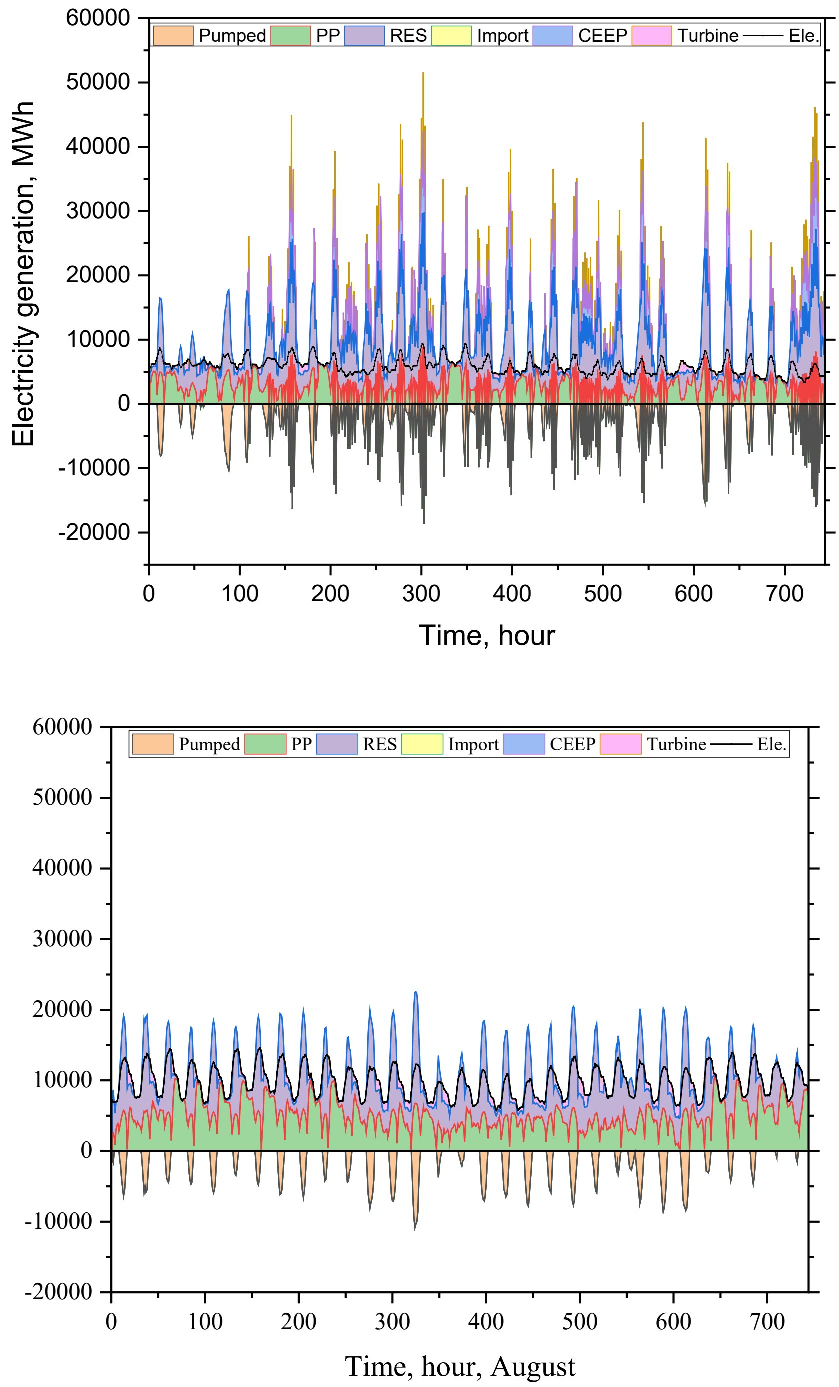


Fig. 7-18 The compositon of different power generators in March and August of Kyushu

Fig. 7-18 compares the adjustment effect of PHS on load in different seasons. Based on Kyushu's March and August data, the installed capacity of thermal power generation is 10490MW, the share of RES power generation is 50%, and the installed capacity of pumped storage is 5000MW. Compared the power load in March and April, it is found that the high demand for cooling in August causes the load to be much higher than that in March during the transition season. Therefore, the amount of VRE power suppression in August was low, and it reached 20,000 MWh in March. In addition, PHS is used to adjust the power supply and demand balance of the power grid, so PHS usage in March was higher than in August.

At March (upper) and August (bottom):

7.3.4. Cost of power generation

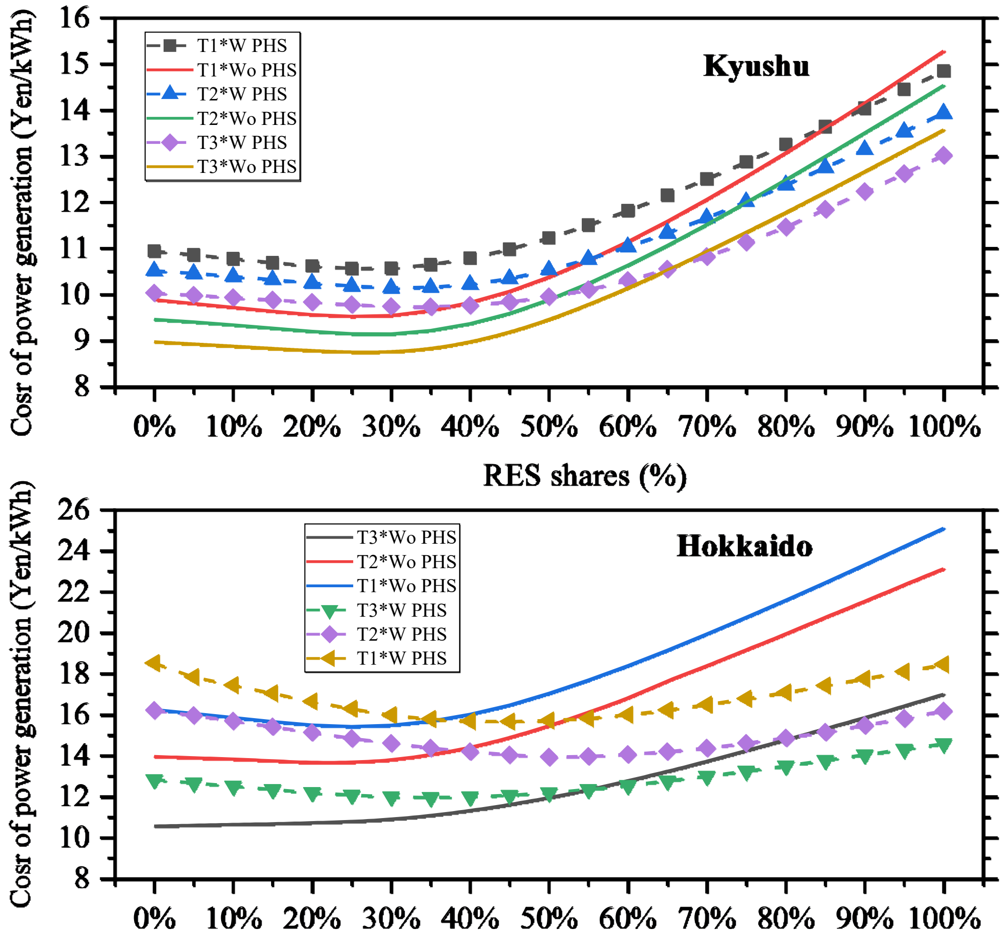


Fig. 7-19 Average cost of power generation profiles with RES proportion changes in Kyushu and Hokkaido

Fig. 7-19 summarizes the fluctuation of average power generation cost with the increase of RES share in different scenarios, which is affected by many factors. It includes the RES curtailment, the power generation proportion of PHS, and the installation of nuclear power. The analysis can be concluded as follows aspect. Firstly, the average power generation cost in Kyushu and Hokkaido does not exceed 16Yen/kWh and 26Yen/kWh respectively. Nuclear power in Kyushu can reduce power generation costs. Thermal power accounts for a larger share in Hokkaido, increasing power generation costs. Secondly, in Kyushu and Hokkaido, the average power generation cost with PHS installed is firstly higher and then lower than that of non-energy storage systems. PHS can significantly reduce the curtailment of RES when its penetration exceeds 25% and decreasing the use of fossil fuel energy whilst. Therefore, the power generation cost will be gradually lower than that without energy storage system. However, the final power generation cost shows an upward trend regardless of PHS facilities. The higher the share of RES power generation, the greater the amount of power suppression when PHS and grid load demand cannot be absorbed, the average cost of electricity therefore continues to increase. Thirdly, the cost of power generation under the same RES share decreases with the initial installation of thermal power (as shown in Fig.7-19). At the same time, the intersection of it and the added energy storage system is also forward. This intersection refers to the crossing of the average power generation cost curve with or without the energy storage equipment for the same thermal power installation capacity. The intersection of Kyushu area shown up after RES was 68%, while that of Hokkaido area appeared at 35%. This is related to the reduction of the PHS operation rate of nuclear power in Kyushu. The maximum PHS power generation in Kyushu and Hokkaido is 20% and 37%, respectively.

7.4. Discussion and imitation of the EnergyPLAN model

According to statistics, Hokkaido has 15GW and 146GW of PV and wind energy installation potential. In this paper, when RES power generation accounts for 100% of the total power generation, the installation capacity of wind energy is less than 10GW. Limited by the electricity demand in Hokkaido, most of the wind resources cannot be utilized. In future research, the utilization of RES resources will be maximized in combination with factors such as power transmission between regions and hydrogen energy transportation. Compared with Hokkaido, Kyushu has a 25% share of nuclear power generation with constant power generation characteristics. The results show that it reduces the average power generation cost and provides night-time load demand. However, due to the limitation of basic load supply unit, the utilization of PHS is reduced by nuclear power.

The operation strategy of PHS in this paper is to satisfy the goal of reducing thermal power utilization and increasing the penetration share of RES while providing grid stability. Therefore, double penstock is used, so that the PHS equipment can generate electricity while absorbing the excess power of RES. The disadvantage of this strategy is reflected in the simultaneous operation of PHS pumps and generators to minimize the amount of stored electricity, and the operation of PHS is mainly concentrated during the daytime when the RES power generation and load are high. Insufficient power supply is more likely to occur at nighttime. Therefore, in case of the installed capacity of thermal power generation in Hokkaido is reduced to 700MW, the import phenomenon still exists even if the penetration of RES increases. Future research will focus on adjusting the operation strategy of PHS in order to seek a public grid suitable for different power generation compositions.

When using EnergyPLAN tool for scenario calculations, it is found that thermal power is substituted into the software as a whole rather than in the independent energy mode of coal, oil and natural gas resources. Coal energy, as a generator with the nature of difficulty starting and stopping, is generally used as the basic load supply. Oil energy is used to provide electricity for peak load because of its characteristic of fast start-stop and high efficiency. These operating modes cannot be implemented in EnergyPLAN. It will be combined with other programming software to realize the adjustment of the operating strategy in the future work.

7.5. Conclusions

This paper analyzes the impact of hybrid PHS equipment of existing power generation units on the penetration of RES in the public grids. Scenario assumptions are based on different thermal power installed capacity, PHS forecasts, and two public power grids in Kyushu and Hokkaido. On the basis of the EnergyPLAN model, the scenario analysis is derived from the perspectives of RES into grid, thermal power suppression, and average power generation cost. The results obtained are shown that:

1). In terms of PHS system, the installation potential of PHS in Kyushu and Hokkaido is enlarged to 18GW and 20GW respectively by using small and medium-sized dams. The operation strategy of PHS is to improve the RES penetration rate and reduce thermal power generation while ensuring the stability of the power grid. Under the same penetration shares of RES, the CEEP under the RES mix is less than that of independent PV and wind energy. Therefore, this paper takes the mixed PV and wind energy as the research object. CEEP appears at 30% and 25% permeability of RES in Kyushu and Hokkaido, respectively, and increases sharply with the growth of RES power generation. Results shown that PHS reduces CEEP of RES, which increases RES into grid by more than 20%. One of the operation strategies of this paper is to ensure that 30% of the total power generation comes from basic load supply units, such as thermal power, nuclear power, and PHS generators. Kyushu region has nuclear power accounting for 25% of stable power generation. In the absence of PHS, Hokkaido's unit used to provide basic stable share is only thermal power. When the power generation share of res exceeds 45%, thermal power will increase the power generation to meet the demand of grid stability, resulting in the reduction of res into grid capacity. The addition of PHS increases the stability of the power grid while reducing thermal power generation.

2). In terms of the initial installed capacity of thermal power plants, the RES into grid and the operation rate of PHS is increased with the decrease in the thermal power installation. However, in case of the thermal power capacity is too small, the power supply is insufficient for the real-time power demand on the user side, so that the power import is occurred, and power grid stability share cannot be satisfied. For example, in the scenario, the thermal power capacity in Hokkaido is 700MW. The phenomenon of electricity import always exists regardless of PHS facilities.

3). The average power generation cost increases with the increase of RES share, and the addition of PHS is firstly higher and then lower than that of non-energy storage equipment. With the same RES penetration, the average power generation cost is lower in scenarios where the installed capacity of thermal power is lower. Compared with Kyushu, the average power generation cost in Hokkaido is higher overall, due to the relatively large proportion of thermal power in Hokkaido, and the nuclear power in Kyushu with a 25% share of power generation.

The phasing out of thermal power and the addition of PHS have improved the RES into grid and reduced the actual power generation of thermal power. The composition of grid power generation units also affects the operation of RES and thermal power. In the future work, we will combine different PHS operation strategies and programming software to seek a larger proportion of RES in a power grid.

7.6. Sensitivity analysis of nuclear power generation

7.6.1. Background

Since the beginning of the Industrial Revolution in the 19th century, global warming has occurred. The inducement of global warming is the emission of greenhouse gases, especially carbon dioxide, which is mainly produced by human beings. As of 2021, 194 countries have signed the Paris Agreement with the European Union, including China, Japan, the United States, and so on. The agreement aims to respond to the threat of global climate change, limit the global temperature rise to well below the pre-industrial level 2 degrees Celsius, and strive to further limit the temperature rise to 1.5 degrees Celsius [25-27]. As the main energy consumption unit, power generation units are expected to reduce the utilization rate of fossil fuels to reduce carbon dioxide emissions [28]. On the other hand, limited by fossil fuel resources, the energy self-sufficiency rate in Japan does not exceed 8% [29]. Faced with the dual threats of the environment and energy supply security, it is imperative to develop renewable energy. Among them, renewable energy represented by PV and wind energy has developed rapidly in recent years. Since Japan implemented the FiT system in 2011, the installed capacity of PV has increased nearly 10-fold compared to 2011 [30,31]. However, with the massive integration of PV and wind into the grid, their periodicity and variability nature put pressure on the supply and demand balance of the power grid [32,33]. PV and wind energy are called VRE because of their variable power generation characteristics [34]. Based on data from

Kyushu Electric Power, the PV power suppression phenomenon occurred for the first time on October 13, 2018 [35], the utilization rate of renewable energy is reduced accordingly.

Therefore, there is imperative to understand the integration of VRE in the power grid. Japan given the priority of nuclear power due to their nature of difficulty starting and stopping operation. The process of power adjustment measures adopted by power companies are summarized in Fig.7-20. As for the management of different power supply strategies, VRE power generation is surpluses when the electricity overproduction occurs.

Under this circumstance, the energy storage system is usually used to compensate the valley load and reduced peak load from the other power generators. Among these power storage systems, pumped hydro storage (PHS) system are selected for large scale power grid. It has over than 100-year history in power supplied. Combined with PHS facilities to understand the potential integration of VRE and its impact on thermal power generators.

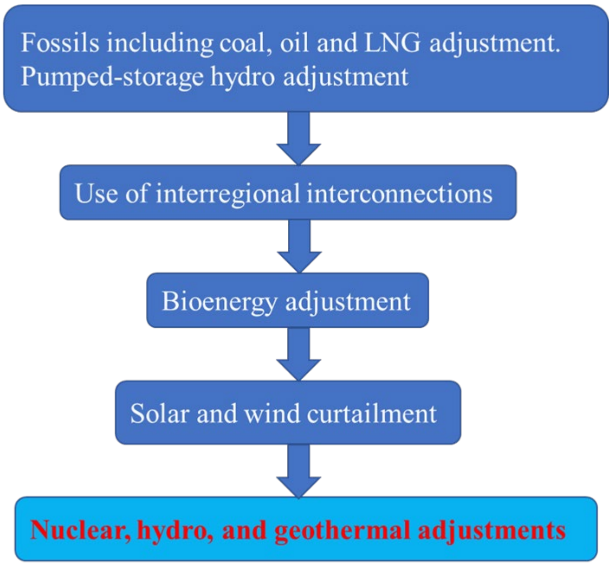


Fig. 7-20 Simplified presentation of curtailment rule of power plants in Japan [36]

7.6.2. Results and analysis

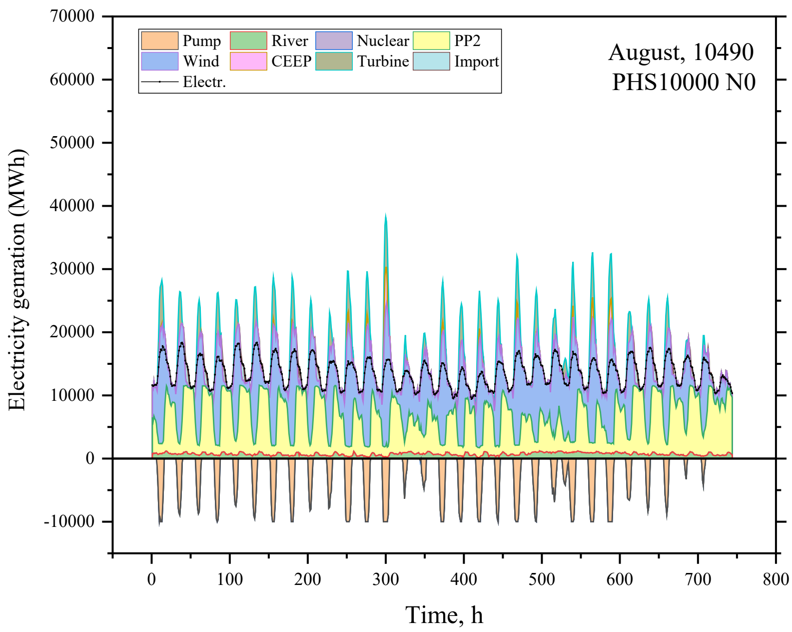
For the output data of EnergyPLAN tools, this paper mainly focuses on the output of critical excess electricity production and the compression on the thermal power generation.

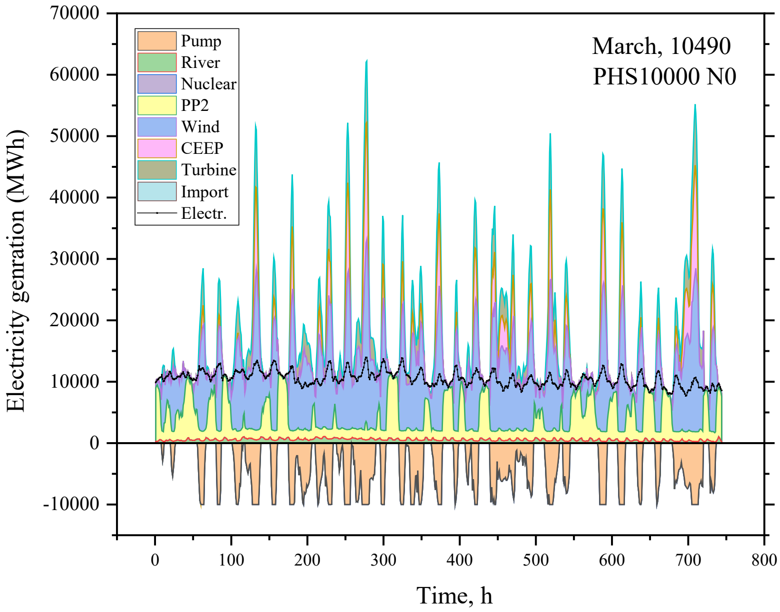
7.6.2.1. Results and analysis on the monthly power generation

Comparison of the nuclear power on the power grid, March with lower electricity demand and August with higher electricity demand are selected. The installed capacity of PHS is 10000MW. Fig. 7-21 depicted the existence of nuclear power, and the load profile changes on the operation of PHS facility. On the one hand, for the circumstance of March, the electricity demand shows lower level compared to the whole year. With the massive integration of VRE power, it caused the overproduction of electricity. PHS is applied to pumping water to restore electricity in the upper reservoir. However, compared with the power structures without nuclear power, the power structures with nuclear power have propounded resulted in the curtailment of VRE production. The reason is the operating strategies of PHS in the EnergyPLAN model, for the 30% of total power generation should be comes from the base load unit.

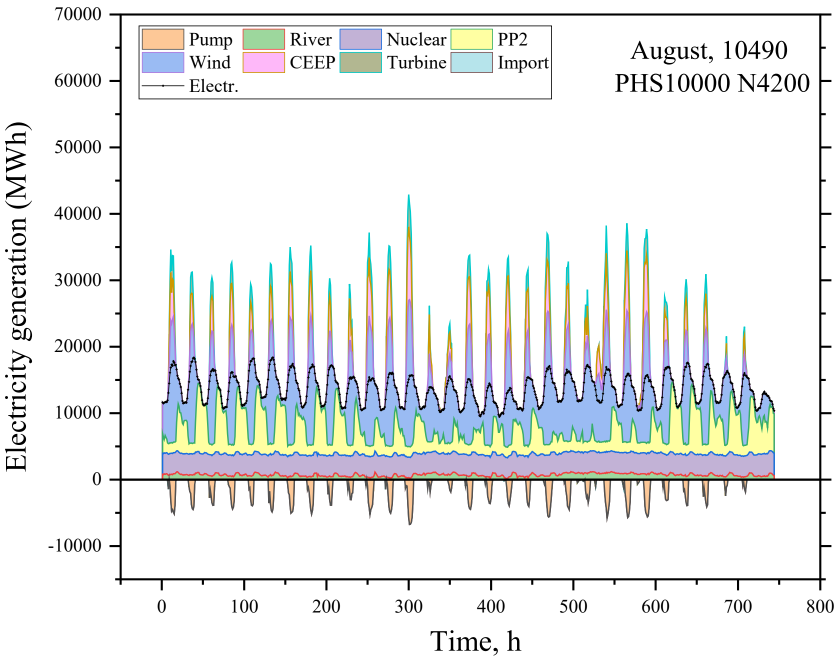
Fig. 7-21 compares the impact of nuclear power on the power generation of each unit. Nuclear power can provide stable power output. When the VRE power generation is large, the principle of prioritizing nuclear power is likely to cause power suppression. However, in August when the load demand is relatively large, the continuous supply of grid load can be met, and the import volume can be reduced. Pumped storage can also be used to provide power grid stability. Compared with the existence of nuclear power, the utilization rate of PHS is higher when there is no nuclear power.

At Nuclear=0:





At Nuclear=4200:



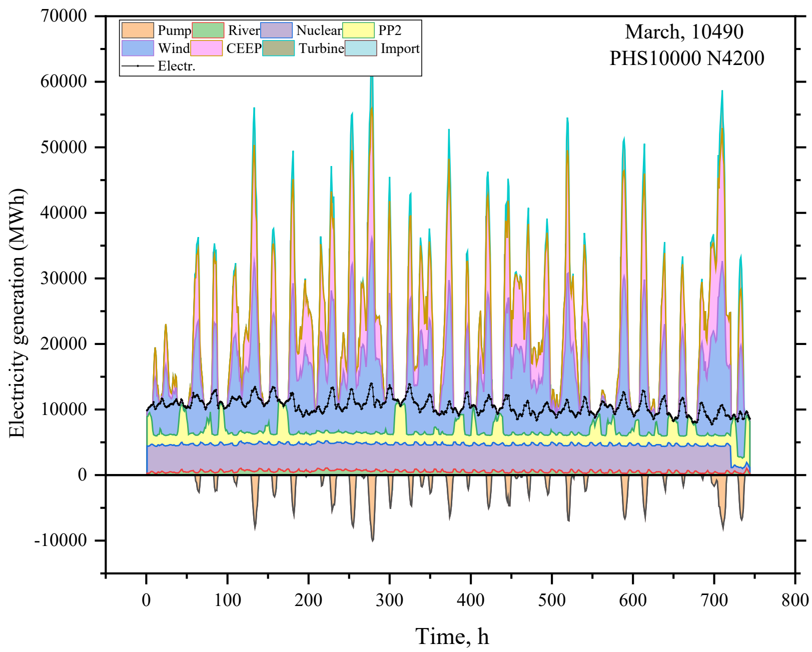


Fig. 7-21 The comparison of electricity generation with or without nuclear power generation in Kyushu area

7.6.2.2. Results and analysis on the critical excess electricity production (CEEP) of VRE

Nuclear power has an impact on each power generation unit. Fig. 7-22 and Fig. 7-23 describe the suppression of VRE power generation by nuclear power and PHS and its penetration into the grid. With the increase in the share of VRE power generation, CEEP has shown a sharp increase. When there is no energy storage system, the CEEP phenomenon occurs when the VRE share exceeds 25%, and the CEEP curve is slightly lower than when nuclear power is zero when nuclear energy exists. And PHS can greatly reduce the production of CEEP. When the PHS is 20000MW, the RES will only show power suppression at 50%, and nuclear power will cause the power suppression to occur earlier than when the RES is 30%. Therefore, when the share of RES power generation exceeds 30%, nuclear power will cause a decrease in the penetration rate of RES (as shown in Fig. 7-23).

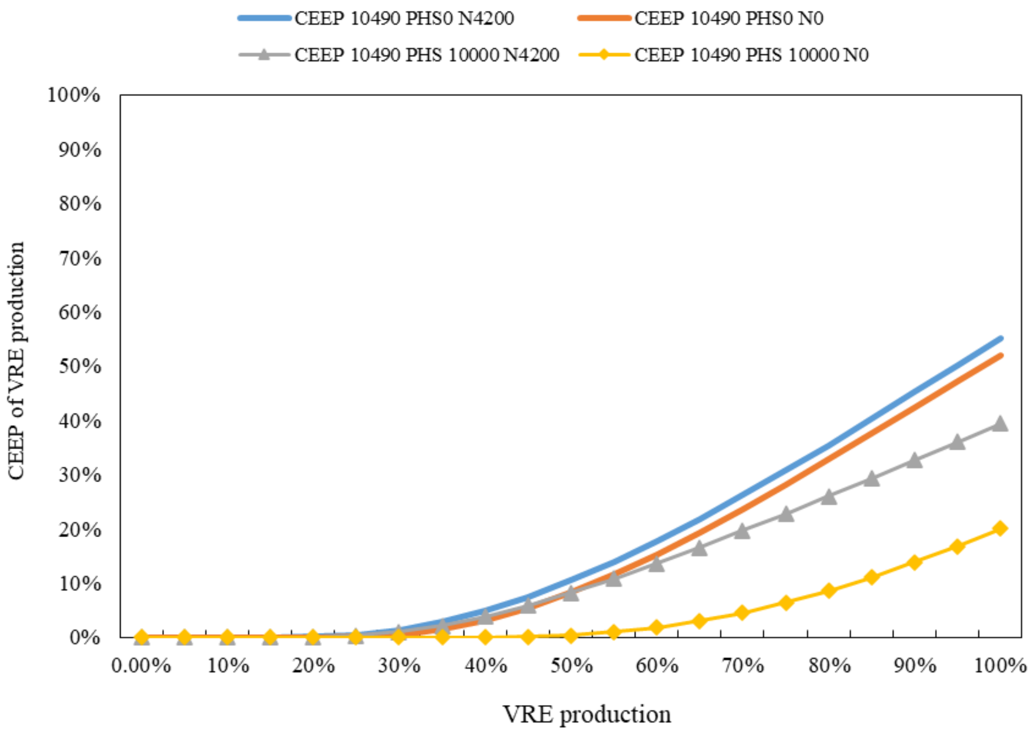


Fig. 7-22 The comparison of electricity curtailment of VRE with or without nuclear power generation in Kyushu area

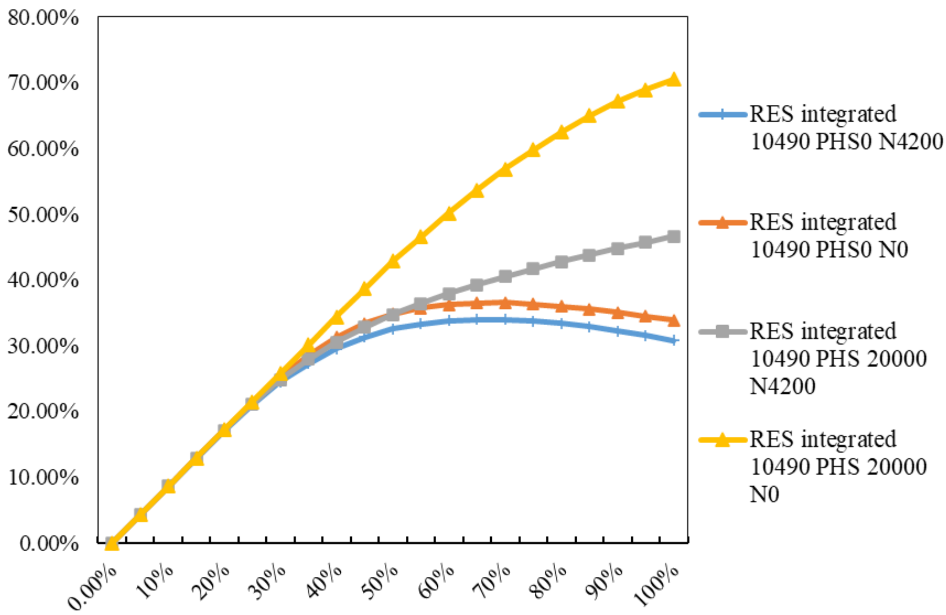


Fig. 7-23 The comparison of VRE into grid of VRE with or without nuclear power generation in Kyushu area

7.6.2.3. Results and analysis on the electricity import

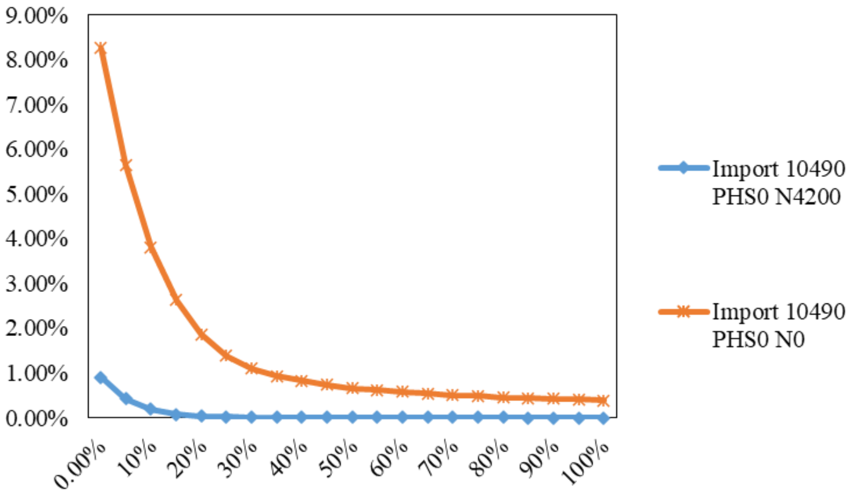


Fig. 7-24 The comparison of electricity load with or without nuclear power generation in Kyushu area

7.6.2.4. Results and analysis on the compression of thermal power

When the load demand is high (such as the scenario in Fig. 7-21, peak demand in August), nuclear power can contribute to the power supply and demand balance of the grid due to its stable power generation characteristics. Therefore, nuclear power will cause a significant decrease in Import power compared to when nuclear power is 0 (as shown in Fig. 7-24).

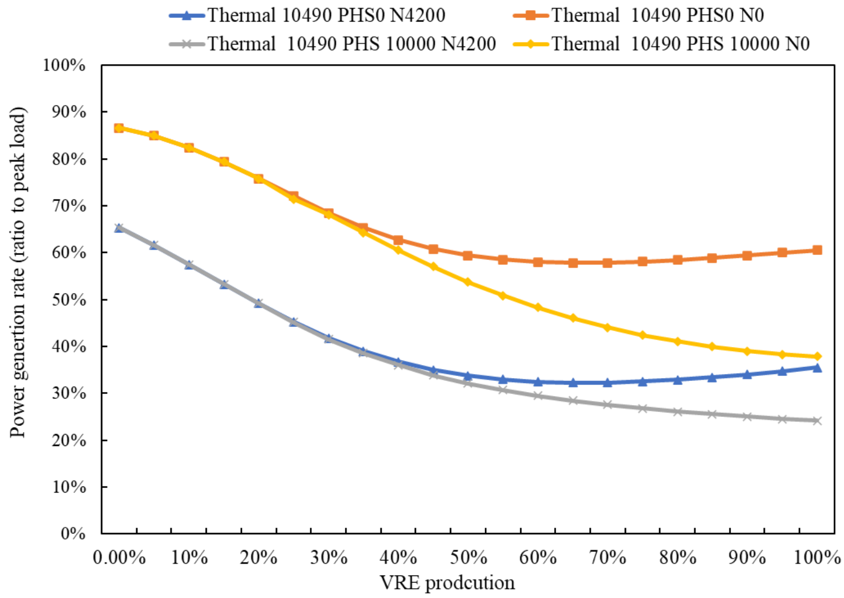


Fig. 7-25 The comparison of thermal power generation with or without nuclear power generation in Kyushu area

While nuclear power provides grid stability, it also compresses the operation of other power generation units. Fig. 7-25 compares the impact of nuclear power and PHS on thermal power. On the one hand, when the installed capacity of pumped storage is the same, the trend of thermal power generation curve is similar, but nuclear power leads to a significant decrease in thermal power operation. This is related to the fact that both nuclear power and thermal power are used to provide a stable share of power generation, while thermal power is adjustable. On the other hand, when the share of nuclear power is the same, PHS can significantly reduce thermal power operation when the share of RES is greater than a certain value (as shown in Fig. 7-26). This is related to PHS's operating strategy to increase the penetration of VRE power generation and reduce the share of thermal power. The impact of nuclear power on the power generation of each unit in different scenarios is shown in Fig. 7-27 in the following part.

7.6.2.5. Operation of PHS

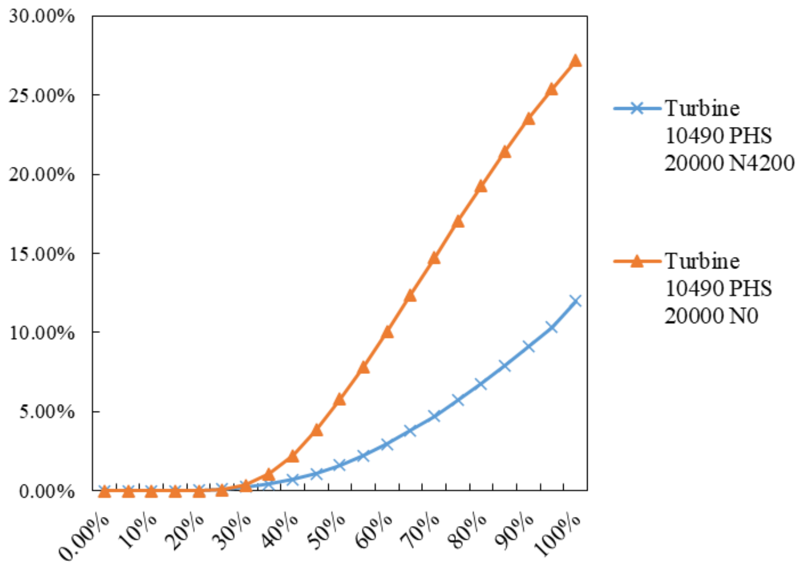
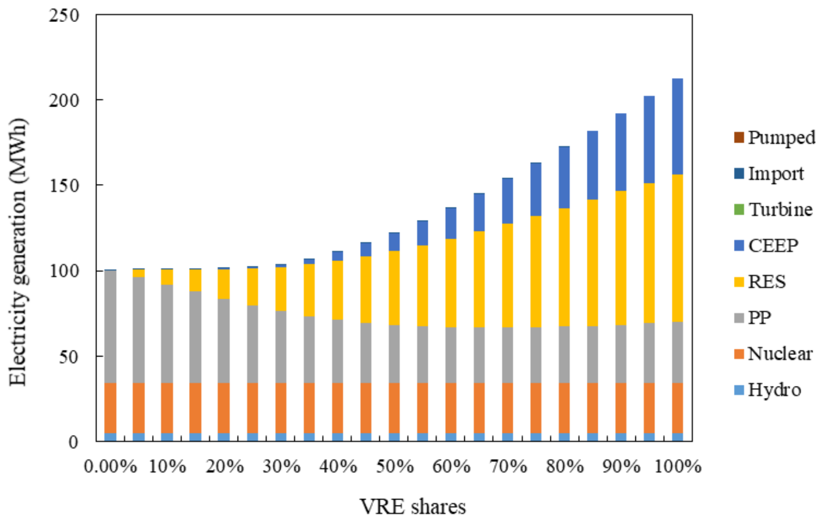


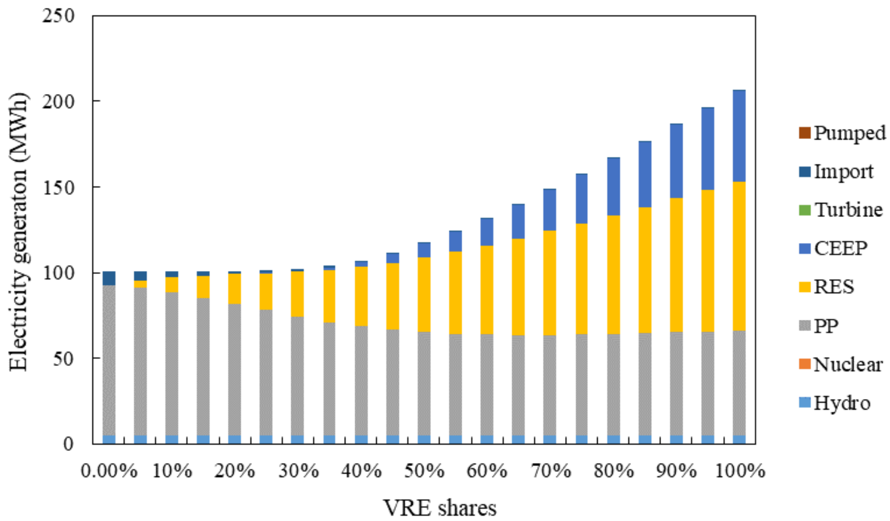
Fig. 7-26 The comparison of PHS power generation with or without nuclear power generation in Kyushu area

7.6.2.6. The composition of total power generation

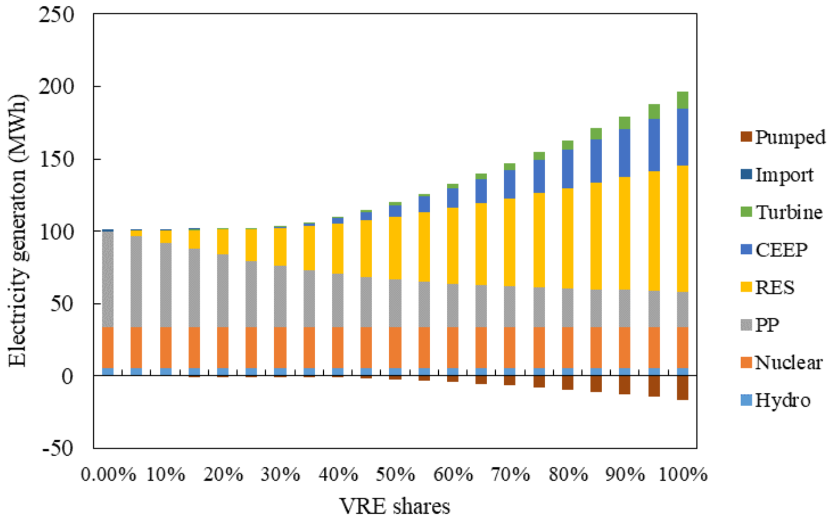
At PHS=0, Nuclear=4200:



At PHS=0, Nuclear=0:



At: PHS=20000, Nuclear=4200:



At: PHS=20000, Nuclear=0:

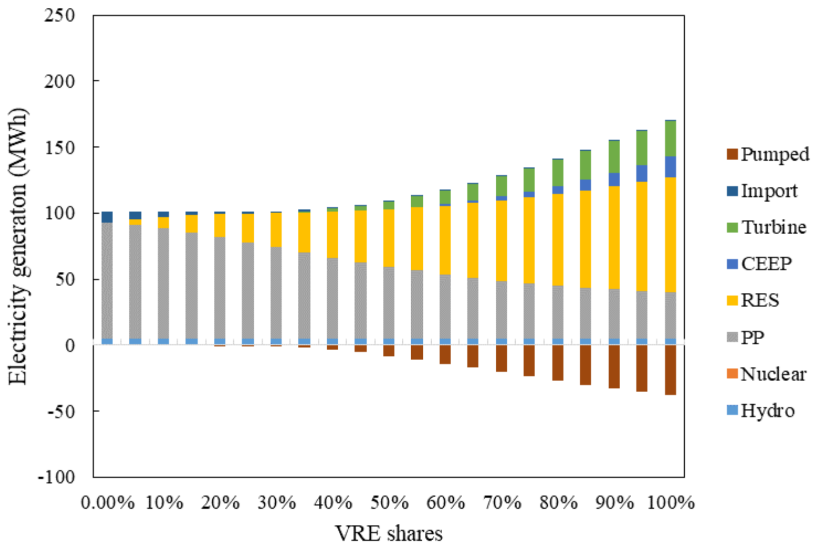


Fig. 7-27 The configuration of electricity generation under the circumstance of PHS and nuclear power facilities

7.6.3. Conclusions and limitations of this research

This Section analyzes the impact of nuclear power and PHS system on the power grid by using EnergyPLAN tools. Its impact is mainly reflected in the penetration of renewable energy and the operation of traditional thermal power generation. Nuclear power accounts for 25% of Kyushu's annual power generation, and it can provide base load power. Limited to 30% of the power production share needs to come from the constraints of the base load unit, nuclear power reduced the use of VRE energy, especially in the transitional season when power demand is low. At the same time, the existence of nuclear power provided a stable power supply for the grid, thus reducing the use of thermal power generation. After adding a pumped storage system, it can reduce the amount of VRE power suppression while compressing traditional thermal power generation. Therefore, pumped storage can increase its actual penetration rate in the grid when the VRE share is high. And have the ability of reducing the operating ratio of thermal power generation. In the future power system, we can consider reducing the operation of nuclear power to increase the penetration of VRE, and at the same time debugging the pumped storage operation strategy to stabilize the power supply and demand balance of the grid, especially during periods of weak wind and no light.

For the prospective of EnergyPLAN model, it only has one operation strategies of PHS system. It can be combined with the programming software to modify the limitation conditions of PHS system. Besides, for the input data of thermal power, the energy types including coal, LNG, and oil cannot be analyzed separately, it is inputted as a whole for the study analysis. However, the coal, LNG, and oil pretend different regulation time in the power system. It needs to be researched further combined with the other programming software in the future research.

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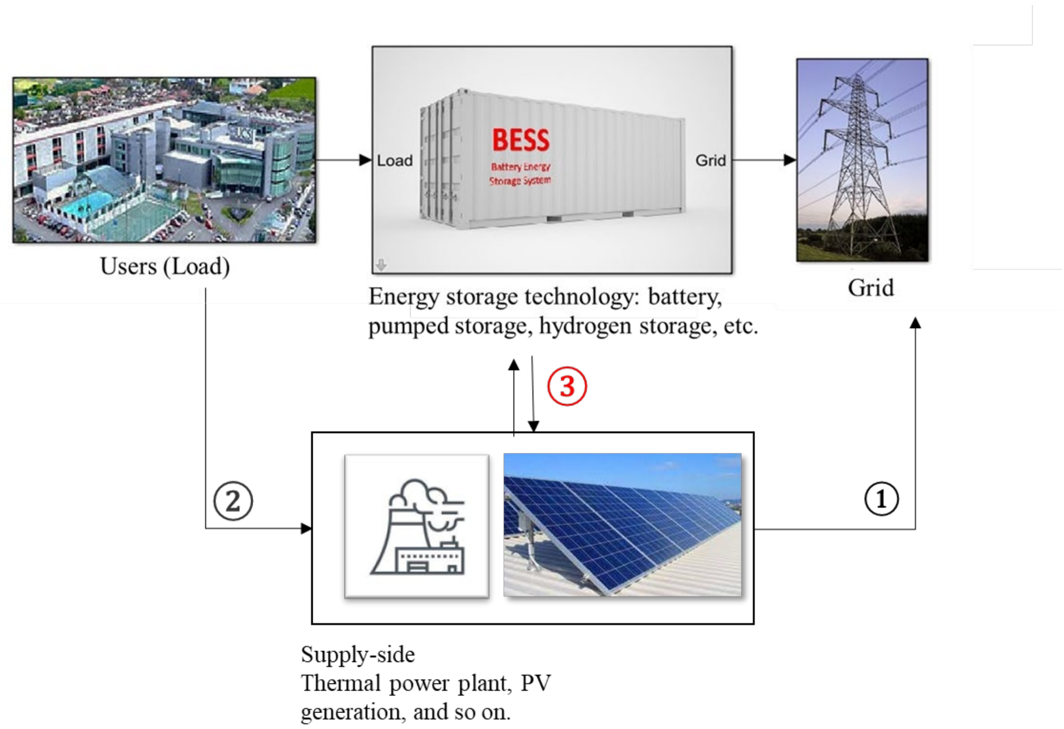
Appendix



This Chapter expressed the interaction of energy storage system on VRE power generation and the other power generator. This paper is submitted to the Journal of Renewable Energy.

Chapter 8

CONCLUSION AND PROSPECT

CHAPTER EIGHT: CONCLUSION AND PROSPECT

8.1 Conclusion

In the context of energy shortages and safe supply requirements, renewable energy has been developing steadily in recent years. Among them, the power sector plays an important role in energy conservation and emission reduction. The development of renewable energy can not only reduce the use of fossil energy, but also increase the rate of energy self-sufficiency. Japan's current energy self-sufficiency rate is only 8%. After the implementation of the FiT system in 2011, renewable energy has experienced explosive growth. Among them, PV and wind energy have shown a leading position in growth. Photovoltaic and wind energy are also called variable renewable energy because of their variable power generation characteristics. Their large-scale introduction affects the stability of the grid, so this research is dedicated to studying the interaction between renewable energy, power demand, grid, and energy storage system to maximize the use of VRE.

The main works and results can be summarized as follows:

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. The research backgrounds of energy resources are introduced in Chapter1, which is including the current status and bottleneck of integrational energy development. As well as the significant of developing variable renewable energy. Then, the development and status of renewable energy in world and Japan is well introduced. It is essential to developing renewable energy in the power generation sector to dealing with the problem of energy security and fossil fuel shortage. At last, the research purpose and logical framework is shown in order to support reviewers understand the content of this paper.

In Chapter 2, LITERATURE REVIEW OF VARIABLE AND RENEWABLE ENERGY. The relevant research of this paper is well reviewed in this Chapter. The development of renewable energy in power systems, including the variable renewable energy studies and its hybrid with pumped storage system studies. Besides, the evaluation indicator used in this paper is also well explained further. At lase, the energy management tool of EnergyPLAN models is reviewed. According to the previously study, the current paper contributes to combined them and promote it in the integration potential of renewable energy.

In Chapter 3, METHODOLOGY. The keyword of this paper is load in demand side, electricity generator in supply side, power grid, and storage system. Therefore, the methodology employed including, evaluation indicators of VRE on the power grid, PHS installed capacity prediction, and EnergyPLAN model are summarized in Chapter 3. It helps us to understand the interplay of load in demand side, electricity generator in supply side, power grid, and storage system to seek a ideal electricity production compositions.

In Chapter 4, DATA RESOURCE AND ENERGY CONVERSION ANALYSIS. The data resource mainly focus on the distribution of research area, the composition of power generation in research area, electricity production profiles, and economic cost. Kyushu, Tokyo, Kansai, and Hokkaido with different power proportions, electricity demand profiles, and renewable energy resources are selected to compared and analysis. The energy conversion of fossil fuel to renewable energy is adopted whist.

In Chapter 5, ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE. This chapter evaluated the impact of PV and wind on the public electricity supply system when they are introduced into the grid. A method of predict the maximum penetration of renewable energy and its impact on the public electricity supply system is explained in Chapter 3, which is capacity credit and dynamic investment payback period. The results indicate that the capacity credit increases with an increase in PV and wind shares in the grid. However, it seems to be saturated when the share of PV and wind power in the grid reaches 25% and 60%, respectively. Compared with the wind integration in Kansai and Hokkaido, the PV penetration in Kyushu and Tokyo reaches saturation more rapidly. In addition, PV shows more power suppression, which prolongs its payback period compared to wind energy. The significant difference in the results of capacity credit and DIPP is limited by the characteristics of power demand in mixed regions and the relevance of renewables distribution.

In Chapter 6, ASSESSMENT OF DEMAND SIDE IN VRE INTEGRATION. The impact of a reduction in load demand on renewable energy in the Japan public power grid under a state of emergency declaration (April to May 2020) is compared. Research area is distributed in Kyushu, Tokyo, Kansai, and Hokkaido. The results are shown that the consumption profiles and amounts of power consumption reduction are different in different areas. Tokyo shows the largest share of reduced load, followed by Kansai, Kyushu, and Hokkaido. The load reduction was mainly seen during the day, which reflects the differences in people's activities relative to the same period in 2019. Different means of power dispatch, including power generators, energy storage systems, and transmission lines are used and compared in terms of responses to the changes in electricity consumption profile. Besides, the overall fall in total load demand and the change in load sequence affected the integration and curtailment of PV power generation and consequentially caused the electricity price to drop. This Chapter clarifies the effects of COVID-19 on the public power grids of Japan. Further, it establishes the impact on policymakers in relation to the development of renewable energy.

In Chapter 7, ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM. The pumped storage system is used in the energy management system in order to promote the integration of renewable energy integrations. the existing small and medium-size dams in Japan is exploited to expend the capacity of PHS installed. Combining with the phase-out of thermal power, analyze the basic load power supply equipment contributes to regional VRE penetration. Its energy conversion analysis is introduced in Chapter 3. Kyushu and Hokkaido power grids with different power generation structure and electricity demand profiles as case study. Scenario settings are based on hourly power demand and supply curves using the EnergyPLAN tool. The result shown that the installed capacity potential of small and medium-sized pumped storage in Kyushu and Hokkaido is 18GW and 20GW, respectively. PHS can reduce RES suppression and thermal power operation while providing a share of grid stability. The reduction of the initial installation of thermal power improves the penetration of RES and the operation rate of PHS. the average power generation cost decreases with the reduction of thermal power installation capacity. Besides, the addition of PHS is first higher and then lower than the scenario without energy storage equipment. Under the same RES share, the maximum cost of Kyushu is 16yen / kWh and that of Hokkaido is 26yen / kWh. Attributed to the nuclear power in Kyushu, which accounts to 25% share of power generation. The penetration of VRE in the future public grid and its impact on other power generation units are covered.

In Chapter 8, CONCLUSION AND PROSPECT. A summarized of each Chapter is concluded.

Therefore, the conclusion of this paper can be concluded as Fig. 8-1. For improving the penetration of renewable energy in Japan power grid, the fourth fold including, supply side, demand side, power grid, and storage system was combined to analyzed.

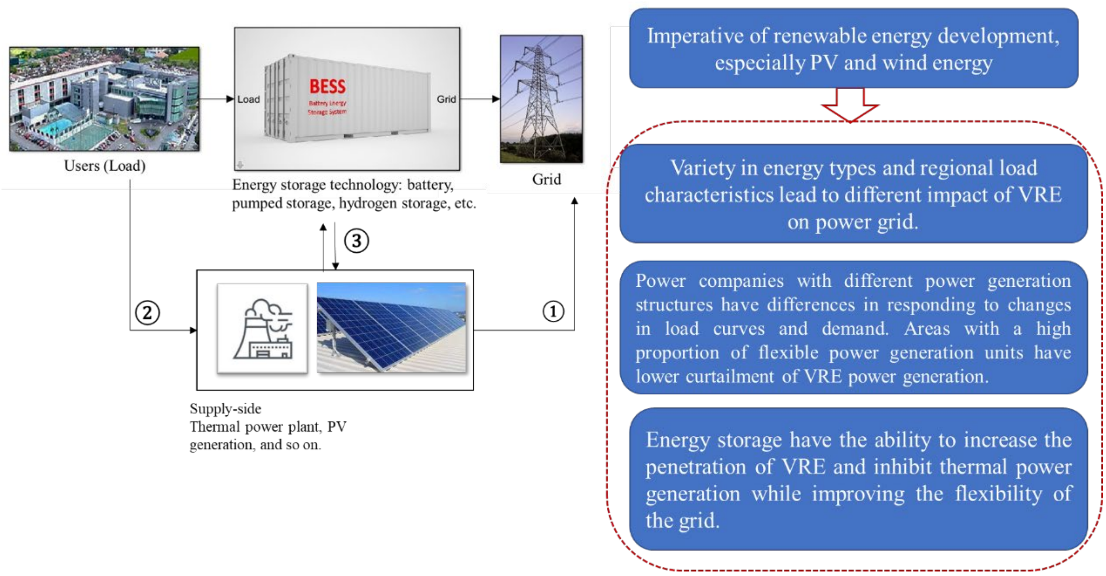


Fig. 8-1 The fourth fold of paper analysis

8.2. Prospect

The main objective of this paper is to seek the maximization of renewable energy. Its limitations are reflected in both methods and energy planning equipment. First of all, the EnergyPLAN model's adjustment to the PHS operating rules is to maximize the use of PV and wind energy and reduce the generation of fossil fuels whist. This led to scenarios where the load is not satisfied. Therefore, in the future research, the EnergyPLAN operating strategy will be adjusted in conjunction with the programming software to pursue the ideal operating mode. Secondly, energy storage facilities only consider PHS suitable for large-scale power grids in energy planning, and cogeneration of variable energy storage system is a major research trend. Future research will combine thermal storage, transportation, and transmission lines to increase the penetration of renewable energy further.