博 士 論 文

Effect of virtual power plant scheme on the supply and demand sides based on the techno-economic analysis

供給と需要側考慮した仮想発電所の経済性と技術性及び評価に関する研究

2023 年 8 月

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ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to all the individuals who have supported me throughout my doctoral journey and contributed to the completion of this thesis.

First and foremost, I am deeply indebted to my advisor, Weijun GAO, for his unwavering guidance, encouragement, and expertise. His mentorship has been invaluable in shaping my research, refining my ideas, and pushing me to achieve my best. His belief in my potential, compassion, and guidance helped me navigate challenges and grow personally and professionally.

I extend my sincere thanks to the members of my dissertation committee, Prof. Hiroatsu FUKUDA, Prof. Hiroki SUYAMA, and Prof. Takaaki ISODA, for their insightful feedback and constructive criticism that greatly improved the quality of this work.

I would also like to acknowledge the support and resources provided by The University of Kitakyushu. The stimulating academic environment and access to state-of-the-art facilities have been crucial in conducting my research effectively.

I am also grateful to my colleagues, especially Fanyue QIAN, and all the group members in GAOLab, for engaging in discussions, and brainstorming sessions, and for the sense of camaraderie that made this journey more enjoyable.

I express my deepest appreciation to all the authors whose works have formed the foundation of my research. Their contributions have been instrumental in shaping the theoretical framework of this thesis.

My gratitude goes out to my family and friends for their unwavering belief in me and their constant encouragement during moments of doubt. Their love and support have been the pillars of my strength. Your understanding and patience made the long hours of research more bearable, and your presence brought joy to my life even in the midst of academic pressure.

Lastly, to You Li, a special person who stood by my side throughout this challenging journey. You were there to celebrate my victories and offer solace during moments of despair. Thank you for being my unwavering support throughout this journey.

In conclusion, I acknowledge the collective efforts of everyone who has played a part, big or small, in shaping this thesis. Your contributions have left an indelible mark on my academic and personal growth.

Thank you all for being an integral part of my Ph.D. journey.

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ABSTRACT

Against the background of energy shortage and secure supply requirements, renewable energy has developed 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 energy self-sufficiency rate. After the implementation of the feed-in tariff system in 2011, renewable energy ushered in explosive growth. However, the large-scale introduction of renewable energy will affect the stability of the grid, so this study is devoted to studying the interaction between community renewable energy, electricity demand, grid and energy storage system to maximize the utilization of renewable energy.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. Under the demand of energy shortage and safe supply, it is imperative to develop renewable energy sources. This chapter analyzes the international as well as Japan's energy situation, bottlenecks, and historical evolution. These factors lead to the necessity of developing renewable energy sources. Secondly, the development trend of renewable energy in the international and Japanese regions is summarized. The international level combines the energy structure evolution and renewable energy promotion strategies of typical countries such as the United States, Germany, Japan, and China. The Japan region details how renewable energy is entering the grid and analyzes the evolution of the energy mix in detail combining the industrial sector, the household sector, and the transportation sector. This demonstrates the importance of the power system in stabilizing energy supply and reducing greenhouse gas emissions. And it is urgent for us to find an optimal method to aggregate those renewable energy sources.

In Chapter 2, LITERATURE REVIEW OF VIRTUAL POWER PLANT. This Chapter provides a detailed review of the application of Virtual Power Plants in this research. Section 2.1 reviews the application of VPP around the world and introduced the principle of. Section 2.2 mainly summarize the previous study of VPPs, especially difference between Technical VPP and economic VPP, etc. Section 2.3 gives a detailed description and summary of the barriers and challenges of VPP. In general, the review in this section focuses on the application of VPP in the power sector.

In Chapter 3, VIRTUAL POWER PLANT MODEL ESTABLISHMENT AND METHODOLOGY. This Chapter describes the research methods used in this research. Firstly, introduced the technology approach involved in this research. And then, the VPP system model was established. Includes the calculation of indicators to evaluate the impact of VPP. Section 3.1 shows the technical technology used in this research. In terms of economy, the dynamic payback period of VPP system is adopted. Compared with the static payback period, the dynamic investment payback period adds a time cost.

In Chapter 4, ENERGY CONSUMPTION CHARACTERISTICS ANALYSIS IN HIGASHIDA SMART COMMUNITY. The data resource and energy conversion analysis in this research is shown in Chapter 4. The power consumption of different type of buildings is investigated, which is featured with different power consumption and load profiles. Besides, the different building's feasibility of VPP introduction was explained.

In Chapter 5, FEASIBILITY, EFFICIENCY AND ECONOMIC ANALYSIS OF VPPS. As most of the distributed energy resources are available in urban areas, there are increasing interests in assessing the potential to develop urban Virtual Power Plant (VPP). This chapter aims to analyze the feasibility of VPPs through the construction of local renewable energy and energy storage technology in Higashida area. The return on investment was carried out through payback period and life cycle cost analysis. The economic performance of the power plant side and the demand side by changing the investment from power plant side and the corresponding electricity price on the demand side were analyzed. Two investment proposal were compared in the aspect of economic analysis.

In Chapter 6, TECHNO-ECONOMIC ANALYSIS of THE TRANSITION TOWARDS THE ENERGY SELF-SUFFICIENCY COMMUNITY BASED ON VIRTUAL POWER PLANT. In this chapter, a VPP model consisted of updating high efficiency appliances, photovoltaic and energy storage systems was proposed. A comprehensive analysis for assessing the technical, economic and environmental benefits deriving from the VPP was presented, indicated the feasibility of a smart community to achieve power self-sufficiency with the support of the VPP. Analysis of the VPP's load leveling performance, return on investment and CO_2 emission reduction are performed. In addition, external factors such as electricity price changes and FiT policies are considered to assess the impact on the economics of the VPP.

In Chapter 7, EVALUATION OF ECONOMIC BENEFITS OF VIRTUAL POWER PLANT BETWEEN DEMAND AND PLANT SIDES BASED ON COOPERATIVE GAME THEORY. This chapter proposed a comprehensive method for analyzing the feasibility of using a VPP to benefit both the plant and demand sides. First, the energy-saving potential of a VPP composed of a photovoltaic (PV) and energy storage system (ESS) was explored, based on historical monitoring data in a Japanese smart community called Higashida District (with a size of approximately 1.2 km^2). Second, the economic performance of the VPP was evaluated based on a payback period and total life cycle cost analysis. Then, considering the imbalance of the benefits between the demand and plant sides, cooperative game theory was applied to explore the cooperation potential. The influence of government subsidy policies on both the plant and demand sides was a simultaneous concern.

In Chapter 8, CONCLUSIONS AND PROSPECT. The conclusion of each Chapter is concluded and the prospect of future development trend of VPP.

王　亜飛　博士論文の構成

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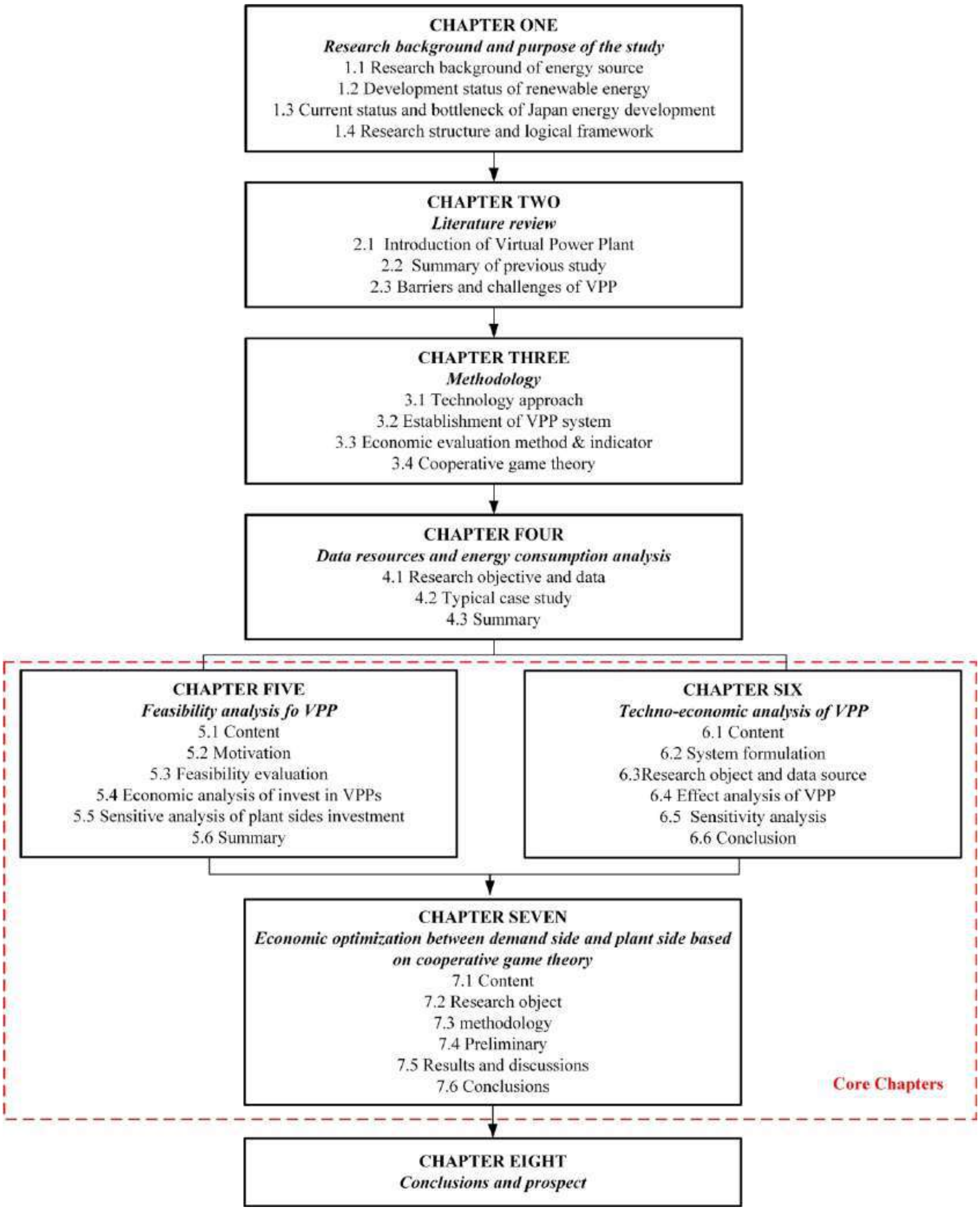

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Chapter 1

RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

CAHPTER 1 RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

1.1 Research background of energy source

Energy sources can be broadly categorized into two types: renewable and non-renewable. Renewable energy sources are those that can be replenished naturally and sustainably, such as solar, wind, hydro, geothermal, and biomass. Non-renewable energy sources are those that are finite and will eventually run out, such as fossil fuels (coal, oil, and natural gas) and nuclear energy. The study of energy sources has become increasingly important due to the growing concerns about climate change, environmental pollution, and energy security. The use of non-renewable energy sources has been linked to the emission of greenhouse gases, which contribute to global warming and climate change. In addition, the extraction, transportation, and combustion of non-renewable energy sources can have negative environmental and social impacts, such as air and water pollution, land degradation, and displacement of communities.

Currently, more than 50% of the world's population lives in cities. And cities emit about 70% of global greenhouse gas emissions. Climate action in cities is necessary for achieving ambitious net-zero emissions goals. Cities account for more than 50% of the global population, 80% of global GDP, two-thirds of global energy consumption and more than 70% of annual global carbon emissions. These factors are expected to grow significantly in the coming decades: it is anticipated that by 2050 more than 70% of the world's population will live in cities, resulting in massive growth in demand for urban energy infrastructure [1].

Smart cities represent an important opportunity to reduce energy consumption while meeting service demand, improving grid stability, and improving the quality of life for all. These solutions are transforming the energy landscape by creating new synergies to reduce emissions, improve energy efficiency and enhance resilience.

Nowadays, all countries worldwide are in a progressive of transforming their energy systems to accomplish the Paris Agreement goals [2]. Consumption of fossil fuels has an increasing trend because of high growth rate of energy demand. Traditional urban development uses fossil fuels and natural resources that people think are inexhaustible. The largest share of the energy demand is satisfied by fossil fuels which increases the global greenhouse gas (GHG) emissions. Global warming, as an important environmental issue, diverts governments attention towards energy systems with low carbon emissions. Our over-reliance on traditional energy sources and strategies has caused environmental degradation, climate change, and various geopolitical issues. The development and construction of cities still rely on energy. However, development and construction can also be achieved by optimizing energy demand and changing energy supply.

1.1.1 Global energy status and energy development

Energy is an important material basis for human survival and civilization development and is a matter of national planning and livelihood and national strategic competitiveness. Currently, economic globalization is facing a new situation, the global energy production and consumption revolution is emerging, in which energy science and technology innovation plays a central leading role. The rational development and scientific use of energy is a necessary guarantee for sustainable development. With the development of society, the energy demand has increased dramatically. Energy is an important material basis for human survival and civilization development and is a matter of national planning and livelihood and national strategic competitiveness. Currently, economic globalization is facing a new situation, the global energy production and consumption revolution is emerging, in which energy science and technology innovation plays a central leading role. The rational development and scientific use of energy is a necessary guarantee for sustainable development. With the development of society, the energy demand has increased dramatically. The energy consumption structure dominated by coal, oil and other fossil fuels has triggered a series of energy crises while promoting social progress and development. However, the energy consumption structure dominated by coal, oil and other fossil fuels has triggered a series of energy crises while promoting social progress and development. Firstly, the world will face a huge challenge to the continued and stable supply of energy. In 2011, the global population exceeded 7 billion and is expected to reach 9 billion by 2045 according to the United Nations [3]. World energy demand will continue to increase as socio-economic development and world population continues to grow. The share of fossil energy in the world's primary energy structure has remained at over 85% for a long time. According to the Statistical Review of World Energy, the primary direct energy consumption of the fossil fuels from negligible levels in 1800 to an output of nearly 140,000 TWh in 2019. According to the International Energy Agency (IEA), shown in Fig.1.1 the world total coal production in 2020 was approximately 7.2 billion tonnes of coal equivalent (Btce). This represents a decline of about 4% from the previous year, mainly due to the impacts of the COVID-19 pandemic on global energy demand. China was the largest producer of coal, accounting for approximately 48% of the world's total coal production in 2020, followed by India with 9% and the United States with 7%. Other major coal-producing countries include Australia, Indonesia, Russia, and South Africa.

Coal remains a significant source of energy globally, particularly in developing countries where it is used for electricity generation, industrial processes, and domestic heating. However, there are growing concerns about the environmental and social impacts of coal production, including air and water pollution, land degradation, and health impacts on local communities. The increasing availability and competitiveness of renewable energy sources are also leading to a shift away from coal in many parts of the world. Globally, the equivalent of more than 11 billion tons of oil is currently consumed annually from fossil fuels. Crude oil reserves are disappearing at a rate of over 4 billion tons every year, and at this rate, oil reserves we already known could be exhausted in just over 53 years. As fossil energy reserves dwindle, the pressure on the world's sustainable supply of energy increases in the long term. Secondly, the exploitation of fossil energy sources also poses a series of challenges to the environment. The development and use of energy can cause problems such as water pollution, includes wastewater discharge from coal utilization, ocean and groundwater pollution due to oil and gas extraction. The use of fossil energy also emits large amounts of air pollutants. Actually, energy production is the main source of CO_2 [4]. The continued increase in particulate matter emissions from thermal power, transport and other industries also cause widespread haze which will threaten human's health.

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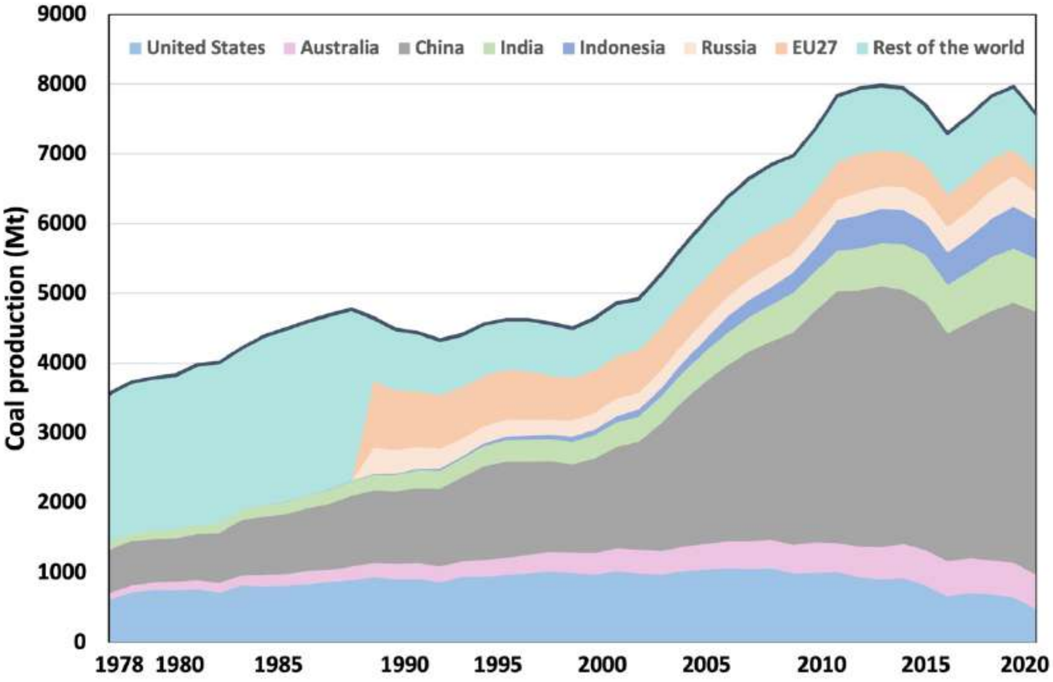


Fig.1.1 World total coal production, 1971-2020

In response to the many challenges facing the world's energy development, changing the way traditional energy is developed and utilized, promoting the application of new energy technologies and building a new energy system will become the main direction of the world's energy development. Shaping a secure and sustainable energy future for world continues to be a development theme today. However, the primary energy still the main source of electricity generation, as shown in Fig 1.2. It's worth noting that these figures can vary by region and country, as different countries have different energy mixes and policies that promote certain types of energy sources over others. In addition, the share of renewable energy sources (hydro, wind, solar, and bioenergy) has been growing in recent years, while the share of coal has been declining. The IEA predicts that by 2040, renewables will surpass coal as the largest source of electricity generation globally. Through the British Petroleum had predicted that renewable energy is growing the most rapidly of all energy sources, contributing for 40% of primary energy growth. To achieve the net zero emission by 2050. Renewable energy will play an increasingly important role in low carbon power generation. The increasing share of uncertain renewables such as solar and wind means that the electricity system should become more flexible. At the same time, the utilization of conventional power plant will gradually decrease, as decarbonization targets requires a reduction in use of primary energy. The development of renewable energy and efficient use of energy will be the key direction of future energy system development.

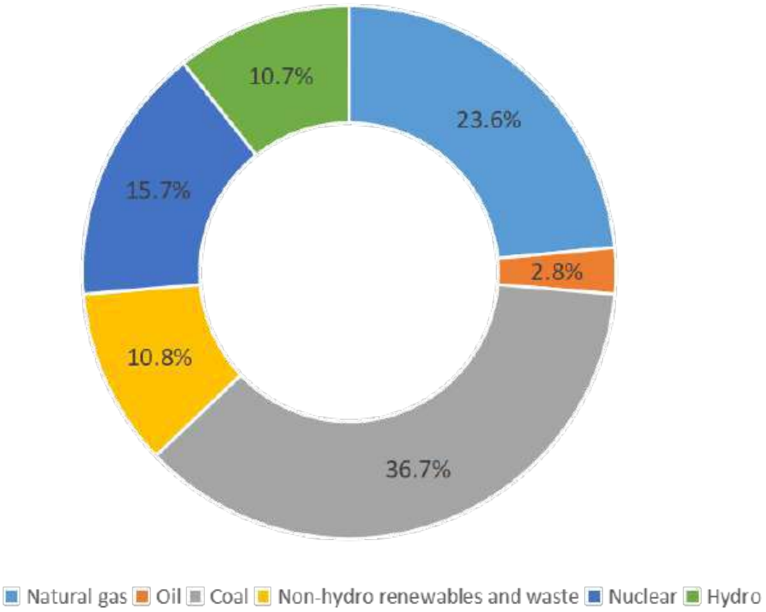


Fig. 1.2 Global share of electricity generation by different energy sources in 2019 [5]

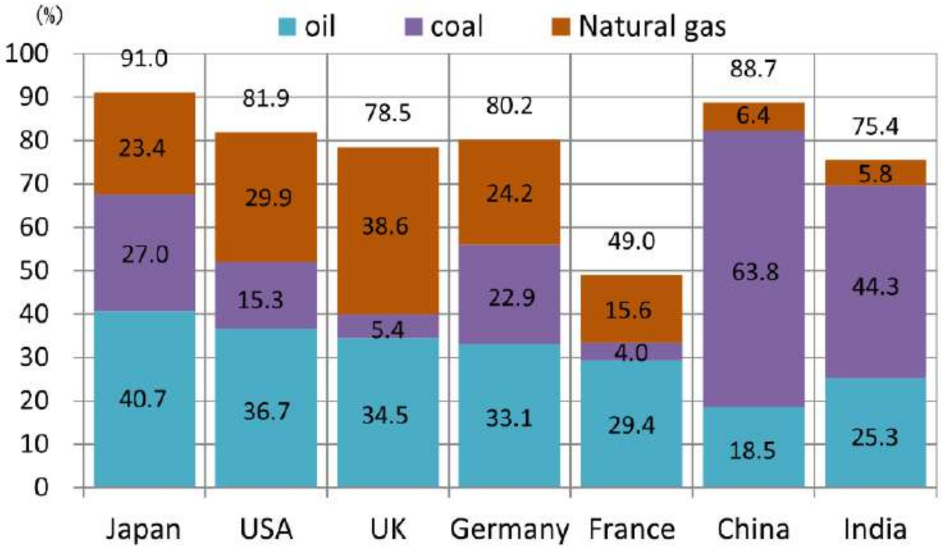


Fig. 1.3 Fossil energy dependence of major countries (2017)

Global primary energy consumption has been increasing in line with economic growth, from 3.7 billion tons of oil equivalent in 1965 to 13.9 billion tons in 2018, with an average annual growth rate of 2.5%. Since the 2000s, consumption growth has been particularly high in the Asia-Pacific region, driven by emerging economies. In contrast, growth in developed countries (OECD countries) has slowed down. This is due to the fact that both economic and population growth rates have remained low compared to developing countries, as well as changes in industrial structure and progress in energy efficiency. As a result, the share of OECD countries in global energy consumption declined from 70.5% in 1965 to 40.9% in 2018, a decrease of about 30 percentage points. As shown in Fig.1.3, fossil energy dependence refers to the percentage of total primary energy supply that comes from fossil fuels (coal, oil, and gas). These figures highlight the degree to which different countries rely on fossil fuels to meet their energy needs, and can have implications for energy security, environmental impact, and economic stability. Countries with high fossil energy dependence rates may be more vulnerable to price fluctuations or supply disruptions in fossil fuel markets and may face greater challenges in transitioning to cleaner and more sustainable energy sources.

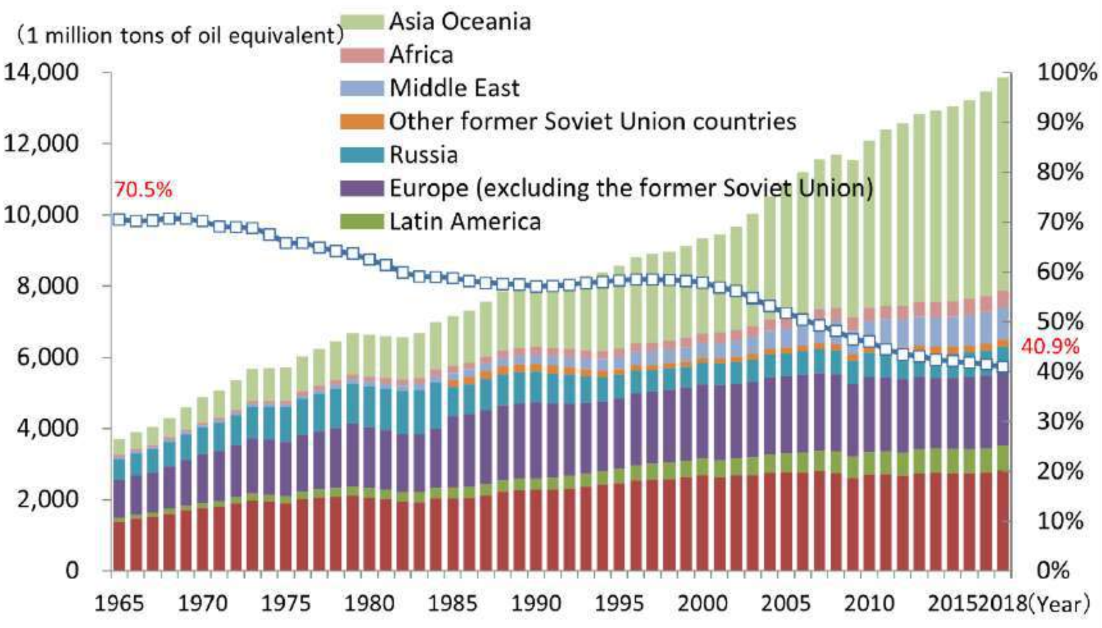


Fig. 1.4 Trends in global energy consumption[6] (By regional, primary energy)

In terms of trends in global primary energy consumption by energy source (Fig.1.5). Until now, oil has been the main source of energy consumption. Although there has been a shift to other energy sources, mainly for power generation, oil consumption grew at an average annual rate of 2.5% between 1965 and 2018, supported by strong transport fuel consumption, and still accounts for the largest share of total energy consumption (33.6% in 2018). During the same period, coal consumption grew at an average annual rate of 1.9%, especially in the 2000s, especially in fast-growing Asian economies, such as China, which were seeking cheap fuels for power generation. However, in recent years, coal consumption has been low, declining year-on-year for two consecutive years in 2015 and 2016, due to a slowdown in demand in China and a reduction in demand due to natural gas substitution in the United States, with a slight increase from 2017. As a result, the share of coal is 27.2% (as of 2018). On the other hand, the growth in natural gas consumption outpaced that of oil and coal. Natural gas consumption for power generation as well as for town gas has grown (at an average annual rate of 3.3%), especially in developed countries, which are under pressure to combat climate change. Over the same period, nuclear power (9.2%) and renewable energy sources such as wind and solar (12.4%) have seen the largest growth rates, but their share of total energy consumption remains modest, at 4.4% and 4.0% respectively as of 2018. The share of renewables is expected to grow in the future due to the decreasing cost of solar and wind energy in recent years.

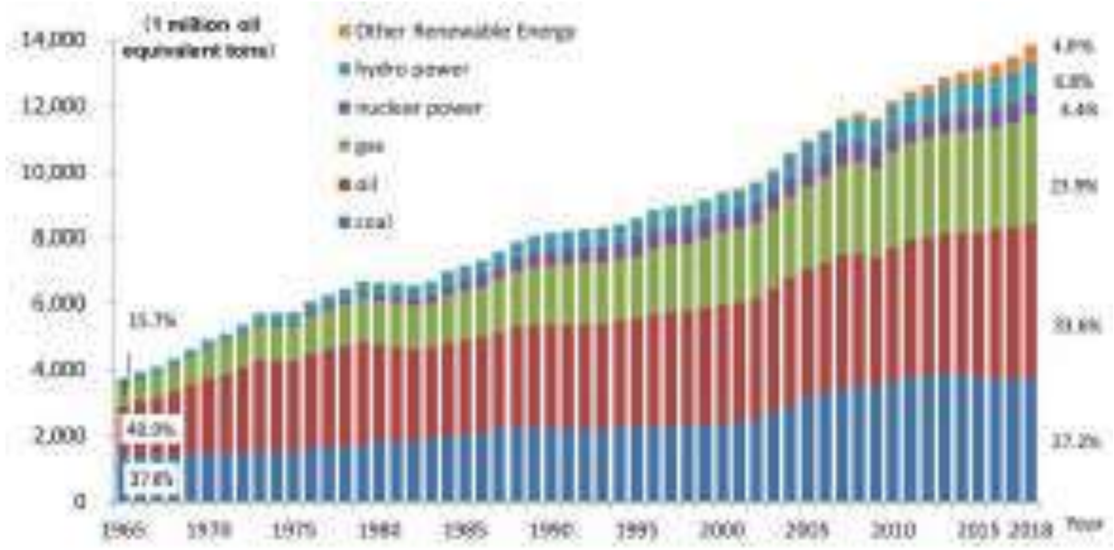


Fig. 1.5 Trends in global energy consumption[6] (By energy source, primary energy)

The Paris Agreement, a fair and effective international framework in which all countries will participate after 2020, was adopted at COP21 (the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change) held in December 2015, and it calls for limiting the temperature increase below 2 degrees Celsius compared to pre-industrial levels and further to 1.5 degrees Celsius. The agreement includes a commitment to make every effort to Subsequently, ratification of the Paris Agreement proceeded in each country, and the agreement entered into force in November 2016. Furthermore, at COP24 (24th Conference of the Parties to the United Nations Framework Convention on Climate Change) held in December 2018, the implementation guidelines of the Paris Agreement were adopted for the full implementation of the Paris Agreement after 2020. The entry into force of the Paris Agreement and the adoption of the Implementation Guidelines are symbolic events that show that many countries around the world are actively working to combat global warming.

However, the U.S. Trump administration, which took office in January 2017, notified the UNFCCC Secretariat in August 2017 that its policy was to withdraw from the Paris Agreement. Under the Paris Agreement, notification of withdrawal becomes possible three years after the Paris Agreement enters into force, and withdrawal takes effect one year after notification of withdrawal; however, the U.S. Trump administration formally notified the United Nations of its withdrawal from the Paris Agreement on November 4, 2019, three years after the Paris Agreement entered into force, so that in 2020 the country is expected to formally withdraw from the Paris Agreement after November 4, 2012. Despite these concerns, there has been a significant increase in the amount of renewable energy installed in the U.S., along with the increasing cost competitiveness of renewable energy. Global warming measures will have a significant impact on energy choices, and we will need to continue to monitor these developments closely.

1.1.2 Energy status and energy development in Japan

During the period of high economic growth until the 1970s, energy consumption in Japan grew faster than gross domestic product (GDP). However, after the two oil crises in the 1970s, energy conservation progressed mainly in the manufacturing sector and the development of energy-efficient products became active. Through these efforts, we were able to achieve economic growth while controlling energy consumption. Although crude oil prices remained low throughout the 1990s, energy consumption increased, particularly in the household and commercial sectors. Since the mid-2000s, crude oil prices have risen again, and final energy consumption has been on a downward trend after peaking in 2005. From fiscal 2011 onwards, this has decreased further due to increased awareness of electricity conservation following the Great East Japan Earthquake. In fiscal 2018, real GDP increased by 0.3% compared to fiscal 2017, but final energy consumption fell by 2.7% as temperatures were higher than in the previous year and heating demand did not increase, as shown in Fig.1.6.

In terms of sectoral energy consumption trends, the increase between 1973 and 2018 was 1.0 times in the corporate/commercial establishments and others sector (20.8 times in the industrial sector and 2.1 times in the commercial and others sector) and 1.9 times in the households and transport sector. This is an increase of 1.7 times. Since the first oil crisis, the level of energy savings in companies, commercial establishments and other sectors has remained at the same level, particularly in manufacturing, despite economic growth. On the other hand, in the household and transport sectors, this figure has increased significantly due to the spread of energy-using devices and cars. As a result, the shares of companies, commercial establishments, households and the transport sector have increased from 74.7%, 8.9% and 16.4% at the time of the first oil crisis in 1973 to 62.7%, 14.0% and 23.4% in 2018.

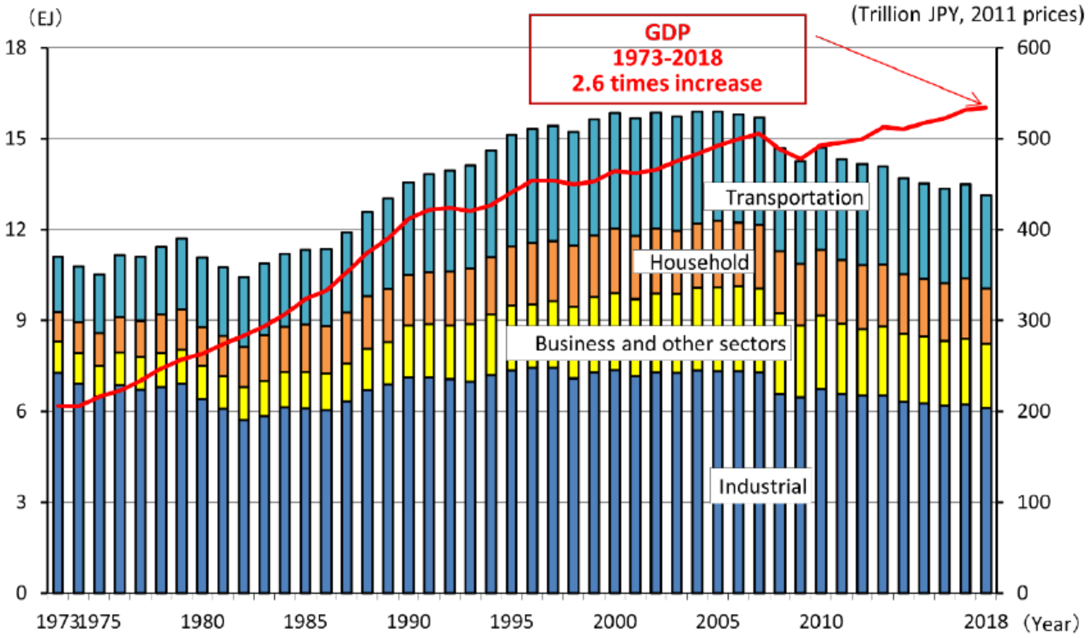


Fig. 1.6 (1) Change of final energy consumption and real GDP of Japan

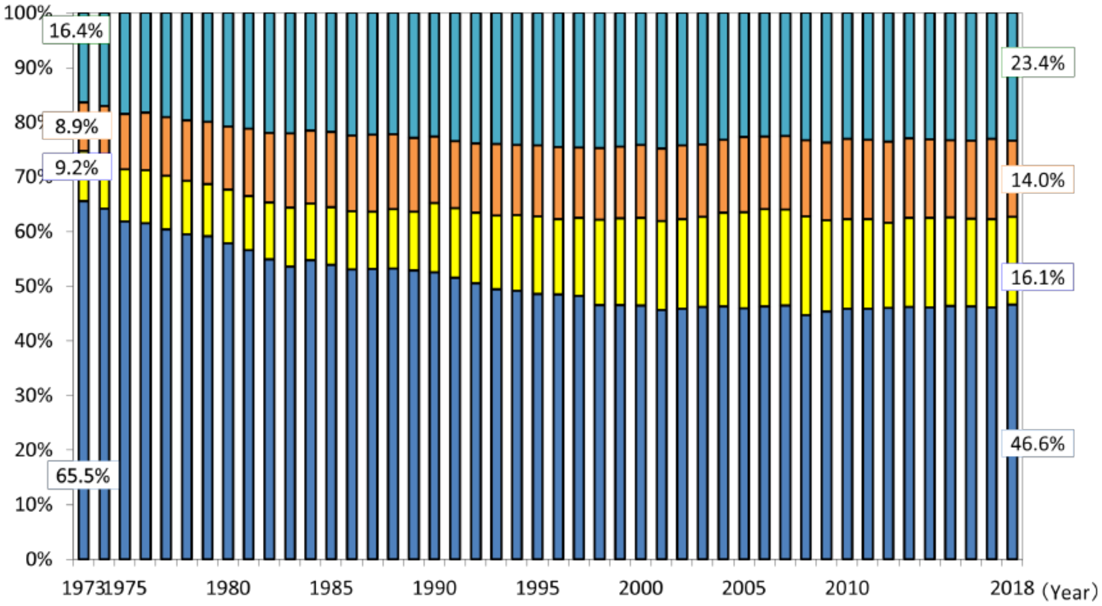


Fig. 1.6 (2) Change of final energy consumption ratio of different sectors in Japan

(Source: Agency for Natural Resources and Energy[7] *J (joule) is the indicator of energy magnitude, 1MJ = 0.0258 x 10^{-3} crude oil equivalent kl;1EJ=10^{18}J; The industrial sector is the sum of agriculture, forestry, fisheries, mining construction and manufacturing; GDP before 1993 is estimated by the Japan Institute of Energy Economics.)

The primary energy supply per unit of gross domestic product (GDP) was 73 PJ/trillion in 1973 and almost halved to 37 PJ/trillion in 2018 Since 2010, it has decreased for eight consecutive years, showing progress in improving energy efficiency, as shown in Fig.1.7. while Japan has experienced fluctuations in its real GDP over the years, the country has made significant progress in improving energy efficiency. This has helped to reduce the country's energy consumption and greenhouse gas emissions, while also improving energy security and reducing costs for consumers and businesses. However, there is still more work to be done to achieve Japan's energy and climate goals, particularly in the areas of renewable energy and decarbonization of the economy. Japan's real GDP has fluctuated over the years, with periods of growth followed by periods of stagnation or contraction. For example, in the 1980s, Japan experienced a period of rapid economic growth, followed by a prolonged period of stagnation and low growth in the 1990s and early 2000s. More recently, the economy has shown signs of recovery, with GDP growth averaging around 1-2% per year in the past few years. Japan has made significant strides in improving energy efficiency over the past few decades. This has been driven by a range of factors, including government policies, technological innovations, and changing consumer behavior. For example, the Japanese government has implemented various energy efficiency standards and regulations, and incentivized the use of energy-efficient technologies through tax breaks and subsidies. Additionally, Japanese companies have invested in energy-saving technologies and processes, and consumers have become more aware of the importance of energy conservation.

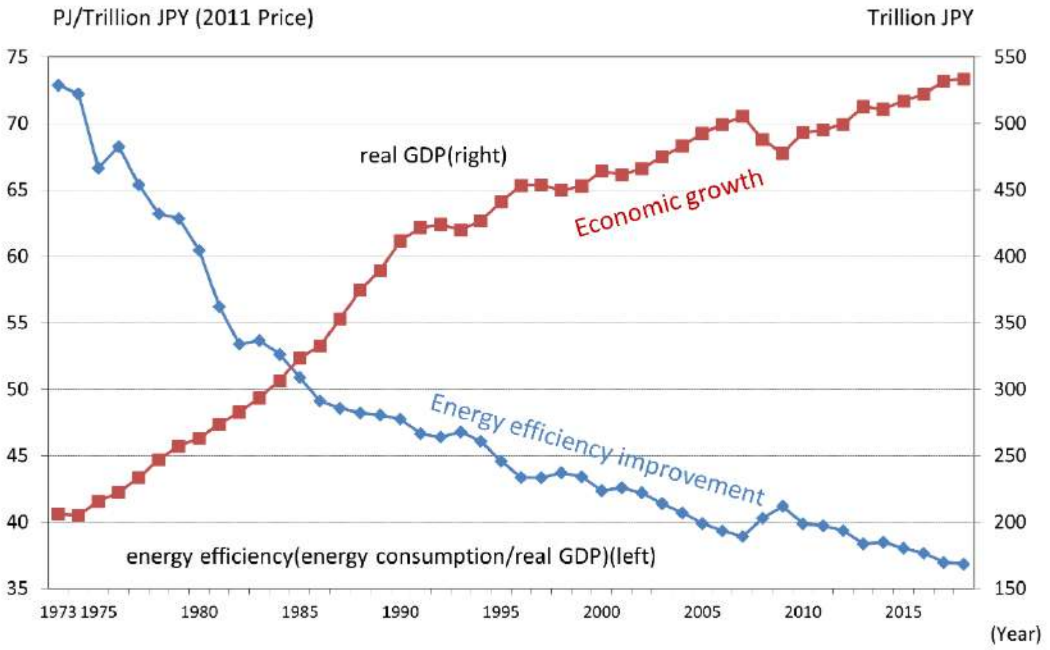


Fig. 1.7 Changes in real GDP and energy efficiency (primary energy consumption / real GDP)

Source: Agency for Natural Resources and Energy[7];1PJ= 1015J

The proportion of primary energy required for people's daily lives and economic activities that can be secured within a country is known as its energy self-sufficiency ratio. In Japan, as energy demand increased during the period of rapid economic growth, the supply side switched from coal to oil and oil was imported in large quantities, as shown in Fig.1.8. The composition of domestic supply of primary energy has been changing in recent years, reflecting the country's energy policy and efforts to transition to a more sustainable energy system. Japan has been working to reduce its dependence on fossil fuels such as oil, coal, and natural gas, which have traditionally been major sources of primary energy in the country. This has been driven in part by concerns over energy security and climate change. As a result, the share of fossil fuels in Japan's primary energy mix has been declining in recent years. Japan has been increasing its use of renewable energy sources such as solar, wind, and geothermal power, as part of its efforts to transition to a more sustainable energy system. The share of renewable energy in Japan's primary energy mix has been increasing steadily in recent years, although it still accounts for a relatively small share of the total. Japan's reliance on nuclear power has declined significantly in the wake of the Fukushima disaster in 2011. While some nuclear power plants have since been restarted, many remain offline and public opposition to nuclear power remains strong. Japan's self-sufficiency ratio, which measures the proportion of domestic primary energy supply that is sourced domestically, has been declining in recent years. This is due in part to the decline in nuclear power and the increased use of renewable energy, which are often more expensive to produce domestically than imported fossil fuels.

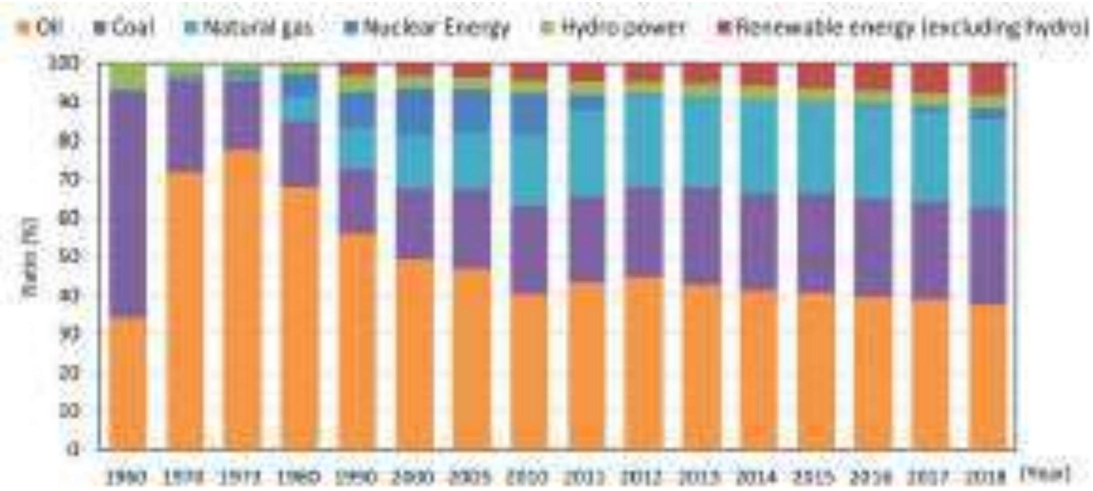


Fig. 1.8 Trends in the composition of domestic supply of primary energy and self-sufficiency ratio [8]

And the change of energy self-sufficiency ratio was shown in Table.1. In addition to coal and oil, almost all-natural gas, which expanded in prevalence after the oil crisis, is imported from abroad; in 2014, energy self-sufficiency ratio is 6.4%, partly because nuclear power generation fell to zero after the Fukushima Crisis. And in 2018, renewable energy sources were introduced, and nuclear power plants restarted, and the energy self-sufficiency rate is 11.8%.

Since the 1960s, Japan’s energy demand has increased rapidly. Until then, domestically produced coal played a central role in Japan’s energy supply. Later, as domestic coal lost price competitiveness, oil produced in large quantities in the Middle East and elsewhere supported Japan's period of rapid economic growth in terms of energy supply. Japan imported large amounts of cheap oil, and in 1973, 75.5% of its domestic primary energy supply came from oil. However, after the first oil crisis in 1973, triggered by the Fourth Middle East War, which led to soaring oil prices and uncertainty about oil supply disruptions, Japan reduced its dependence on oil and promoted the introduction of nuclear energy, natural gas, and coal as alternative sources of energy to oil to stabilize energy supplies. The government also took measures to improve the quality of products and services. The second oil shock (1979), when oil prices rose sharply again after the Iranian revolution led to disruptions in oil production, further encouraged the introduction of nuclear power, natural gas, and coal, and further accelerated the development of new energy sources.

As a result, the share of oil in the domestic primary energy supply fell sharply from 75.5% in 1973 during the first oil crisis to 40.3% in 2010, with coal (22.7%), natural gas (18.2%) and nuclear energy (11.2%) replacing it. The diversification of energy sources has been achieved. However, the 2011 Great East Japan Earthquake and subsequent nuclear plant closures led to an increase in the share of fossil fuels as an alternative generation fuel to nuclear power, and the share of oil, which had been declining in recent years, rose to 44.5% in 2012. In 2018, the introduction of renewable energy in power generation and the reduction in oil-fired generation, largely due to the restart of nuclear power, saw the share of oil fall for the sixth consecutive year to 37.6%, the lowest since 1965 and the third consecutive year of decline below 40%. Detailed data are provided in the Fig.1.9.

Table.1 Energy self-sufficiency ratio

Year	Self-sufficiency ratio (%)
1960	58.1
1970	15.3
1973	9.2
1980	12.6
1990	17
2000	20.2
2005	19.6
2010	20.3
2011	11.6
2012	6.7
2013	6.6
2014	6.4
2015	7.4
2016	8.2
2017	9.5
2018	11.8
2019	12.1

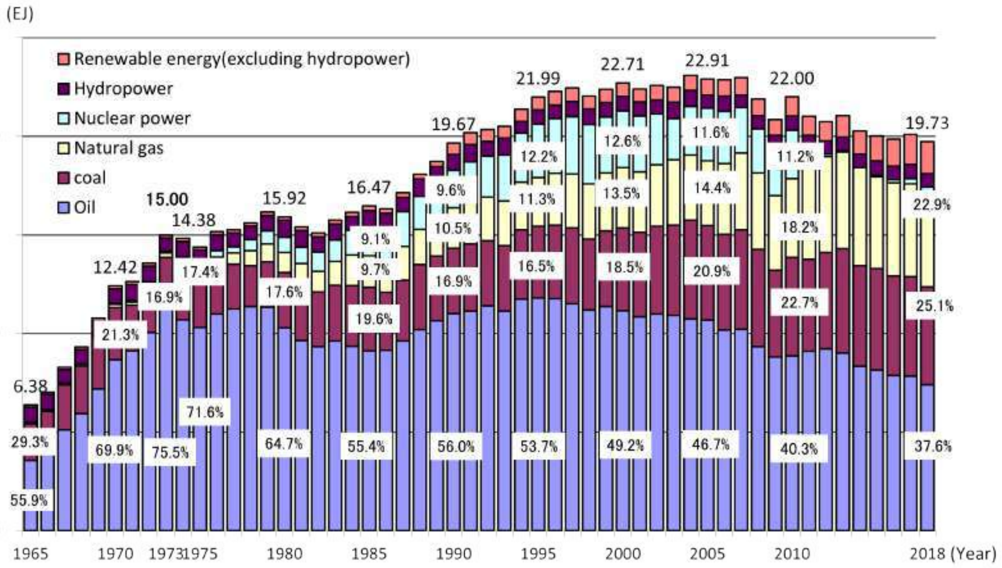


Fig. 1.9 Changes in domestic supply of primary energy ("Renewable energy (excluding hydropower)" refers to solar power, wind power, biomass, geothermal power, etc.)

And in the view of trends in final electricity consumption by sectors, Electricity use has grown steadily since the 1973 oil crisis, increasing 2.6 times between 1973 and 2007. On the other hand, from 2008 to 2009, the economy was in the doldrums due to the global financial crisis, and electricity consumption began to decline, especially for businesses. Then, as the economy recovered, electricity consumption increased by 4.7% year-on-year to 1,035.4 billion kWh in 2010. However, with the TEPCO Fukushima Crisis as an opportunity to tighten power supply and demand, the decline continued in 2011 by 3.7% from the previous year to 2015 due to the issuance of power restriction orders and the setting of power saving targets. 2017 increased from the previous year, but 2018 decreased by 1.9% from the previous year to 945.5 billion kWh.

In terms of sectoral composition ratio, industry remains the largest consumer of electricity, but since the 1990s, demand has turned to a downward trend, decreasing by 18.0 % from its peak in 1991 to 350.6 billion kWh, due to low production in the materials sector and progress in energy conservation and emission reduction. In the long term, the growth in electricity consumption is mainly driven by strong consumer consumption such as work and other households. The increase in electricity consumption in other business sectors is due to the increase in office buildings and the rapid spread of office equipment in office buildings, reflecting the progress of computerization and services in the economy. In the household sector, electricity consumption maintained an increasing trend through fiscal 2005 due to the rapid spread of air conditioning applications such as air conditioners and electric blankets and other household appliances as a result of rising living standards. Since then, the market share of energy-efficient home appliances has expanded and leveled off as equipment ownership has become saturated. From 2011, the accident at TEPCO's Fukushima Daiichi nuclear power plant raised awareness of electricity conservation and turned to a downward trend. In 2018, commercial and other household demand accounted for 61.1% of final electricity consumption. The electrification rate of end-use energy consumption was 12.7% in 1970 and reached 25.9%

in 2018.

The way electricity is used varies greatly depending on seasonal changes and daytime power changes. Especially in recent years, there has been a high ratio of “summer demand” and “winter demand” due to air conditioning and other reasons, so the difference in the way electricity is used is increasing. The electrification rate in final energy consumption was 12.7% in 1970 and reached 25.9% in 2018.

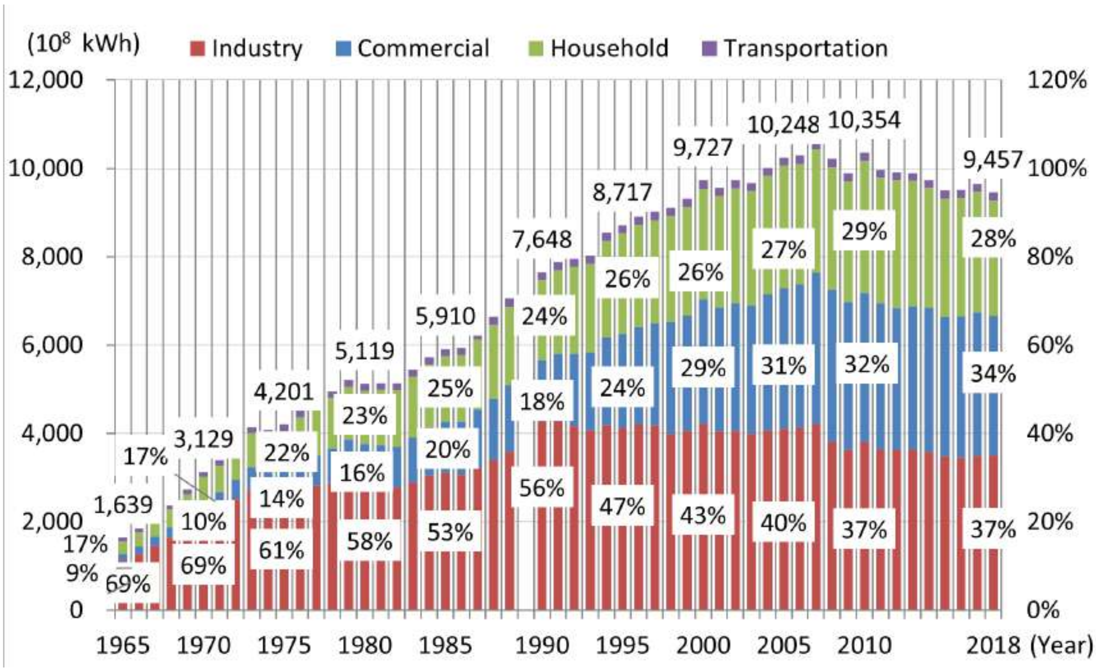


Fig. 1.10 Trends in final electricity consumption by sector

And about the supply trends, In Japan, the first oil shock in 1973 triggered the diversification of power sources. On the other hand, nuclear power plants have been shut down since September 2013 due to the Great East Japan Earthquake, but Kyushu Electric Power’s Kawauchi Nuclear Power Plant Unit 1 resumed operation in August 2015, and nuclear power plants are being restarted in sequence. As shown in Fig.1.10, in 2018, the power source composition was 38.3% (402.9 billion kWh) LNG-fired, 31.6% (332.4 billion kWh) coal-fired, 7.0% (73.7 billion kWh) oil and other thermal, 9.2% (96.3 billion kWh) new energy and other, 7.7% (81 billion kWh) hydro, and 6.2% (64.9 billion kWh) nuclear. Compared to 2017, the share of fossil fuels decreased while that of nuclear power and new energy increased.

More than 60 years have passed since Japan’s Basic Act on Nuclear Power (Act No. 186) was enacted in 1955, and the country’s first commercial nuclear power plant, the Japan Nuclear Power Company Tokai Power Station (166 MW), began commercial operation in 1966, and in 2010, nuclear power generation reached 288.2 billion kWh. The total amount of electricity generated was 188.2 billion kWh. However, due to the gradual increase in the number of nuclear power plants shut down for inspections and other reasons following the Fukushima Crisis in 2011, the amount of electricity generated in 2012 decreased to 15.9 billion kWh, 9.3 billion kWh in 2013, and 0 kWh in fiscal 2014. The aforementioned nuclear power plants have been restarted since 2015, and the amount of electricity generated in 2018 increased to 64.9 billion kWh. Although the composition ratio has increased from the previous year, it remains low relative to the installed capacity (excluding decommissioning).

As shown in Fig.1.11, Electricity load leveling measures to mitigate these factors will reduce the risks in electricity supply associated with rapid increases in electricity demand and will also contribute to stabilizing the electricity supply system and improving its reliability. The annual load factor (the ratio of annual average power to annual maximum power), which expresses the efficiency of power generation facilities, was generally above 60% in the 1970s, but declined to the 50% level in the 1990s. The rate has been improving and is now hovering in the 60% range. However, the annual load factor is also greatly affected by summer temperatures, with a high value of 66.7% in 2009, which was a cool summer. Conversely, it dropped to 62.5% in 2010, which was the hottest summer on record. After the Great East Japan Earthquake, the rate reached as high as 67.8% in 2011 due to the introduction of energy-saving equipment and the promotion of peak shaving. Thereafter, it remained above 65% except in 2015, but dropped to 62.1% in 2018 the introduction of energy-saving equipment and the promotion of peaking, with the increasing awareness of environmental protection and the popularization of high-efficiency appliances, there has been a significant decrease in electricity consumption.

Japan is prone to natural disasters such as typhoons and earthquakes, which can have a significant impact on electricity usage. For example, in 2018, a heatwave led to a surge in electricity demand as people turned up their air conditioning, leading to power outages in some areas. Similarly, in 2019, a series of powerful typhoons caused widespread damage to power infrastructure, leading to disruptions in electricity supply.

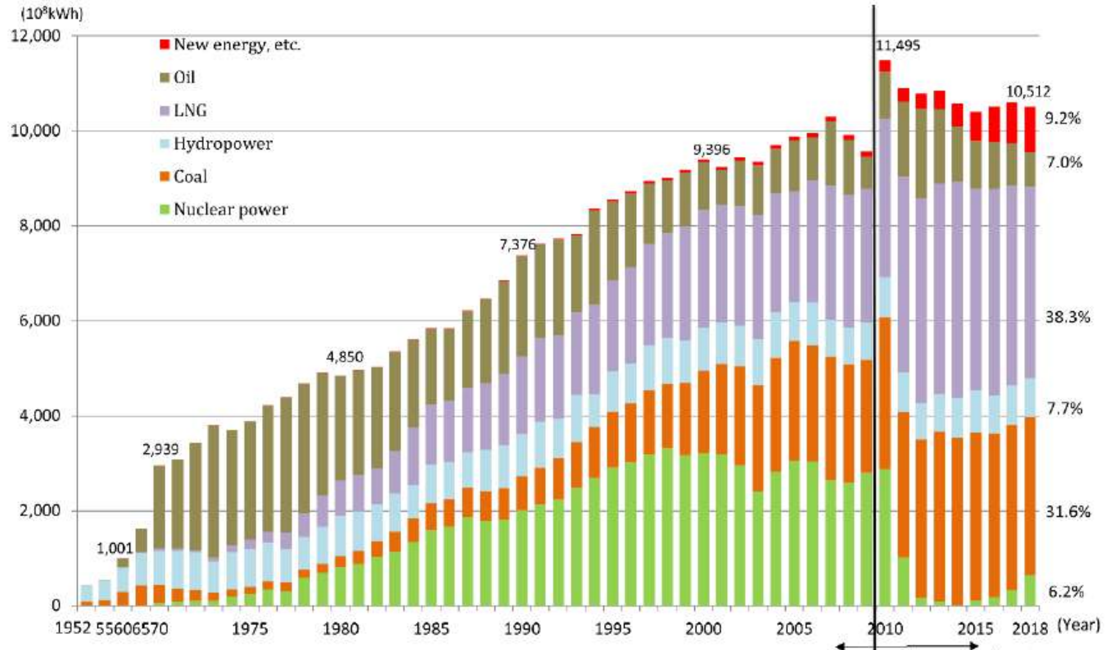
Fig. 1.11 Changes in electricity usage for one year in Japan

Coal is an energy source that is relatively cheaper than oil, LNG, and other fossil fuels because of its abundance in proven and probable reserves and its widespread availability in countries with relatively stable political conditions, making it an excellent source of supply stability. Coal-fired power generation has been introduced as part of the shift from an oil-centered energy supply structure in the wake of the two oil shocks. 332.4 billion kWh of electricity was generated by coal-fired power plants in 2018, down 4.3% from the previous year.

Since LNG purchase from Alaska in 1969, it has been introduced as an extremely effective fuel for power generation, taking advantage of its characteristics as a stable and clean energy source and as a measure to prevent air pollution in urban areas with strict environmental regulations. After two oil shocks, LNG has become an important pillar of alternative energy to oil, and its introduction has been promoted; since 2011, its use as an alternative to nuclear power has increased, and the amount of electricity generated by LNG-fired power plants in 2018 was 402.9 billion kWh.

After the first oil crisis, the generation of electricity from petroleum continued to decline in the first half of the 1980s due to the development and introduction of alternative energy sources to oil, etc. After 1987, it temporarily turned to an increasing trend, but due to new nuclear power plants starting operation and operating at high capacity, it has been changing from a base power source to a middle power source and then to a peak power source. Since 2011, the amount of electricity generated had been rising to compensate for the decline in the operating rate of nuclear power plants, but due to the restart of nuclear power plants and the spread of renewable energy, the amount of electricity generated in 2018 decreased by 17.2% from the previous to 73.7 billion kWh.

Development of hydropower began before World War II, and by the 1960s development was nearly complete at sites suitable for large-scale hydropower plants. The amount of electricity generated has remained flat, with hydropower, including pumped storage, totaling 81 billion kWh in 2018.

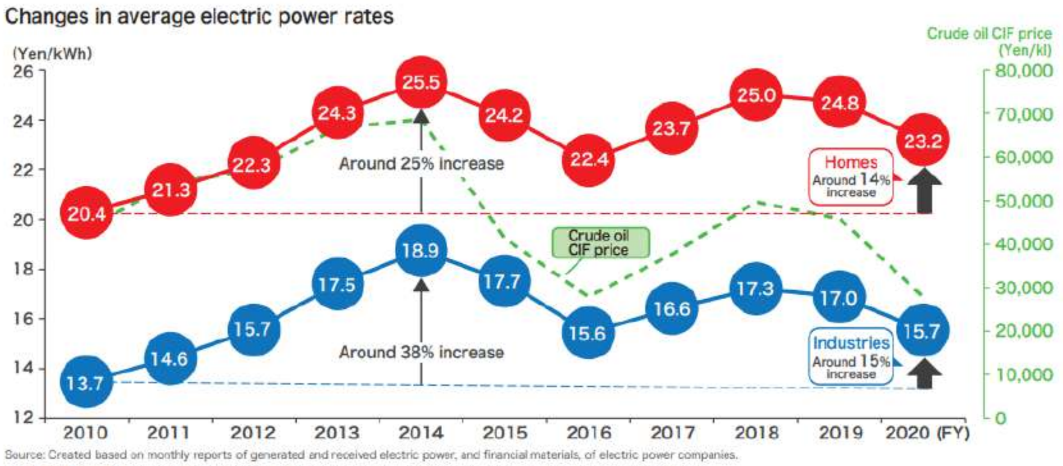


Based on "Summary of Power Source Development" and "Summary of Electric Power Supply Plan" by Agency for Natural Resources and Energy

Based on Comprehensive Energy Statistics, Agency for Natural Resources and Energy

Fig. 1.12 Changes in electricity usage for one year in Japan (Excluding Okinawa Electric Power until 1971.)

Another important issue is the electricity price. Electricity prices rose sharply after the oil shocks, partly because oil-fired thermal power was the mainstream at the time but have since been on a downward trend. In 2010, electricity prices returned to 2007 levels due to lower prices for crude oil and other fuels, but since 2011, electricity prices have risen again due to the shutdown of nuclear power plants and the impact of higher thermal power generation costs resulting from soaring fuel prices and other factors, as shown in Fig.1.13. Electricity rates increased multiple times since the Great East Japan Earthquake. Japan relies heavily on imported fossil fuels, which can be subject to price fluctuations in the global market. In recent years, changes in fuel prices have led to changes in electricity rates. For example, in the aftermath of the Fukushima disaster in 2011, Japan shut down its nuclear reactors and increased its reliance on fossil fuels, which led to a surge in electricity rates. This was attributable to increased utilization of thermal power to alleviate the effects caused by the shutdown of nuclear power plants. It was also due to fuel prices rising until 2014. In 2015 and 2016, electricity prices declined significantly due to lower thermal generation costs associated with lower fuel prices. In 2016, Japan's electricity market was fully liberalized, opening up the market to competition from new suppliers. This led to a decline in average electricity rates, as new suppliers entered the market and offered lower prices to customers. According to the Ministry of Economy, Trade and Industry (METI), the average electricity rate for households in Japan decreased by around 10% between 2015 and 2019. Electricity rates had increased by around 16% for homes and around 21% for industries in 2017 compared with rates before the Great East Japan Earthquake. In 2018, electricity prices increased by 4.3% on average for electric light and power due to higher thermal generation costs associated with higher fuel prices. Electricity rates are influenced largely by power sources (methods of generation). Thermal power, using fossil fuels such as oil and LNG (liquefied natural Gas) mostly imported from abroad with high energy costs, is vulnerable to changes in international energy prices. Dependence of power sources on fossil fuels was as high as 80.9% in 2017.



Source: Created based on monthly reports of generated and received electric power, and financial materials, of electric power companies.
Crude oil CIF price: Transaction price consisting of the import price plus related costs, such as transport cost and insurance cost.

Fig. 1.13 Changes in average electricity rates [9] (Created based on monthly reports of generated and received electric power, and financial materials of each electric power company)

Another factor that has influenced electricity prices in recent years is renewable energy. Japan introduced a feed-in tariff (FIT) program in 2012, under which electricity generated by renewable energy sources will be purchased at a fixed price. Thanks to the FIT program, the installed capacity of renewable energy sources has increased rapidly. Although the expansion of renewable energy is important for the future, the purchase cost has reached 3.6 trillion-yen, part of which is collected through a “surcharge” paid by electricity consumers. The surcharge has been rising year by year, which is one of the reasons for the increase in electricity prices. Electric power rates greatly influence economic activities. Rates rose after the Great East Japan Earthquake. They declined from 2014 to 2016 thanks to falling crude oil prices, but they have been on an upward trend thereafter. They have increased by 14% for homes and 15% for industry compared with 2010 levels. Due to the scarcity of energy resources in Japan, electric power rates are largely influenced by imported fuel oil prices. In fact, the rates have been linked to the prices of fuels such as crude oil and LNG. Fuel oil prices were relatively stable for several years, but increased in 2020 and 2021, which impacted the current power rates.

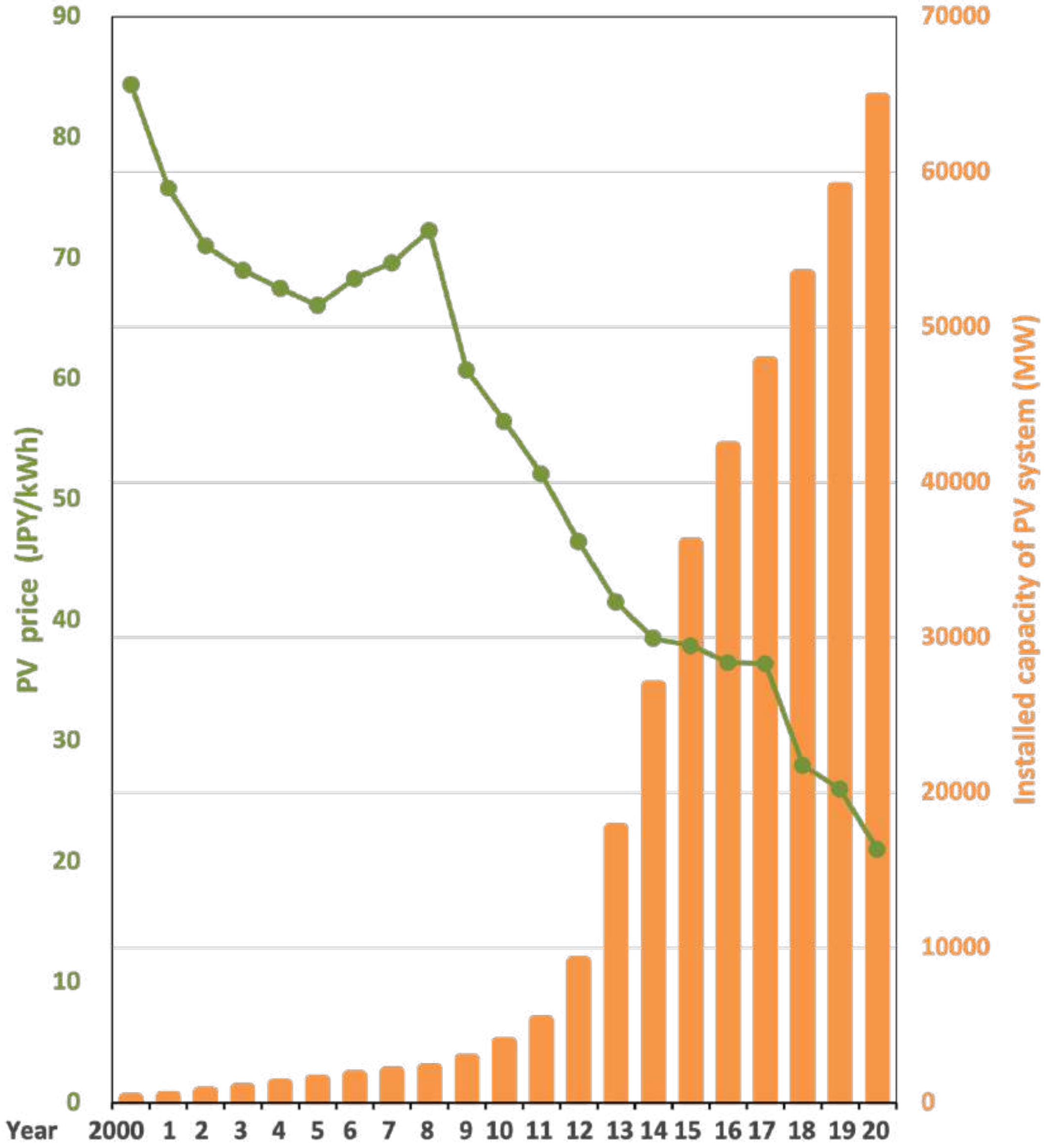


Fig. 1.14 Changes in the installed capacity of PV system in Japan (Source: IEA, Trends

2021 in Photovoltaic applications)

The installed capacity of photovoltaic (PV) systems in Japan has undergone significant changes in recent years, driven by changes in government policies and incentives, as well as improvements in technology and declining costs, as shown in Fig.1.14.

Rapid growth from 2012-2015: Following the introduction of the Feed-in Tariff (FIT) system in 2012, which provided generous subsidies for renewable energy, the installed capacity of PV systems in Japan grew rapidly. In 2015, Japan surpassed Germany to become the world's largest solar energy market, with an installed capacity of over 34 gigawatts (GW).

Decline from 2016-2019: In 2016, the Japanese government began scaling back FIT subsidies for solar energy, leading to a decline in new installations. In addition, changes to grid connection rules and other regulations made it more difficult for new PV projects to get off the ground. As a result, the total installed capacity of PV systems in Japan declined from its peak in 2015 to around 58 GW by the end of 2019.

Recovery in 2020: In 2020, the Japanese government announced a new set of incentives and policies aimed at promoting the growth of renewable energy, including solar. This led to a rebound in new installations of PV systems, with an estimated 3.2 GW installed in the first half of 2020 alone. As of the end of 2020, the total installed capacity of PV systems in Japan was around 66 GW, making it one of the largest solar energy markets in the world.

In summary, the installed capacity of PV systems in Japan has undergone significant changes in recent years, driven by shifts in government policies, regulations, and technological and cost improvements. Despite the challenges, solar energy continues to play a significant role in Japan's energy mix and is expected to continue to grow in the coming years.

1.1.3 Energy supply and demand prospect in the world

Electricity is the fastest growing source of final energy demand and is set to grow faster than overall energy consumption over the next 25 years. The rapid spread of renewable energy sources such as wind and solar photovoltaics is putting electricity at the forefront of the clean energy transition, providing access to nearly 800 million people who are currently disenfranchised, and helping to reduce air pollution and meet climate targets.

This radical shift also requires new approaches to the design and operation of electricity systems. Sunlight and wind are not always available, and a range of back-up generation options and smarter and better-connected grids are needed. The electricity sector now attracts more investment than oil and gas combined - necessary both to change the generation mix and to upgrade ageing infrastructure. Further policy action is essential to ensure that rapid electrification is matched by an equally rapid roll-out of low-carbon energy and does not lead to a reduction in energy system security.

The world energy demand depends on various factors, including economic growth, population growth, technological advances, energy policies, and climate goals. Here are some key trends and projections for global energy demand:

Steady growth in energy demand: Despite efforts to promote energy efficiency and decarbonization, global energy demand is expected to grow over the next few decades, driven by population growth, rising living standards, and economic development in emerging economies. The International Energy Agency (IEA) projects that global energy demand will increase by 4% between 2019 and 2025 and 20% by 2040.

Shifts in energy mix: The share of renewable energy sources in the global energy mix is expected to increase, driven by declining costs, supportive policies, and technological advances. The IEA projects that renewable energy sources will account for 80% of the growth in global electricity generation over the next decade. However, fossil fuels are expected to remain a significant part of the energy mix for the foreseeable future.

Regional differences: Energy demand growth and energy mix trends will vary by region and country, depending on economic development, population growth, and energy policies. Emerging economies in Asia, Africa, and the Middle East are expected to account for much of the increase in energy demand. In contrast, developed economies in Europe and North America will likely see slower growth or even declines in energy demand.

Uncertainties and risks: The outlook for global energy demand is subject to various uncertainties and risks, including geopolitical tensions, fluctuations in energy prices, technological disruptions, and policy changes. The pace of energy transition and the extent to which countries can meet their climate goals will also be critical factors shaping the future of global energy demand.

In general, while the world energy demand outlook suggests continued growth in the coming decades, efforts to shift towards a more sustainable, low-carbon energy system are also gaining momentum, driven by technological advances, policy support, and growing awareness of the risks of climate change.

Let's take a look at the International Energy Agency’s (IEA) projections of future global energy demand and compare them with the actual results for 2017 (Fig.1.15). The Current policies scenario is a case in which no additional policy measures are taken beyond those currently in force, while the Stated policies scenario is a case in which the currently announced policy targets, such as greenhouse gas reduction targets, are not implemented. The sustainable development scenario is a "backward-looking" scenario in which the measures necessary to reduce the temperature increase well below 2°C are achieved and existing technologies continue to advance scenario.

Global primary energy consumption in 2040 is projected to be 19.2 billion tons of oil equivalent, about 1.37 times higher than in 2017 under the current policy scenario, whereas consumption under the published policy scenario will be lower than under the current policy scenario, but still 1.27% higher than in 2017. The difference between the published policy scenario and the sustainable development scenario (0.95 times the 2017 level) is stark, and the “2°C target” will not be reached under the greenhouse gas emission reduction targets pledged by the world's nations under the Paris Agreement.

Next, let’s look at each energy source: the IEA scenarios show stronger climate action in the order of current policy, announced policy, and sustainable development; it’s easy to imagine that the stronger the climate action, the more low-carbon energy and technology will be used, and that's exactly what the scenario analysis shows.

Coal is seen as the most affected fossil energy source: compared to coal consumption in 2017, the current policy scenario increases coal consumption by a factor of 1.18, while it remains flat at 1.00 in the published policy scenario. sustainable development The scenario reduces coal consumption to less than half, 0.39 times the 2017 actual consumption; the same trend is observed for oil, but the reduction in consumption in the published policy scenario (1.11 times the 2017 level) and the sustainable development scenario (0.68 times the 2017 level) is less than in the coal This is because coal and oil have different primary uses: coal is used primarily for power generation and industrial applications, which can be replaced relatively easily by natural gas and renewable energy. Petroleum, on the other hand, is used primarily as a fuel for automobiles, and it is not easy to convert it to other forms of energy, which is why the decline in consumption of petroleum has been slower. The exception among fossil energies is natural gas, whose use is expected to increase in various sectors because it is cleaner than coal and oil, and even under the sustainable development scenario, consumption is projected to increase slightly, by a factor of 1.01 compared to 2017.

Renewable energy, including hydroelectricity with very low carbon emissions, and nuclear power are expected to increase under both scenarios, with the most notable increases in renewable energy, especially wind and solar. The published policy scenario predicts a 1.99-fold increase, and the sustainable development scenario predicts a 2.44-fold increase.

The future is uncertain, and these scenarios are only estimates based on certain assumptions, but it is of utmost importance to think about a better energy future while conducting such scenario analysis.

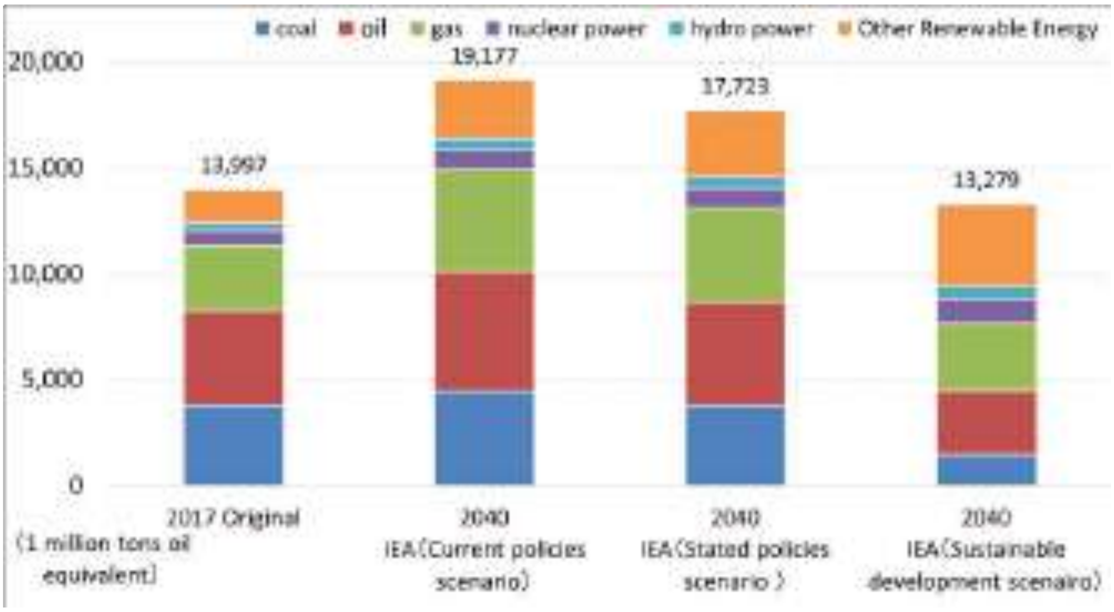


Fig.1.15 World Energy Demand Outlook [10] (by energy source, primary energy)

1.1.4 Energy supply and demand prospect in Japan

National Institute of Population and Social Security Research has estimated the population change of Japan by region (Fig.1.16).

The population of Japan has been undergoing significant changes in recent years, driven by factors such as low birth rates, an aging population, and migration. Here are some projections for the population change in Japan from 2015 to 2045, based on data from the United Nations:

Total population: Japan's total population was around 127 million in 2015 but is projected to decline gradually over the next few decades. By 2045, the population is projected to be about 109 million, a decline of about 14% compared to 2015.

Aging population: Japan has one of the oldest populations in the world, and this trend is expected to continue in the coming years. The proportion of the population aged 65 and above was around 26% in 2015 but is projected to increase to about 34 % by 2045.

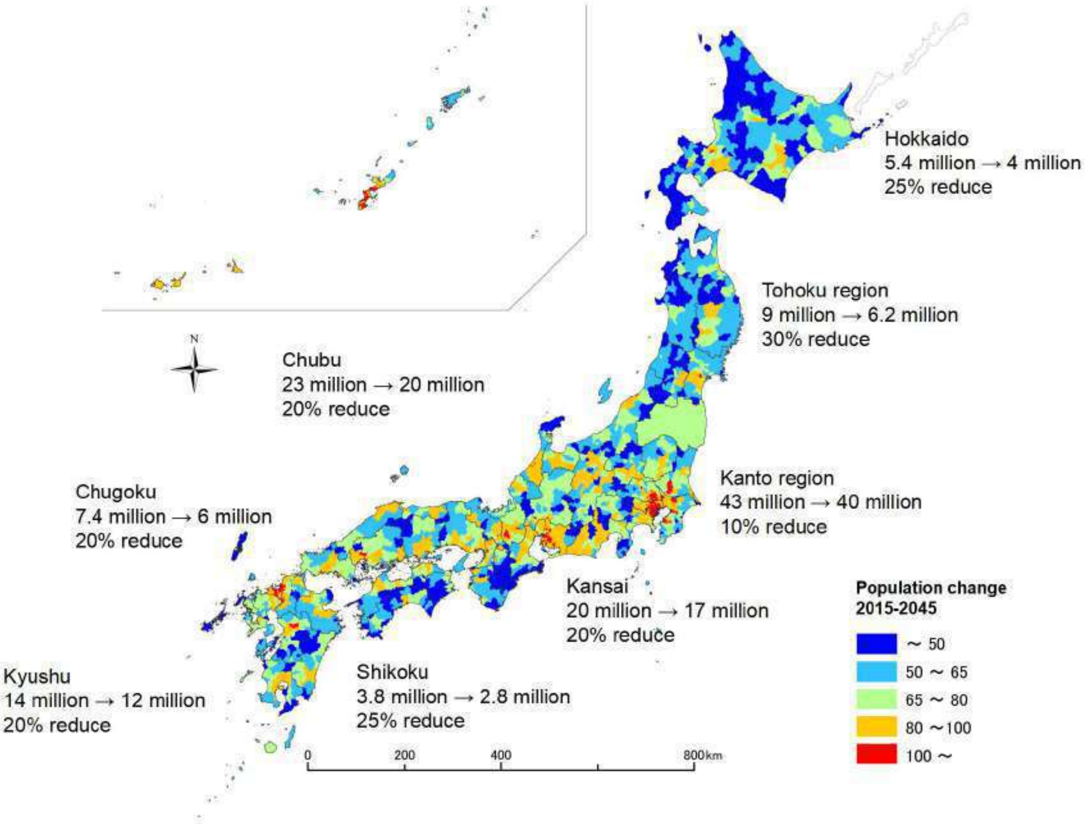


Fig.1.16 Japanese population change from 2015 to 2045[11]

Declining workforce: The aging population and low birth rates are also leading to a decline in the size of the force in Japan. The number of people aged 15-64, representing the working-age population, was around 75 million in 2015 but is projected to decline to about 56 million by 2045, a decline of about 25%.

Impacts on economy and society: The demographic changes in Japan are expected to significantly impact the economy and society, including increased healthcare and social welfare costs, labor shortages in specific sectors, and declining consumer demand. The Japanese government is implementing various policies and initiatives to address these challenges, including promoting immigration, increasing support for families with children, and encouraging longer working lives.

In general, the population change in Japan from 2015 to 2045 is expected to be characterized by a gradual decline in the total population, an aging population, and a declining workforce. These trends are expected to challenge Japan's economy and society significantly. Still, the government and other stakeholders are addressing these challenges through various policies and initiatives.

By 2045, the population of various regions of Japan will decrease by 10%-30%. In the future, although the population decline in many regions is expected to lead to a decline in electricity demand, there are also factors that will lead to an increase in electricity demand due to the progress of population inflow and the further advancement of electrification in some cities.

Japan’s future power demand depends on various factors, including economic growth, population change, technological advances, energy policies, and climate goals.

Declining power demand: Japan's power demand has declined in recent years due to population aging and energy efficiency measures. The Ministry of Economy, Trade, and Industry (METI) projects that Japan's power demand will decline gradually over the next decade, reaching around 856 billion kWh in 2030, down from about 925 billion kWh in 2018.

Shifts in power generation mix: The share of renewable energy sources in Japan's power generation mix is expected to increase, driven by supportive policies, declining costs, and technological advances. METI projects that the share of renewable energy sources in Japan's power generation mix will increase from 18% in 2018 to 22-24% in 2030. However, fossil fuels are expected to remain a significant part of the power generation mix for the foreseeable future.

Nuclear power: Japan's nuclear power sector has been undergoing significant changes recently following the Fukushima disaster in 2011. While some nuclear power plants have resumed operation, others remain offline, and public opinion remains divided on the role of nuclear power in Japan's energy mix. METI projects that nuclear power will account for around 20-22% of Japan's power generation in 2030, down from about 30% before the Fukushima disaster.

Climate goals: Japan has set a goal of achieving net-zero greenhouse gas emissions by 2050, which is expected to have significant implications for the power sector. The government has pledged to increase the share of renewable energy sources in the power generation mix and promote energy efficiency. Still, the pace and scale of the energy transition will depend on various factors.

While the prospect for Japan's power demand suggests a continued decline in the coming years (Fig.1.17), efforts to shift towards a more sustainable, low-carbon power system are also gaining momentum, driven by policy support, declining costs, and growing awareness of the risks of climate change.

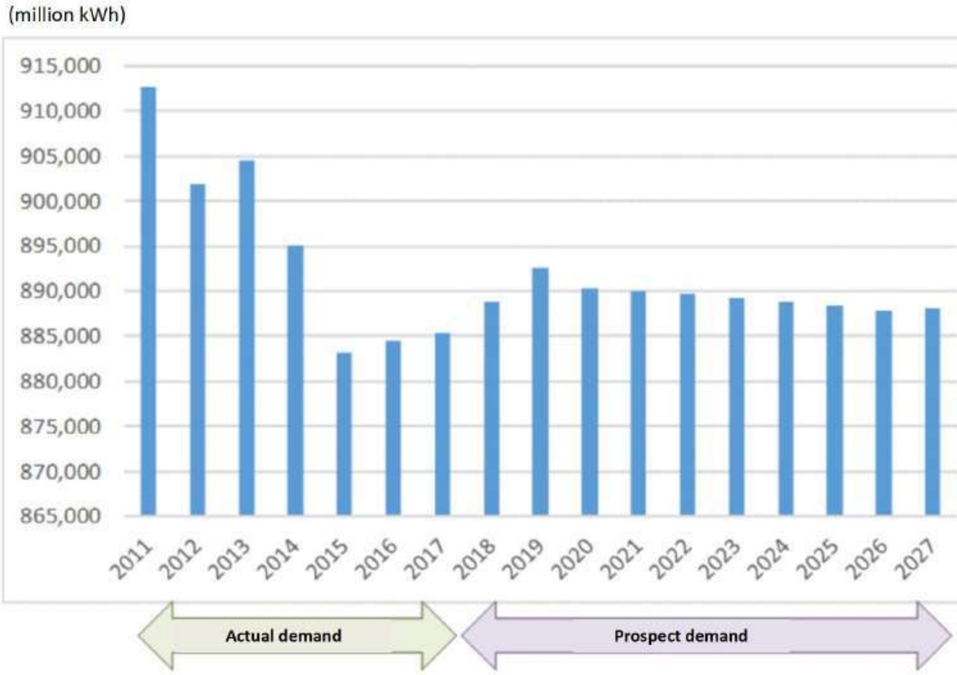


Fig.1.17 Prospect of Japanese future power demand [12]

1.2 Development status of renewable energy

Renewable energy is clean, naturally renewable, regionally distributed, low in energy density and intermittent. And it remains an underutilized resource within urban environments[13]. Renewable energy technologies like solar and wind are essential for reducing emissions of the power sector, which currently account large amount of GHG emissions. There is no possibility of energy depletion from renewable energy sources. Therefore, the development and use of renewable energy sources is receiving increasing attention in many countries, especially in countries with energy shortages. With the recovery of nuclear energy and the rapid development of renewable energy worldwide, the development of clean energy is on a year-on-year upward trend and its growth rate is second only to that of natural gas. According to statistics, global renewable energy consumption increased by 16% in 2017 compared to 2016 and maintained a double-digit growth rate. Of this, solar energy grew at 29.6% and wind energy at 15.6%. Taking into account nuclear, hydro and natural gas, the global share of clean energy consumption reached 38% in 2017, surpassing the 28% of coal consumption and 34% of oil consumption. At the same time, electricity generation structures also changed with the renewable energy development. Among the renewable energy sources, solar and wind power generation is considered to be an important component of a hybrid distributed energy system. Renewable energy technologies play an important role in the energy systems of the future, not only in achieving a low carbon society but also in providing socio-economic benefits [14].

1.2.1 The development and status of renewable energy in the world

Renewable energy is the fastest-growing energy source in the world. Globally, about 11.2% of the energy consumed globally for heating, power, and transportation came from modern renewables in 2019 (i.e., biomass, geothermal, solar, hydro, wind, and biofuels), up from 8.7

percent a decade prior. Renewables made up 29% of global electricity generation by the end of 2020. Led by wind power and solar PV, more than 256 GW of capacity was added in 2020, an increase of nearly 10% in total installed renewable power capacity. The International Energy Agency notes that the development and deployment of renewable electricity technologies are projected to continue to be deployed at record levels, but government policies and financial support are needed to incentivize even greater deployments of clean electricity (and supporting infrastructure) to give the world a chance to achieve its net zero climate goals.

As shown in Fig.1.18, despite pandemic-induced supply chain challenges and construction delays, renewable capacity additions in 2020 expanded by more than 45% from 2019 and broke another record. An exceptional 90% rise in global wind capacity additions led the expansion. Also underpinning this record growth was the 23% expansion of new solar PV installations to almost 135 GW in 2020. Policy deadlines in China, the U.S. and Vietnam have spurred an unprecedented boom in renewable energy capacity additions in 2020.

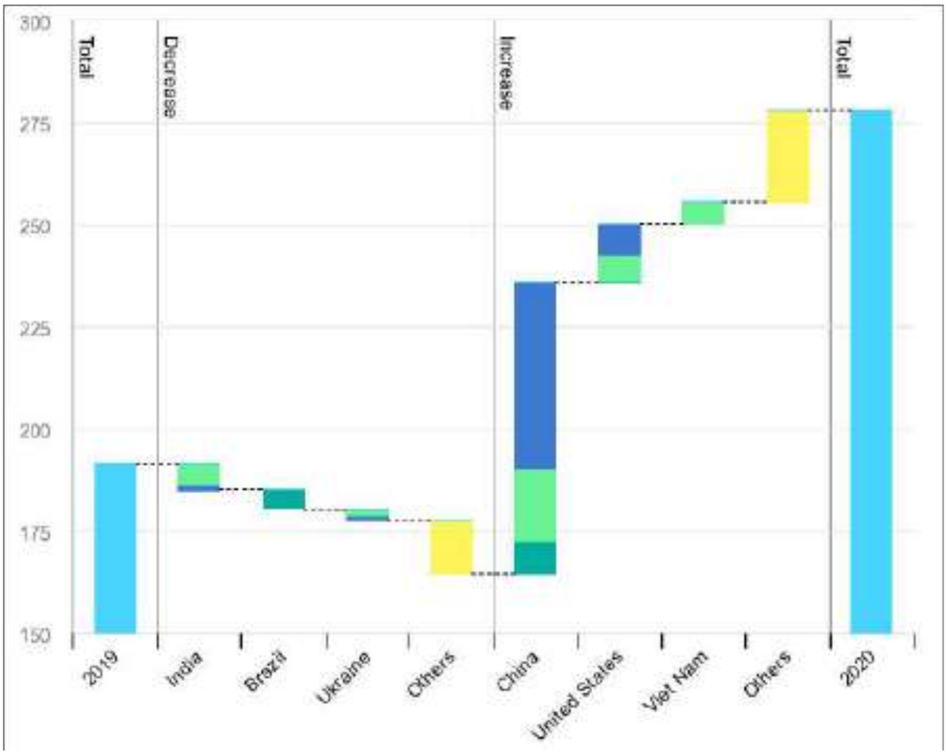


Fig.1.18 Renewable capacity addition changes from 2019 to 2020[15]

China alone accounts for more than 80% of annual installed capacity growth from 2019 to 2020, as onshore wind and solar PV projects contracted under China's previous FIT program, as well as those awarded in previous central or provincial competitive auctions, must be connected to the grid by the end of 2020. In the U.S., wind developers are eager to complete their projects before the Production Tax Credit (PTC) expires, even though it has been extended by one year, to December 2020. In Vietnam, the phasing out of the FIT for solar PV projects has led to an unprecedented boom in commercial and residential installations.

Renewable energy capacity additions are expected to remain exceptional, with 270 GW coming online in 2021 and 280 GW in 2022. This expansion is more than 50% higher than the record annual capacity additions in 2017-2019, so renewables are expected to account for 90%

of total global electricity capacity growth in 2021 and 2022.

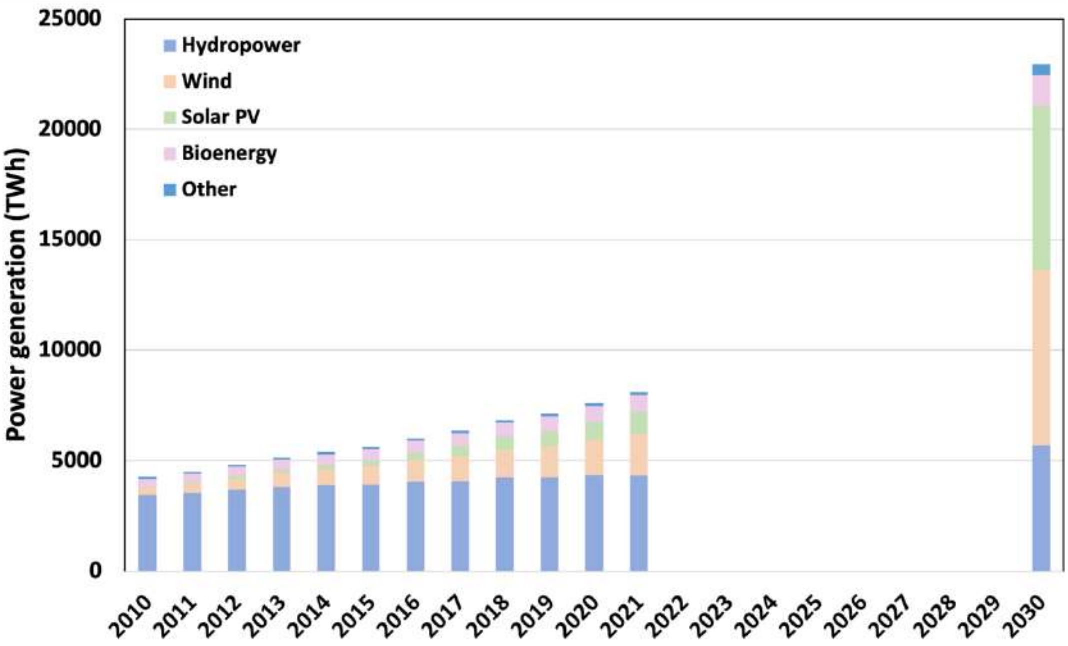


Fig.1.19 Renewable power generation by technology in the Net Zero Scenario, 2010-2030

Renewable energy capacity additions are expected to remain exceptional, with 270 GW coming online in 2021 and 280 GW in 2022. This expansion is more than 50% higher than the record annual capacity additions in 2017-2019, so renewables are expected to account for 90% of total global electricity capacity growth in 2021 and 2022.

In the global energy structure transformation stage, Renewable energy is the fastest growing of all energy sources, and it plays a key role in clean energy transitions and the deployment of renewable power is one of the main enablers of keeping the rise in average global temperatures below 1.5°C.

Fig.1.19 shows renewable power generation by technology in the Net Zero Scenario. Solar PV has been the fastest growing technology by capacity additions in recent years; however, even the record 150 GW added in 2021 is only about one-third of the average annual additions during 2022-2030 in the Net Zero Scenario milestones. Solar PV and wind are driving the growth in renewables generation, but activity needs to increase rapidly be in step with the Net Zero Scenario. Still, renewable electricity needs to expand faster to reach the milestones in the Net Zero Emissions by 2050 Scenario, where the renewable share of generation increases from almost 29% in 2021 to more than 60% by 2030.

As show in Fig.1.20, net renewable capacity additions reached a record high of 261 GW in 2020, despite the challenges posed by the COVID-19 pandemic. This represents an increase of 45% compared to 2019 and is more than double the net capacity additions from fossil fuel sources in the same year.

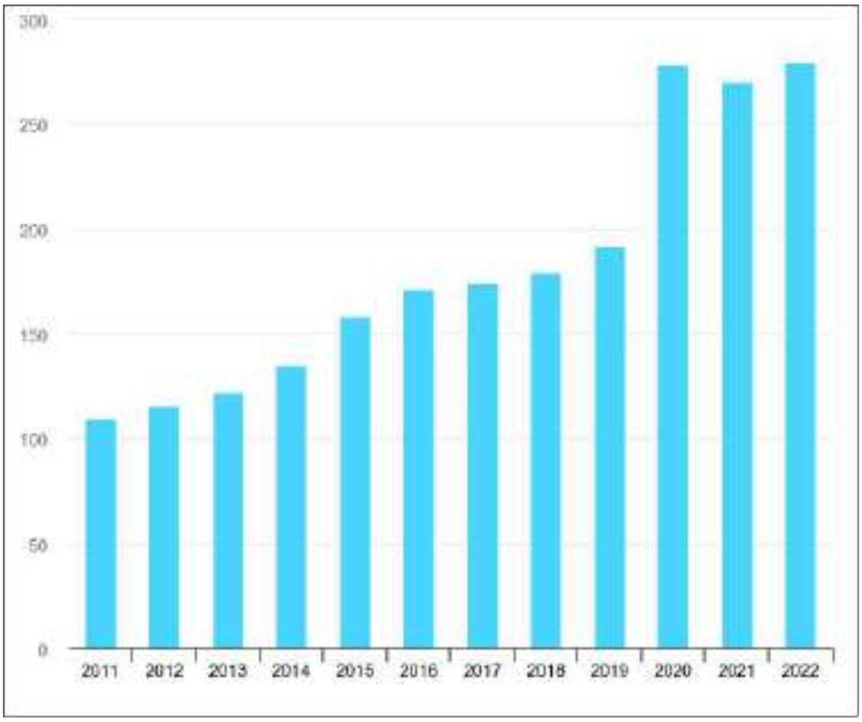


Fig.1.20 Net renewable capacity additions, 2011-2022

The discovery and use of fossil energy has brought a huge leap in human history. In the nineteenth century, coal was burned in steam engines, igniting the flame of the Industrial Revolution and illuminating the way forward for human civilization. However, with the continuous development of human society, the excessive exploitation and use of fossil energy has also caused increasingly serious environmental problems. Since the Industrial Revolution, the total amount of carbon dioxide 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. Following this trend, it will exceed 2°C by the middle of this century. Climate change has become a global non-traditional security issue. Global air pollution threatens the basic living conditions of human beings. Under climate risks, the transformation of the global energy structure is imminent.

In the course of historical development, the first two energy structure transitions have gone through a long process. In this process, technological breakthroughs and institutional arrangements were 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 technology areas, but also the integration and coordination of many interest groups. Therefore, the positioning of development strategies and institutional arrangements will be decisive factors for the new energy revolution. In different development periods, different countries have different strategic positioning for renewable energy. This strategic positioning determines the direction of policy support for renewable energy and determines its development process.

1.2.2 The development and status of renewable energy in Japan

Renewable energy currently has various problems in terms of stable supply and cost, but it is promising and diverse because it does not emit greenhouse gases, can be produced domestically, contributes to energy security, and is an important low-carbon domestic energy source that will be utilized in the long run while reducing the environmental load. In view of the rising momentum of decarbonization triggered by the Paris Agreement and environmental changes such as the reduction in the cost of renewable energy generation around the world, it will continue to develop as a major energy source for long-term stability and will play a role in Japan's energy. The Japanese government is actively promoting the introduction of renewable energy.

In order to vigorously promote the introduction of renewable energy, the FIT policy was introduced in July 2012 as a special temporary measure with a burden on the public. Under the FIT policy, Under the FIT system, renewable energy power producers are guaranteed to purchase electricity from electric utilities for a long period of time at a fixed price at which investment incentives are secured and are also exempted from the appropriate market transactions as a power producer. This has ensured a strong predictability in the return on investment. On the other hand, the costs required for electric utilities to purchase renewable electricity at a fixed price based on the purchase obligation are borne by general electricity users as part of their electricity charges, making the system directly linked to the burden on the public to expand the introduction of renewable electricity.

Since the propose of the FIT policy in July 2012, the introduction of renewable energy has expanded rapidly, with the amount of renewable energy introduced approximately 3.4 times greater than before the start of the policy. Specifically, as of the end of September 2019, the number of facilities that have newly started operation since the start of the FIT policy is approximately 50.62 million kW, and the number of facilities that have been certified under the FIT policy is approximately 89.18 million kW. The introduction of renewable energies under the FIT policy has led to a significant increase in the burden on the public, and although the introduction of renewable energies such as solar power has been progressing since the FIT policy was introduced and the cost of power generation has been decreasing, it is still high compared to international standards, resulting in an increased burden on the public.

In fact, between 2012 and 2018, the amount of renewable energy, excluding hydropower, has tripled, and the share of renewable energy in the power supply has expanded to 16.9% in 2018, as shown in Table.2. With the expansion of installation, some power sources have been able to reduce their costs. For example, the purchase price of solar power has been successively reduced in line with the decrease in the unit cost of power generation as it spreads, and as of 2019, the purchase price of solar power and the price of electricity in the market have reached almost the same price level. In order for renewable energy to become a major power source, these competitive power sources must be integrated into the electricity market in the same way as other power sources to further expand the market.

Table.2 International Comparison of Installed Renewable Energy Generation Capacity (Excluding Hydropower)[16]

Year	Installed capacity 2012 (billion kWh)	Installed capacity 2018 (billion kWh)
Japan	309	963
EU	4,319	6,743
Germany	1,217	1,962
England	358	934
World	10,693	21,870

Despite concerns over the impact of the current energy crisis, global carbon dioxide (CO2) emissions from fossil fuel combustion are expected to grow by less than 1% in 2022 due to the strong expansion of renewable energy.

Solar PV and wind are leading an increase in global renewable electricity generation in 2022 of more than 700 terawatt-hours (TWh), the largest annual rise on record. Without this increase, global CO2 emissions would be more than 600 million tonnes higher this year. The rapid deployment of solar and wind is on course to account for two-thirds of the growth in renewable power generation. Despite the challenging situation that hydropower has faced in several regions due to droughts this year, global hydropower output is up year-on-year, contributing over one-fifth of the expected growth in renewable power.

While electricity generation from both wind and solar PV is growing far more than any other source in 2022, coal is expected to post the next largest increase as some countries revert to coal use in response to soaring natural gas prices. In total, global CO2 emissions from coal-fired power generation are set to grow by more than 200 million tonnes, or 2%, this year, led by increases in Asia. The European Union's CO_2 emissions are on course to decline this year despite an increase in coal emissions. The rise in European coal use is expected to be temporary, with a strong pipeline of new renewable projects forecast to add around 50 gigawatts of capacity in 2023. These additions would generate more electricity than the expected increase in coal-fired power generation in the EU in 2022. In China, CO_2 emissions are set to remain broadly flat this year, reflecting the mixture of different forces at work, including weaker economic growth, the impacts of drought on hydropower, and major deployments of solar and wind.

As well as the challenges for hydropower in some regions, the world's low-emissions electricity supply has suffered a setback from a series of nuclear power plant outages, which are set to reduce global nuclear power production by over 80 TWh. This has largely been due to more than half of France's fleet of nuclear reactors being offline for part of the year. The drop in nuclear power generation globally has contributed to an increased use of coal and oil for electricity generation. The world's use of natural gas is expected to decline following Russia's invasion of Ukraine, resulting in a decrease in CO_2 emissions of around 40 million tonnes in 2022. Demand for oil is set to grow more than for any other fossil fuel in 2022, with oil-related

CO_2 emissions up by around 180 million tonnes. This has been driven largely by the transport sector as travel restrictions have been lifted and pre-pandemic commuting and travel patterns have resumed. Aviation is expected to contribute around three-quarters of the rise in emissions from oil use, notably due to increases in international air travel. However, the aviation sector's emissions are still only around 80% of their pre-pandemic levels.

Uncertainty in global natural gas markets will continue to shape many key energy trends for the rest of this year and in 2023. However, promising signs of lasting structural changes to the CO_2 intensity of global energy are evident in 2022 – and they are set to be reinforced by major increases in government support for clean energy investment, notably in the US Inflation Reduction Act, as well as in decarbonization plans such as the European Union's Fit for 55 package and Japan's Green Transformation (GX) plan, and in ambitious clean energy targets in China and India. The Paris Agreement was adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in December 2015, will enter into force in November 2016, and will be fully operational from 2020. Japan has declared that it will aim to reduce greenhouse gas emissions to zero by 2050, that is, to realize a carbon-neutral, decarbonized society by 2050.

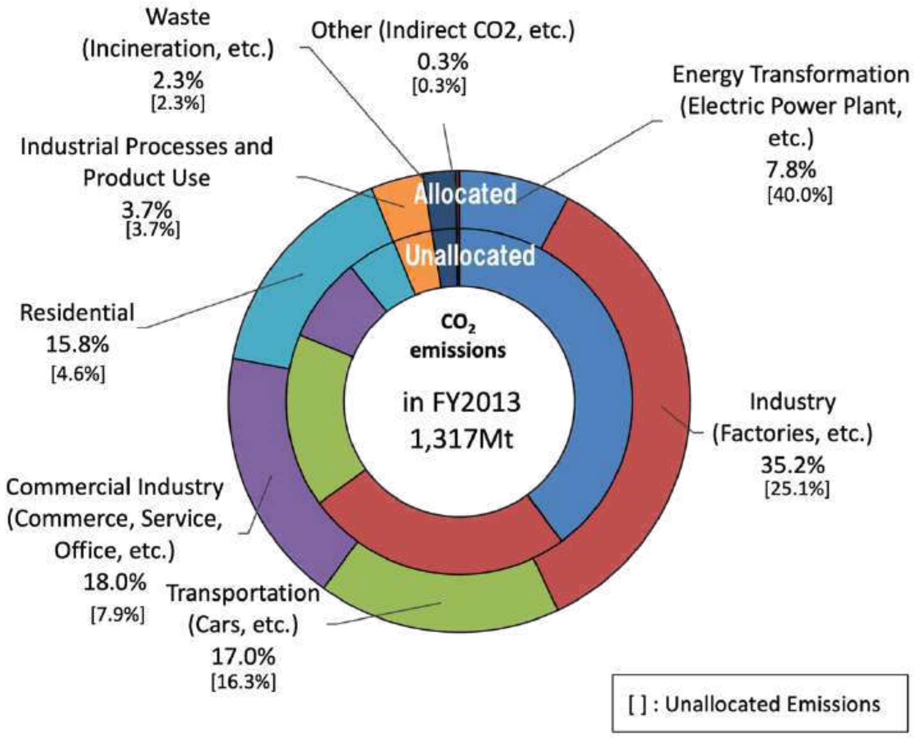


Fig.1. 21.a Japan's CO2 emissions by sector (Share of Unallocated and Allocated emissions) 2013

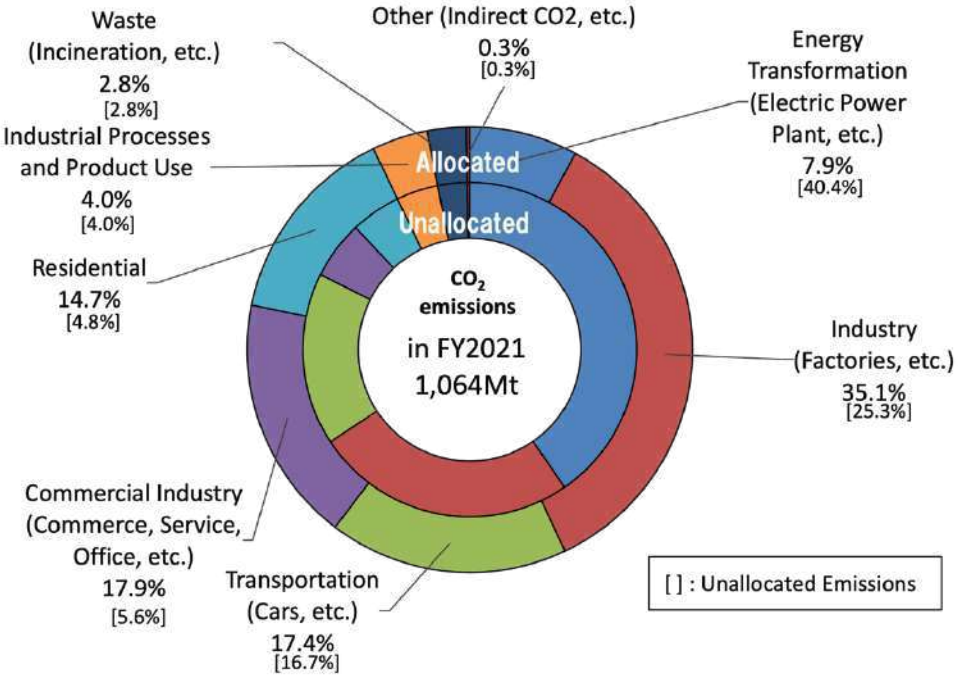


Fig.1. 21.b Japan’s CO2 emissions by sector (Share of Unallocated and Allocated emissions) 2020

Fig.1.21 shows the comparison of CO_2 emission in different sectors in Japan between 2013 and 2020. Japan’s total CO2 emissions declined by around 20% between 2013 and 2020, reflecting efforts to improve energy efficiency, shift towards renewable energy sources, and reduce dependence on fossil fuels. The electricity sector saw the largest reduction in CO2 emissions, reflecting a shift away from coal and towards natural gas and renewables. The manufacturing sector also saw a significant reduction in CO2 emissions, driven by energy efficiency measures and process improvements. The transportation sector's CO2 emissions remained relatively stable, reflecting the continued dependence on fossil fuel-powered vehicles. The residential and commercial sector saw a modest reduction in CO2 emissions, reflecting efforts to improve energy efficiency and shift towards renewable energy sources in buildings.

1.2.3 History of Japan’s Electric Power Industry

Electricity was first used in Japan on March 25, 1878, at the Institute of Technology in Toranomon, Tokyo when an arc lamp was switched on in commemoration of the opening of the Central Telegraph Office. In those days, electricity was still unfamiliar and uncommon not only in Japan but also in Europe and the United States. In 1886, Tokyo Electric Lighting, a private company, commenced operations as the nation’s first electric power company, and began supplying electricity to the public in the following year.

In the early days, use of electricity grew primarily for lighting because of its safety and cleanness, and gradually found broader applications as a power source to replace the steam engine. By 1896, the number of electric companies established throughout the nation reached a total of 33. The early 20th century marked the establishment of long-distance transmission technology. As larger thermal and hydro power plants were introduced, generation costs fell and electricity came into wider use throughout the country. Consequently, electricity became an indispensable energy source for people's lives and industry.

In the years that followed, the electricity utility business grew in tandem with the modernization of Japan and development of its industry. At the same time, the electric utility industry experienced a major restructuring that led to the dissolution of 700 electric companies, which merged to create five major electric companies after the First World War. During the Second World War, the electric utility industry was completely state-controlled and companies were integrated into Nihon Hatsusoden Co. (a nationwide power generating and transmitting state-owned company) and nine distribution companies.

After the end of the second World War in 1945, supply and demand for electricity remained very tight in Japan. A series of intense discussions were held on restructuring the electric utility industry as one of the measures for democratizing the economy. As a result, nine regional privately owned and managed General Electricity Companies— Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku and Kyushu Electric Power Companies — were established in 1951 and assumed the responsibility of supplying electricity to each region. This fundamental structure remains to this day, and with the return of Okinawa to Japan in 1972, Okinawa Electric Power Co. joined as a tenth member.

At the end of the 20th century, a trend toward deregulation and competition took hold throughout society, and the electric utility industry started to be liberalized. In December 1995, organizations such as the independent power producers (IPP) were allowed to provide electricity wholesale services and in March 2000, electricity retail supply for extra-high voltage users (demand exceeding 2MW) was liberalized. The scope of retail liberalization was then expanded in April 2004 to users of more than 500kW, and subsequently in April 2005 to users of more than 50kW. Thus, a Japanese model of liberalization based on fair competition and transparency while maintaining the vertical integration of generation, transmission, and distribution to ensure a stable supply of electricity, was established.

With the Fukushima Daiichi Nuclear Power Station accident and subsequent tight demand and supply brought about by the Great East Japan Earthquake in March 2011 as a turning point, numerous discussions were held to maintain a stable supply and reduce energy costs, and in November 2013, the policy to implement three-phase reforms of the electric power system was adopted. As a result, full retail liberalization will finally start in April 2016.

Japan has gone through a couple of crucial turning points in terms of energy, namely the transition from “coal to oil”, and the movement “away from a heavy dependence on oil” through two oil crises. It is now in the middle of the movement toward decarbonization as a number of countries have experienced economic growth thereby increasing greenhouse gas emissions, a cause of global warming. It is necessary for Japan to further reduce the use of fossil fuels in order to achieve its target pursuant to the Paris Agreement, a global framework to cope with global warming, as well as to materialize the proposed “energy mix” in 2030 showing an ideal composition of power sources (methods of generating electricity).

1.2.4 Energy policy in Japan

According to the regional power promotion agency, industrial power demand will increase by about 1 million kW in nine years. It is expected to increase from 3,402.22 million kW in 2019 to 3,403.42 million kW in 2028. The restarting of nuclear power plants is extremely difficult, and it is difficult for renewable energy to make up for the electricity. As a result, thermal power generation will be able to cover the portion of the power that is increasing in demand.

The energy policy in Japan aims to ensure a stable supply of energy while addressing climate change and promoting the use of renewable energy sources. Here are some key aspects of Japan's energy policy:

Energy Mix: Japan aims to reduce its dependence on fossil fuels and increase the use of renewable energy sources. The government has set a target of generating 22-24% of the country's electricity from renewable sources by 2030. Nuclear power, which provided around 30% of Japan's electricity before the Fukushima disaster in 2011, will also play a role in the energy mix, with the government targeting a 20-22% share of electricity from nuclear power by 2030.

Energy Efficiency: Japan has implemented various measures to improve energy efficiency in buildings, appliances, and transportation. The government has set a target of reducing the country's energy consumption by 30% by 2030 compared to 2013.

Renewable Energy: The government is promoting the development and deployment of renewable energy sources, including solar, wind, hydro, and geothermal power. Various incentives and subsidies are in place to encourage the adoption of renewable energy, and the government has established feed-in tariffs to support the development of renewable energy projects.

Carbon Pricing: Japan has introduced a carbon pricing scheme, which imposes a carbon tax on certain fossil fuels and requires companies to purchase carbon credits. The government plans to increase the carbon tax gradually over time.

International Cooperation: Japan is actively participating in international efforts to address climate change, including the Paris Agreement and the United Nations Framework Convention on Climate Change. The government has pledged to reduce the country's greenhouse gas emissions by 26% below 2013 levels by 2030.

Overall, Japan's energy policy reflects a commitment to reducing greenhouse gas emissions and promoting the use of renewable energy sources while ensuring a stable supply of energy to meet the country's needs.

The basic principle of Japan’s energy policy for the future, known as 3E+S, shown in Fig 1.22, has been established to cope with various challenges. Keeping in mind that Safety always comes first, the principle is to simultaneously achieve Energy Security, Economic Efficiency and Environment.

Based on the above principle, the ideal energy supply and demand structure for 2030 has been presented. It is essential to create a multi-layer energy supply structure whereby each energy source delivers maximum strength and compliments the weaknesses of the others. The structure is also called “energy mix” implying the necessity to combine various energy and power sources.

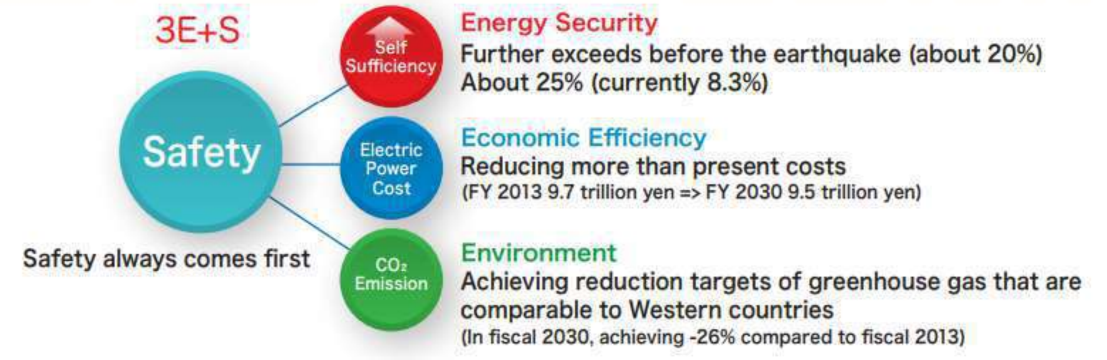


Figure 1.22. Energy policy in Japan

In order to solve the problem of power supply stability, the Japanese government and enterprises have already begun to study solar power generation, a relatively safe renewable energy power generation mode. Now, in order to solve the problem of uneven power generation in different regions according to local conditions, Japan has recently accelerated the pace of promoting “photovoltaic + energy storage”.

Virtual Power Plant (Virtual Power Plant, hereinafter referred to as “VPP”) test is one of the methods chosen by the Ministry of Economy, Trade and Industry (hereinafter referred to as “Ministry of Economy, Trade and Industry”). VPP is like an energy collection platform. It integrates the photovoltaic system, storage battery and other power supply systems in a certain area for unified management and supplies corresponding power according to different power needs. Although the scale of each power is very small, but the accumulation is small, it can be collected to output power like a power station.

The Japanese government plans to increase the renewable energy ratio from the current 16% to 22-24% by 2030, but due to climate and other uncertain factors, the amount of renewable energy generation cannot be determined. If thermal power generation is used for power allocation, the equipment utilization rate will decrease, and the investment funds will not be recovered. For large power companies, the advantage of VPP is that it can reduce the initial investment in power generation equipment and increase the ability to purchase solar power flexibly in the future.

In recent years, Japan has experienced quite a few extreme natural disasters which occurred one after another, having an enormous impact on society. Typhoons and torrential rains damaged power generation facilities and knocked over pylons and utility poles. Earthquakes caused large-scale blackouts together with tsunami damage. As there may be more natural disasters in the future because of global warming, it is crucial to ensure safety in supplying energy. We must construct disaster-resilient infrastructure for a quick recovery from such damage.

In June 2020, a cabinet decision was made to enact the Act of Partial Revision of the Electricity Business Act and Other Acts for Establishing Resilient and Sustainable Electricity Supply Systems. This Act revised the Electricity Business Act and other acts which stipulate rules to be adhered to by electricity businesses. Based on this revision, the plan is to enhance collaboration between businesses to cope with disasters, construct more resilient power transmission/distribution networks and introduce disaster-resilient dispersed electricity systems.

One important effort to ensure safety is to make the power infrastructure more resilient. To enhance resilience to disasters, plans are underway to strengthen power networks across the nation for transition to next-generation networks that are also suitable for the introduction of large volumes of renewable energy. For example, the project to duplicate the cross-regional transmission lines between Hokkaido and Tohoku has been given the green light. On the other hand, the backup systems for power supply to metropolitan areas are still to be strengthened.

Regarding nuclear power, if the Nuclear Regulation Authority recognizes that a nuclear power plant conforms with the new regulatory standards, the restart of the power plant will be advanced with the judgment of the authority respected. It must proceed on the primary premise of safety, while obtaining understanding from the local stakeholders.

1.2.5 The significance of distributed energy system

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.

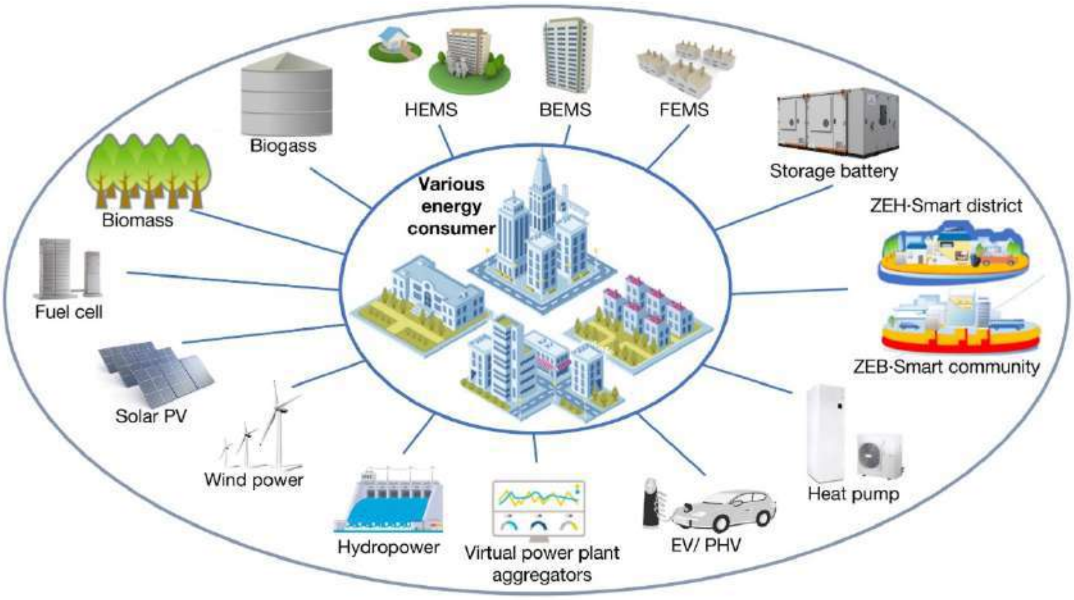


Fig.1. 21 Schematic diagram of distributed energy system

Distributed Energy Systems (DES) is a term which encompasses a diverse array of generation, storage and energy monitoring and control solutions. DES can be tailored to very specific requirements and users' applications including cost reductions, energy efficiency, security of supply and carbon reduction. Currently, practice shows that DES offers great advantages. It is a system that determines the unit configuration and capacity scale by optimizing the resources, environment, and economic benefits. It pursues the maximization of terminal energy utilization efficiency, adopts demand-responsive design and modular combination configuration, which can meet various energy needs of users and optimize and integrate the supply and demand of resource allocation. The DES is a complex system, which mainly can be reflected in the following points. 1) Various energy resources input, and multiple energy output is a reason of the complex, for example, the input resources can include fossil energy (oil, coal, natural gas, etc.), hydrogen (H_2), biomass, solar energy, wind energy and so on; the multiple energy output may include the electricity, heating (for space heating, hot water and so on) and cooling. That may the DER system is more complex than the conventional power plant only uses one resource for power generation, or the thermal plant only uses one resource for the thermal generation. 2) The DES may consist of multiple devices and components. Such as, the power generation can adopt a variety of devices, like gas engine, gas turbine, fuel cell, reciprocating engine and so on; if the system should meet the heating and cooling demand, the heart recovery devices, absorption chiller, adsorption chiller, electrical chiller, solar thermal, geothermal thermal gas engine and so on; in order to overcome the fluctuation of energy supply, the power system must have certain energy storage capacity, the storage device can classify to electrical storage device and thermal storage device.

In addition to the power generation device, thermal generation, thermal convention and energy storage devices, some auxiliary devices and components also constitute the complexity of system, like DC-DC converter, DC-AC converter, pump, fans, pipe, wire and so on. Fig.1. 21is a schematic diagram of distributed energy system. The DERs always can be divided into distributed generation technologies and energy storage technologies [6, 7].

DES have significant potential to transform the way we generate, distribute, and consume energy. DES can help increase energy resilience by creating a more decentralized and distributed energy system less susceptible to interruptions and blackouts. That's because DES can integrate multiple energy sources, including renewables, energy storage, and backup generators, to provide power during emergencies or outages. DES can also help improve energy efficiency by generating and using energy closer to where it is needed, reducing transmission losses and energy waste. Additionally, DES can incorporate energy management systems that optimize energy use and reduce energy consumption during times of high demand. DES can offer cost savings by reducing the need for expensive transmission and distribution infrastructure and by enabling energy consumers to generate and use their own energy. Additionally, DES can help reduce the overall cost of energy by incorporating more renewable energy sources, which have lower operating costs over their lifetime compared to traditional fossil fuel-based energy sources. DES can help reduce greenhouse gas emissions and improve air quality by incorporating more renewable energy sources and reducing the need for fossil fuel-based energy sources. Additionally, DES can help promote local biodiversity by reducing the environmental impact of large-scale energy infrastructure projects. DES can also help improve energy access in remote or underserved areas by providing localized energy solutions that are not dependent on large-scale energy infrastructure. DES have significant potential to transform the way we generate, distribute, and consume energy, and can help address a range of energy-related challenges, including energy resilience, energy efficiency, cost savings, environmental benefits, and improved energy access.

1.3 Current Status and Bottleneck of Japan Energy Development

Japan is a country that lacks resources such as oil and LNG (liquefied natural gas) and needs to take various measures to ensure a stable supply of energy. Japan relies on imports from abroad for most of its demand for fossil fuels. In 2018, the proportion of fossil fuels dependent on imports was 99.7% for oil, 97.5% for liquefied natural gas (LNG), and 99.3% for coal. The energy self-efficiency ratio of Japan in 2017 was 9.6% [19], which is lower compared to other OECD countries. However, low energy self-sufficiency leads to dependence on the resources of other countries. This makes a country vulnerable to international situations, making it difficult to obtain energy in a stable manner.

In the year prior to the Fukushima Crisis, Japan’s dependence on fossil fuels accounted for 81.2% of its total primary energy supply. And after the Fukushima Crisis, Japan's energy self-sufficiency rate has fallen sharply, as low as 6.4% in 2014, and then slowly increased, shown in Fig.1. 4. And dependence rose to 87.4% in 2017 as increased utilization of thermal power generation was used to compensate for power shortages caused by nuclear plant closures. Despite these improvements, oil still accounts for about 40% of Japan’s primary energy supply, and more than 80% of imported oil comes from the politically unstable Middle East. Moreover, prospects for importing electricity from neighboring countries are very poor because Japan is an island nation. In addition, there is an urgent need for global warming countermeasures such as reduction of carbon dioxide emissions from the use of energy. To ensure Japan’s stable electricity supply, it is crucial to establish an optimal combination of power sources that can concurrently deliver energy security, economic efficiency, and environmental conservation, while placing top priority on safety. In 2018, the dependence ratio of fossil fuels on imports was: 99.7% for oil, 97.5% for liquefied natural gas (LNG), and 99.3% for coal [13]. It has also brought electricity prices to unsustainable levels.

Another question is where Japan imports resources from. About 88% of crude oil is imported from the politically unstable Middle East. As the Middle East is one of the world's most important energy suppliers, ensuring the safety of navigation in the region is vital for Japan and the international energy market. Regarding coal, there is a high level of dependence on Australia. On the other hand, LNG (Liquefied Natural Gas) is being sourced from diverse regions such as Australia, Asia, Russia and the Middle East.

Since the Fukushima Crisis, electricity prices have risen several times. This is due to the increased use of thermal power generation to mitigate the effects caused by the closure of nuclear power plants. This was also due to an increase in fuel prices until 2014. Compared to the period before the Great East Japan Earthquake, household electricity bills increased by approximately 16% and industrial electricity bills increased by approximately 21% in 2017.

Faced with these challenges, the government of Japan has revised its energy policy in recent years to focus on further diversifying its energy mix (less use of fossil fuels, more reliance on renewable energy, restarting nuclear plants when declared safe) and curbing carbon emissions. Building on these plans, Japan has outlined ambitious goals to cut greenhouse gas emissions by 26% between 2013 and 2030. This emissions reduction commitment requires a balancing act between energy security, economic efficiency, environmental protection, and safety. The 2016 in-depth review of Japan’s policies highlights three areas that are critical to its success: energy efficiency, increasing renewable energy supply and restarting nuclear power generation.

Japan has commitment to reduce greenhouse gas emissions by at least 46% by 2030 and achieve net zero emissions by 2050 is one of the most laudable climate targets in the world. Unlike many other countries, Japan is not rich in renewable energy resources and its high population density, mountainous terrain and steep coastline are serious barriers to expanding the resources it has, particularly because many of its few plains are already heavily covered with solar panels. It has been a world leader in energy efficiency for decades, and much of the potential offered by this fast and efficient way of decarbonizing the economy has already been realized. Japan has already made great strides in reducing energy consumption through behavioral and lifestyle changes, such as reducing the use of air conditioning in the summer and supporting public transport. Its geology is not conducive to carbon storage and this technology will play an important role in some other parts of the world. In the long term, Japan will need a broader range of new technologies to continue to achieve net zero emissions. Fortunately, this plays to the country's strengths, as it has long been a global leader in energy innovation through technologies such as hybrid electric vehicles, solar photovoltaics, smart grids, high-speed trains and robotics. Offshore wind looks particularly promising, although Japan needs to help push the frontiers that could reap the major benefits it offers.

Japan's energy development faces several challenges, including dependence on fossil fuels, public opposition to nuclear power, and barriers to greater energy efficiency and renewable energy adoption. Addressing these challenges will require a coordinated and sustained effort from government, industry, and civil society. Japan remains heavily dependent on fossil fuels, particularly oil and natural gas, for its energy needs. This dependence makes Japan vulnerable to price volatility and supply disruptions, as well as contributing to greenhouse gas emissions and air pollution. The Fukushima disaster in 2011 led to the shutdown of all of Japan's nuclear power plants, which had provided around 30% of the country's electricity. While some of these plants have since been restarted, public opposition to nuclear power remains strong, and many plants are unlikely to be restarted in the near future. While Japan has made progress in improving energy efficiency in buildings, appliances, and transportation, there is still significant room for improvement. Some of the barriers to greater energy efficiency include a lack of awareness among consumers and businesses, outdated building codes and standards, and a lack of incentives for energy efficiency improvements. Japan has made significant progress in developing renewable energy sources such as solar, wind, and geothermal power, but there are still some challenges to their widespread adoption. These include high installation costs, limited available land for large-scale solar and wind projects, and a lack of interconnection infrastructure to transport renewable energy from remote locations to population centers. Japan's carbon pricing scheme, which was introduced in 2012, has been criticized as being too weak and having limited impact on emissions reductions. The carbon tax is relatively low compared to other countries, and the system for purchasing carbon credits has not been widely used.

1.4 Research structure and logical framework

1.4.1 Research purpose and core content

In the background of energy security use and the decreasing trend of energy self-sufficiency, the development of renewable energy is imperative. At present, the world's dependence on fossil energy ratio still more than 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. The paradigm shifts in the electricity market towards smart grids, involving large-scale energy transfers between entities, requires effective policy support under an integrated framework.

A VPP provides a solution for improving an energy self-sufficiency rate, as an alternative to expanding the capacity of a conventional power plant (CPP). This research proposed a comprehensive method for analyzing the feasibility of using a VPP to benefit both the plant and demand sides. First, the energy-saving potential of a VPP composed of high efficiency appliance, photovoltaic (PV) generation devices and energy storage system (ESS) was explored, based on historical monitoring data in a Japanese smart community called Higashida District (with a size of approximately 1.2 km^2). Second, the economic performance of the VPP was evaluated based on a payback period and total life cycle cost analysis. Then, considering the imbalance of the benefits between the demand and plant sides, cooperative game theory was applied to explore the cooperation potential. The influence of government subsidy policies on both the plant and demand sides was a simultaneous concern. Finally, the profit of the alliance, comprising both the demand and plant sides was allocated, based on the Shapley value. This study highlights the excellent energy-saving potential from implementing a VPP. The results show that there is substantial economic cooperation potential between the demand and plant sides. In addition, both the plant and demand sides have better profits in cooperative games than with non-cooperation. This research provides policy guidance for the Japanese government to promote VPPs in the future and provides a solution for coordinating the profit allocations of the plant and demand sides.

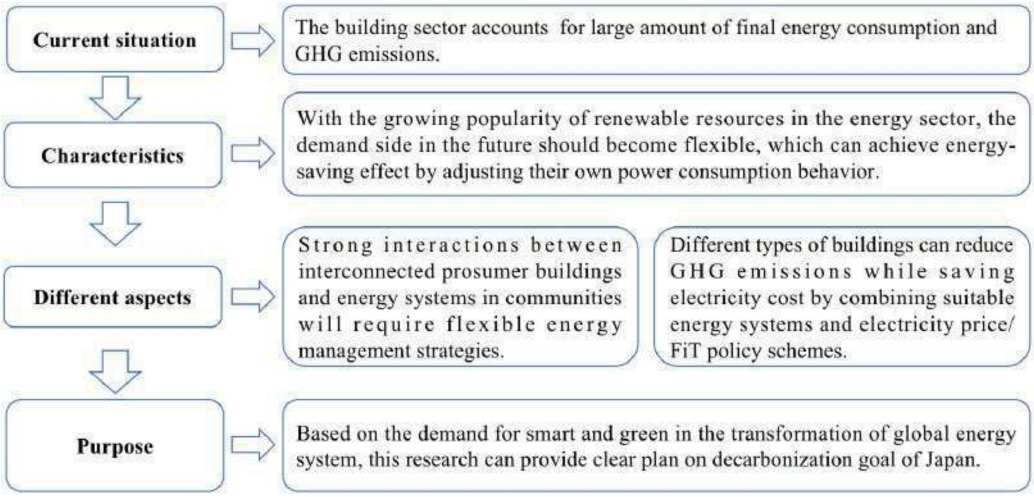


Fig.1. 22 Research gap identification

1.4.2 Chapter content overview

The chapter titles and basic structure of this paper are shown in Fig 1.23. Besides, the brief introduction of chapters schematic is shown in Fig 1.24.

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

Under the demand of energy shortage and safe supply, it is imperative to develop renewable energy sources. This chapter analyzes the international as well as Japan's energy situation, bottlenecks, and historical evolution. These factors lead to the necessity of developing renewable energy sources. Secondly, the development trend of renewable energy in the international and Japanese regions is summarized. The international level combines the energy structure evolution and renewable energy promotion strategies of typical countries such as the United States, Germany, Japan, and China. The Japan region details how renewable energy is entering the grid and analyzes the evolution of the energy mix in detail combining the industrial sector, the household sector, and the transportation sector. This demonstrates the importance of the power system in stabilizing energy supply and reducing greenhouse gas emissions. And it is urgent for us to find an optimal method to aggregate those renewable energy sources.

In Chapter 2, Literature Review of Virtual Power Plant:

This Chapter provides a detailed review of the application of Virtual Power Plants in this research. Section 2.1 reviews the application of VPP around the world and introduced the principle of. Section 2.2 mainly summarize the previous study of VPPs, especially difference between Technical VPP and economic VPP, etc. Section 2.3 gives a detailed description and summary of the barriers and challenges of VPP. In general, the review in this section focuses on the application of VPP in the power sector.

In Chapter 3, Virtual Power Plant model establishment and Methodology:

This Chapter describes the research methods used in this research. Firstly, introduced the technology approach involved in this research. And then, the VPP system model was established. Includes the calculation of indicators to evaluate the impact of VPP. Section 3.1 shows the technical technology used in this research. In terms of economy, the dynamic payback period of VPP system is adopted. Compared with the static payback period, the dynamic investment payback period adds a time cost.

In Chapter 4, Energy Consumption Characteristic Analysis in Higashida Smart Community:

The data resource and energy conversion analysis in this research is shown in Chapter 4. The power consumption of different type of buildings is investigated, which is featured with different power consumption and load profiles. Besides, the different building's feasibility of VPP introduction was explained.

In Chapter 5, Feasibility, Efficiency and Economic analysis of VPPs:

As most of the distributed energy resources are available in urban areas, there are increasing interests in assessing the potential to develop urban Virtual Power Plant (VPP). This chapter aims to analyze the feasibility of VPPs through the construction of local renewable energy and energy storage technology in Higashida area. The return on investment was carried out through payback period and life cycle cost analysis. The economic performance of the power plant side and the demand side by changing the investment from power plant side and the corresponding electricity price on the demand side were analyzed. Two investment proposal were compared in the aspect of economic analysis.

In Chapter 6, Techno-economic Analysis of the Transition towards the energy self-sufficiency community based on VPP:

In this chapter, a VPP model consisted of updating high efficiency appliances, photovoltaic and energy storage systems was proposed. A comprehensive analysis for assessing the technical, economic and environmental benefits deriving from the VPP was presented, indicated the feasibility of a smart community to achieve power self-sufficiency with the support of the VPP. Analysis of the VPP's load leveling performance, return on investment and CO_2 emission reduction are performed. In addition, external factors such as electricity price changes and FiT policies are considered to assess the impact on the economics of the VPP.

In Chapter 7, Evaluation of Economic Benefits of VPP between Demand and Plant Sides Based on Cooperative Game Theory:

This chapter proposed a comprehensive method for analyzing the feasibility of using a VPP to benefit both the plant and demand sides. First, the energy-saving potential of a VPP composed of a photovoltaic (PV) and energy storage system (ESS) was explored, based on historical monitoring data in a Japanese smart community called Higashida District (with a size of approximately 1.2 km2). Second, the economic performance of the VPP was evaluated based on a payback period and total life cycle cost analysis. Then, considering the imbalance of the benefits between the demand and plant sides, cooperative game theory was applied to explore the cooperation potential. The influence of government subsidy policies on both the plant and demand sides was a simultaneous concern.

In Chapter 8, Conclusions and Prospect:

The conclusion of each Chapter is concluded and the prospect of future development trend of VPP.

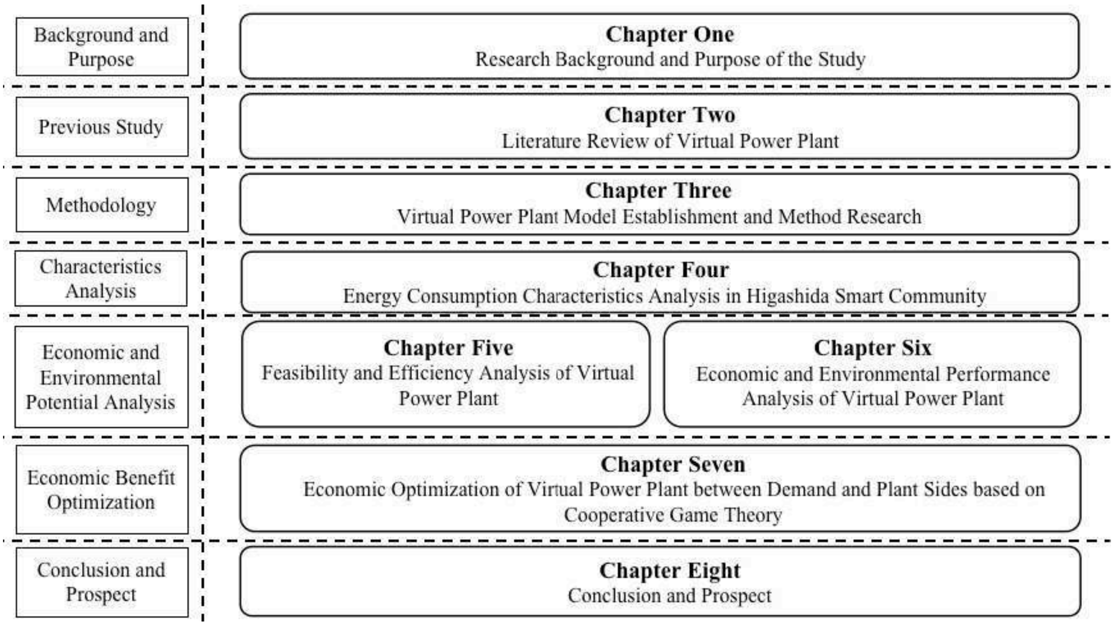


Fig.1. 23 Chapter name and basic structure

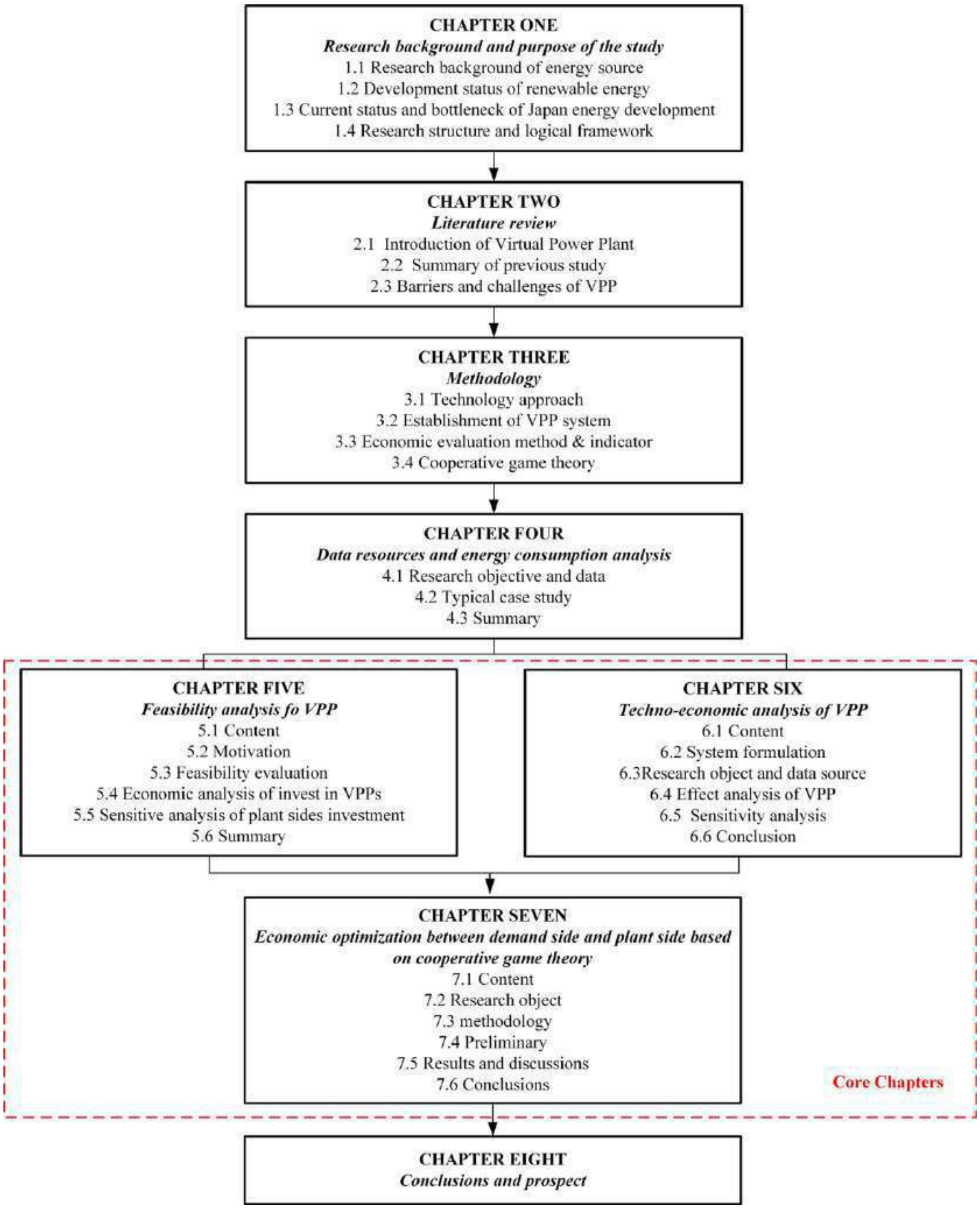


Fig.1. 24 Brief chapter introduction

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Chapter 2

LITERATURE REVIEW OF VIRTUAL POWER PLANT

CHAPTER 2: LITERATURE REVIEW OF VIRTUAL POWER PLANT

2.1 Introduction of Virtual Power Plant

The word “virtual” has been heard a lot recently. Virtual reality, which allows you to experience immersive virtual spaces, is already well known, and “virtual currencies” such as Bitcoin are a hot topic. In fact, the word ‘virtual’ is also starting to be used in the energy sector. What is becoming virtual in the energy sector is the power plant itself. In most people’s minds, tall chimneys, huge plants, endless stretches of “white smoke”, coupled with dense high-voltage lines, this is the image of power plants should be. As show in Fig 2.1, a traditional power system with energy flow from the generation side to the consumption side, that is, the power generation side needs to ensure the stability of the grid while generating electricity, and the demand side only needs to turn on the switch when electricity is needed. However, in the 21st century, both the generation side and the consumption side have changed dramatically. The power generation side has introduced uncontrollable power generation technologies such as scenic power, but because of its uncontrollability and dependence on external conditions, it also poses a danger to the power grid. And the electricity consumption side is not only consuming electricity, new generation and consumption technologies have been introduced, resulting in a bi-directional energy flow, which also brings great difficulties to the balance and stability of the grid.

Conventional energy supply systems that rely on large power plants are being challenged by the increasing popularity of distributed energy sources, including solar and wind energy. Since the amount of renewable energy generated depends heavily on the weather, energy supply will become unstable as usage expands. The new energy service concept is a solution to maintain a stable power supply. This means, for example, that decentralized energy sources such as distributed power supplies and batteries can be controlled remotely via Internet of Tings (IoT) devices and function as a power plant. As a result, Virtual Power Plant (VPP) with hierarchical zoning and elastic balancing is born! A VPP is a network of decentralized, medium-scale power generating units such as wind farms, solar parks, and Combined Heat and Power units, as well as flexible power consumers and storage systems.

The main difference between a conventional power plant and a virtual power plant (VPP) lies in their generation and management of electricity.

A conventional power plant is a large-scale facility that generates electricity from a single source of energy, such as coal, natural gas, nuclear fuel, or oil. The electricity is then transmitted to the grid for distribution to end-users. Conventional power plants are usually owned and operated by utilities or other energy companies.

In contrast, a VPP is a network of distributed energy resources (DERs) such as solar panels, wind turbines, and battery storage systems that are connected and managed as a single entity. VPPs use software and control systems to coordinate the output of multiple DERs, and provide grid services such as peak shaving, load balancing, and voltage control. VPPs are typically owned and operated by aggregators, who bring together multiple DER owners and manage their energy production and distribution.

Some of the key differences between conventional power plants and VPPs are:

Flexibility: Conventional power plants are typically inflexible and designed to operate at a fixed output level, while VPPs are designed to be flexible and adjust their output according to the needs of the grid. This means that VPPs can respond quickly to changes in energy demand and supply and can provide a range of grid services that conventional power plants cannot.

Ownership: Conventional power plants are usually owned and operated by large utilities or energy companies, while VPPs are owned and operated by aggregators who bring together multiple DER owners. This means that VPPs can be more decentralized and diverse than conventional power plants.

Cost: The capital cost of building a conventional power plant is typically much higher than the cost of installing a VPP, especially if the VPP is built using existing DERs. VPPs can also provide cost savings to end-users by reducing the need for grid infrastructure upgrades and by providing lower energy prices.

Environmental Impact: Conventional power plants typically generate large amounts of greenhouse gas emissions and other pollutants, while VPPs can be built using renewable energy sources and can reduce the overall environmental impact of electricity generation.

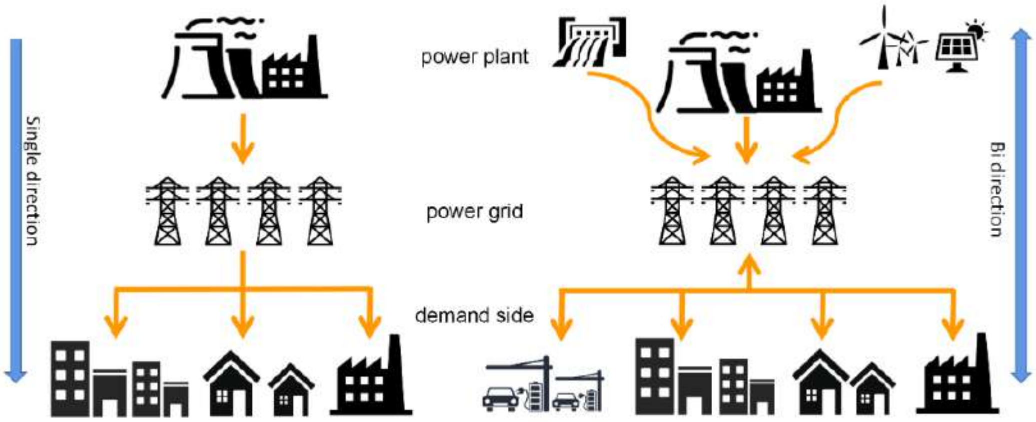

Fig.2.1 Difference between conventional power plant and virtual power plant

In recent years, small-scale power generation devices such as solar power and fuel cells have been widely installed in homes and offices (small, distributed power supplies). This means that we (consumers) who used to only consume electricity can now generate it just like the power company. Despite the huge potential of renewable energy, due to the instability of its power generation, the energy supply will become unstable as its use spreads. How to maximize the use of renewable energy and ensure the stability of the grid is a problem to be solved. With the widespread use of batteries, electric vehicles, heat pumps etc., it has become possible to disperse and store energy. VPP works as aggregator that manage scattered energy sources, such as distributed power sources and storage batteries, can be remotely controlled and worked as one power plant. In this way, the electricity generated by the generating plant can be used, or when there is a surplus of electricity generated, it can be stored in a battery and used when needed, and each consumer saves electricity. VPP is expected to promote the introduction and expansion of renewable energy and contribute to a decarbonized society. The new concept of VPP comes as a solution to maintain the stability of the power supply. Fig 2.2 shows the composition of VPP. A virtual power plant (VPP) is composed of a network of distributed energy resources (DERs) such as solar panels, wind turbines, battery storage systems, and demand response programs that are aggregated and managed as a single entity. The composition of a VPP can vary depending on the type of DERs that are included and their capacity. Typically includes:

Solar panels: Solar panels are one of the most common types of DERs in a VPP. They generate electricity from sunlight and can be installed on rooftops or in larger solar farms.

Wind turbines: Wind turbines generate electricity from wind and can be installed onshore or offshore. They are another common type of DER in a VPP.

Battery storage systems: Battery storage systems store excess energy generated by DERs during periods of low demand and release it during periods of high demand. They are an essential component of a VPP as they allow for more efficient use of renewable energy sources.

Demand response programs: Demand response programs incentivize customers to reduce their energy consumption during periods of high demand in exchange for lower energy prices. They can be used to balance supply and demand within the VPP.

Other DERs: Other types of DERs that can be included in a VPP include small-scale hydroelectric systems, geothermal systems, and biomass generators.

The DERs in a VPP are typically connected and managed through software and control systems that allow for real-time monitoring and management of energy production and consumption. This allows the VPP to respond quickly to changes in energy demand and supply, and to provide grid services such as peak shaving, load balancing, and voltage control.

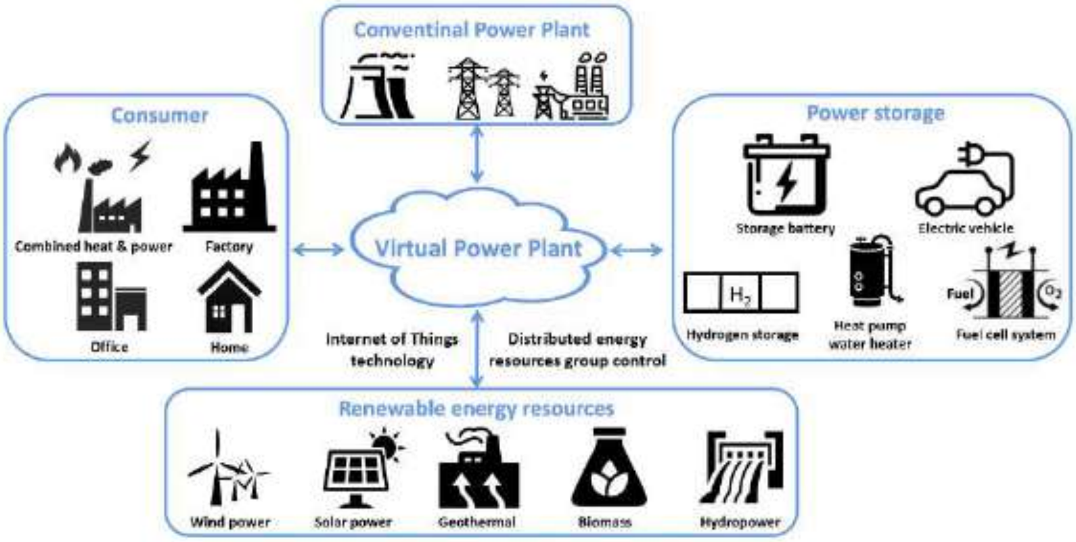

Fig.2.2 Composition of Virtual Power Plant

Generally, VPP is related to the following three departments: power generation system, energy storage system, and communication systems. Specifically, the VPP uses advanced information and communication technology and software systems to aggregate and optimize the DER of distributed power sources, energy storage systems, controllable compounding, and electric vehicles, to participate in the power market and grid as a special power plant, which can be equated to a controllable power management system. This system can be used externally as a “positive power plant” to supply power to the system, or as a “negative power plant” to consume power from the system, playing a flexible role in peak and valley reduction. In a sense, the VPP can be seen as an advanced regional centralized power management model, providing management and ancillary services to the distribution and transmission grids.

2.1.1 Main Concept of VPP

The concept of VPP: an effective option to aggregate and operate Distributed Energy Resources to participate in wholesale energy markets and provide flexibility and associated grid services that are needed in a renewable-rich energy system.

The VPP idea was born a few years ago and has a couple of advantages working in its favor. However, there is no uniform definition of the VPP framework.

P.Asmus[1] defines VPP as an energy Internet that relies on software systems to remotely and automatically allocate and optimize generation, demand response and energy storage resources. H.Morais[2] defines VPP as the same network as an autonomous micro net. C.Schulz [3] defines VPP as a combination of many cogeneration generator sets connected to a low-voltage distribution network. F.Bignucolo[4] defines VPP as a collection of different types of distributed energy dispersed in different nodes of medium voltage distribution network. D.Pudjianto[5] believe that VPP consists of a series of technologies with rich operation modes and availability that can be connected to any node of the power distribution network. M.Braun[6] defines VPP as an information communication system that aggregates controllable distributed energy (CDE) units or active customer networks (ACN) in a direct centralized control manner.

In summary, the purpose of the VPP concept can be summarized as "communication" and “aggregation”. VPP can be considered as an advanced information and communication technology and software system to achieve DG, ESS, controllable load, EV and other DER aggregation and coordination optimization, as a special power plant to participate in the power market and grid operation power coordination management system.

In a VPP, the DERs are linked through a centralized control system that can balance supply and demand in real-time and adjust the output of each generator according to the needs of the grid. This allows the VPP to act as a single, controllable entity that can provide a range of services to the grid, such as peak shaving, load balancing, frequency regulation, and voltage control.

By aggregating DERs and providing flexible energy services, VPPs can help to reduce the need for new grid infrastructure and support the integration of renewable energy into the grid. VPPs can also help to increase grid resilience and reliability by providing backup power during grid outages or disruptions. Additionally, VPPs can provide economic benefits to energy consumers by reducing their energy costs and providing new revenue streams for DER owners.

The basic concept is to aggregate distributed power, controllable load and energy storage devices in the power grid into a virtual controllable aggregate through the distributed power management system. participate in the operation and scheduling of the power grid and coordinate the relationship between the smart grid and the distributed power source. Contradictions, fully exploit the value and benefits of distributed energy for the grid and users. The virtual power plant is mainly composed of power generation system, energy storage equipment and communication system.

2.1.2 Operating Principle of the Virtual Power Plant

Why was there no VPP before? This is because of the former single direction of the power flow, and there are very few distributed energy sources. As mentioned earlier, the VPP is proposed to integrate various distributed energy sources, including distributed power sources, controllable loads, and energy storage devices. The basic concept is to aggregate distributed power sources, controllable loads, and energy storage devices in the grid into a virtual controllable aggregate through a distributed power management system, to participate in the operation and dispatch of the grid, to coordinate the contradictions between the smart grid and distributed power sources, and to fully exploit the value and benefits that distributed energy sources bring to the grid and users.

The main types of power generation systems are domestic distributed generation (DDG) and public distributed generation (PDG). The main function of a DDG is to meet the demand side's own load, and if there is a surplus of electricity, the surplus is fed to the grid; if there is a shortfall, the grid supplies the customer with electricity. A typical DDG system is a small, distributed power supply which serving a residential, commercial, or industrial sector, etc. A PDG is a system that delivers its own electricity to the grid and operates to sell the electricity it produces. A typical PDG system consists mainly of renewable energy generators such as wind and photovoltaic.

Energy storage systems can compensate for the volatility and uncontrollability of renewable energy generation output, adapt to changes in electricity demand, improve the weakness of the grid caused by fluctuations in renewable energy, enhance the system's ability to accept renewable energy generation and improve energy efficiency.

The communication system is an important part of the VPP for energy management, data collection and monitoring, and communication with the power system dispatch center. By interacting with information from the grid or with other VPPs, the management of the VPP is more visualized, and it is easier for the grid to monitor and manage the VPP. The management algorithm is the core of the VPP. Through the input of multi-dimensional time series and information, including the price forecast of the power trading center, the node data of the transmission operator, the weather forecast data, the real-time power generation asset status data, historical data, etc., the output Optimal operation strategy to complete automatic control of power generation assets.

Traditional power plant adopts the form of generation following demand, on the other hand, the VPP adopt the form of demand chasing generation. However, individual consumer often has low electricity consumption, irregular consumption patterns and a lack of response mechanisms. Against the background, a VPP is a solution to aggregate consumers loads, which can then be centrally regulated. For example, the VPP operate like import/ export business. It can produce and sell by itself. It is also can provide services to organizations outside the VPP (such as the grid). Internal storage or production reduction is also possible in case of overcapacity.

The operating principle of a VPP involves the aggregation and management of multiple DERs to provide grid services and generate revenue. The use of software and control systems allows for real-time monitoring and management of the DERs, enabling the VPP to respond quickly to changes in energy demand and supply. The VPP operator aggregates multiple DERs such as solar panels, wind turbines, battery storage systems, and demand response programs into a single entity using software and control systems. This allows the DERs to be managed and operated as a single power plant, with the VPP operator having control over the energy production and consumption of each DER. The VPP operator monitors the energy production and consumption of the DERs in real-time using software and control systems. This allows the operator to respond quickly to changes in energy demand and supply, and to optimize the use of the DERs to maximize revenue and grid services. The VPP can provide a range of grid services such as peak shaving, load balancing, and voltage control. This involves adjusting the energy production and consumption of the DERs in response to changes in grid conditions and energy demand. The VPP can generate revenue by selling energy and grid services to the grid operator or energy markets. The revenue generated is shared among the DER owners and the VPP operator.

The profit modes of VPP can be considered from the following aspects. The profit modes of a VPP can be considered from several aspects, including:

Energy Trading: A VPP can generate revenue by participating in energy trading markets, such as the wholesale electricity market or ancillary service markets. By leveraging its aggregated DERs, a VPP can offer a range of services, such as balancing services, capacity services, and flexibility services, to energy markets and earn revenue from the sale of energy and other grid services.

Capacity Payments: VPPs can receive payments for their capacity to provide grid services, such as peak shaving, load balancing, and frequency regulation. These payments are typically made to ensure that there is enough capacity available to meet the needs of the grid during periods of peak demand.

Demand Response: A VPP can earn revenue by providing demand response services, which involve reducing energy consumption during periods of peak demand. This can be achieved by using smart meters and other devices to control the energy consumption of customers who are part of the VPP.

Energy Retail: VPPs can also generate revenue by selling energy directly to end-users. This is achieved by aggregating the energy generated by DERs and selling it to customers at a lower price than the retail price offered by traditional energy providers.

Carbon Credits: VPPs can generate revenue by earning carbon credits through the reduction of greenhouse gas emissions. This is achieved by using renewable energy sources and by reducing the need for traditional energy generation through the use of energy efficiency measures and demand response programs.

These are just a few examples of the profit modes that can be considered by a VPP. The specific revenue streams that are available to a VPP will depend on a range of factors, including the energy market structure, the regulatory environment, and the availability of DERs.

2.1.3 Function of VPP

The function of the virtual power plant is to effectively integrate the newly added new energy system with the traditional power generation system and the energy storage system, and manage it through a control center, so as to participate organically in the grid operation. At the same time, virtual power plants are also an effective means of responding to the demand side. By installing some devices such as smart meters on the power side, a power supply combination that meets the customer's specific energy needs and is economical is designed to balance the supply and demand on both sides of power generation and power consumption.

VPP provides an opportunity to lower the load in the power network. More power is generated locally and is shared by participants without needing to transmit it over long distances at high tension. Therefore, one energy loss factor can be minimized or eliminated. VPP causes a dramatic change in energy relations. Participants are no longer just passive users. Being a part of VPP means everyone involved can influence the power system in a positive way, although naturally only to a certain extent: it does not mean that participants are responsible for switching devices on and off.

By combining multiple DERs, such as solar panels, wind turbines, batteries, and electric vehicles, into a single virtual entity, a VPP can act as a single large power plant and provide a range of services to the grid and its customers. Here are some of the key functions of a VPP:

Grid Stability: VPPs can help stabilize the grid by providing grid-balancing services, such as frequency regulation and voltage support. By adjusting the output of its aggregated DERs in response to changes in grid conditions, a VPP can help maintain a stable and reliable supply of electricity.

Demand Response: VPPs can participate in demand response programs, where they adjust the output of their DERs in response to changes in grid demand. By reducing or increasing their output, a VPP can help balance supply and demand on the grid and avoid the need for expensive peaking power plants.

Energy Trading: VPPs can participate in energy markets, such as selling excess energy from their DERs to the grid or buying energy when prices are low. By optimizing their trading strategies, VPPs can help DER owners to maximize their revenues and reduce their energy costs.

Ancillary Services: VPPs can provide a range of ancillary services to the grid, such as reserve capacity and reactive power. By providing these services, a VPP can help improve the reliability and resilience of the grid.

Renewable Energy Integration: VPPs can help integrate renewable energy sources, such as solar and wind, into the grid by managing their output and balancing their intermittency. By combining multiple renewable energy sources into a single entity, a VPP can help ensure a more stable and reliable supply of renewable energy.

In summary, the function of a VPP is to provide a flexible and coordinated platform for managing DERs and maximizing their value to the grid and its customers. By leveraging advanced technologies and business models, VPPs can help promote a more sustainable and efficient energy system.

2.1.4 Development Status and Achievements of VPP

At present, virtual power plants are still in the development stage of theoretical research and preliminary pilots. From a global perspective, the research and implementation of VPP is mainly concentrated in Europe and North America. According to data released by Pike Research, as of the end of 2009, the global VPP total capacity was 19.4GW, of which 51% in Europe and 44% in the US; as of the end of 2011, the global VPP capacity increased to 55.6GW. However, the application forms of VPP in Europe and the United States are significantly different, and the VPPs in European countries also have their own characteristics.

Currently, VPP is still a brand-new concept in China, but the characteristics of VPP are in line with the needs and direction of China's power development. It has broad development prospects in China, which are embodied in:

1) VPP is an effective form of efficient use and promotion of alternative energy and renewable energy generation. The development of VPP will enable renewable energy generation to obtain maximum economic benefits from the electricity market, shorten the cost recovery cycle, and attract and expand investment in renewable energy generation, thereby promoting the development of new and renewable energy.

2) VPP technology is an important method to realize large-scale wide-area distributed power coordination and grid-connected management to realize stratified optimization of energy Internet.

3) The development of VPP technology plays an important role in promoting the construction of smart grids in China. In the future, VPP should become an important part of the smart grid.

4) Learning from VPP's participation in the operation mode and scheduling framework of various power markets will play a positive role in promoting and guiding China's power market system.

With the development of renewable energy and emerging technologies, VPPs will become an important form of energy aggregation in the construction of smart grids and the global energy internet, with a wide scope for development. However, the complementary nature of distributed power sources reduces the uncertainty of power output. Due to the large randomness, volatility and intermittency of renewable energy output, the dynamic mix of distributed power sources needs to be addressed.

Multiple distributed units can be flexibly and dynamically combined to form a VPP. The main difference between a VPP and a microgrid is that the multiple distributed generation units that make up a VPP are not necessarily located in the same geographical area, and their scope of aggregation and interaction with the market depends on communication capabilities and reliability. Multiple distributed generation units are aggregated according to certain rules or objectives and participate as a whole in the electricity market or ancillary services market, with the benefits being allocated to each distributed generation unit. The VPP acts as an intermediary for the flexible dynamic combination of multiple distributed generation units according to rules such as dynamic combination algorithms or dynamic game theory. The real-time nature and flexibility of the dynamic combination avoids the cost problems associated with real-time imbalances and the combination deviations caused by plant shutdowns and errors in load and renewable energy output forecasting.

Depending on the control structure of the information flow transmission of the VPP, the control of the VPP can be divided into centralized control methods, decentralized control methods and fully decentralized control methods. A VPP in this structure requires that the plant has complete information about each unit involved in the distributed operation and that its operational settings meet the different needs of the local power system. This type of VPP has great potential for achieving optimal operating modes. However, scalability and compatibility are often limited due to the constraints of specific operational realities. A VPP under centralized control has full access to all information about the distributed units within its jurisdiction and has full control over all generation or consumption units.

The VPP in the decentralized control approach is divided into several levels. The control co-ordination center of the VPP at the lower level controls the generation or consumption units within its jurisdiction, and the control co-ordination center of the VPP at that level then feeds information back to the control co-ordination center of the VPP at the higher level, thus forming an overall hierarchy. This one refers to the locally controlled distributed mode of operation, which constitutes an overall hierarchy in a locally controlled system. In response to the weaknesses in the previous centralized control model, the DCVPP model effectively improves on the deficiencies through a modular local operation model and information gathering model. However, the central control system still needs to be at the top of the entire decentralized virtual power generation system during operation in order to ensure safety during system operation and overall operational economy.

In the fully decentralized control approach, the VPP control and coordination center is replaced by a data exchange and processing center, which only provides information on market prices, weather forecasts, etc. In turn, the VPP is divided into autonomous, intelligent subunits that are independent of each other. These subunits are not controlled by the data exchange and processing center, but only receive information from the data exchange and processing center and optimize their own operation according to the information received. This mode of operation can be considered as an extension of the decentralized controlled VPP. The central control system in the decentralized control mode is replaced by data exchange agents which provide valuable information such as market prices, weather forecasts and data records. For small units in the decentralized control model, running in this model will be very scalable and open compared to the previous two models due to the plug and play capability in the fully decentralized controlled VPP model.

Using big data for renewable energy forecasting and increasing the speed of data processing in VPPs. Big data is a collection of data that cannot be sensed, acquired, managed, processed and analyzed in an affordable time frame using traditional IT technologies, hardware and software tools and mathematical analysis methods. Big data technologies allow for load forecasting and renewable energy output forecasting, including wind and solar. Wind energy forecasting is essential because data shows that the actual capacity of wind farms varies considerably during peak electricity consumption periods. Accurate forecasting of solar and wind energy requires analysis of large amounts of data, including meteorological data such as wind speed and cloud cover. At the same time, the use of big data technology to process various information within the VPP can effectively increase the processing speed of the data exchange and processing center, providing the data exchange and processing center of the VPP with a real-time, accurate flow of data and information from the various subsystems.

VPP participate in multiple markets for optimal dispatch and bidding. By aggregating several distributed units into one, VPPs can operate in the electricity market, taking advantage of the stable output and volume sales of traditional power plants, but also being complementary by aggregating multiple generation units. The market in which the VPP participates includes the day-ahead market, the real-time market and the ancillary services market, which allows for a variety of market models such as day-ahead markets, bilateral contracts, balancing markets and hybrid markets. Considering the uncertainties of renewable energy output, load and real-time tariffs in the VPP, scheduling and bidding models can be developed in different market environments to make the VPP more widely applicable.

The VPP plays a delicate role in the relationship between the grid operator, the various electricity markets, the customers of distributed generation assets and the energy consumers. By interacting with the data between the four players, the VPP performs an optimization function in the electricity system. There is a large amount of research establish a scientific cooperation mechanism based on game theory to ensure the stability of the VPP. Game theory focuses on the theory of how multiple decision makers with conflicting interests can each make decisions that benefit themselves or the group of decision makers, depending on their own capabilities and the information they know. Based on game theory, all generation and consumption units within the VPP and all operators outside the VPP are cooperative games. A scientific cooperation mechanism based on cooperative game theory, including cooperation between multiple generation or consumption units aggregated within the VPP and between the VPP and the integrated operator, the distribution or transmission grid and the electricity market operator, ensures a reasonable return for all participants, keeps participants motivated to participate in the long term and ensures the stability of the VPP.

✧ VPP in America

VPPs have gained traction in America in recent years, and several initiatives and projects are underway to implement VPP technology in the country. Here are some examples:

Pacific Gas & Electric (PG&E) - PG&E is a California-based utility that has been working on implementing VPPs. In 2019, the utility announced plans to launch a VPP program that would integrate distributed energy resources into the grid to improve grid reliability and reduce greenhouse gas emissions.

Ameren Missouri - Ameren Missouri is a utility company that has launched a VPP program in collaboration with Nest. The program uses Nest's thermostat technology to manage energy consumption in households during peak demand periods. The program aims to reduce peak energy demand and improve grid reliability.

New York State Energy Research and Development Authority (NYSERDA) - NYSERDA is a public-benefit corporation that has launched a VPP initiative in collaboration with industry partners. The initiative aims to develop and deploy VPP technology to improve the integration of renewable energy into the grid and increase grid stability.

Duke Energy - Duke Energy, a North Carolina-based utility, has launched a VPP program that uses battery storage to manage energy supply and demand. The program aims to reduce peak energy demand and improve grid reliability.

These are just a few examples of VPP initiatives and projects underway in America. As renewable energy technologies continue to gain traction in the country, it is likely that VPPs will become increasingly important for integrating these resources into the grid and improving grid stability.

✧ VPP in Europe

At present, VPPs are still in the development stage of theoretical research and preliminary pilots. From a global perspective, the research and implementation of VPP is mainly concentrated in Europe and North America. According to data released by Pike Research, as of the end of 2009, the global VPP total capacity was 19.4GW, of which 51% in Europe and 44% in the US; as of the end of 2011, the global VPP capacity increased to 55.6GW. However, the application forms of VPP in Europe and the United States are significantly different, and the VPPs in European countries also have their own characteristics. The concept of VPPs has been existed for more than 20 years, emerging in the early 21st century in European countries such as Germany, the UK, France and the Netherlands, and has a number of mature demonstration projects that focus on the reliable grid connection of distributed energy while constructing a stable business model in the electricity market. In Europe, VPPs can also be called grid aggregators (aggregators). Among market participants, grid aggregators are responsible for pooling the control of distributed small-scale generation plants (new energy sources) into a pool, reaching a minimum threshold for participation in the electricity market, equivalent to the role of an agent.

For Europe, take the example of Next-Kraftwerk, the largest VPP in Germany. The project of the German company Next-Kraftwerk, which realizes the management of more than 4,000 distributed generation facilities, also including a portion of adjustable loads, has already realized the management of more than 7,000 distributed energy and adjustable loads across five countries at the end of 2019, with a total scale of nearly 3 million kW. founded in 2009, Next-Kraftwerk employs with a total of no more than 200 employees, sales revenue of around 400 million euros and 140 GWh of traded power, the performance is outstanding. VPPs exist to help Germany achieve its goal of increasing the proportion of new energy sources connected to the grid as part of the energy transition.

- ➢ Aggregate distributed new energy generation assets.
- ➢ Automatically control generation assets through flexible algorithms.

- Reconcile deviations between electricity production and consumption and balance forecast fluctuations.
- Reduce the impact of new energy sources injected into the grid.

Table 2.1 Main projects related to VPP in EU countries

Project	Time	Country
VFCPP	2001-2005	Germany
KONWERL	2002-2003	Germany
VIRTPLANT	2005-2007	Germany
UNNA	2004-2006	Germany
CPP	2003-2007	Germany
STADG VPP	2003-2007	Germany
HARZ VPP	2008-2012	Germany
ProVPP	2008-2012	Germany
VATTENFALL VPP	2010-2012	Germany
VGPP	2007-2008	Austria
PM VPP	2005-2007	Netherlands
FENIX	2005-2009	Britain, Spain, France, Romania, etc
EDISON	2009-2012	Denmark
GVPP	2006-2012	Denmark
WEB2ENERGY	2010-2015	Germany, Poland

It obtains benefits through several aspects, the first is the lower marginal cost of photovoltaic, wind power and other power sources, participate in market-based trading profit, the second is biomass, combustion engines and other power sources with better regulation performance, participate in frequency regulation profit, thirdly is the regulation of distributed power sources and controllable load, use the peak-valley difference in the power market profit. For resource coordination and aggregation capabilities, the requirements are very high. The characteristics of the source network, load and storage, how to interface with the business model of the power market, how to respond in a timely manner, efficient control, are great topics.

VPPs are becoming increasingly popular in Europe as a way to manage distributed energy resources (DERs) and integrate renewable energy sources into the grid. Here are some of the key trends and developments in VPPs in Europe:

Regulatory Frameworks: Many countries in Europe have implemented policies and regulations to promote the deployment of VPPs. For example, in Germany, the Renewable Energy Act (EEG) incentivizes the deployment of VPPs by providing feed-in tariffs for renewable energy sources.

Technology Integration: VPPs are becoming more sophisticated and integrated with advanced technologies such as artificial intelligence (AI) and blockchain. These technologies can help optimize the performance and management of DERs and improve the reliability and resilience of the grid.

Business Models: There are various business models for VPPs in Europe, including utility-owned, aggregator-owned, and community-owned models. Some utilities are also partnering with technology companies to develop VPPs and other DER management solutions.

Market Integration: VPPs are increasingly being used to participate in energy markets, such as providing grid-balancing services and participating in demand response programs. This can help DER owners to monetize their assets and reduce energy costs.

Growth Potential: The VPP market in Europe is expected to grow significantly in the coming years, driven by the increasing adoption of DERs and the need to integrate renewable energy sources into the grid. According to a report by Navigant Research, the European VPP market is expected to grow from $1.3 billion in 2020 to $5.2 billion by 2029.

Overall, VPPs are seen as a key solution for managing the growing number of DERs and promoting a more sustainable and resilient energy system in Europe.

✧ VPP in China

VPPs are also gaining attention in China as a way to manage the country's growing distributed energy resources (DERs) and promote a more sustainable and efficient energy system. Here are some of the key developments and trends in VPPs in China:

Government Support: The Chinese government has been promoting the adoption of VPPs as part of its energy policy. In 2019, the National Energy Administration issued guidelines on the development of VPPs, which aim to accelerate the integration of renewable energy into the grid.

Technology Advancements: China has a rapidly growing technology industry, and many companies are developing advanced technologies to support VPPs, such as AI, big data analytics, and blockchain. These technologies can help optimize the performance and management of DERs and improve the stability and reliability of the grid.

Market Potential: China has a large and growing market for VPPs, with a high penetration of renewable energy sources and a large number of DERs. According to a report by Wood Mackenzie, the VPP market in China is expected to grow at a compound annual growth rate (CAGR) of 30% between 2020 and 2025.

Business Models: There are various business models for VPPs in China, including utility-owned, aggregator-owned, and customer-owned models. Some companies are also developing platform-based business models that enable DER owners to participate in VPP programs and monetize their assets.

Pilot Projects: Several VPP pilot projects have been launched in China, including projects in Shanghai, Guangdong, and Zhejiang provinces. These projects aim to demonstrate the feasibility and benefits of VPPs and pave the way for larger-scale deployments in the future.

Overall, VPPs are seen as a key solution for managing China's growing DERs and promoting a more sustainable and efficient energy system. The government's support and the rapidly advancing technology industry are expected to drive the growth of the VPP market in China in the coming years.

With the advancement of the global energy internet, three Chinese ministries and commissions (Ministry of Finance, Chinese Ministry of Propaganda, Ministry of Education) have jointly released the “the Belt and Road Initiatives” development strategies for renewable energy, with countries along the “the Belt and Road Initiatives” having abundant wind and solar resources, promoting the transmission of electricity from large renewable energy bases and the exchange of electricity between continents.

The energy internet strategy promotes the construction of cross-border power and transmission channels, actively carries out cooperation in upgrading and transforming regional power grids, gives full play to the complementary time-lag and seasonal characteristics of distributed power sources in different regions, and improves the utilization rate of renewable energy and the benefits of VPPs.

For China, take the example of VPP project in Huangpu District, in 2020. The largest trial run with over 50 participating buildings, releasing power load of about 10,000 kW. During peak hours of electricity consumption, the system automatically adjusts several characteristic parameters such as temperature, air volume and speed of the central air conditioners of the buildings involved, within the VPP system, with little impact on the user experience. How do users participate in VPP projects and realize profits? Take the Huangpu project as an example, the load aggregator bids on the system platform. The subsidy price is differentiated based on response time. The user is within 30 minutes of peak shaving, the subsidy to you is 3 times the price (there is a benchmark value), between 30 minutes and 2 hours is 2 times, longer time is lower. At present, the subsidies mainly come from the surplus of the inter-provincial renewable energy power spot trading purchase price difference, so there are still some constraints, many provinces have not started power spot trading.

✧ VPP in South Korea

South Korea has implemented a Virtual Power Plant (VPP) program to promote renewable energy and energy storage systems. The program aims to deploy 1.3 GW of VPP capacity by 2025. The VPP program is part of the government's efforts to reduce the country's dependence on fossil fuels and promote the use of renewable energy sources.

The VPP program in South Korea is being implemented by the Korea Electric Power Corporation (KEPCO) and other energy companies. The program involves aggregating various distributed energy resources, such as rooftop solar panels, energy storage systems, and electric vehicles, into a single network. The VPP is managed by a central control system that coordinates the generation, storage, and distribution of energy.

The VPP program in South Korea aims to improve the stability of the country's electricity grid by providing a more flexible and responsive system. The VPP can quickly respond to changes in energy demand and supply, providing a more efficient and reliable energy system. The program also aims to increase the use of renewable energy sources and reduce the country's carbon emissions.

The VPP program in South Korea is an important step towards a more sustainable and efficient energy system, as the country seeks to reduce its dependence on fossil fuels and increase the use of renewable energy sources.

- ✧ VPP in Singapore

Singapore has implemented a Virtual Power Plant (VPP) program as part of its efforts to increase the use of renewable energy and promote energy efficiency. The VPP program is being implemented by the Energy Market Authority (EMA) and the Infocomm Media Development Authority (IMDA) in partnership with various energy companies.

The VPP in Singapore involves aggregating various distributed energy resources, such as solar panels, energy storage systems, and demand response programs, into a single network. The VPP is managed by a central control system that coordinates the generation, storage, and distribution of energy.

The VPP program in Singapore aims to improve the efficiency and reliability of the country's electricity grid, as well as promote the use of renewable energy sources. The VPP can help to balance the supply and demand of electricity in real-time, ensuring that the grid remains stable and reliable. The program also aims to encourage the adoption of energy efficiency measures, such as demand response programs, which can help to reduce energy consumption during peak periods.

- ✧ VPP in Russia

There has been limited development of Virtual Power Plants (VPP) in Russia compared to other countries, although some companies have started exploring the potential for VPPs in the country. The development of VPPs in Russia is driven by the need to improve the efficiency and reliability of the electricity grid, reduce energy consumption, and promote the use of renewable energy sources.

One example of a VPP project in Russia is the "Smart Energy System" project, which is being developed by the Russian energy company Rosseti. The project involves the installation of distributed energy resources, such as solar panels and energy storage systems, in residential and commercial buildings. These resources are then aggregated into a VPP, which is managed by a central control system that optimizes the use of energy resources and balances the supply and demand of electricity.

The Smart Energy System project aims to reduce energy consumption and promote the use of renewable energy sources in Russia. The project is being implemented in several regions of the country, including the Moscow region, and is expected to contribute to the development of a more sustainable and efficient energy system in Russia.

- ✧ VPP in Japan

Since the Great East Japan Earthquake, conventional energy supply systems that depended on large-scale power plants have been challenged, and the spread of distributed power sources such as renewable energy, including solar power and wind power, has been increasing. As the amount of renewable energy generated greatly depends on the weather, the energy supply will become unstable as its use spreads. The new concept of energy service comes as a solution to maintain the stability of the power supply. This means, for example, that scattered energy sources, such as distributed power sources and storage batteries, can be remotely controlled by IoT equipment and function as if they were one power plant.

Therefore, it is necessary to control many geographically spread power generation and storage facilities in real time, according to the ever-changing supply and demand situation. For that purpose, it is necessary to have excellent technology for remotely controlling dispersed devices and technology for more accurately predicting electricity demand and solar power generation.

By adjusting the balance between supply and demand with VPP, renewable energy power can be used stably. VPP is expected to promote the introduction and expansion of renewable energy and contribute to a decarbonized society.

In Japan, which wants to further increase the introduction of renewable energy, the "Japan Revitalization Strategy" decided by the government in June 2015 states that VPP will be used. The Ministry of Economy, Trade, and Industry's Energy Innovation Strategy, announced in April 2016, states that it will promote demonstration trials and commercialization of VPP technology and provide subsidies in a five-year plan ending in fiscal 2020. The government established it to support companies working on VPP.

Virtual power plants (VPPs) are emerging as an innovative solution for managing distributed energy resources (DERs) in Japan. A virtual power plant is a network of decentralized power-generating units, such as solar panels and battery storage systems, that are connected and managed through a central control system.

In Japan, the government has been promoting the adoption of renewable energy sources as part of its energy policy. As a result, there has been a significant increase in the number of DERs such as solar panels and storage batteries in the country. However, the integration of these DERs into the existing power grid has been challenging due to the intermittency and variability of renewable energy sources.

VPPs offer a solution to this challenge by aggregating DERs and managing their output to provide reliable and stable power to the grid. VPPs can also help to reduce energy costs by enabling the sale of excess power generated by DERs back to the grid.

Several companies in Japan have started to develop and deploy VPPs, including Toshiba, Mitsubishi Electric, and Panasonic. In addition, some utilities such as Tokyo Electric Power Company (TEPCO) have also launched VPP pilot projects.

Overall, the deployment of VPPs in Japan has the potential to transform the country's energy landscape by enabling the integration of renewable energy sources and promoting a more sustainable and resilient energy system.

There are several models of Virtual Power Plants (VPPs) in Japan, each with its own unique approach to aggregating and managing distributed energy resources (DERs). Here are a few of the main models:

a) Aggregator Model: In this model, a VPP aggregator collects data from multiple DERs, such as solar panels and batteries, and manages their output to sell to the grid or to provide ancillary services. The aggregator takes on the risk and responsibility of managing the DERs and ensuring their performance.

b) Utility-Owned Model: In this model, a utility company owns and operates the VPP, which aggregates DERs from its customers. The utility is responsible for managing the DERs and selling their output to the grid.

c) Customer-Owned Model: In this model, customers own and operate their own DERs, such as solar panels and batteries, and participate in a VPP program that aggregates their output with other customers. The VPP operator manages the aggregated output and sells it to the grid.

d) Community-Owned Model: In this model, a community or group of customers collectively own and operate DERs, such as solar panels and batteries, and participate in a VPP program that aggregates their output. The community manages the DERs and sells their output to the grid or uses it locally.

e) Hybrid Model: In this model, multiple parties, such as utilities, aggregators, and customers, work together to aggregate and manage DERs in a VPP program. This model allows for greater flexibility and collaboration among different stakeholders.

Table 2.2. Main modes of VPP in Japan

Beneficiary	**Main function**		**Basic contents**
Transmission and distribution side	Stabilization system	Frequency modulation	Integrate distributed power generation on the user side, energy storage devices, load control and demand saving, and provide various services to power transmission and distribution companies through real-time markets
		Pressure regulation	
		Supply and demand balance	
	Investment optimization		Utilize storage batteries to reduce system or substation transformation and capacity expansion
Retail side	Power deployment to make up for the cost difference caused by insufficient power		Load aggregators and electricity retailers conduct indirect transactions of deployed electricity through the load side market, futures market, and hourly market
Demand side	Reduce electricity bills		peak clipping protocol, optimizing electricity purchase and consumption time
	Maximize equipment utilization		Trade the surplus space of decentralized power sources and energy storage devices through the load-side market
	Business Continuity Planning		Using distributed power and energy storage to ensure power supply during disasters
	Incentive agreement demand response		Users participate in demand response to obtain incentive rewards
Plant side	Reducing curtailment of renewable energy		Utilize the deployment of energy storage devices to maximize the use of renewable energy

Overall, the different VPP models in Japan reflect the diverse needs and priorities of various stakeholders, including utilities, customers, and communities. As shown in Table.2.2.

2.2 Summary of previous study

The worldwide decarbonization of power systems is bringing significant changes, with traditional large-scale synchronous generators.

Being replaced by emerging low-carbon technologies. Since energy and environmental problems become very serious, distributed energy resources (DERs), especially wind power and solar photovoltaic power, are playing increasingly important roles in the energy structure. However, constraints of small installed capacity, intermittence, uncertainty and other characteristics, make entrance and operation of the power market difficult for DERs [7].

So, the virtual power plant (VPP) was proposed as a new technology for DERs in the power market [8]. Without changing the DERs grid connection method, VPP integrates different types of DERs, such as distributed power sources, energy storage. systems and controllable loads, by using advanced control, calculation and communication technology [9]. In recent years, smart grid technology has received extensive attention. The government implements a series of policies to improve the development of smart grids, accelerates the construction of ultra-high voltage networks and distribution networks, promotes the rational allocation of resources, strengthens the interaction between power grids, power resources and energy consumers, and provides support for VPP development. According to the example of VPP subsidies in 2017 of Japan, up to one third of the equipment cost can be subsidized.

VPP is conducting pilot projects at home and abroad. In 2007, the Cassell University integrated wind turbines, solar photovoltaic systems, biogas power plant and hydroelectric power plant into a VPP with the world’s largest installed capacity [10]. In 2009, the electric vehicle grid connection project in Denmark used VPP technology to control electric vehicle smart charging–discharging considering large-scale wind power output uncertainty [11]. In 2008, a distributed energy power plant was operated at China Guangdong University City, including a gas-steam combined cycle unit to meet the electric power demand and heat demand [12]. In 2011, the China Zhangbei wind–photovoltaic–storage-transmission project began operation, which is a new energy comprehensive utilization platform to integrate wind power, photovoltaic power, a storage system, and power transmission [13]. In 2014, the Xiaozhongdian wind–photovoltaic–hydro distributed demonstration project of China National Electric Power Group Corporation successfully connected into the grid and started its business operations in Yunnan province [14].

Research on VPP generally begins from the VPP itself and focuses on how to realize optimal VPP operation based on the capacity configuration and coordinate operation. Morteza et al have defined the concept and control mode of VPPs and summarized the essential statue and development prospects [15]. Then, mathematical models were constructed for VPP scheduling. Hrvoje et al. have presented a mixed integer linear programming based on the optimum operation of a wind hydro VPP [16]. João et al. have applied VPP to manage the day-ahead energy resource scheduling in the smart grid, considering the intensive use of distributed generation and Vehicle-To-Grid [17]. Tiago et al. proposed a methodology for day-ahead energy resource scheduling for smart grids considering the intensive use of distributed generation and Vehicle-to-Grid managed by a virtual power player [18]. Spyros et al. have optimized the installed capacity and control generation mode to realize VPP economical scheduling [19]. Zapata et al. have proposed an optimization model to improve VPP operation income by making use of a controllable load to reduce the influence of wind power output uncertainty [19]. Saeed et al. have analyzed the coordination problem among wind power, solar photovoltaic power and hydro power [20].

From a technical point of view, the concept of VPP is particularly useful in managing the uncertainty caused by renewable energy (RES) and increasing the much-needed flexibility requirements of the power system [21-27]. Take an example, the VPP concept in [22] is deployed to minimize RES spillage and network congestion issues in distribution networks. In methodologies to estimate the feasibility of active distribution network is put forward. proposes a model that can estimate both the feasibility and flexibility of VPP.

Riaz S. et al. deployed thermal loads and energy storage for day-ahead scheduling of VPP [28]. A transactive energy framework is modeled to schedule DER aiming to maximize overall profit in day-ahead and real-time energy markets [29]. Qiu J.et al. [30] proposes a model to maximize VPP profit in the DA electricity market and minimize the anticipated production and consumption imbalance charges; this is done through a stochastic bi-level approach similar to [31]. A bidding strategy to address the operation of multiple VPPs through interactive dispatch modes and game theoretical models is presented in [32]. The above works mainly focus on VPP participation in (day-ahead and real-time) energy markets and did not discuss the possibility of participating in other potential markets.

The VPP will play an important role in the development of smart grids in the future. At present, the concept of the VPP is still relatively new. The concept of a VPP was firstly introduced by V. K. Dielmann. et al. [33], aiming to overcome the issues regarding the participation of distributed energy resources (DERs) in system operation. The VPP also was defined as an effective option for aggregating and operating DERs so as to allow them to participate in wholesale energy markets, and to provide the flexibility and associated grid services required in a renewable-rich energy system [34]. K. Mahmud.et al. [35] defined a VPP as an advanced automated power plant that combines variously distributed generators, battery storage units, and prosumers with a demand response capability, thereby forming an exceptional power plant. VPPs can be classified into two types: commercial VPP and technical VPP [36]. A Virtual Power Plant (VPP) is a practical concept that aggregates various Renewable Energy Sources (RESs) to enhance energy management efficiency and promote energy trading [37]. The VPP is receiving increasing attention as a means of integrating distributed energy systems (DESs) to provide stable electricity. Compared with conventional power plants, the VPP allows for higher energy efficiency and better flexibility. Essentially, VPPs are clusters of distributed generation resources, energy storage systems, and controllable loads connected to a centralized entity that superintends the energy flow within the aggregation [38]. VPP can be divided into commercial VPP (CVPP) and technical VPP (TVPP) [39]. The main objective of CVPP is financial efficiency. However, TVPP always relates complex computations and analysis, as well as technological applications.

A considerable number of studies have primarily focused on technical perspectives, such as smart grid control [40-42], the structure of the VPP[43, 44], and power quality and load support based on distributed energy storage (DES)[45, 46]. S.M. Nosratabadi. et al. [47] presented a comparative study of VPPs and microgrids considering various DES systems. S. Monie. et al. [48] explored how a VPP in a local residential area with single-family houses could provide power balancing services to a power system with large shares of variable renewable electricity generation sources. W. Guo. et al. [49] proposed a new optimal dispatching method for electric-thermal interconnected VPPs considering market transaction problems. L. Ju. et al. [50] applied a stochastic chance-constrained planning method to build a multi-objective optimization model for VPP scheduling, considering the uncertainties and demand response. However, in these studies, the financial implications have mostly been ignored. In fact, without economic profits, a VPP cannot deploy its technical flexibilities. In terms of economic analyses of the VPP, most studies have been conducted with an aim to maximize the profits of the VPPs participating in the energy market. Z. Li. et al. [51] discussed the feasibility of introducing a VPP in China based on technological and economic aspects. M. Loßner. et al. [52] discussed the economic performance of a VPP in the German energy market. In [30], a transactive energy framework was modeled to manage and schedule DERs, so as to maximize the overall benefit of a VPP in day-ahead and real-time energy markets. Y. Liu. et al. [53] combined interval and deterministic methods to design a scheduling model for maximizing the operating profits of VPPs. L.F.M. van Summeren. et al. [54] adopted a multiple-methods approach to explore the community-based VPPs as a novel model for energy provision. F. Fang. et al. [55] developed a novel method of profit allocation for multiple DERs co-existing in a combined heat and power-virtual power plant. S. Hadayeghparast. et al. [56] proposed a model for managing the energy of a VPP, focusing on maximizing the expected day-ahead profit of the VPP and minimizing the expected day-ahead emissions. Y. Li. et al. [57] analyzed the economic feasibility of a VPP by constructing a renewable energy power plant and updating high efficiency appliances located on the demand side. Many researchers have also focused on bidding strategies for VPPs. X.Kong et al. [58] focused on the optimal scheduling for a multi-operator VPP considering the fluctuation costs and penalties in the bidding mechanism. H.T. Nguyen. et al. [59] presented a mathematical model for an energy bidding problem of a VPP participating in a regular electricity market and intraday demand response exchange market. J. Zapata Riveros. et al. [60] focused on developing a bidding strategy for a VPP composed of a combined heat and power plant with district heating and renewable energy source (RES) generation to maximize the profit and cover the heat demand, as well as to compensate for possible forecast errors in the RES-based generation.

The financial efficiency of CVPP participates in energy market has been widely discussed in many studies. [61] discussed strategies for the provision of VPP for participation in energy and reserve power markets. [62, 63] proposed the modeling of a cooperation system among neighboring commercial VPPs to maximize the opportunities for power commercialization. [64] designed a novel concept of power-to-gas based VPP, as well as considering the variability of VPP profits when risk management participates in competitive markets. [60] provided a stochastic optimization evaluates the optimal bidding strategy of a VPP considering combined heat and power and intermittent renewables. [65] considered a VPP composed by an intermittent source, a storage facility, and a dispatchable power plant, which sells and purchases electricity in both the day-ahead and the balancing markets seeking to maximize its profit. [66] maximized the profit of the VPP and minimized the cost of self-consumption of the VPP by the method of iterative process using CPLEX solver. [67] took the Lankao Rural Energy Revolution Pilot program as an example proposed a benefit allocation strategy based on Nash negotiations, considering the following factors of risks, benefits, and carbon emission reduction into account. [68] addresses the participation of VPPs in different electricity markets. Studies mentioned above have well demonstrated the economic feasibility of CVPPs in the aspect of for power commercialization. CVPP can be seen as an aggregator between DERs and the energy market, as it can trade energy on behalf of smaller DERs that are unable to participate in the electricity market. As CVPP only performs commercial aggregation, thus the network limitations and the impact to power load are always not taken into account in its operation.

In the aspect of TVPP, there is a large amount of literature focused on the energy management and dispatching of various distributed energy sources (DESs). In view of energy management, [43] developed an optimization meta-heuristic algorithm to determine optimal energy management of a VPP with RESs, energy storage and load control in a case study. Azimi Z, Hooshmand R-A. et al. [69] presents energy management of industrial VPPs using both demand response loads and available electric vehicles in car parks to improve grid reliability under peak load conditions. Yang Q, Wang H. et al. [70] developed a blockchain-based energy management platform for a VPP. As for optimal scheduling, Liu X. [71] proposed a multiple regions VPP optimal scheduling method for multi energy complementarity and low-carbon, which solves the threat of high-permeability renewable energy power generation and grid connection faced by the VPP. Rahimi M, Ardakani FJ. et al. [72] modeled a stochastic scheduling problem for a VPP, while considering network security constraints and uncertainties in power and thermal loads, wind speed, solar radiation, and market prices to satisfy thermal and electrical loads. Sheidaei F, Ahmarinejad A. et al. [73] proposed a hierarchical model for simultaneous modeling of an microgrids scheduling and VPPs energy management problems. Technologies for integrating different DESs also a hot spot all over the world. Tan C, Wang J. et al.[74] proposed a VPP model containing carbon capture devices, and explored the cooperative operation mode of a carbon capture system and power-to-gas, and develops a comprehensive demand response mechanism for the VPP. Naval N, Sánchez R. et al. [75] present a VPP combining large and small-scale distributed renewable energy generation technologies, and its practical application in the operation of irrigation systems is introduced. Royapoor M, Pazhoohesh M. et al. [76] aggregated various controllable loads in a commercial office building, including air conditioning, lighting, and elevators, into heterogeneous and reliable components of a VPP, described the substantial flexibility that exists in commercial office buildings. The studies reviewed generally present models that include control variables of different types of DESs and have well discussed the optimization of power flow, network architectures within VPPs and operational specifications solutions. However, few of these models involve a combination of distributed rooftop PV self-consumption facilities, energy storage devices and the management of building-side efficient appliances (This combination of VPP model always has great application potential in urban areas).

In the current academic field of VPP, the practice of integrating VPP with communities to achieve energy self-sufficiency is still exist limitation. A simulation case study select a coastal site in Hong Kong which comprises 8 high-rise residential buildings and 2 mid-rise office buildings to evaluate the technical and economic feasibility of a zero energy community using a hybrid offshore wind and tidal stream energy generation [77], and the carbon emission reduction potential also be identified. Another simulation case study in Cairo, Egypt has carried out to explore different RESs and uses different building materials to reduce energy consumption and carbon emissions in a community [78]. A recent study proposes the concept of Building-VPP [79], they have discussed building design and support technologies for aggregating buildings into VPP. However, these case studies are based on simulation data and are rarely supported by real-world data. In the real-world cases, different building types (e.g. residential, office, commercial and industrial), different geographical location, different technologies combination will lead to different energy consumption patterns.

2.3 Barriers and challenges of VPP

Distributed energy resources and controllable loads can be aggregated in VPPs to participate in bidding in day-ahead power markets, intra-day demand response markets, regulation markets, real-time electricity markets, and carbon trading markets. However, the uncertain output of distributed energy generation brings higher transaction risks to VPPs. The bidding models and strategies for VPPs have been extensively researched both nationally and internationally. The market bidding problem for VPPs consists of single day-ahead market bidding and joint market bidding.

And another problem is coordinate control of VPPs, it can be divided into 2 types. (1) Internal dispatch, where the VPP optimizes the capacity allocation or output of multiple power sources within itself; (2) External dispatch, where the VPP is optimally dispatched by the grid. The rapid development of communication and computer technology has enabled VPPs to communicate in real time. Most of the current grid dispatch and monitoring uses supervisory control and data acquisition system and energy management system, these systems have disadvantages such as slow processing speed and limited information that can be stored in the system. The system is weak in online analysis and most of the time requires human brain experience to solve problems. These weaknesses make these systems unsuitable for the increasingly complex and changing power systems of today’s world. VPPs require advanced computer algorithms to collect, organize, classify, and process massive amounts of information in the smart grid in real time, providing operators with assistance in decision making based on data and analysis. In addition, the VPP needs to have fast guidelines and simulation capabilities for real-time monitoring and analysis of the current state of the system to help the VPP respond and forecast quickly.

The key technology of VPP is still immature and has yet to be effectively solved. For China’s national, national and electric conditions, the following problems need to be solved: (1) Reasonable positioning of resource functions, including: identification of regulable distributed energy resources on the distribution network side; analysis of the technical and economic characteristics of various types of distributed energy resources; reasonable positioning of potential distributed energy resources in combination with specific distribution network operation constraints, clarifying the type of services they provide, response speed, response frequency, etc. (2) Need to develop supporting software and hardware technologies. 3) Need to stimulate active participation of all parties, including establishing a cooperation mechanism for VPP operation-related participants; establishing an incentive mechanism conducive to mobilizing grid enterprises to participate actively. If the optimal strategy of the VPP is not managed uniformly by the distribution network operator, i.e., the operator of the VPP takes the liberty of minimizing all its short-term costs, including production costs and transaction costs with the grid, thus forcing the provision of their heat and power, this will cause the voltage and current of the distribution network to exceed the allowable limits. As a result, VPPs are still not widely used around the world.

VPPs have the technical characteristics of diversity, synergy, and flexibility to meet the future needs of new power systems such as green, flexible, multi-interactive, and highly market-oriented operations, and are an important technical support, as well as providing a full participation mechanism for the development of the energy storage industry. With the certainty of the vision of the dual carbon target, VPPs are bound to usher in a good development in the world.

And several barriers and challenges that need to be addressed for their widespread adoption. Here are some of the main barriers and challenges of VPPs:

Regulatory Barriers: The regulatory framework for VPPs can be complex and vary depending on the region and country. Some regulations may not be fully supportive of VPPs or may not allow for the aggregation and control of DERs. This can create uncertainty and delay the deployment of VPPs.

Technical Challenges: Integrating and managing multiple DERs from different manufacturers and technologies can be challenging, particularly when it comes to ensuring interoperability and security. VPPs require advanced control systems, communication networks, and data management infrastructure to operate effectively, which can be expensive and time-consuming to implement. One of the primary regulatory barriers for VPPs is grid connection and interoperability with the existing power grid. VPPs need to comply with the technical requirements of the grid operator and ensure that they can connect and operate seamlessly with the grid. This can be challenging in some regions, where the grid infrastructure is outdated or unsuitable for distributed energy resources. VPPs must compete with conventional power plants and other energy resources. In some cases, the regulatory framework may favor traditional power plants or may not provide a level playing field for VPPs. This can make it difficult for VPPs to access the market and compete effectively. The regulatory framework and policies can play a crucial role in developing and implementing VPPs. In some regions, the regulatory framework may not provide clear guidelines or support for VPPs, hindering their development. Furthermore, VPPs may face regulatory hurdles such as complex permitting requirements or high fees, which can increase the cost of implementation. VPPs rely on real-time data and analytics to optimize energy resources and balance the supply and demand of electricity. However, data access and privacy can be significant regulatory barriers for VPPs. Data ownership and privacy issues must be addressed to ensure that VPPs can access the necessary data without infringing on consumers' privacy rights. The development and implementation of VPPs require significant investments, and financial incentives can play a crucial role in promoting their adoption. However, the lack of adequate financial incentives or unfavorable economic policies can hinder the development of VPPs.

Business Models: VPPs require a new business model that enables multiple stakeholders to share the benefits and risks of the aggregated DERs. Developing a viable and sustainable business model that incentivizes DER owners to participate in VPPs and ensures a fair distribution of benefits can be challenging. One of the most significant barriers to VPP implementation is the high initial investment costs, which can challenge smaller companies or startups. It requires substantial investment in infrastructure, software, hardware, and communication technologies, which can be a significant barrier to entry into the market. The delay in the return on investment (ROI) can be a significant business model barrier for VPPs. The ROI for VPPs can be challenging to estimate due to the dynamic nature of electricity markets, regulatory changes, and technological developments. This uncertainty can discourage investors from investing in VPP projects. The lack of a well-developed and mature market for VPPs can be a significant business model barrier. The need for VPPs is still in its early stages, and there is a lack of standardization and transparency in pricing and trading mechanisms. This can make it difficult for VPPs to compete with conventional power plants. VPPs rely on advanced technologies such as smart meters, communication networks, and control systems. Technical challenges such as system integration, data management, and cybersecurity can pose significant business model barriers for VPP implementation.

Data Availability: VPPs require access to large amounts of data from DERs, such as their output, performance, and status. However, data availability can be limited, particularly in regions with poor data infrastructure or where DERs are owned by multiple stakeholders. The availability and quality of data are critical for the successful implementation of VPPs. However, many developing countries lack the necessary data infrastructure to support VPPs. This includes data collection systems, data management software, and communication networks. The VPP system requires sensitive data such as energy consumption patterns, grid data, and user information. The security and privacy of this data are critical to protect users' privacy and prevent cyber-attacks. However, many developing countries lack strong data protection laws, and data security and privacy can be a significant barrier for VPP implementation. The VPP system relies on data sharing between different stakeholders, including consumers, energy producers, and grid operators. However, data sharing can be a significant barrier due to the lack of trust between stakeholders and concerns about data ownership. The lack of data standards can also be a significant barrier for VPP implementation. Without standardized data formats and protocols, it can be difficult to share and analyze data between different stakeholders. In some cases, data may be available, but its quality may be poor or unreliable. This can be a significant barrier for VPP implementation, as inaccurate data can lead to incorrect predictions and suboptimal decisions. In some markets, a single company may dominate the electricity sector. This can create barriers to entry for new VPP operators, as they may face difficulties in accessing the grid or negotiating fair prices.

Market Structure: The current energy market structure may not fully support the adoption of VPPs, particularly in regions where the market is dominated by large, centralized power plants. VPPs require new market structures that enable them to participate in energy trading and provide grid services in a competitive and efficient manner. The current market design may not be favorable to VPPs. For example, some markets may not have enough incentives to encourage the participation of VPPs, or the rules may not be flexible enough to accommodate VPPs' operations. The lack of competition in some markets can also be a barrier to the development of VPPs. If there are only a few dominant players in the market, they may not have enough incentives to adopt VPPs or invest in new technology. The uncertainty surrounding VPPs and their operations can also create barriers. For example, if the market rules are unclear, or if there is a lack of understanding about VPPs' potential benefits and costs, market participants may be reluctant to adopt VPPs.

Public Perception: The public may not fully understand the benefits and potential of VPPs, which can create resistance and slow down their adoption. Educating the public and stakeholders on the benefits and potential of VPPs is essential for their widespread adoption. Many people may not be aware of what VPPs are and how they work. This can make it difficult for VPP operators to gain support for their projects. Some people may have concerns about the safety of VPPs. For example, they may worry about the risk of fires or explosions. Some people may worry that VPPs are not as reliable as traditional power sources, and that they may not be able to provide a stable supply of electricity. Overcoming these public perception barriers may require VPP operators to engage in education and outreach efforts to help people better understand the benefits of VPPs and address their concerns. Additionally, involving the public in the decision-making process for VPP projects can help increase public acceptance and support for VPPs.

Overall, addressing these barriers and challenges will require collaboration and coordination among multiple stakeholders, including regulators, utilities, DER owners, and technology providers. Addressing these challenges will be essential for the widespread adoption of VPPs and their contribution to a more sustainable and efficient energy system.

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Chapter 3

VIRTUAL POWER PLANT MODEL ESTABLISHMENT AND METHODOLOGY

CHAPTER 3 VIRTUAL POWER PLANT MODEL ESTABLISHMENT AND METHODOLOGY

3.1 Technology approach

Renewable energy is clean, naturally renewable, regionally distributed, low in energy density and intermittent. And it remains an underutilized resource within urban environments. Renewable energy technologies like solar and wind are essential for reducing emissions of the power sector, which currently account large amount of GHG emissions. There is no possibility of energy depletion from renewable energy sources. Therefore, the development and use of renewable energy sources is receiving increasing attention in many countries, especially in countries with energy shortages. With the recovery of nuclear energy and the rapid development of renewable energy worldwide, the development of clean energy is on a year-on-year upward trend and its growth rate is second only to that of natural gas. According to statistics, global renewable energy consumption increased by 16% in 2017 compared to 2016 and maintained a double-digit growth rate. Of this, solar energy grew at 29.6% and wind energy at 15.6%. Taking into account nuclear, hydro and natural gas, the global share of clean energy consumption reached 38% in 2017, surpassing the 28% of coal consumption and 34% of oil consumption. At the same time, electricity generation structures also changed with the renewable energy development. Among the renewable energy sources, solar and wind power generation is considered to be an important component of a hybrid distributed energy system. Renewable energy technologies play an important role in the energy systems of the future, not only in achieving a low carbon society but also in providing socio-economic benefits.

A sustainable power supply framework should be suitable for the situation in the region. Currently, renewable energy utilization still accounts for a small proportion of the total electricity demand in Higashida District. By aggregating distributed energy generation and energy storage systems, a VPP would provide multi-facade flexibility, e.g., to accommodate the intermittence in renewable energy generation and improve the reliability of the power supply. The composition of VPP in this article mainly includes PV system and SB system. Compared with large-scale PV power generation systems, we consider installing PV on the roof of buildings, which will not restrict the location and cause too much economic burden, it is also can reduce the initial investment (Due to the shortage of land resources in Japan, rooftop PV is the best promoted in Japan.). Also, the VPP is equipped with storage battery system, the battery has two functions here: 1. Store the electricity generated by PV not consumed by the demand side; 2. Store electricity when the grid's power demand is low and discharge at the peak of grid demand to stabilize the load curve. As for we did not consider gas turbines. On the one hand, currently PV and SB systems are the most popular distributed energy system with the best effect in Japan. On the other hand, gas prices in Japan are relatively expensive, the overall economic benefits of gas turbine not so good, thus, it is rarely used on the demand side currently. Today, due to global warming, the usage of clean fuels in power systems get more importance. Regarding Japan's current GHG emission reduction goals, gas turbines use gas as fuel, cannot contribute to reducing GHG emissions, and solar energy as renewable energy source can reduce GHG emissions. Considering the above reasons, we used a combination of PV system and SB system in this paper.

The energy system begins with the extraction of primary energy in nature, including energy conversion, energy transportation, and energy utilization stages. Energy conversion includes purification, gasification, combustion, power generation, etc., and the production of secondary energy products, such as fuel, heat, and electricity. Energy use is the use of secondary energy products to provide energy services corresponding to consumer needs, such as electricity, lighting, air conditioning and heating.

Conventional energy system refers to the collection of primary energy and the production and transportation of secondary energy products. The energy industry is responsible for providing secondary energy products for consumers to use in various occasions, such as various household appliances and automobiles.

The distributed energy system is a system that can convert natural energy (such as solar heat, biomass, wind, etc.) in appropriate places and use these converted energy and fossil fuels to meet consumer energy needs. From the perspective of the public power grid, diversified energy systems can help improve the stability and safety of energy supply systems. Also, for the end user's consideration, they can achieve power quality and reliability while enjoying reduced energy costs. The energy system has made many contributions in terms of energy-saving performance and environmental protection, and has also created huge advantages in economic terms, for example, making early investment possible. Therefore, in many countries, the input of power generation equipment using distributed energy systems such as gas-fired cogeneration systems tend to increase year by year. Based on the above explanation, the decentralized energy system can not only help users reduce load, but also save energy costs.

In this study, the distributed energy system is composed by photovoltaic system and storage battery. There are different kinds of energy saving technologies which can be introduced into buildings to reduce the energy consumption of consumers, meanwhile, solve the environmental issues. At present, the most common energy saving technologies were used in whether residential house or commercial building are storage battery and photovoltaic, owing to its convenience and policy support. Both of them all can help customers to use less electricity from utility grid during the peak period which equipped with high electricity tariff. As for the whole area which contains various types of buildings, distributed energy system was considered to be introduced into the area to realize the better energy allocation due to the large load value and complex load characteristics. The introduction of related energy saving technologies will be presented in following contents.

3.1.1 Renewable sources

The fuel used for thermal power generation is affected by import costs, and the electricity price itself will rise. In response to the shift from fossil fuels to renewable energy, the spread of photovoltaic power generation in Japan has been promoted throughout the country. In addition, improvements in the technology of manufacturers in various countries have also contributed to lower prices.

The utilization of renewable resources can not only release the pressures of greenhouse gas emission reduction and local air pollutant pressure, but also improve the power self-sufficiency ratio and power dependency in the Higashida Area. Currently, renewable energy utilizations still account for a small ratio of the total electricity demand in Japan. In order to achieve the planed scope of smart community, distributed renewable energy power units will play an important role in the future sustainable electricity supply framework, the renewable penetration in the public grid will increase further. In addition, a broad application of renewable energy technologies is favorable to the security and diversity of power supply. A better understanding of the local renewable resources is essential for the power sustainable development.

✧ Solar energy power generation

Conversion of solar energy directly to electricity has been technologically possible since the late 1930s, using photovoltaic systems (PVs). These systems are commonly known as solar panels. PV solar panels consist of discrete multiple cells, connected either in series or parallel, that convert light radiation into electricity. PV technology could be stand-alone or connected to the grid. Solar photovoltaic power generation is a power generation method that uses the photovoltaic effect of solids (semiconductors) to directly transfer light energy to electrical energy. The solar photovoltaic power generation system consists of three parts: solar panels, batteries, and controllers. The continuous reduction of manufacture cost, solar photovoltaic power generation will present a good development prospect. And Fig 3. 1 shows a solar power station in Japan.

PV power generation has attracted attention as a means of raising electricity prices, lowering the cost of introducing power generation equipment, and preparing for disasters. The introduction of solar power generation facilities on the roof of the company's warehouse has the benefit of tax breaks, and in some cases subsidies may be available. Solar energy is a renewable source of energy. It is not depleted by usage and will never run out. And it is sustainable because it does not generate greenhouse gas emissions, air pollution or waste.

Solar power has several advantages, including:

1) Renewable: Solar power is renewable and abundant, as it is sourced from the sun.
2) Clean: Solar power is a clean source of energy that does not emit greenhouse gases or air pollutants.
3) Cost-effective: The cost of solar power has decreased significantly in recent years, making it more affordable than ever before.
4) Low maintenance: Solar panels require little maintenance, as they have no moving parts and are designed to last for decades.
5) Versatile: Solar power can be used in a variety of applications, from small-scale residential systems to large-scale power plants.
6) Energy independence: Solar power allows individuals and businesses to generate their own energy, reducing their dependence on traditional power sources.
7) Job creation: The growth of the solar industry has created jobs in manufacturing, installation, and maintenance.

Fig 3. 1 Solar power station in IKISHIMA, Japan (photo by Yafei Wang)

PV is a device which generating electrical power using sun resources. Photovoltaic are arrays of cells containing a solar photovoltaic material that converts solar radiation or energy from the sun into direct current electricity. Due to the growing demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years, and its costs also have dropped.

The design of a PV power station should take into account sunlight conditions, land and building conditions, as well as installation and transport conditions. It needs to meet the requirements of safety, reliability, economy, environmental protection, aesthetics, ease of installation and maintenance. PV systems installed on buildings must not lower the sunlight standards of adjacent buildings. The choice of site for a PV power station should be in line with the national medium and long-term development plan for renewable energy, taking into account regional natural conditions, solar energy resources, transportation, access to the power grid, regional economic development planning and other factors.

Solar radiation situation primarily influences the selection of local site for PV installation. Local climate and environment factors such as temperature, humidity, precipitation, and wind will constrain the output of PV array. Nevertheless, these are all secondly effects when compared with isolation intensity. As the third largest island of Japan, Fukuoka has the advantaged conditions of climate and geothermal character.

The solar radiation on Fukuoka is abundant, annual average utilized time is about 1860 h, with average annual solar radiation 4500MJ/m^2. The annual cumulated hourly irradiation and hourly maximal irradiation are shown as Fig 3. 4. According to this profile, it can be seen that maximum irradiation is at 12:00 in the midday. In this research, solar energy is suitable for Higashida area. There is a potential to reduce dependency on power plant and share peak load for the public grid.

The study found that the configuration capacity of PV is related to the area that can be installed. Fig 3. 2 shows the roof area available for PV installation. After investigation, the maximum installation ratio of the area on the roof where PV panels can be installed is 43.3%. The profit of PV system can be equivalent to the electricity cost saved during the working period of PV system.

Japan has a high potential for photovoltaic power due to its location and climate, as shown in Fig.3.3. The country is located in the temperate zone and has a long coastline, which provides a suitable environment for solar power generation. According to the National Institute of Advanced Industrial Science and Technology (AIST), Japan has the potential to generate up to 10 times its current energy demand using solar power.

In recent years, Japan has made significant investments in solar power, and the government has implemented policies to promote the development of renewable energy sources, including solar. The country has also been a leader in the development of photovoltaic technology and has some of the most advanced solar panels in the world.

However, there are also challenges to the expansion of photovoltaic power in Japan, such as land use issues and grid capacity constraints. Nevertheless, the potential for solar power in Japan remains high, and it is likely that the country will continue to invest in this renewable energy source in the coming years.

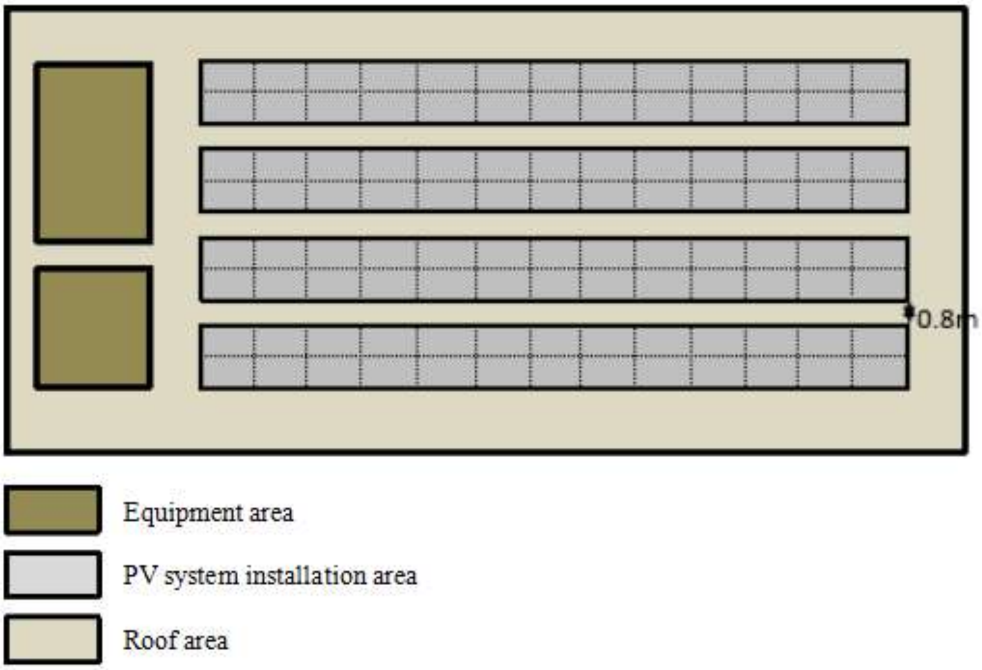

Fig 3. 2 PV installation area

Fig 3. 3 Photovoltaic power potential in Japan [1] (The maps and data for Japan have been released in parallel with Global Solar Atlas, which is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. All maps on this page are licensed by The World Bank under the Creative Commons Attribution license (CC BY 4.0) with the mandatory and binding addition presented in Global Solar Atlas terms. You are free to download, share, adapt, use the maps but you must give appropriate attribution:2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.)

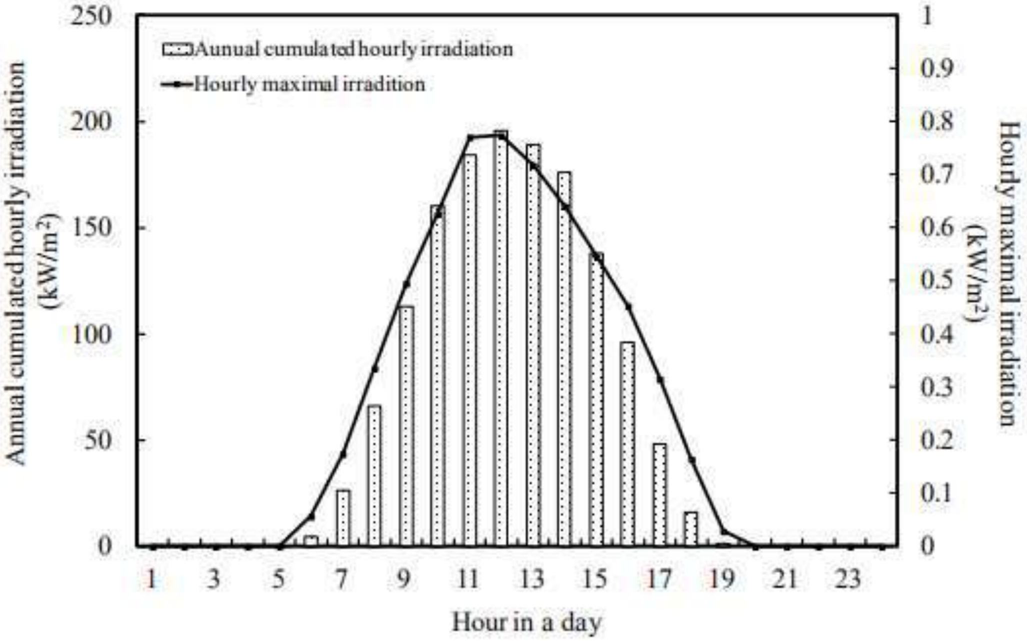

Fig 3. 4 Annual cumulated hourly irradiation and hourly maximal irradiation

Table 3. 1 Features of the PV used in this research

Items	Characters
Brand	Panasonic HIT N245
Life expectancy	20 years
Initial cost (JPY/kw)	250000
Module capacity	250w
Module Dimension	1.58m×0.798m（1.26m²）

There are many distributed generation technologies. Currently, gas turbine units, wind turbines and PV are relatively mature distributed generation technology [2]. Tidal stream energy, offshore wind energy also attract the attention of many researchers [3, 4]. The development of renewable and clean energy sources offers a great prescription to ease the increasingly serious energy crisis and environmental issues. PV systems are an essential substitution energy source with a wide range of applications [5]. The maturity of PV technology has been well studied by many researchers [6, 7]. There have been numerous studies showing that widespread urban rooftop PV deployments can cover a significant portion of electricity consumption [8, 9]. [10] has proposed a integrated system of cities' roof-top PV and EVs provide affordable and dispatchable electricity to urban research without CO2 emission. In the "2050 Carbon Neutral and Green Growth Strategy", the plan for the PV industry is included in the "Home and Office" section. This reflects the close integration between Japanese PV power generation and building. Due to terrain constraints, Japan lacks large-scale centralized PV power generation sites, so distributed building attached PV is the main direction of PV development. Building attached

PV, also known as “installed” solar PV buildings. Its main function is to generate electricity, which does not conflict with the function of the building, nor does it destroy or weaken the function of the original building and not restricted by the site. While renewable energy is widely believed to reduce carbon emissions, challenge such as the intermittency of renewables will pose an increasing pressure to the stability of the main grid. Consume the renewable energy locally instead of interacting with main grid can be one of the solutions. As the FiT price of PV power is declining year by year which has dropped to 10 JPY/kWh in 2022, the self-consumed PV gains increasingly popular.

The life expectancy of PV system used in this research is 20 years. In this research, we adopt the Panasonic’s PV module with unit price of 250,000 JPY/kW (1US dollar=108JPY, this price already includes the PV panel fee, construction fee, invertor fee, and other fee), the module dimension is 1.26 m^2 with capacity of 250 W [11]. Panasonic’s PV module have many advantages.

- High Performance at High Temperatures.

  As temperature increases, HIT continues to perform at high levels due to the industry leading temperature coefficient of -0.258% /°C. No other module even comes close to our temperature characteristics. That means more energy throughout the day and particularly in summer.

- 25 Year Product and Performance Guarantee.

  Industry leading 25 year product workmanship and performance guarantee is backed by a century old company - Panasonic. Power output is guaranteed to 86.2% after 25 years.

- Quality and Reliability.

  Panasonic’s vertical integration, over 20 years of experience manufacturing HIT and 20 internal tests 3-times beyond those mandated by current standards provide extreme quality assurance.

- Higher Efficiency of 19.8% and compact size.

  Enables higher power output and greater energy yields. HIT provides maximum production for your limited roof space.

- Low Degradation.

  HIT “N-type” cells result in extremely Low Light Induced Degradation (LID) and zero Potential Induced Degradation (PID) which supports reliability and longevity. This technology reduces annual degradation, guaranteeing more power for the long haul.

- Unique water drainage.

  The water drainage system gives rain, water and snow melt a place to go, reducing water stains and soiling on the panel. Less dirt on the panel means more sunlight getting through to generate power.

And the weather data in Kitakyushu was shown in Table 1. The PV power generation can be described as:

$$\boldsymbol{p_{pv}(t) = P_R \times \left(\frac{R}{R_{ref}}\right) \times \left[1 + N_T + \left(T_c - T_{ref}\right)\right]} \qquad \text{(Eq.3. 1)}$$

Here, $p_{pv(t)}$ represents PV panel generated electricity at time (t), P_R refers to the rated power of the PV module, and R refers the region solar radiation which is equal to 4500 MJ/m2. The R_{ref} is 1000 W/m2, and the T_{ref} is equivalent to 25℃. N_T represents module temperature coefficient equals to -3.7×10^{-3} (1/℃). The module temperature can be calculated by Eq. 3.2, as follows:

$$\boldsymbol{T_C = T_{\mathrm{air}} + \left[\left(\frac{NOCT-20}{800}\right) \times R\right]} \qquad (Eq.3.\ 2)$$

Here, T_{air} is ambient temperature (℃), T_C refers to normal operating temperature (℃). $NOCT$ refers to a specification stated by PV module manufacturers, respectively. And w refers to the quantity of modules. Therefore, we can calculate the PV power generation by Eq. 3.3,

$$\boldsymbol{Gen_{pv} = w \times p_{pv}(t)} \qquad (Eq.3.\ 3)$$

✧ Wind power generation

Fig 3. 5 Wind power station in IKISHIMA, Japan (photo by Yafei Wang)

Power generation is the main form of wind energy utilization. Wind turbines can be powered either individually or in combination with other forms of power generation, such as diesel generators or micro-gas turbines, to supply power to a unit or an area, or to integrate power into conventional grid operations. Windmills or wind turbines convert the kinetic energy of the streaming air to electric power. Investigation has revealed that power is produced in the wind speed of 4–25 m/s range. The size of the wind turbine has increased rapidly during the last two decades with the largest units now being about 4 MW compared to the 1970s in which unit sizes were below 20 kW. For wind turbines above 1.0 MW size to overcome mechanical stresses, they are equipped with a variable speed system incorporating power electronics. Single units can normally be integrated to the distribution grid of 10–20 kV, though the present trend is that wind power is being located offshore in larger parks that are connected to high voltage levels, even to the transmission system. The power quality depends on the system design. Direct connection of synchronous generators may result in increased flicker levels and relatively large active power variation. At present, wind energy has been found to be the most competitive among all renewable energy technologies. And Fig 3. 5 shows a wind power station in Japan.

3.1.2 Energy storage system

The rapid growth in the use and development of renewable energy sources in today's power grids requires the development of energy storage technologies to eliminate intermittent power disparities [12]. And the clean energy group has provided summarizes of the important role of battery storage systems in all areas and applications, as shown in Table 3. 2.

Table 3. 2 Value of battery energy storage system [13]

Utilities	• Increase renewable energy integration • Reduce dependence on fossil-fuel peaker plants • Reduce operating expenses
Grid operators	• Balance electricity supply and demand • Improve power quality and reliability • Avoid costly system upgrades
Commercial consumers	• Keep critical equipment online during power disruptions • Reduce utility bills and generate revenue
Residential consumers	• Reliable backup power during severe weather and other blackouts • Reduce utility bills and generate revenue

Energy storage technology meets the demand for electricity or heat/cooling energy over a period by storing electricity, with functions such as peak shaving, frequency and voltage regulation, smooth transition, and reduction of grid fluctuations. Energy storage technology can solve the problem of intermittent renewable energy limited by environmental factors and ensure the balance of supply and demand of energy system. As mentioned earlier, global energy consumption is steadily increasing, some of which is due to the increased consumption of inefficient peak plants to accommodate industrial facilities. One promising way to reduce the power demand of facilities is to discharge energy storage system equipment during peak hours and recharge it during off-peak hours, this is known as “peaking” and “valley filling”. Energy can be stored in different forms, including electrical, electrochemical, magnetic, thermal, and mechanical. A classification by form of energy storage, as shown in Table 3. 3.

These different functions of ESS will only expand over time, making battery storage technology so important for clean energy and climate change. Although we are in the earliest stages of this technology's development, storage could be a key transformative energy technology of this century. With the advancement of technology, energy storage systems have become less and less expensive in recent years. It is believed that as prices fall, ESS will become more popular.

Table 3. 3 Overview of energy storage technologies

Energy storage	Electrical and Electrochemical	Battery	Li-ion
			NAS
			Lead-acid
			Flow
		Capacitor	Supercapacitor
	Thermal	Sensible	
		Latent	
		Thermochemical	
	Mechanical	Flywheel	High Speed
			Low Speed
		Pumped Hydro	
		Compressed Air	Conventional
			Adiabatic
			Isothermal
			Variable Pressure Ratio
	Magnetic		

Electricity cannot be stored without storage batteries, and in order to supply high-quality electricity, it is necessary to always maintain a balance between supply and demand. Storage battery is an electrochemical device storing the chemical energy and releasing the energy when necessary. The batteries usually have been charged in the case of low peak load or electricity consumption at night and using them in the on-peak period of the day. Owing to its unique characteristic, storage battery is suitable for us to solve the contradiction between the improvement of whole grid and the consumers’ economic benefit.

In this study, we choose NAS battery as power storage technologies. NAS battery has large capacity, low self-discharge, and because it does not use toxic metals, it is very safe. In addition, it has a high charge and discharge tolerance, with an expected life of 15 years and approximately 4,500 charge and discharge cycles. The application range is quite large, from 600kW to tens of thousands of kilowatts. Table2-3 shows the characteristics of the storage battery used in this research.

The NAS battery is a megawatt-level energy storage system that uses sodium and sulfur. The NAS battery system boasts an array of superior features, including large capacity, high energy density, and long service life, thus enabling a high output of electric power for long periods of time. NAS battery system can charge at night when power demand is low and provide power in the daytime to reduce peak power. Moreover, the NAS battery system can be used as an emergency power supply in power outages and during momentary drops in voltage. NAS batteries are increasingly being utilized in stabilizing output from wind and solar power generators while proving useful to the spread of renewable energies and establishment of the smart grid. These batteries can be incorporated in microgrids, small-scale localized power supply networks that feature reduced energy costs and environmental impact, in demand response programs that make effective use of stored electric power, and with other new energy solutions spreading throughout the world to contribute to their widespread use and development. And Fig 3. 6 shows the stricture of NAS battery.

The NAS battery system is designed to be easily able to expand the capacity as much as needed in one site or several separate sites. The scalability of NAS installation to many 10s or 100s of MW for durations of 6 to 7 hours is at a scale that can defer or eliminate some transmission, distribution, and generation investments especially when used in association with variable renewables for a clean solution. (The current largest system at one site is 50MW, 300MWh.) The construction lead-time is significantly shorter than upgrading or building transmission/distribution lines or substations. A NAS battery system consists of battery enclosures, battery modules and a PCS (AC/DC power conversion system) as the main components. The NGK scope is the battery enclosures and battery modules. NGK works with several PCS manufacturers to complete the battery system. It is also suitable to install in severe weather conditions, because the battery enclosure and insulated battery modules can resist a wide range of environmental conditions and climate. By absorbing fluctuating renewable energy such as wind and solar during off-peak times, NAS batteries can provide additional power during periods of peak demand as show in Fig 3. 7.

✧ Operation principle

1) During discharge

Molten sodium donates electrons to the external circuit at the anode.

The resulting ions Na+ migrate to the cathode through the beta-alumina solid electrolyte that separates the two liquid electrodes and that acts as a superionic conductor.

The volume of liquid at the anode therefore decreases.

Arriving at the cathode, Na+ ions combine with molten sulfur which reacts with the electrons coming from the external circuit, forming sodium polysulfide Na2Sx.

The volume of liquid at the cathode therefore increases.

$2\,Na + x\,S \rightarrow Na_2S_x$ with $3.3 \le x \le 5$.

2) During charge

The reverse process takes place.

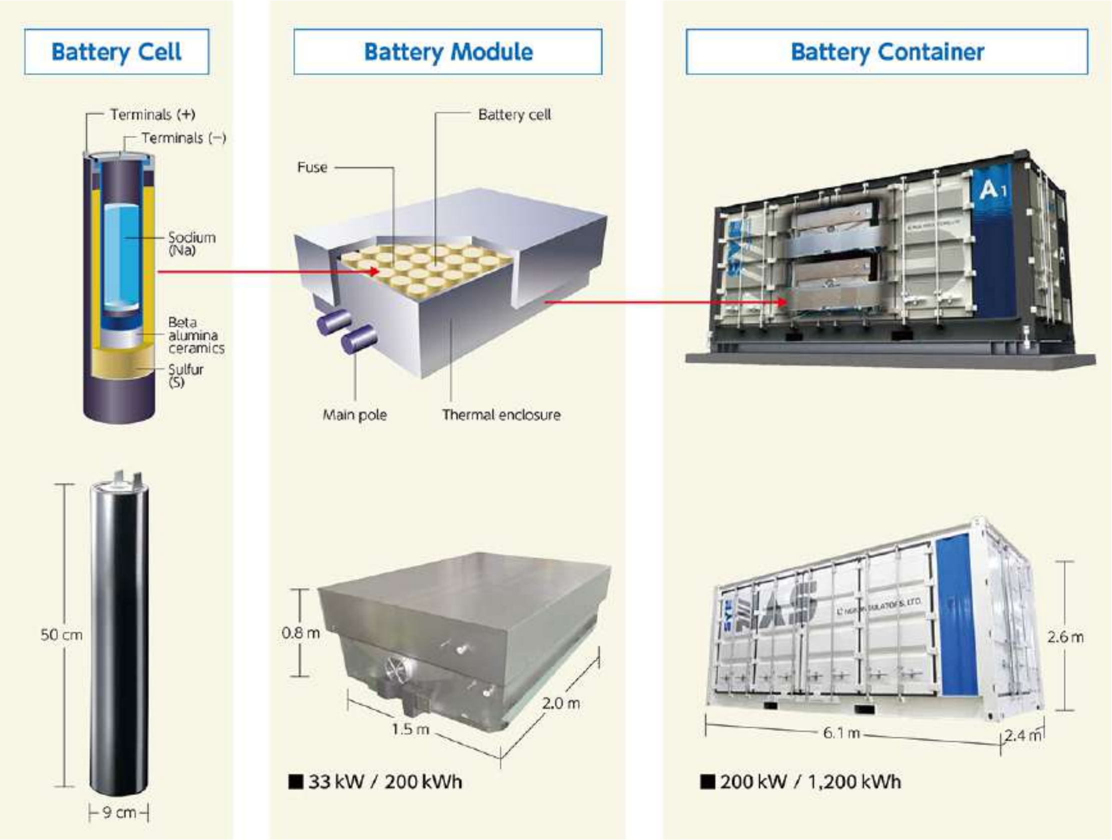

Fig 3. 6 Structure of NAS Energy Storage System [14]

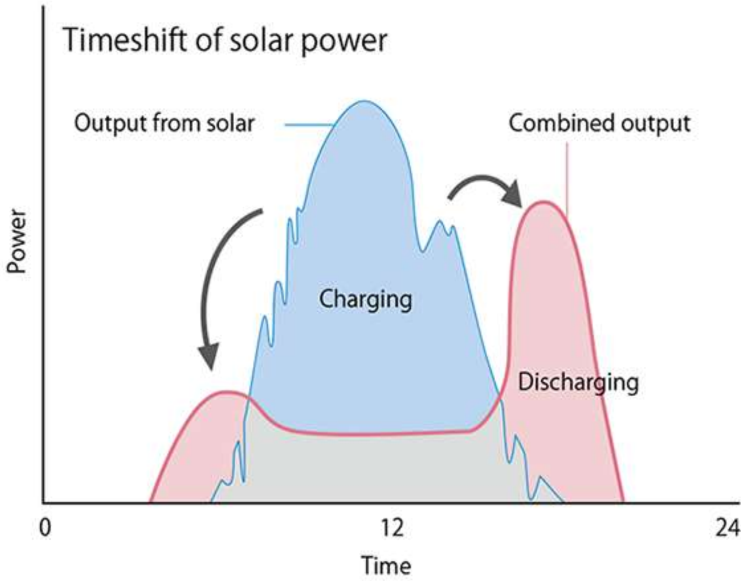

Fig 3. 7 Renewable stabilization solution of Storage battery

Table 3. 4 Features of the storage battery

Items	Characters
Life expectancy	15years
Initial cost (JPY/kWh)	25000
Charge time	23:00~9:00
Discharge time	9:00~23:00
Charge-Discharge efficiency	0.9
Rated output	1,200kW and 8,640kWh
Configuration	40 NAS modules, each rated at 30 kW and 216 kWh
Dimension	10.2W *4.4D*4.8H (m)
Weight	132 tonnes

Because the instability of renewable energy power generation poses a risk to the safety and reliability of the power grid, in regard to provide high-quality power, the renewable energy generation system should be incorporated with other power sources to ensure a steady supply of electricity and increase the local utilization of renewable energy. [15] has demonstrated that networked microgrids with rooftop solar PV and battery storage system can improve distribution grid resilience to natural disasters. ESS as an attractive option can significantly increase the availability of loads while not being sufficient to provide long-term energy demand [16, 17]. In this research, we select the sodium-sulfur (NAS) battery with a life expectancy of 15 years or approximately 4,500 charge/discharge cycles [18]. The charge-discharge efficiency of NAS battery is 0.9, and there is no self-discharge [19, 20]. And the unit price of this NAS energy storage system (ESS) is 25,000 JPY/kWh. In this research, the ESS is restricted to work within an allowable range.

An important characteristic of the ESS is the time coupling characteristic in relation to charge/discharge status (SOC). The SOC (%) dynamics can be defined as follows,

$$\boldsymbol{SOC(t+1) = SOC(t) + \frac{\eta_{cha} \cdot \sum E_{cha}(t) \times \Delta T}{Cap_{ESS}}} \quad (Eq.3.\ 4)$$

$$\boldsymbol{SOC(t+1) = SOC(t) - \frac{\sum E_{dis}(t) \times \Delta T}{Cap_{ESS} \cdot \eta_{dis}}} \quad (Eq.3.\ 5)$$

Here, $SOC(t)$ indicates the charge status of ESS at time t, η indicates the efficiency, and Cap_{sb} represents the capacity of ESS. T refers a one-day time series with a time step of ΔT, and is characterized as $T = \{1,2,3,..24\}$.

3.1.3 Energy efficiency equipment

According to the decomposition of carbon emission change factors from 2006 to 2019 by the

Ministry of the Environment of [21], energy conservation measures contributed more emission reductions until 2011, but electricity saving measures were not significant (and even increased carbon emissions in 2007 and 2010). The demand side can reduce energy consumption by upgrading the building with advanced high efficiency appliances (HEA), such as lighting, air conditioner, etc., which responsible for a large amount of energy consumption in buildings. Load shedding potential through updating HEA in the building sector will be modelled in this part. According to the Agency for Natural Resources and energy, compared with 10 years ago, high efficiency lighting can save 20~86% of electricity and high efficiency air-conditioning can save 17% of electricity [22]. Through investigation, fluorescent lamps were mainly popular in the market 10 years ago, so in this article we plan to replace fluorescent lamps with LED, with an estimated energy saving rate of 21% [23].

Update HEA can provide persistent power demand reduction regardless of time. And the energy saved by HEA can be described as follows:

$$\boldsymbol{E_{save,ac} = E_{ac} \times r_{ac}} \qquad (Eq.3.\ 6)$$

In the above, E_{ac} represent the electricity demand of AC, r_{ac} is the electricity saving ratio of updating AC, and the $E_{save,ac}$ is the electricity saving potential of updating AC.

$$\boldsymbol{E_{save,light} = E_{light} \times r_{light}} \qquad (Eq.3.\ 7)$$

Here, E_{light} represent the electricity demand of lighting, r_{light} is the electricity saving ratio of updating AC, and the $E_{save,light}$ is the electricity saving potential of updating lighting. Based on the above conditions, we can calculate the VPP capacity of updating high efficiency appliance by Eq.3.8:

$$\boldsymbol{Cap_{VPP,HEA} = Cap_{origin,ac} \times r_{ac} + Cap_{origin,light} \times r_{light}} \qquad (Eq.3.\ 8)$$

3.2 Establishment of VPP system

As distributed energy is already widely used around the world, there is still concern about how to efficiently aggregate and integrate various resources within a community. Against this background, the VPP in this research is comprised power saving technology, distributed photovoltaic (PV) and energy storage systems (ESSs). Reducing energy demand is the most important and cost-effective strategy. Energy efficiency can be increased by using appliances with lower energy requirements. As price advantages become increasingly prominent and technology continues to develop, cities and regions can turn their attention to alternative energy sources such as renewable energy to meet their own energy needs. Fig.1 briefly described the main components of proposed VPP system, as well as energy, cash and information flow. The system boundary is set at the interface with the public grid. The community-owned co-generation power plant and rooftop PV are the main power generators for self-sufficient. Considering the limited capacity of co-generation power plant and the intermittence of the PV generation, the community energy system is also connected with the public grid to guarantee a reliable power supply. All buildings are consumers. In terms of electricity demand reduction, the power saving technologies (e.g., lighting and AC) are responsible for energy saving to directly reduce the power demand. In addition, the surplus and shortage of renewable energy can cause communities to export or import power from the public grid at any time of the year. Consequently, energy storage system is essential to control the instantaneous system load matching at 100%. It is worth noting that the technologies we mentioned above (including energy saving technologies, rooftop PV, and energy storage system) are all distributed rather than centrally deployed. Therefore, the building sector is no longer a mere consumer, but has been converted to a prosumer. The ability to perform energy arbitrage is the biggest motivation for individual users to install distributed technologies. Improving the economic benefits of distributed application technologies on the demand side will facilitate negotiations and profit allocation among upstream stakeholders (government as well as power contractors), meanwhile this is the keystone of the realization of VPP. In proposed system, energy saving technologies, rooftop PV directly reduce electricity bills by reducing electricity demand or by self-supply. The individual EESs are aggregated into a large portfolio to provide community-scale ancillary services (load leveling), thus, ESS can gain revenue based on optimal market management. Therefore, an overview analysis of the introduction of VPP in the Community from the perspectives of “energy production”, “energy storage” and “energy saving” will be proposed. The three aspects mentioned above will also determine the capacity of the VPP.

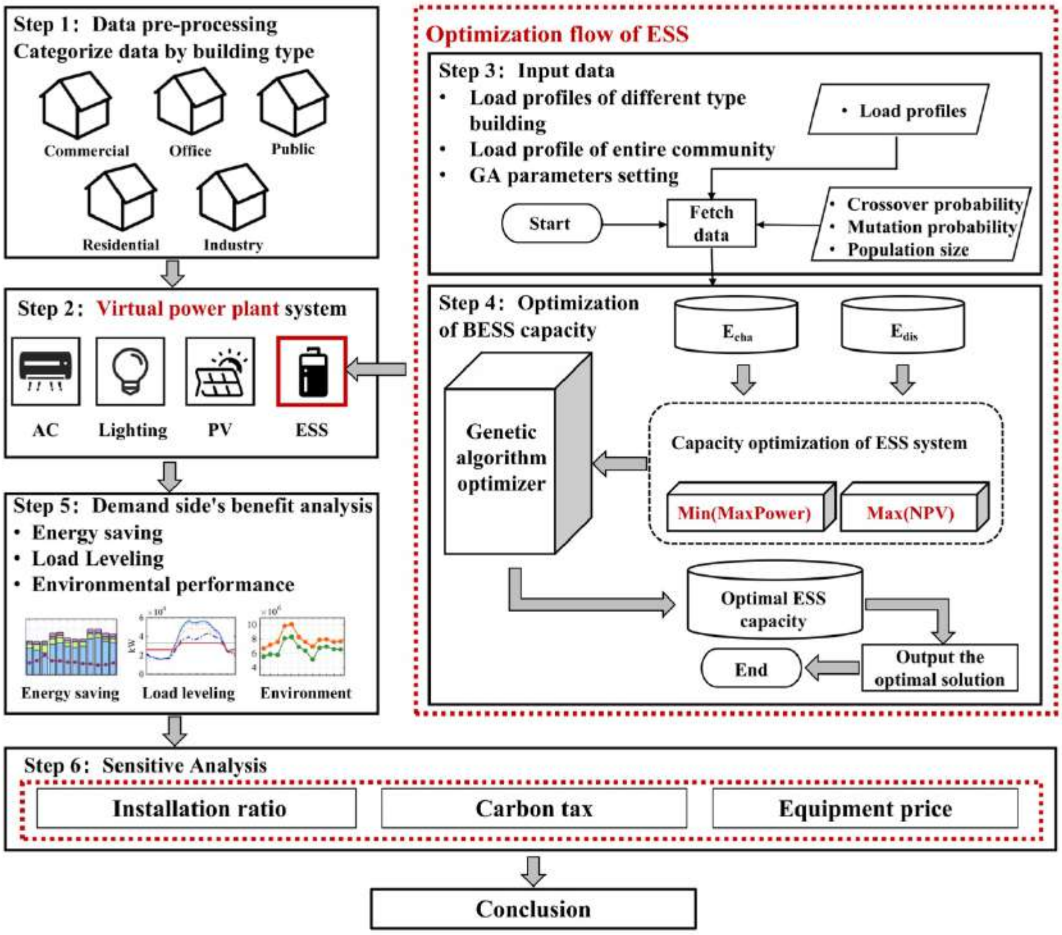

Fig 3. 8 VPP system program

3.2.1 Energy flow modeling

There always a balance between PV generation, energy saved by high efficiency appliance, grid, and the actual demand. This can be calculated by the following equation：

$$\boldsymbol{E_{net}(t) = E_{load}(t) - E_{PV}(t) - E_{HEA}(t)} \qquad (Eq.3.\ 9)$$

Here $E_{net}(t)$ is the net energy demand and $E_{load}(t)$ is the energy demand, $E_{PV}(t)$ is the PV generation at time t, and $E_{HEA}(t)$ represents the energy saved by high efficiency appliance. The relationship between net energy demand and ESS charge/ discharge state can be described by Eq. 3.10:

$$\boldsymbol{|E_{net}(t)| = \begin{cases} \sum E_{cha}(t)\,/\eta_{cha}, & (\,E_{net}(t) < 0) \\ 0\,, & (E_{net}(t) = 0) \\ \sum E_{dis}(t) \cdot \eta_{dis} + \sum E_{load}(t), & (E_{net}(t) > 0) \end{cases}}$$

(*Eq.3. 10*)

Where $E_{cha}(t)$ represents the charge energy at time t, and $E_{dis}(t)$ is the discharge energy at time t. η_{cha} and η_{dis} are the efficiency rate in charging/discharging process. pw is the power rating, and j represent the building sectors. The individual ESSs can be aggregated into a large portfolio through VPP to provide community-scale ancillary services (such as load leveling). The relationship between the community level distribution network and individual ESS can be developed so that individual ESS management systems can adjust charge and discharge power with peak information from the distribution network based on intelligent communication system to achieve better load leveling performance. The battery charge and discharge states can be described as：

$$\boldsymbol{E_{cha}(t) = \begin{bmatrix} E_{cha}^{1,1}(t) & 0 & \cdots & 0 \\ 0 & E_{cha}^{2,2}(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & E_{cha}^{j,j}(t) \end{bmatrix}} \qquad (Eq.3.\ 11)$$

$$\boldsymbol{E_{dis}(t) = \begin{bmatrix} E_{dis}^{1,1}(t) & 0 & \cdots & 0 \\ 0 & E_{dis}^{2,2}(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & E_{dis}^{j,j}(t) \end{bmatrix}} \qquad (Eq.3.\ 12)$$

And there are two stages for ESS, ESS cannot be charged and discharged at the same time. First is charging state: When there are surplus PV power generation, for example, when $\sum \mathrm{E_{net}(t)} < 0$, the ESS is in a charging stage.

$$E_{cha}^{j} = \sum E_{cha}^{j,j}(t) = \begin{cases} |\sum E_{net}(t)| \cdot \eta_{cha}, & if\ |\sum E_{net}(t)| \leq pw \\ pw, & if\ |\sum E_{net}(t)| > pw \end{cases}$$

(*Eq.3. 13*)

Another is discharging state: When there is insufficient PV power generation, for example, when $\sum \mathrm{E_{net}}(\mathrm{t}) > 0$, ESS is in a discharging stage.

$$E_{dis}^{j} = \sum E_{dis}^{j,j}(t) = \begin{cases} |\sum E_{net}(t)|/\eta_{dis}, & if\ |\sum E_{net}(t)| \leq pw \\ pw, & if\ |\sum E_{net}(t)| > pw \end{cases}$$

(*Eq.3. 14*)

3.2.2 Optimization method

This research adopts a genetic algorithm (GA) as optimization algorithm to find the fittest ESS capacity. It is a search heuristic that is inspired by Charles Darwin’s theory of natural evolution [24]. Li Y. et al. [25] proposed a method using GA that optimally deployed BESS and determined their capacities in an energy sharing framework. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. You can apply the genetic algorithm to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear. The genetic algorithm can address problems of mixed integer programming, where some components are restricted to be integer valued.

In the context of energy systems, genetic algorithms can be used to optimize the operation or design of power generation, transmission, and distribution systems, as well as other related systems, such as demand response and energy storage.

The basic principle of genetic algorithms is to represent candidate solutions to the optimization problem as strings of binary or real-valued numbers, which are then subjected to a series of evolutionary operators, including selection, crossover, and mutation, in order to produce a new generation of candidate solutions. The fitness of each candidate solution is evaluated based on its ability to satisfy the objectives and constraints of the optimization problem, and the process is repeated until a satisfactory solution is found.

One of the main advantages of genetic algorithms is their ability to search a large solution space efficiently and effectively, even when the problem is complex and nonlinear. They can also handle multiple objectives and constraints simultaneously, and can be adapted to different types of optimization problems, including mixed-integer, nonlinear, and dynamic problems.

In the context of energy systems, genetic algorithms have been applied to a wide range of problems, including unit commitment, economic dispatch, transmission expansion planning, distribution system optimization, renewable energy integration, and demand response scheduling, among others. These applications have demonstrated the potential of genetic algorithms to improve the efficiency, reliability, and sustainability of energy systems, and to help achieve a more optimal and cost-effective use of energy resources.

The genetic algorithm differs from a classical, derivative-based, optimization algorithm in two main ways, as summarized in the following table:

Table 3. 5 Features of the storage battery

Classical Algorithm	**Genetic Algorithm**
Generates a single point at each iteration. The sequence of points approaches an optimal solution.	Generates a population of points at each iteration. The best point in the population approaches an optimal solution.
Selects the next point in the sequence by a deterministic computation.	Selects the next population by computation which uses random number generators.
Typically converges quickly to a local solution.	Typically takes many function evaluations to converge. May or may not converge to a local or global minimum.

The genetic algorithm uses three main types of rules at each step to create the next generation from the current population:

a) Selection rules select the individuals, called parents, that contribute to the population at the next generation. The selection is generally stochastic and can depend on the individuals' scores.

b) Crossover rules combine two parents to form children for the next generation.

c) Mutation rules apply random changes to individual parents to form children.

The optimization flow was shown in Fig 3. 8, which described the design and optimization methods of distributed ESS under a VPP framework.

1). Input the data such as original load profiles, update high efficiency appliance, PV system capacity and solar radiation as well as GA parameters. The values of the genetic parameters in this study were as follows. the maximum generations were 100 generations, the population size was 20, the crossover rate was 0.8, the mutation probability was 0.05, the mutation rate was 0.5, and the elitism was 0.5.

2). Calculate the net load of each building.

3). Initialize the battery matrix that needs to be optimized.

4). Calculate the energy exchange between buildings and ESS.

5). Optimize each building's ESS capacity aim at minimizing the peak demand for electricity in the area (with the goal of less than 33000kW) and maximizing the profit. The objective function of this step can be described as:

$$\boldsymbol{MP = Max(Load(t))} \qquad (Eq.3.\ 15)$$

Where MP is the max load in the time t.

$$\boldsymbol{J_{fitness} = \begin{cases} min\ (MP) \\ max\ (NPV_{ESS}) \end{cases}} \qquad (Eq.3.\ 16)$$

In the above, NPV_{ESS} is the net present value of ESS.

Last step is output the optimal solution.

The optimization process is implemented in Matlab, while the programming models are also built using GA in Matlab. Moreover, the entire process is conducted on a computer with Intel Core i7-8700 processor, 16GB RAM and 3.2GHz Clock Speed. The elapsed time for the process is found to be 493.2 seconds.

3.3 Economic evaluation method & indicator

In this research, the economic benefit of VPP comprises the electricity cost saved by update HEA, PV system and ESS. Therefore, economic benefit of the VPP can be determined by Eq. (3.16), as follows:

$$\boldsymbol{B_{total} = B_{HEA} + B_{PV} + B_{ESS}} \qquad (Eq.3.\ 17)$$

In the above, B_{HEA} is the benefit of the updating high efficiency appliance and can be calculated using Eq. 3.18. B_{PV} refers to PV system's benefit which can be determined by Eq. 3.19. B_{ESS} the ESS system's benefit and can be computed by Eq. 3.20.

$$\boldsymbol{B_{HEA} = \sum_d \sum_t [\,E_{save,ac} \times PR(t)] + \sum_d \sum_t [\,E_{save,light} \times PR(t)]\,, \forall d \in \vartheta\,; t \in T} \qquad (Eq.3.\ 18)$$

Here, $PR(t)$ refers to the electricity price at time t, ϑ represents day collection ϑ = {1, 2, 3, ... 365}.

$$\boldsymbol{B_{PV} = \sum_d \sum_t [PR(t) \times E_{PV}(t)]} \qquad (Eq.3.\ 19)$$

Here, $E_{PV}(t)$ refers to the PV power generation at the time t.

$$\boldsymbol{B_{ESS} = \sum_d [\Delta PR \times E_{cha} \times \eta_{dis} + E_{cur} \times PR(t) \times \eta_{dis} \times \eta_{cha}]} \qquad (Eq.3.\ 20)$$

In the above, ΔPR refers to electricity prices difference caused by the peak-to-valley electricity plans, different electricity consumers will choose different plans. E_{cha} refers to the electricity stored by the ESS, E_{cur} represents the surplus PV power generation stored by ESS.

The overall investment of the VPP can be described by Eq. 3.21, as follows:

$$\boldsymbol{Invest_{total} = Cap_{VPP,HEA} \times MP_{HEA} + Cap_{PV} \times MP_{PV} + Cap_{ESS} \times MP_{ESS}} \quad (Eq.3.\ 21)$$

Here, $Cap_{VPP,HEA}$ is the installed capacity of the HEA, Cap_{PV} is the PV system's capacity, and Cap_{ESS} is the ESS system's capacity, MP_{HEA} is the unit prices of HEA, MP_{PV} is the unit prices of PV and MP_{ESS} is the unit prices of ESS system, respectively.

In 2012, the Japanese government launched the new Feed-in Tariff Act (FiT) [26]. This study also adopts different export feed-in tariff (FiT) schemes to evaluate the economic.

$$\boldsymbol{B_{FiT} = \sum_d \sum_t [FiT \times E_{PV}]} \quad (Eq.3.\ 22)$$

In the above, $\boldsymbol{B_{FiT}}$ is the benefit of export PV generation to public grid, and $\boldsymbol{FiT}$ is the price of FiT policy.

This study adopts net present value and return on investment to forecast the economy of VPP's life cycle. The expense of installing and maintaining the equipment and the energy loss from the depreciation of the equipment are ignored, and only the expense of the equipment is taken as the investment of construct VPP.

✧ Net Present Value (NPV)

The net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is always used in capital budgeting and investment planning to evaluate the profitability of a projected investment or project. NPV accounts for the time value of money. It provides a method for evaluating and comparing capital projects or financial products with cash flows spread over time. The calculation of NPV involves discounting future cash flows back to their present value using a discount rate, which represents the minimum acceptable rate of return for the investor. If the NPV is positive, then the project is considered profitable and worth pursuing. If the NPV is negative, then the project is not profitable and should be rejected. By ignoring the operation and maintenance costs, the NPV can be determined as follows:

$$\text{NPV}=\boldsymbol{\sum_{n=1}^{j} B_n/(1+i)^n - Co_0} \quad (Eq.3.\ 23)$$

where B_n is the annual benefit of the system, initial investment, and generic year n= [1,2, 3...], i is discount rate generally refer to bank rate. This research uses the Fukuoka Bank's annual interest rate: 4.5%.

where:

B_n=Net cash inflow-outflows during a single period t

i = Discount rate or return that could be earned in alternative investments n=Number of timer periods

A positive net present value indicates that the projected earnings generated by a project or investment, exceeds the anticipated costs. It is assumed that an investment with a positive NPV will be profitable, and an investment with a negative NPV will result in a net loss. This concept is the basis for the Net Present Value Rule, which dictates that only investments with positive NPV values should be considered.

Decision criteria: NPV ≥ 0, the plan is feasible; NPV <0, The plan is not feasible.

While NPV> 0, the plan with the largest net present value is the optimal plan.

Advantages: Considering the time value of funds and enhancing the evaluation of investment economy; considering the net cash flow of the entire process, reflecting the unity of liquidity and profitability.

✧ Return on investment (ROI)

Return on investment (ROI) is a performance measure used to evaluate the efficiency or profitability of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost. ROI is calculated by dividing the net profit of an investment by its cost. The net profit is the difference between the revenue earned from the investment and the costs associated with it, such as operating expenses, taxes, and other expenses.

ROI can be expressed as a percentage or a ratio. A higher ROI indicates a more profitable investment. ROI is commonly used in financial analysis to compare the profitability of different investments or to evaluate the performance of a company's investments over time. To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment. The result is expressed as a percentage or a ratio.

$$\boldsymbol{ROI(x)} = \frac{\boldsymbol{B(x)}}{\boldsymbol{Invest(x)}} \qquad (Eq.3.\ 24)$$

where $B(x)$ is the annual benefit of the $x,\ x = [Lighting,\ AC,\ PV,\ ESS, VPP]$.

✧ Payback period (PBP)

The payback period (PBP) is an acknowledged indicator for evaluating the economic performance of a project and considers both the cost and revenue of the entire system. Payback period is calculated by dividing the initial investment cost by the annual cash inflows generated by the investment. The result is the number of years it will take to recover the initial investment. It is crucial for conducting a comprehensive life-cycle analysis of the VPP system. The annual revenue equals the sum of the revenues caused by the saved electricity cost from the direct-use PV electricity, as well as the revenue of electricity sold back to the grid. Payback period is a simple and useful tool for evaluating the risk and feasibility of an investment. A shorter payback period indicates a less risky investment, as the initial investment cost can be recovered more quickly. However, payback period does not consider the time value of money and does not account for cash inflows generated beyond the PBP. The PBP (years) can be expressed as follows:

$$\boldsymbol{PBP} = Co_{intial} + \sum_{n=1}^{m} [\frac{C_{annual}\,(n)}{(1+i)^n}] / [\sum_{n=1}^{m} \frac{B_{annual}}{(1+i)^n} / m] \qquad \textit{(Eq.3. 25)}$$

Here, m is the number of minimum years by which the total revenue of the system is larger than the total cost.

3.4 Cooperative game theory

Cooperative game theory is a branch of game theory that studies the behavior of individuals or groups who work together in order to achieve a common goal. In contrast to non-cooperative game theory, where players act independently to maximize their individual payoffs, cooperative game theory studies how players can form coalitions and cooperate to achieve better outcomes for all the members of the coalition.

In a cooperative game, players can form coalitions and share the benefits of their actions. The value of a coalition is defined as the sum of the payoffs that the members of the coalition can achieve by working together. The players in the coalition can then use various mechanisms to distribute the benefits among themselves. Cooperative game theory studies how to allocate the value of the coalition in a fair and efficient way, so that all players are willing to participate and cooperate. Cooperative game theory has many applications in economics, political science, sociology, and other fields. It has been used to study the behavior of firms in oligopolistic markets, the formation of international coalitions, the design of voting systems, and the allocation of public goods.

Cooperative game theory can be applied in virtual power plants (VPPs) to improve their economic and environmental performance. VPPs are composed of various distributed energy resources (DERs), such as solar panels, wind turbines, and battery storage systems, that are owned by different entities. Cooperative game theory can be used to model the interactions between these entities and design mechanisms that encourage cooperation and efficient use of resources.

One of the main challenges in VPPs is the coordination of DERs to achieve optimal operation and maximize their economic benefits. Cooperative game theory can be used to design mechanisms that incentivize DER owners to cooperate and contribute to the VPP's overall performance. For example, a cooperative game model can be used to allocate the benefits of VPP operation among the DER owners in a fair and efficient way, taking into account their individual contributions and costs.

Cooperative game theory can also be used to design mechanisms that encourage DER owners to invest in new technologies and expand the VPP's capacity. For example, a cooperative game model can be used to allocate the costs and benefits of VPP expansion among the DER owners in a way that encourages them to make investments that are beneficial for the VPP as a whole.

Cooperative game theory can be a useful tool for designing mechanisms that encourage cooperation and efficient use of resources in VPPs. By improving the economic and environmental performance of VPPs, cooperative game theory can contribute to the development of sustainable energy systems.

3.4.1 Parameters and experiments setting

In this research, two players were considered to participate in the game. The first is the demand side, denoted by D, and the second is the plant side, denoted by P. The set $N = \{D, P\}$ constitutes the set of players in the model, each player in the set is an independent interest individual.

The profit of different players in cooperation game can be expressed by the characteristic function $\omega(\bullet)$. When the alliance has no participants, the set is an empty set, can be defined as $\omega(\emptyset) = 0$.

When there is no cooperation, the profit of the demand side can be described as:

$$\omega(D) = \sum_{n=1}^{30} \frac{BD_{total}}{(1+i)^n} - CD_{total} \times (1 - SU) \qquad (Eq.3.\ 26)$$

In the above, SU is the subsidy rate from government.

The profit of the plant side can be described as follows:

$$\omega(P) = \sum_{n=1}^{30} \frac{Gen_{plant} \times PR_{sold} \times (1-\varepsilon) - CP_{annual}}{(1+i)^n} - CP_{total} \qquad (Eq.3.\ 27)$$

Here CP_{annual} is the power generation cost, CP_{total} is the total cost of power plant construction.

3.4.2 Profit allocation in cooperative game based on Shapley value

The Shapley value is a concept in cooperative game theory that helps to fairly distribute the gains or payoffs among the players or participants in a cooperative game. It was introduced by Lloyd Shapley in 1953. The Shapley value determines the contribution of each player in a coalition to the total worth of that coalition. It considers all possible permutations of coalitions and calculates the average marginal contribution of each player across all permutations.

The Shapley value has been applied in various fields, including economics, political science, and computer science. In the context of VPP, the Shapley value can be used to fairly distribute the benefits or costs among the participating agents or energy resources. By assigning a value to each agent or resource's contribution, it can help to determine the optimal allocation of resources and ensure that each participant receives a fair share of the benefits.

In the process of profit allocation, the allocation is made according to the increase in the marginal profit of the combination that the players participate in, so that the players who raise more revenue for the combination will be allocated additional profit. When players participate in the cooperation game, the plant side needs to provide investment for the VPP. The investment proportion of the plant side can be defined as IP, simultaneously, the power plant can coordinate the electricity price with the demand side to realize the return on investment. The rising electricity price (bargain price) is represented by BP, where ε represents the self-use rate of the plant side. The profit of the demand side can be described as follows:

$$\omega(D)' = \sum_{n=1}^{30} \frac{BD_{total} + \sum_d \sum_t [BP \times Gen_{pv}(t)] - E_{com} \times BP}{(1+i)^n} - CD_{total} \times (1 - SU - IP) \quad (Eq.3.\ 28)$$

The profit of the plant side can be described as:

$$\omega(P)' = \sum_{n=1}^{30} \frac{Gen_{plant} \times (\sum_t^T PR(t) + BP) \times (1-\varepsilon) - CP_{annual}}{(1+i)^n} - CP_{total} - CD_{total} \times IP \quad (Eq.3.\ 29)$$

The total profit of the alliance is equal to the sum of the players' profits, defined as $\omega(\{D, P\})$.

$$\omega(\{D, P\}) = \omega(D)' + \omega(P)' \quad (Eq.3.\ 30)$$

After participating in the cooperative game, players allocate the total profit of the alliance according to the Shapley value:

$$\omega(D)' = \frac{1}{2}\omega(\{D, P\}) + \frac{1}{2}\omega(D) \quad (Eq.3.\ 31)$$

$$\omega(P)' = \frac{1}{2}\omega(\{D, P\}) + \frac{1}{2}\omega(P) \quad (Eq.3.\ 32)$$

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Chapter 4

ENERGY CONSUMPTION CHARACTERISTICS ANALYSIS IN HIGASHIDA SMART COMMUNITY

CHAPTER 4: ENERGY CONSUMPTION CHARACTERISTICS ANALYSIS IN HIGASHIDA SMART COMMUNITY

4.1 Research objective and data

A brief introduction about the electricity power industry in Higashida area is given in the following section, mainly includes the geographical scope, power supply and demand condition.

The Higashida area is located in Kitakyushu City, Fukuoka Prefecture, Japan. Japan is an island country of East Asia in the northwest Pacific Ocean. It borders the Sea of Japan to the west and extends from the Sea of Okhotsk in the north to the East China Sea and Taiwan in the south. Japan is part of the Pacific Ring of Fire and comprises an archipelago of 6,852 islands covering 377,975 square kilometers; its five main islands, from north to south, are Hokkaido, Honshu, Shikoku, Kyushu, and Okinawa. Tokyo is the country's capital and largest city; other major cities include Osaka and Nagoya.

Japan is the 11th most populous country in the world, as well as one of the most densely populated and urbanized. About three-fourths of the country's terrain is mountainous, concentrating its population of 126.2 million on narrow coastal plains. Japan is administratively divided into 47 prefectures and traditionally divided into eight regions. The Greater Tokyo Area is the most populous metropolitan area in the world, with more than 37.4 million residents.

The islands of Japan were inhabited as early as the Upper Paleolithic period, though the first mentions of the archipelago appear in Chinese chronicles from the 1st century AD. Between the 4th and 9th centuries, the kingdoms of Japan became unified under an emperor and imperial court based in Heian-kyo. Starting in the 12th century, however, political power was held by a series of military dictators, feudal lords, and a class of warrior nobility. After a century-long period of civil war, the country was reunified in 1603 under the Tokugawa shogunate, which enacted a foreign policy of isolation. In 1854, a United States fleet forced Japan to open trade to the West, leading to the end of the shogunate and the restoration of imperial power in 1868. In the Meiji era, the Empire of Japan adopted a Western-style constitution and pursued industrialization and modernization. Japan invaded China in 1937; in 1941, it entered World War II as an Axis power. After suffering defeat in the Pacific War and two atomic bombings, Japan surrendered in 1945 and came under an Allied occupation, during which it adopted a post-war constitution. It has since maintained a unitary parliamentary constitutional monarchy with an elected legislature known as the National Diet.

Japan is a great power and a member of numerous international organizations, including the United Nations (since 1956), the OECD, and the G7. Although it has renounced its right to declare war, the country maintains a modern military ranked as the world's fourth most powerful. Following World War II, Japan experienced record economic growth, becoming the second-largest economy in the world by 1990. As of 2019, the country's economy is the third largest by nominal GDP and fourth largest by purchasing power parity. Japan is a global leader in the automotive and electronics industries and has made significant contributions to science and technology. Ranked “very high” on the Human Development Index, Japan has the world's second-highest life expectancy, though it is currently experiencing a decline in population. Culturally, Japan is renowned for its art, cuisine, music, and popular culture, including its prominent animation and video game industries.

As of June 1, 2019, Kitakyushu has an estimated population of 940,978, making it the second-largest city in both Fukuoka Prefecture and the island of Kyushu after the city of Fukuoka. It is one of Japan's 20 designated cities, one of three on Kyushu, and is divided into 7 wards. Fig 4.1 shows the wards of Kitakyushu.

Higashida area covers an area of 1.2 square kilometers. As of 2012, there have 1,000 residents, 6,000 employees and 10 million visitors every year. Fig 4.3 shows the location of Higashida area. And Table 4.1 shows the basic information of Higashida Area.

Fig 4. 1 Wards of Kitakyushu

Table 4.1 Information of the Kitakyushu Smart Community (Source: New Energy and Industrial Technology Development Organization)

Items	Contents
City	Kitakyushu
Area	448.78 km^2
Population	940,978 (June 1, 2019)
Name of research area	Higashida Area
Area of research area	1.2 km²

The Kitakyushu Smart Community Creation Project illustrates the ideal situation of the development of regional energy management systems, meanwhile, tries to build a low-carbon society through changing lifestyle, business style and city planning policies. By setting up and operating a management base unit called “regional power saving station”, it aims to establish a two-way communication mechanism that both citizens and business operators are able to participate in the energy distribution process. In addition, visualization of energy will also realize a great breakthrough.

Fig 4. 2 Wards of Kitakyushu

The project covers the Higashida area of Bahat District, Kitakyushu City (about 1.2 km^2). The Higashida area is the birthplace of modern Japanese industry, where the Yawata Steel Works was built and started operations in 1901, and thermal power plants were built. It invested about 65 billion yen and redeveloped more than 120 billion hectares of factory land. The Higashida area also attracts many families and businesses, as well as AEON shopping centers, hospitals, museums, etc.

Fig 4. 3 Related Facilities of Kitakyushu Smart Community Creation Project

The Higashida Smart Community demonstration test is conducted in Yahata Higashida district of Kitakyushu City, that is redeveloping the former site of the Nippon Steel & Sumitomo Metal Corporation Yawata Works plant to promote next-generation urban development that symbiotically combines advanced urban infrastructure and the environment. More than 70 companies and organizations are the participants.

In Japan, electricity is transmitted at a reduced voltage. The voltage of the base trunk system in the project is 6600V, and power is supplied to the demand side by stepping down to 200V and 100V. The electricity generated is transmitted to the demand area through the grid while gradually lowering the voltage, but along the way it also includes electricity from renewable energy sources such as solar power installed in factories, office buildings, hospitals, etc. There are both power flow and reverse power flow. Demand-side energy such as small-scale solar power generation, stationary batteries, and electric vehicles (EVs) are introduced and installed at the consumer side (general households, stores, etc.) of the grid located at the end.

Due to the large amount of renewable energy imported, frequent voltage as well as power regulation is a big challenge. Therefore, the project area is equipped with a smart power conditioning system (PCS). The Smart PCS (consisting of a PCS and a controller) typically operates at around 400 to 600V. It converts the DC power generated by the autonomous operating system into AC power and boosts it to 6600V for connection to the main system. And Fig 4. 4 shows the configuration of community-installed energy storage systems.

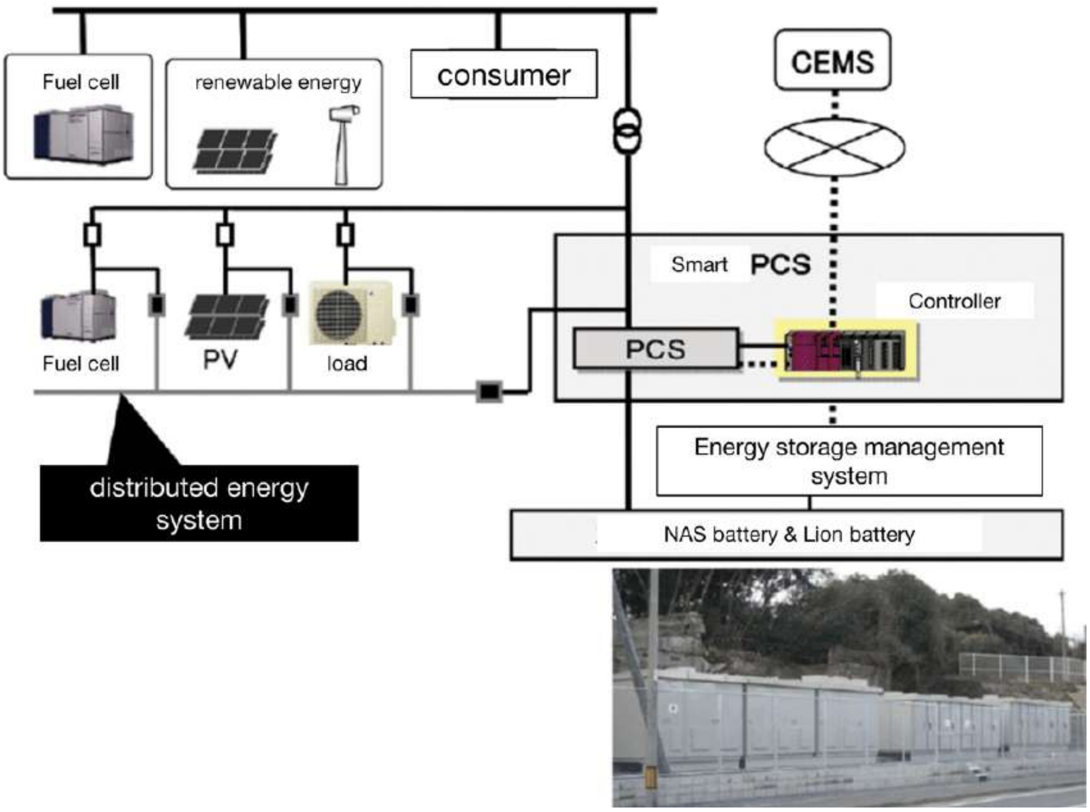


Fig 4. 4 Configuration of community-installed energy storage systems

4.2 Typical case study

This part will analyze the power load characteristics of different buildings in Higashida area, as well as energy saving potential of PV and SB system and economic characteristics in different buildings.

4.2.1 Public Buildings

There are 6 public buildings in the target area, and we selected typical days for each season to analyze the typical load curves. Results are shown in the Fig 4.5.

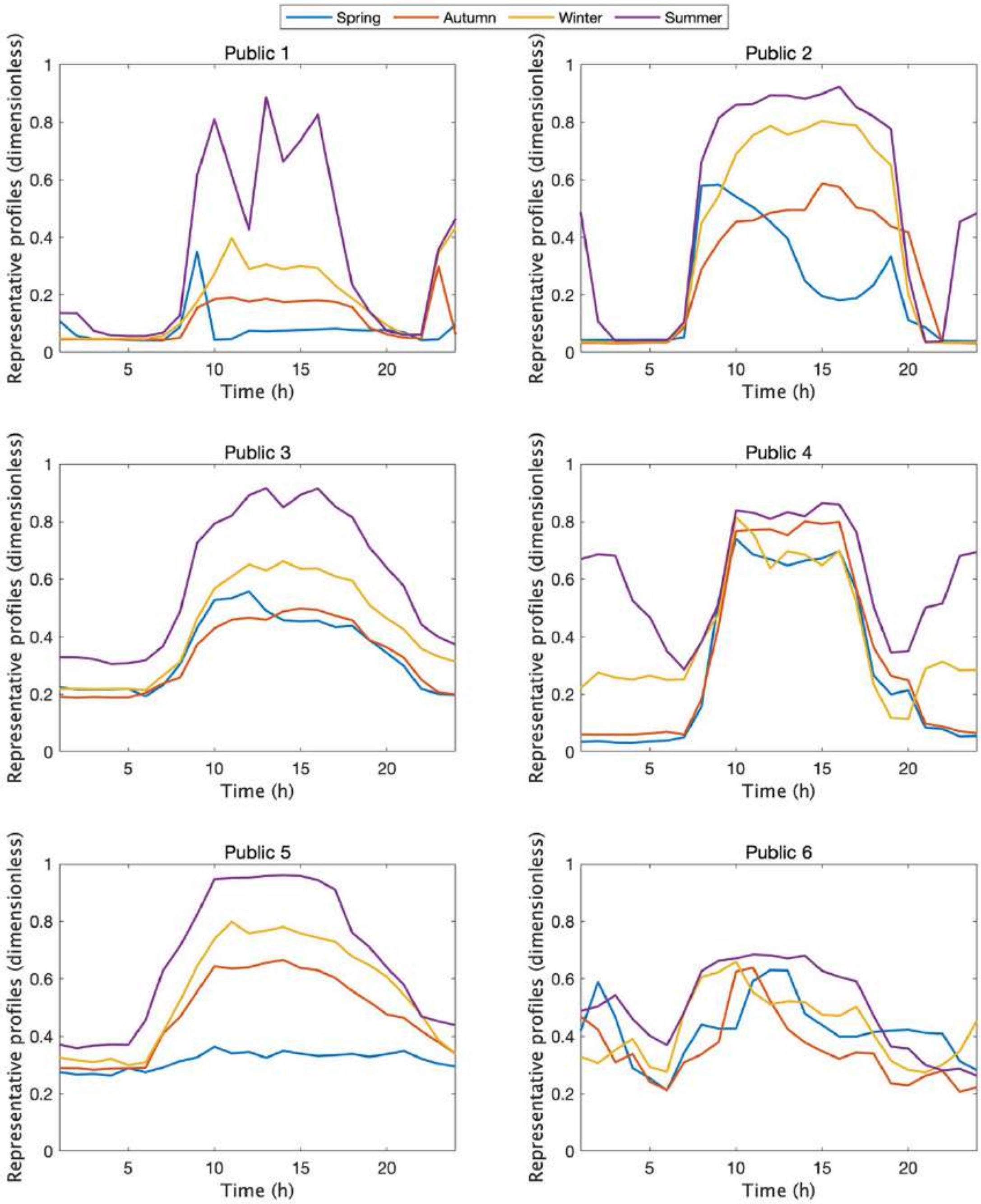


Fig 4. 5 Dimensionless representative load curve of public buildings

✧ **Steel Memorial Yawata Hospital (Public 5)**

Steel Memorial Yawata Hospital is located 1.2 km East of Yahata station, Kagoshima line. The electricity price of Steel Memorial Yawata Hospital is unified, and the electricity price is 7.45yen.

It has roof area of 8839 m². So, we can calculate that capacity of PV system is 706 kW. Because the PV system without curtailment, there's no need to install SB system. Table 4.2 is the basic information of hospital. Steel Memorial Yawata Hospital has a roof area of 8839 m^2, so we can calculate the capacity of PV system is 706 kW. And Fig 4.4 is the roof of hospital.

A typical day from each season was selected to analyze the power load characteristics. As shown in Fig 4. 7, the load curve has obvious fluctuation characteristics. It can be seen from the typical daily load curves of the four seasons that the load curve is similar in different season. As a public building, peak electricity consumption mainly occurs between 10:00~17:00. This phenomenon is mainly related to its working hours. The largest electricity consumption appears in summer. Fig 4. 8 shows the load proportion of Steel Memorial Yawata Hospital, blue line shows the original situation, and red line means the load proportion after adding PV system, the energy saving effect of PV system is obvious.

Fig 4.9 shows the NPV of PV system within 30 years. Only consider the profits of the PV system. The NPV of the PV system of the Steel Memorial Yawata Hospital in 30 years was calculated. As shown in picture, in this case, PV system cannot recover the cost in the life cycle. So, we calculated when NPV of 30th year is 0, The electricity price at that time is 10.31 JPY.

From this, a simple judgment can be made on the PV system. When the electricity price is high than 10.31 JPY, the PV system can get profit. Otherwise, it will produce negative returns.

So, for Steel Memorial Yawata Hospital, it is uneconomical to install the PV system. And because of there is no PV curtailment, no need to install SB system too.

Table 4.2 Information of Steel Memorial Yawata Hospital

Name	Roof area (m^2)	PV capacity (kW)	Type	Electricity price (JPY/kWh)
Steel Memorial Yawata Hospital	8839	706	Public	7.45

Fig 4. 6 Roof of Steel Memorial Yawata Hospital

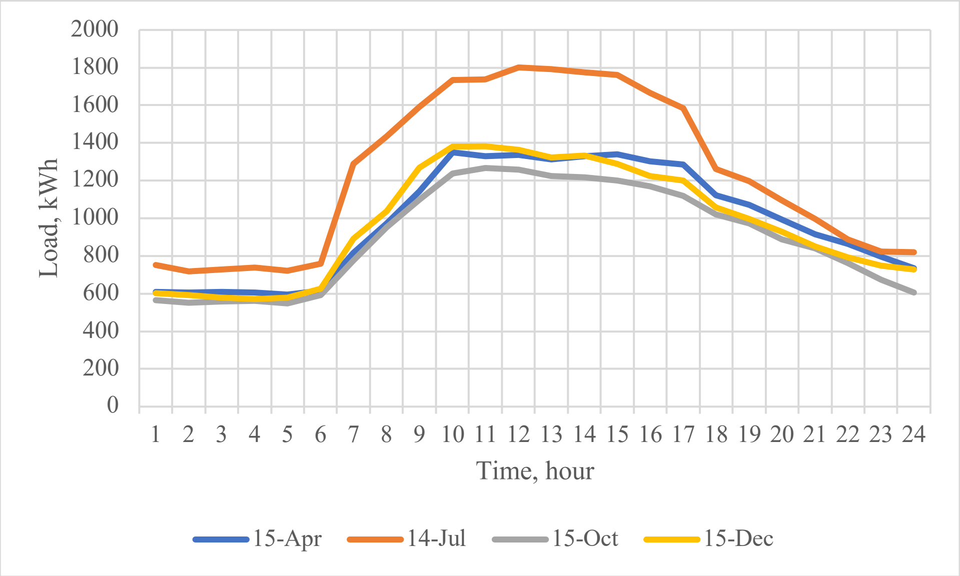


Fig 4. 7 Load characteristics of Steel Memorial Yawata Hospital

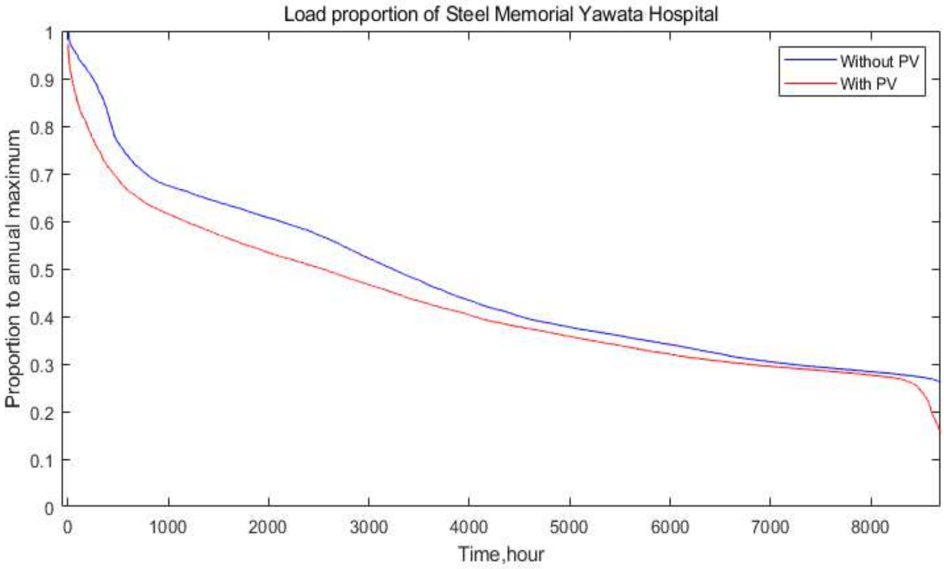


Fig 4. 8 Load proportion of Steel Memorial Yawata Hospital

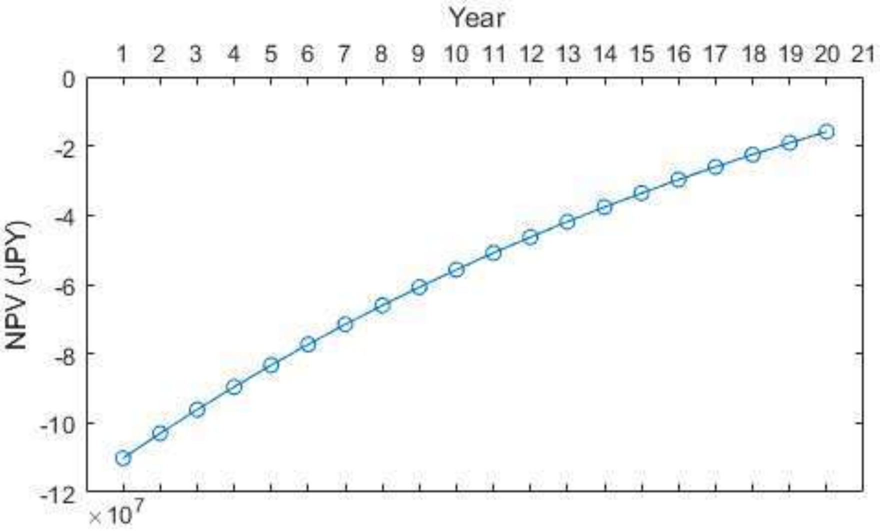


Fig 4. 9 The NPV of PV within 20 years Steel Memorial Yawata Hospital

✧ Case study of Kitakyushu Museum of Natural History (Public 4)

Kitakyushu Museum of Natural History has peak and valley electric charges, the price 8:00-22:00 is 15.32 JPY, and 22:00-8:00 is 9.06 JPY. It has roof area of 8839 m². So we can calculated that capacity of PV system is 706kW. Because the PV system without curtailment, there's no need to install SB system. Table 4.3 is the basic information of hospital. And Fig4-11 is the roof of hospital.

Table 4.3 Information of Steel Memorial Yawata Hospital

Name	Roof area (m²)	PV capacity (kW)	Type	Electricity price (JPY/kWh)
Kitakyushu Museum of Natural History	7435	594	Public	8:00~22:00 17.82
				22:00~8:00 11.89

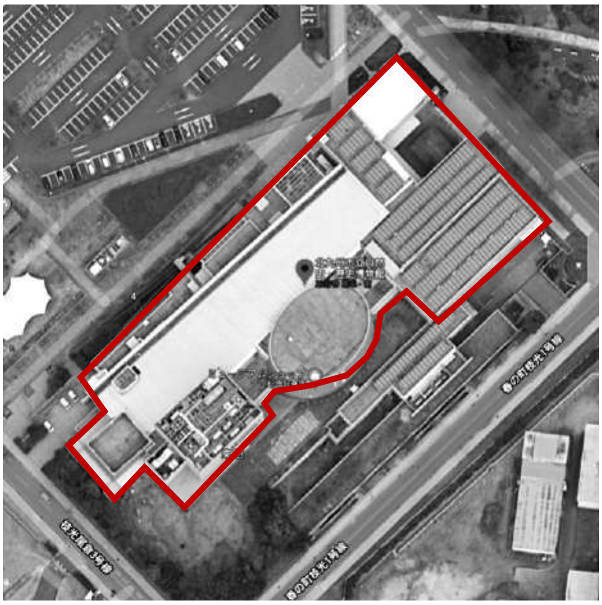


Fig 4. 10 Roof of Kitakyushu Museum of Natural History

A typical day from each season was selected to analyze the power load characteristics. As shown in Fig 4. 11, the load curve has obvious fluctuation characteristics. It can be seen from the typical daily load curves of the four seasons that the load curve is similar in spring, summer and winter, autumn has least electricity consumption. As a public building, Peak electricity consumption mainly occurs between 10:00~17:00. The largest electricity consumption appears in summer. In addition, there is peak valley not only in daytime, but also in midnight. And in the working time, the electricity consumption is stable without obvious fluctuations.

Fig 4.12 shows the load proportion of Kitakyushu Museum of Natural History, blue line shows the original situation, and red line means the load proportion after adding PV system, the energy saving effect of PV system is obvious. And there is PV curtailment phenomenon.

Then we analyze the energy saving potential and economic benefit characteristics of Kitakyushu Museum of Natural History of introducing PV and SB system.

From Fig 4.13, the PV system of Kitakyushu Museum of Natural History can recover costs within 10 years. Fig 4.14 shows the result of 15 year’s NPV of different capacity of SB system of Kitakyushu Museum of Natural History. It can be seen that SB system of Kitakyushu Museum of Natural History with the increase of the installed capacity of the battery, the profit yield curve is in the form of a parabola. When reach the best profit, the capacity of SB system is 713 kW. And Fig 4.15 shows the NPV of SB system in the capacity of 713 kW, the SB system can recover investment within 12 years.

For Kitakyushu Museum of Natural History, introduce PV system and SB system is feasible. Both PV system and SB system can generate revenue. The PV system can recover the cost within 10 years. The SB system can recover the cost within 12 years.

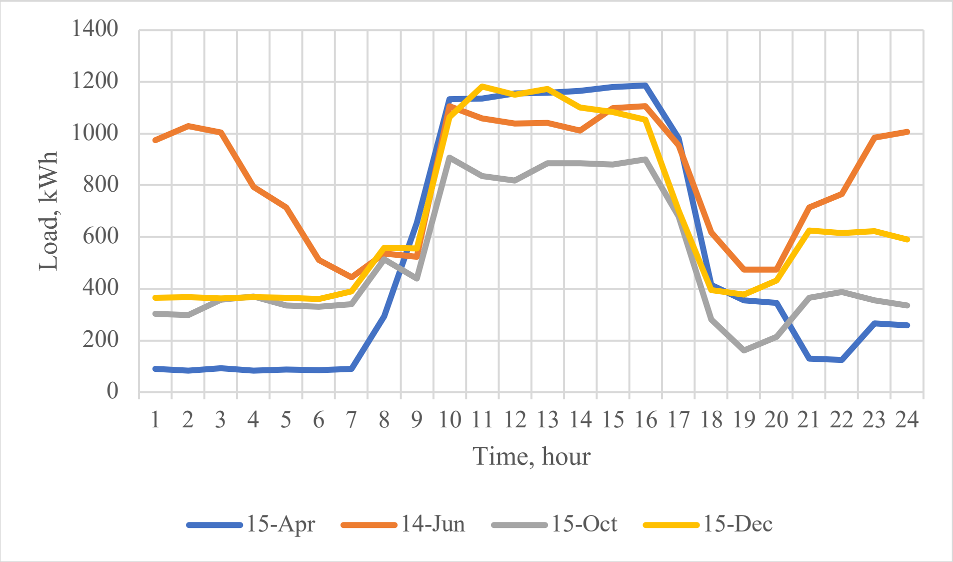


Fig 4. 11 Load characteristics of Kitakyushu Museum of Natural History

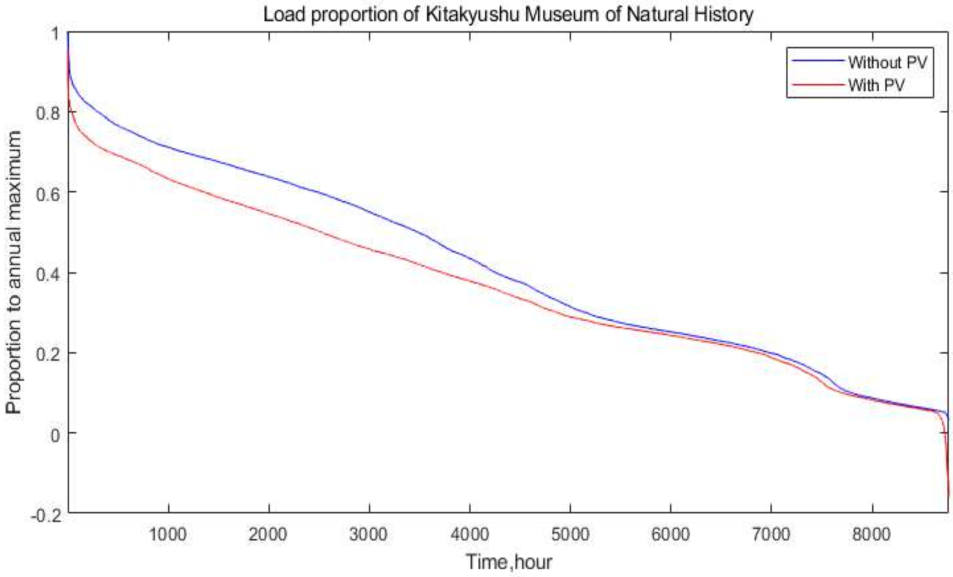


Fig 4. 12 Load proportion of Kitakyushu Museum of Natural History

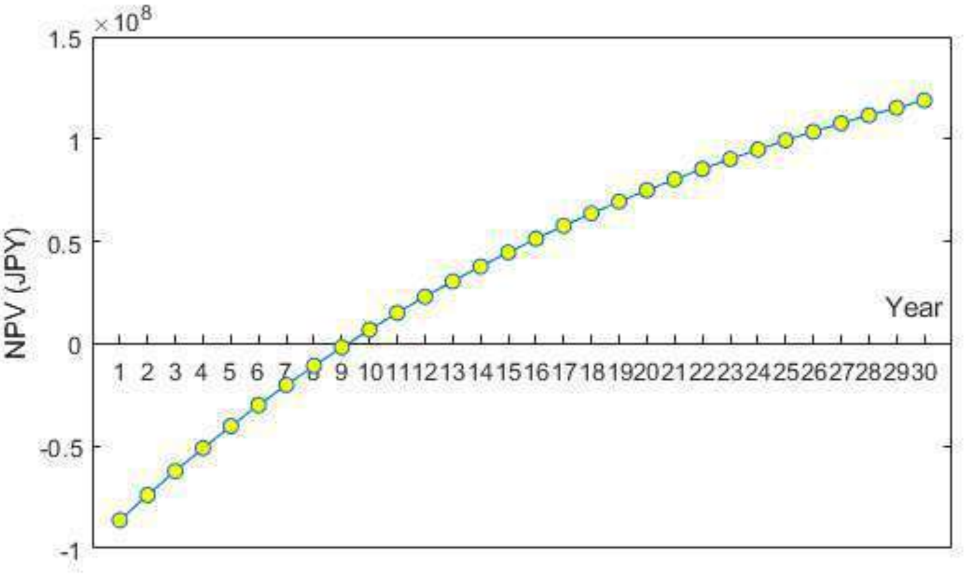


Fig 4. 13 NPV of PV system of Kitakyushu Museum of Natural History

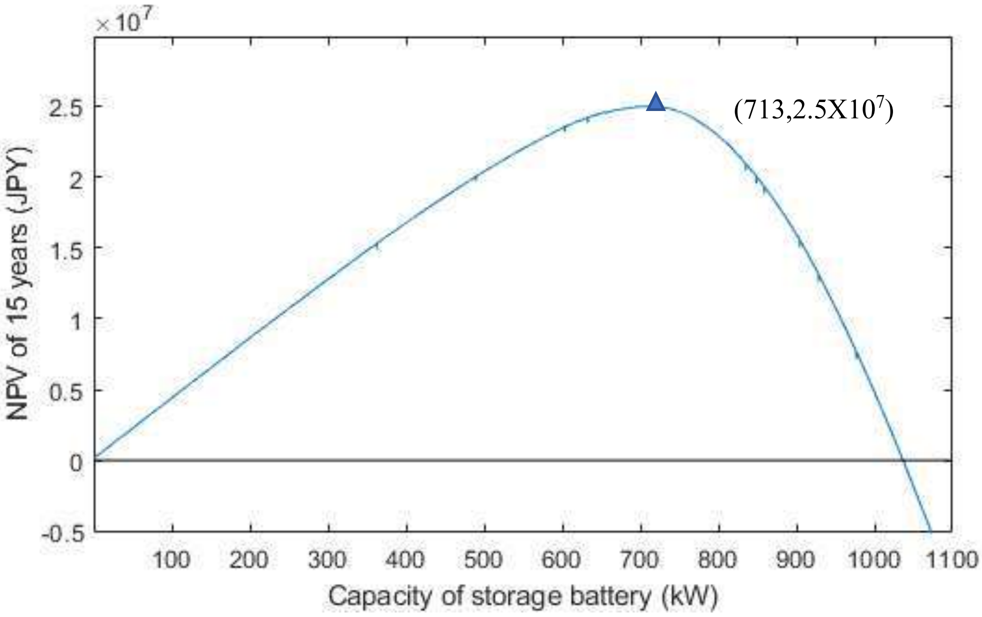


Fig 4. 14 15 year's NPV of different capacity of SB system of Kitakyushu Museum of Natural History

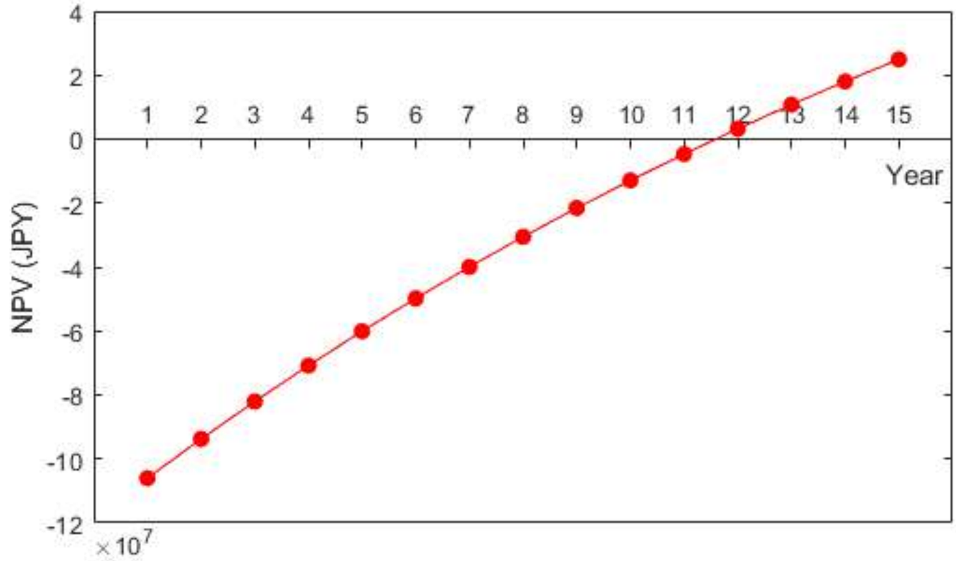
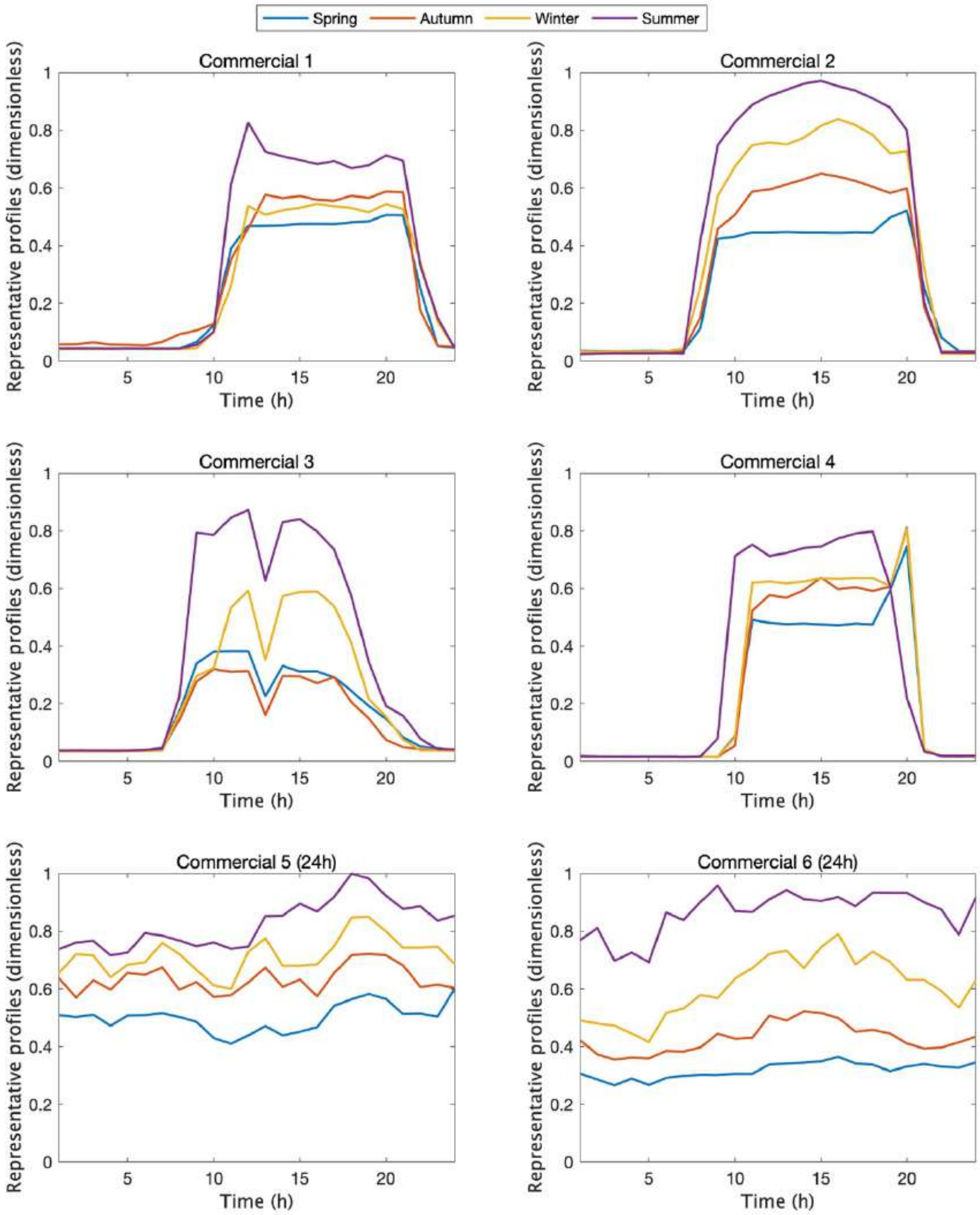


Fig 4. 15 NPV of SB system Kitakyushu Museum of Natural History

4.2.2 Commercial buildings

There are 10 commercial buildings in the target area, and we selected typical days for each season to analyze the typical load curves. Results are shown in the Fig 4.16. Commercial 5 and Commercial 6 has the different load characteristics, because these two buildings are 24-hour open convenience store. Other buildings show evident peak-valley changes in the electricity demand.



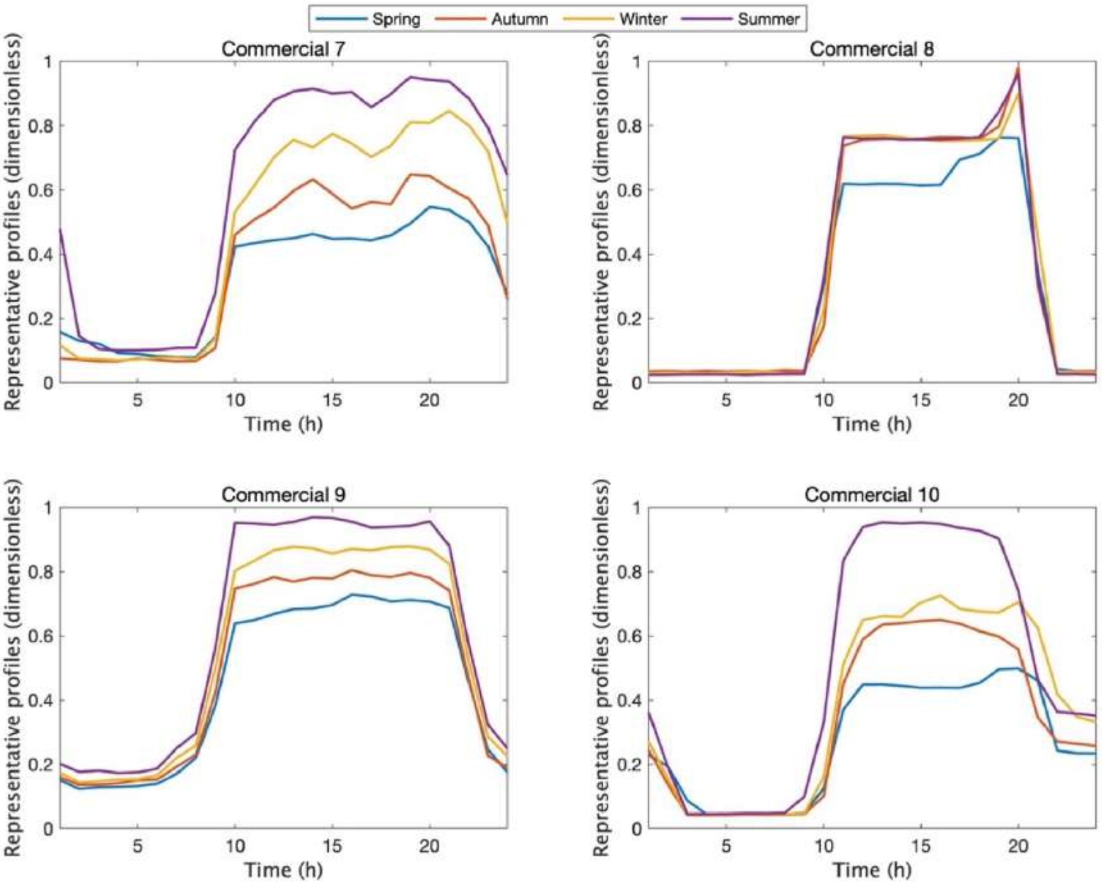


Fig 4. 16 Dimensionless representative load curve of commercial buildings

✧ **Case study of Aeon Mall (Commercial 9)**

Aeon Mall has peak and valley electric charges, the price 8:00-22:00 is 15.32 JPY, and 22:00-8:00 is 9.06 JPY. It has roof area of 23169 m². Therefore, the capacity of PV system is 1852 kW. Because the PV system has phenomenon of curtailment, the SB system need to be installed. Table 4.4 is the basic information of Aeon Mall. And Fig 4. 17 shows the roof of Aeon Mall.

Table 4.4 Information of Aeon Mall

Name	Roof area (m²)	PV capacity (kW)	Type	Electricity price (JPY/kWh)	
Aeon Mall	23169	1852	Commercial	8:00~22:00	15.32
				22:00~8:00	9.06

We select a typical day from each season to analyze the power load characteristics. As shown in Fig 4. 18, the load curve has obvious fluctuation characteristics. Peak-to-valley difference reached about1200 kW to 1600 kW. It can be seen from the typical daily load curves of the four seasons that the load curve is similar in different season. As a commercial building, peak electricity consumption mainly occurs between 10:00~21:00. This phenomenon is mainly related to its working hours. The largest electricity consumption appears in summer. And in the working time, the electricity consumption is stable without obvious fluctuations.

Fig 4. 19 shows the load proportion of Aeon Mall, blue line shows the original situation, and red line means the load proportion after adding PV system, the energy saving effect of PV system is obvious. And there is PV curtailment phenomenon. Significantly reduced annual maximum load utilization hours.

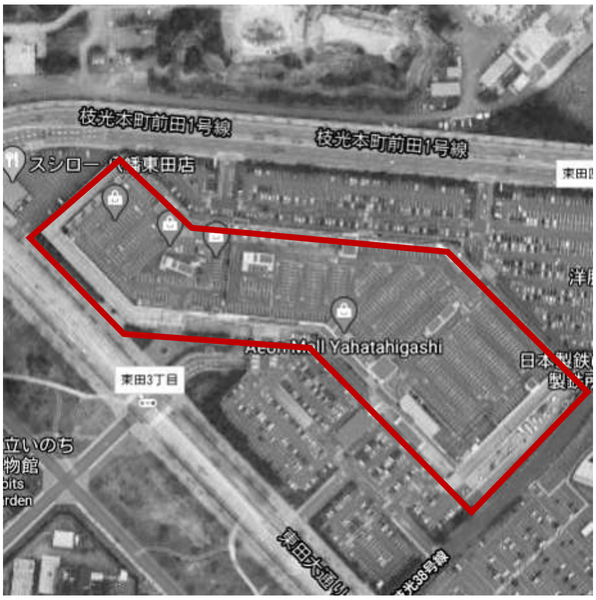


Fig 4. 17 Roof of Aeon Mall

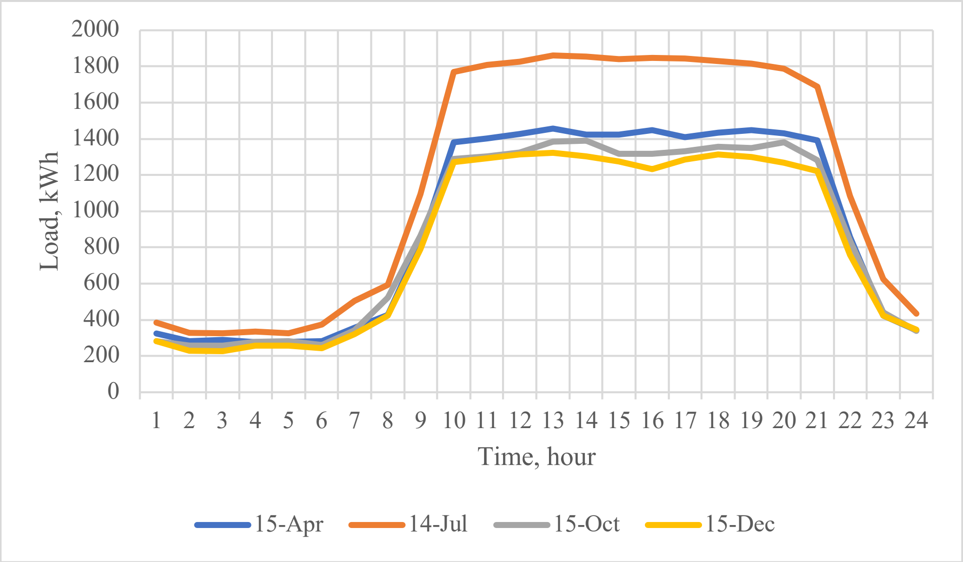


Fig 4. 18 Load characteristics of Aeon Mall

Then the energy saving potential and economic benefit characteristics of Aeon Mall of after introducing PV and SB system was analyzed.

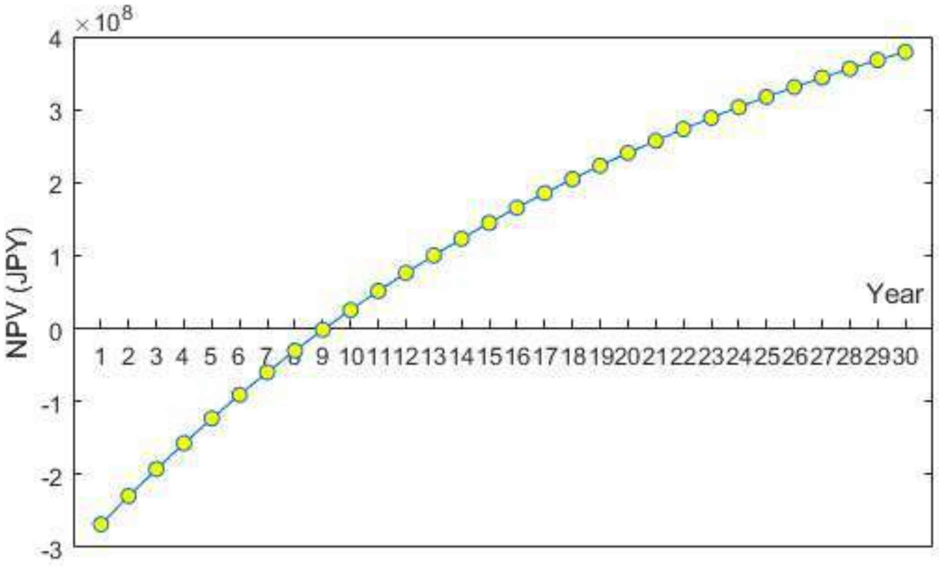


Fig 4. 20 PV system of Aeon Mall can recover costs within 9 years.

Fig 4. 21 shows the 15 year's NPV of different SB capacity. It can be seen that SB system of Aeon Mall with the increase of the installed capacity of the battery, the profit yield curve is in the form of a parabola. When reach the best profit, the capacity of SB system is 1166 kW. And Fig 4. 22 shows the NPV of SB system in the capacity of 1166 kW. From Fig 4.10 we can see the SB system can recover investment within 11 years.

For Aeon Mall, introduce PV system and SB system is feasible. Both PV system and SB system can generate revenue. According to calculation PV system can recover the cost within 9 years. The SB can recover the cost within 11 years.

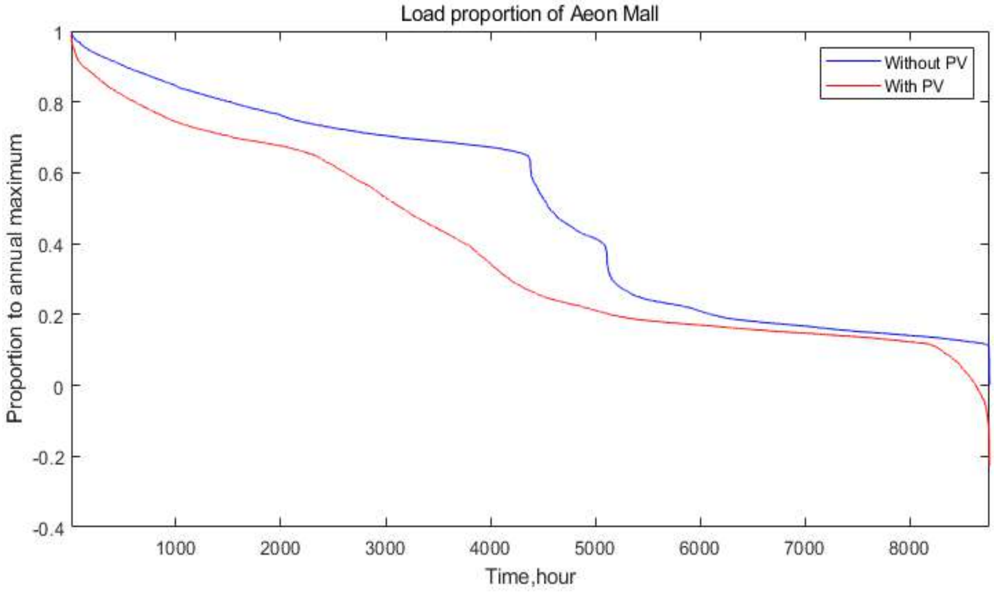


Fig 4. 19 Load proportion of Aeon Mall

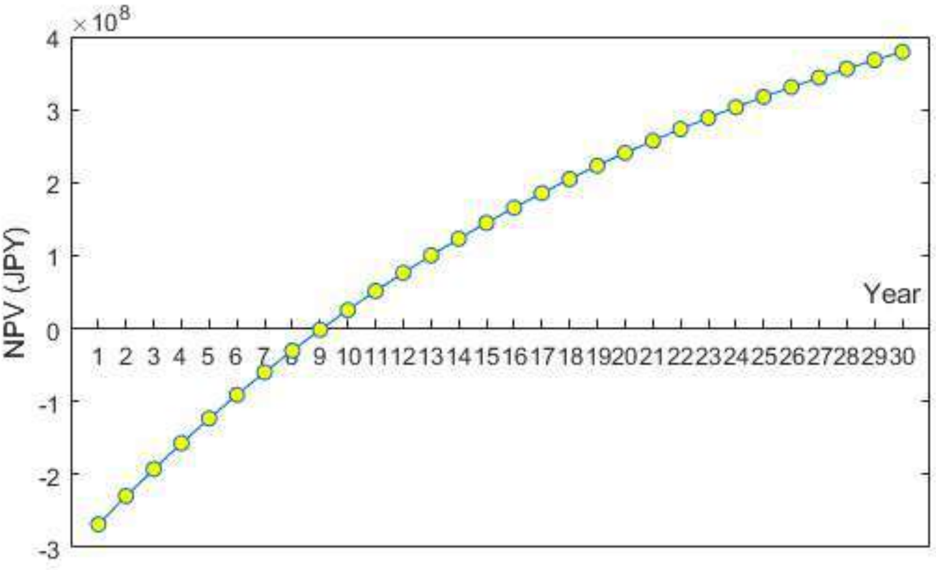


Fig 4. 20 NPV of PV system of Aeon Mall

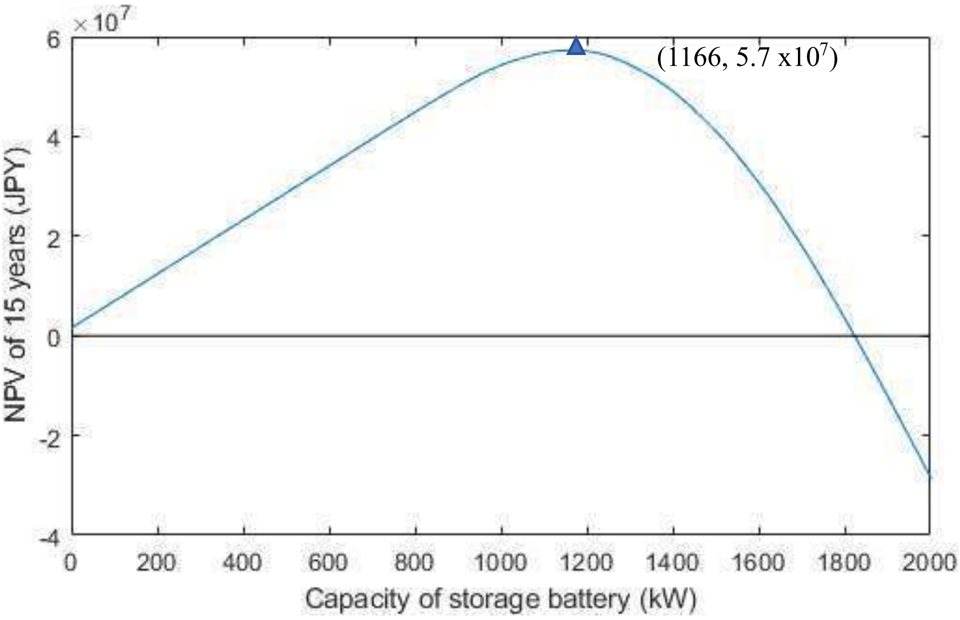


Fig 4. 21 15 year’s NPV of different capacity of SB system of Aeon Mall

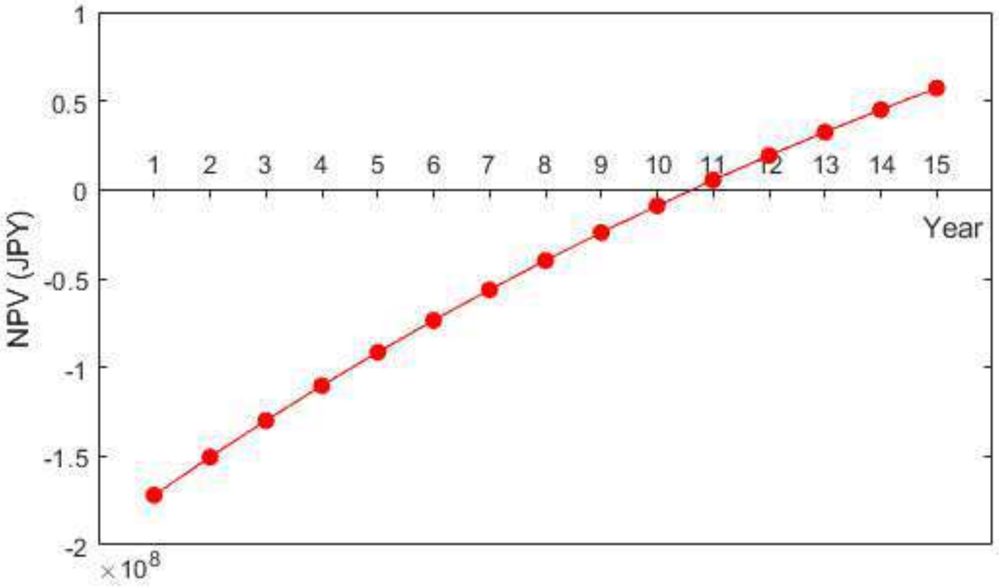


Fig 4. 22 NPV of SB system of Aeon Mall

4.2.3 Industry buildings

There are 8 industry buildings in the target area, and we selected typical days for each season to analyze the typical load curves. Results are shown in the Fig 4.23. Industry 4 ~ 8 shows the similar load characteristics.

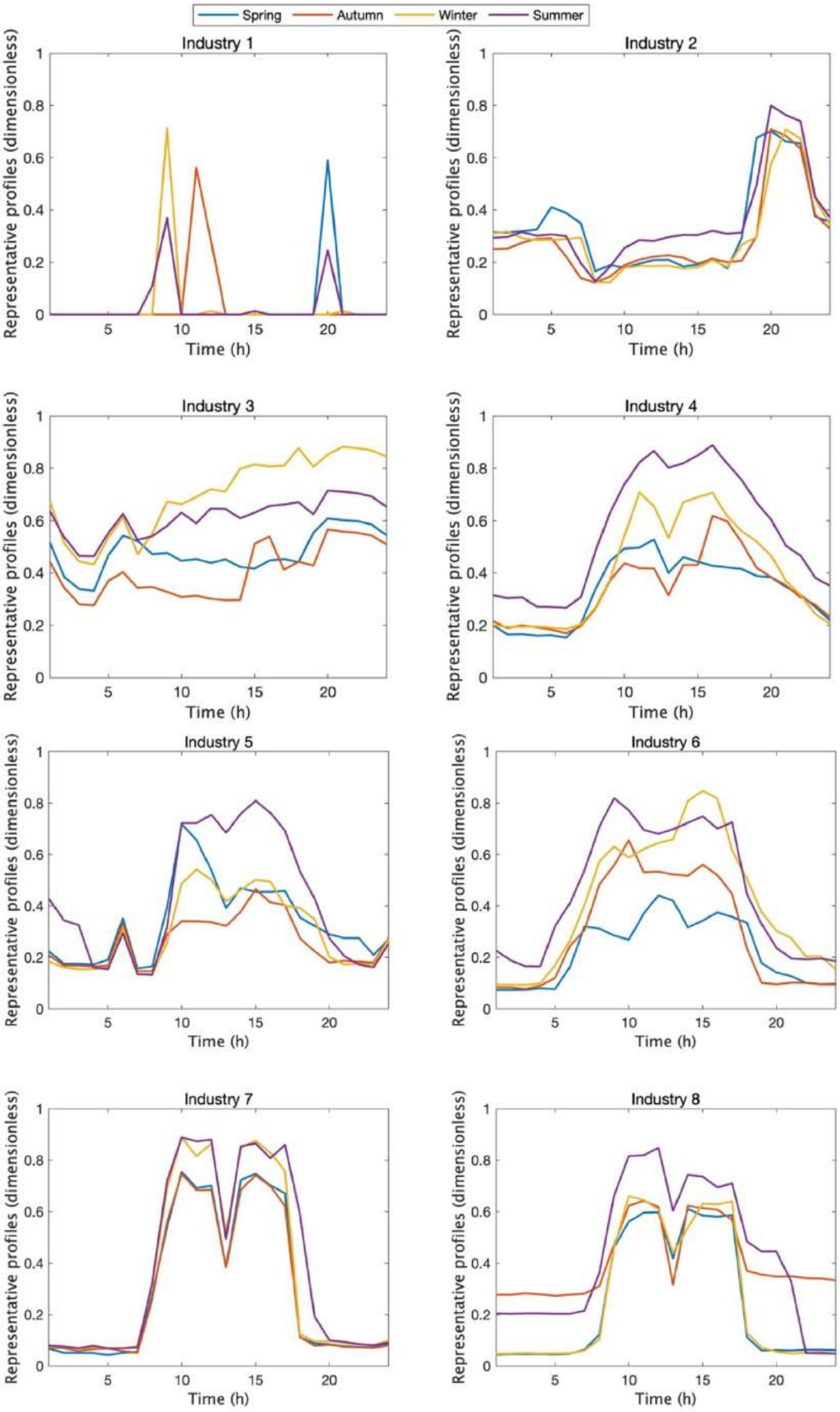


Fig 4. 23 Dimensionless representative load curve of industry buildings

✧ Case study of Nakazono Factory (Industry 8)

Nakazono Factory has peak and valley electric charges, the price 8:00-22:00 is 13.13 JPY, and 22:00-8:00 is 8.59 JPY. It has roof area of 1182 m². So we can calculated that capacity of PV system is 94 kW. Because the PV system has phenomenon of curtailment, the SB system need to be installed. Table 4.5 is the basic information of Aeon Mall. And Fig 4. 24 shows the roof of Nakazono Factory.

Table 4.5 Information of Nakazono Factory

Name	Roof area (m²)	PV capacity (kW)	Type	Electricity price (JPY)
Nakazono Factory	1182	94	Industry	8:00~22:00 13.13
				22:00~8:00 8.59

Fig 4. 24 Roof of Nakazono Factory

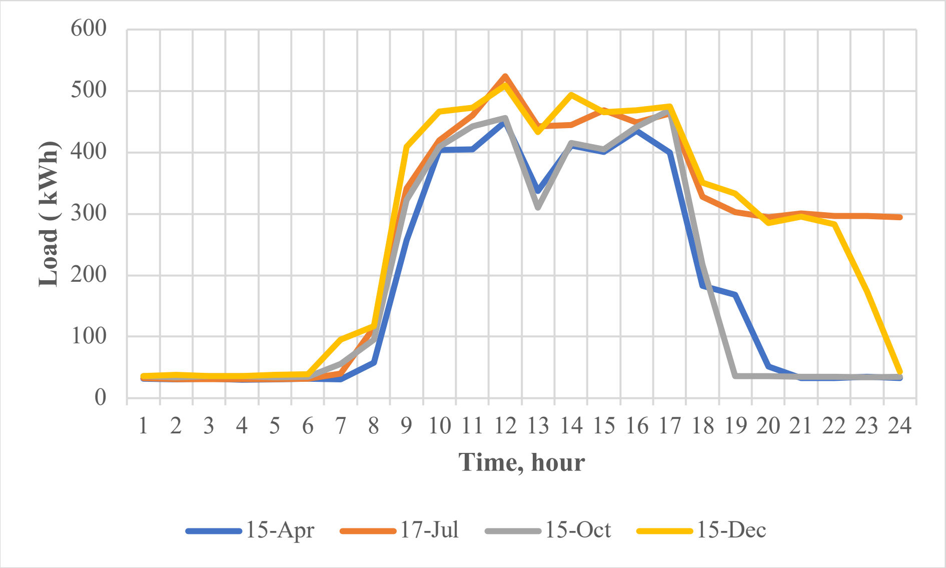


Fig 4. 25 Load characteristics of Nakazono Factory

A typical day from each season was selected to analyze the power load characteristics. As shown in Fig 4. 25, the load curve has obvious fluctuation characteristics. It can be seen from the typical daily load curves of the four seasons that the load curve in summer and winter are similar, autumn and spring similar too. As a industry building, Peak electricity consumption mainly occurs between 11:00~12:00. In addition, in the 12:00-13:00 electricity consumption has a significantly decrease.

Fig 4. 26 shows the load proportion of Nakazono Factory, blue line shows the original situation, and red line means the load proportion after adding PV system, the energy saving effect of PV system is obvious. And there is PV curtailment phenomenon. Then the energy saving potential and economic benefit characteristics of Nakazono factory after introducing PV and SB system was analyzed.

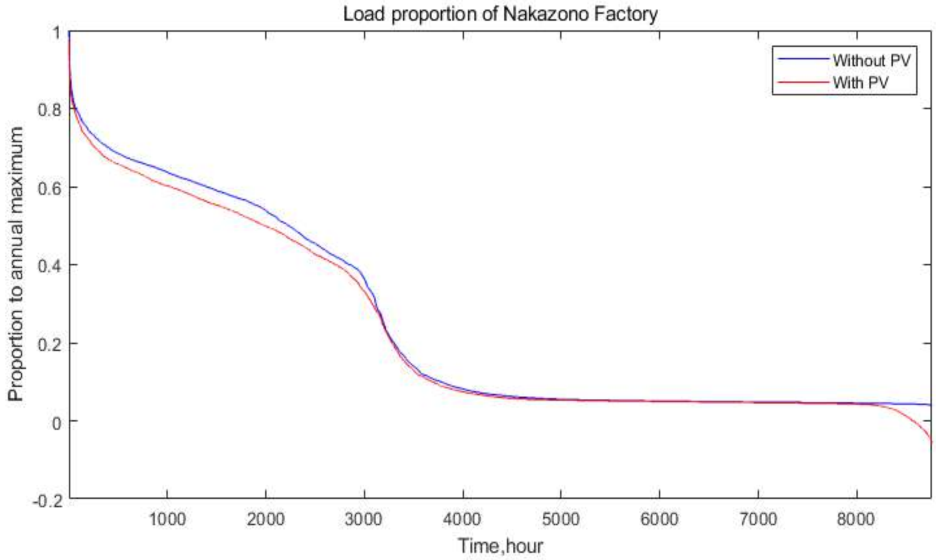


Fig 4. 26 Load proportion of Nakazono Factory

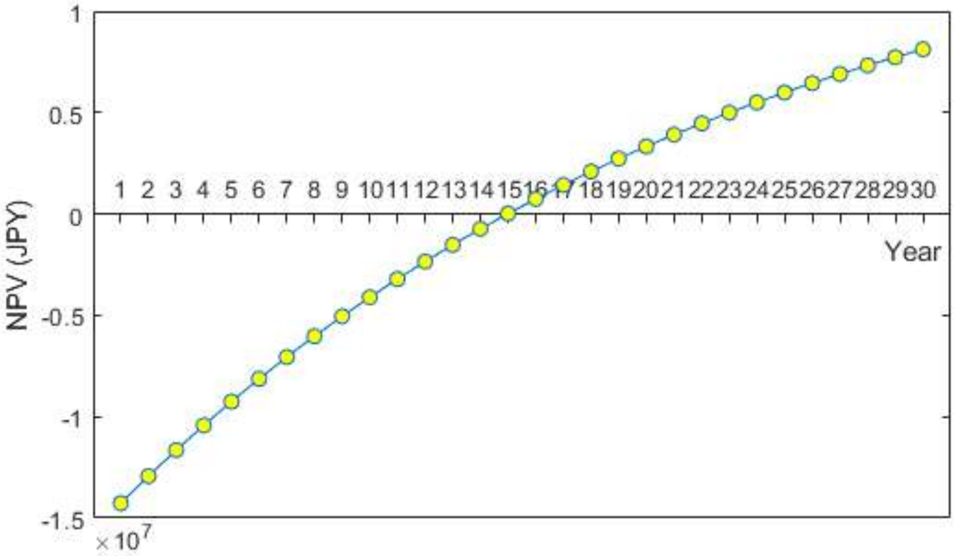


Fig 4. 27 NPV of PV system of Nakazono Factory

From Fig 4. 26, we can know that PV system of Nakazono Factory can recover costs within 15 years. Fig 4. 28 shows the 15 year's NPV of different SB capacity. It can be seen that SB system of Nakazono factory with the increase of the installed capacity of the battery, the profit has decreased. Showing a negative correlation. So, for Nakazono factory, it is better only installed PV system.

For Nakazono Factory, introduce PV system is feasible. The PV system can recover the cost within 15 years. However, it is uneconomic for Nakazono Factory to introduce the SB system.

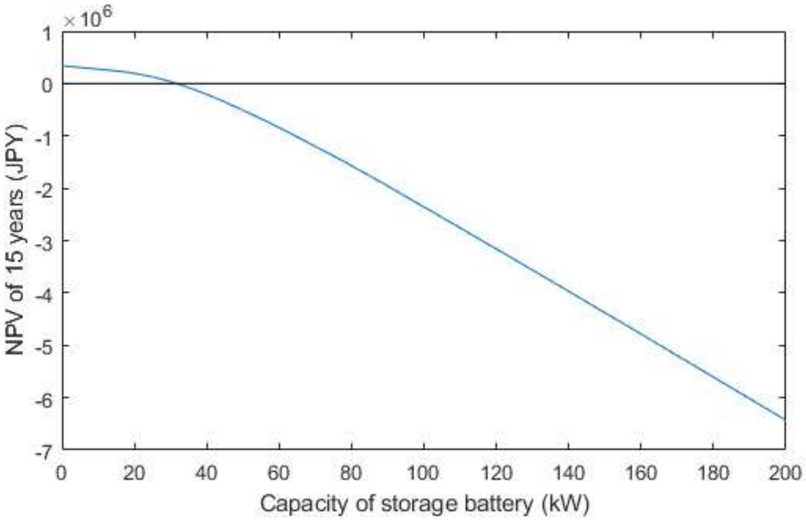


Fig 4. 28 15 year's NPV of different capacity of SB system of Nakazono Factory

4.2.4 Residential buildings

There are 4 residential buildings in the target area, and we selected typical days for each season to analyze the typical load curves. Results are shown in the Fig 4.29.

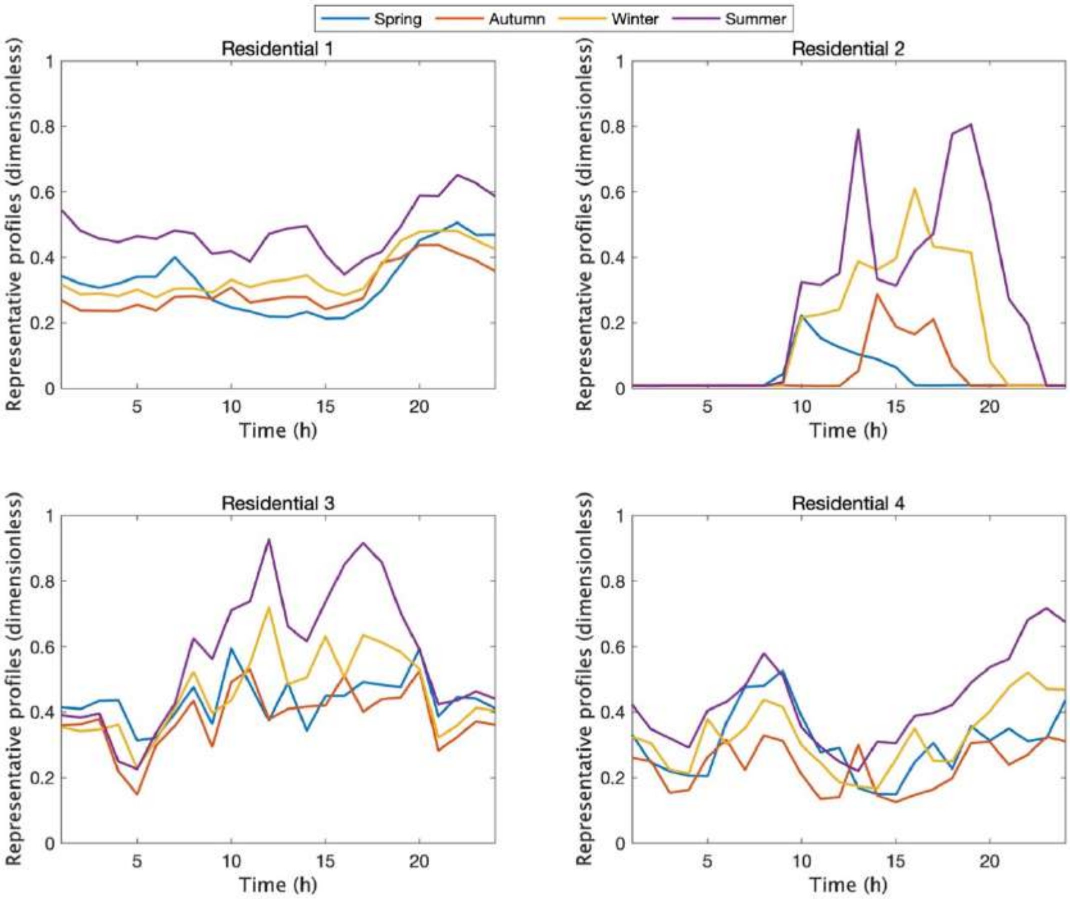


Fig 4. 29 Dimensionless representative load curve of residential buildings

✧ **Case study of Aikouen Residential (residential 3)**

Aikouen residential has peak and valley electric charges, the price 8:00-22:00 is 21.21 JPY, and 22:00-8:00 is 10.15 JPY. It has roof area of 780 m^2. So, we can calculate that capacity of PV system is 62 kW. Because there is price difference, the SB system can get profit from price difference, so Aikouen residential can install SB system. Table 4.6 is the basic information of Aikouen residential. And Fig 4. 30 shows the roof of Aikouen residential.

Table 4.6 Information of Aikouen Residential

Name	Roof area (m^2)	PV capacity (kW)	Type	Electricity price (JPY)
Aikouen Residential	780	62	Residential	8:00~22:00 21.21
				22:00~8:00 10.15

Fig 4. 30 Roof of Aikouen residential

A typical day from each season was selected to analyze the power load characteristics. As shown in Fig 4.24, the load curve has obvious fluctuation characteristics. It can be seen from the typical daily load curves of the four seasons that the load curve is similar in different season. As a residential building, electricity consumption is closely related to households' schedule.

Fig 4. 32 shows the load proportion of Aeon Mall, blue line shows the original situation, and red line means the load proportion after adding PV system, the energy saving effect of PV system is obvious.

Then the energy saving potential and economic benefit characteristics of Aikouen Residential of introducing PV and SB system was analyzed.

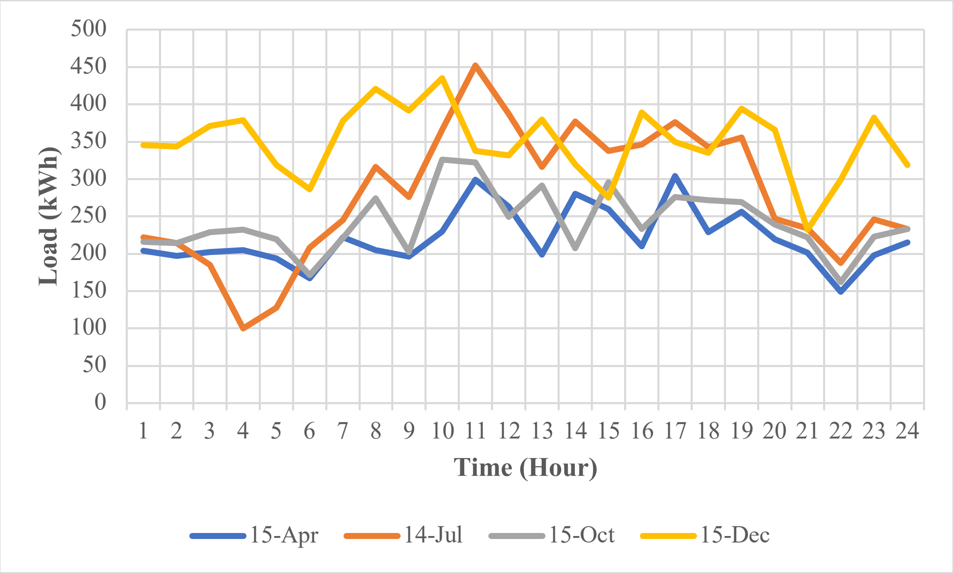


Fig 4. 31 Load characteristics of Aikouen residential

From Fig 4. 33 we can know that PV system of Aikouen Residential can recover costs within 7 years. Fig 4. 34 shows the 15 year's NPV of different SB capacity. It can be seen that SB system of Aikouen Residential with the increase of the installed capacity of the battery, the profit yield curve is in the form of a parabola. When reach the best profit, the capacity of SB system is 346 kW. And Fig 4. 35 shows the NPV of SB system in the best situation. The SB system can recover investment within 6 years. For Aikouen Residential, introduce PV system and SB system is feasible. Both PV system and SB system can generate revenue. The PV system can recover the cost within 7 years. The SB can recover the cost within 6 years.

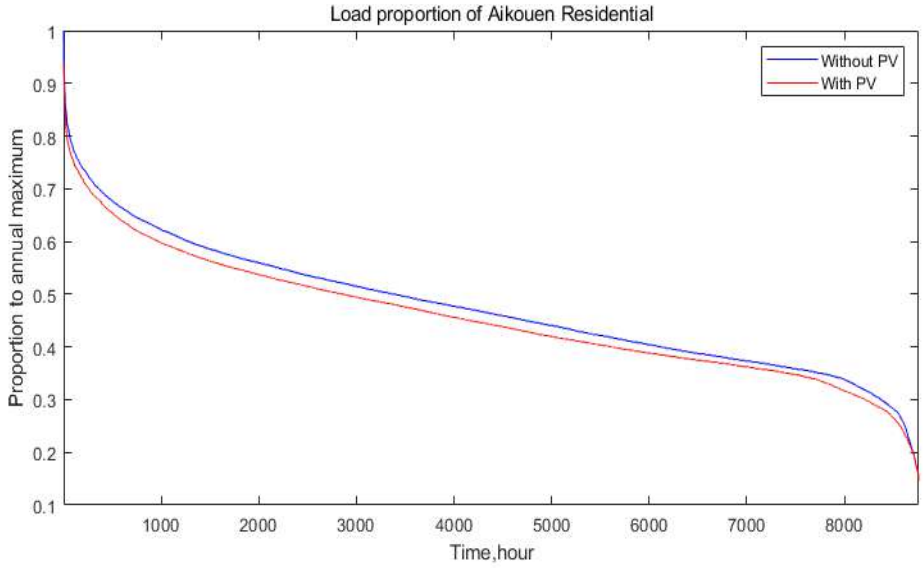


Fig 4. 32 Load proportion of Aikouen residential

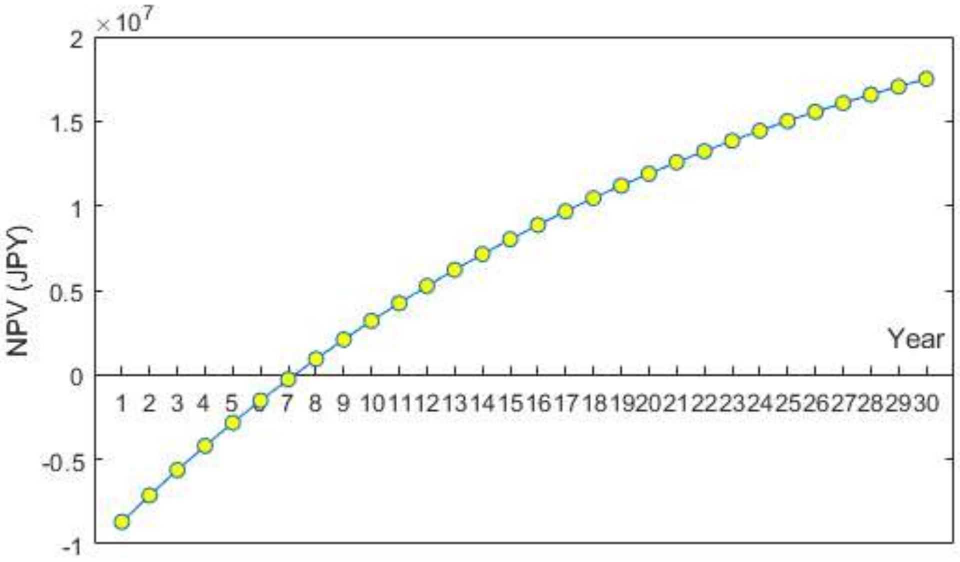


Fig 4. 33 NPV of PV system of Aikouen Residential

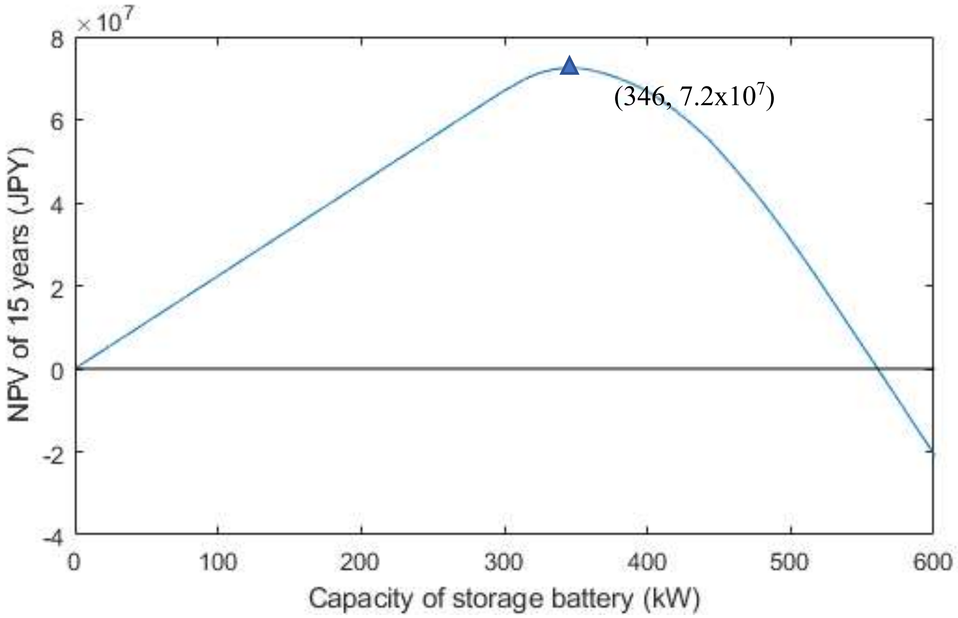


Fig 4. 34 15 year’s NPV of different capacity of SB system of Aikouen Residential

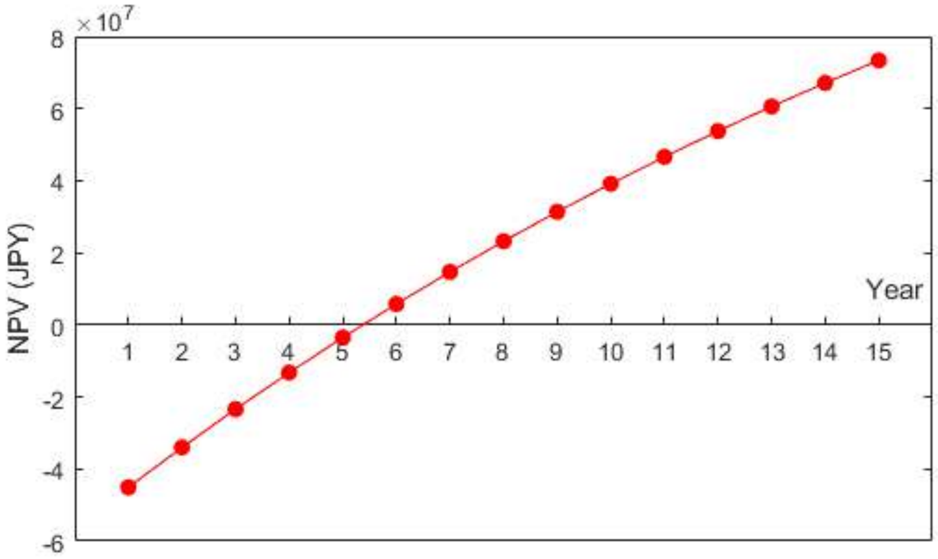
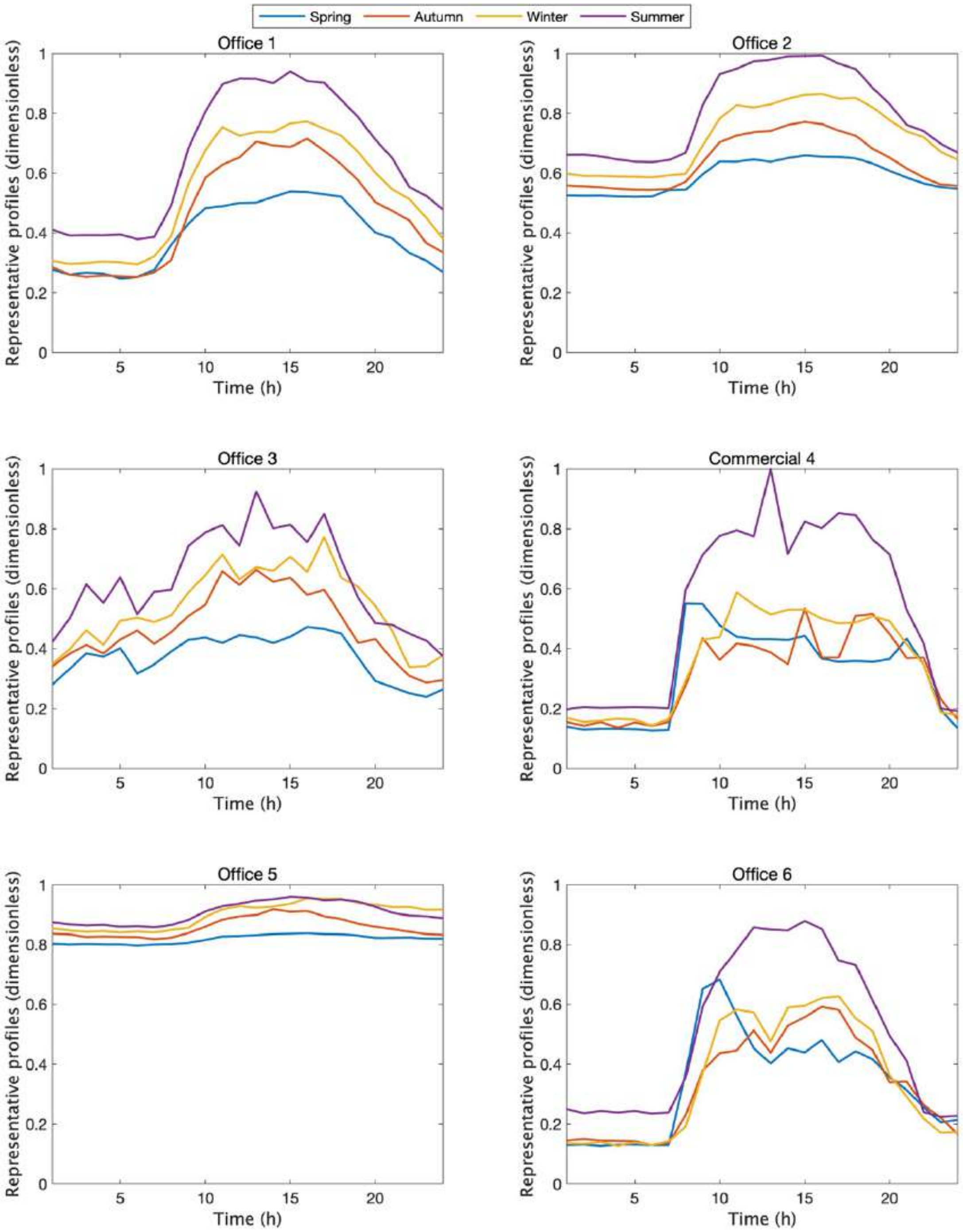


Fig 4. 35 NPV of SB system of Aikouen Residential

4.2.5 Office buildings

There are 13 office buildings in the target area, and we selected typical days for each season to analyze the typical load curves. Results are shown in the Fig 4.36.


Spring
Autumn
Winter
Summer
Office 1
Office 2
Office 3
Commercial 4
Office 5
Office 6
Representative profiles (dimensionless)
Time (h)
0
0.2
0.4
0.6
0.8
1
5
10
15
20

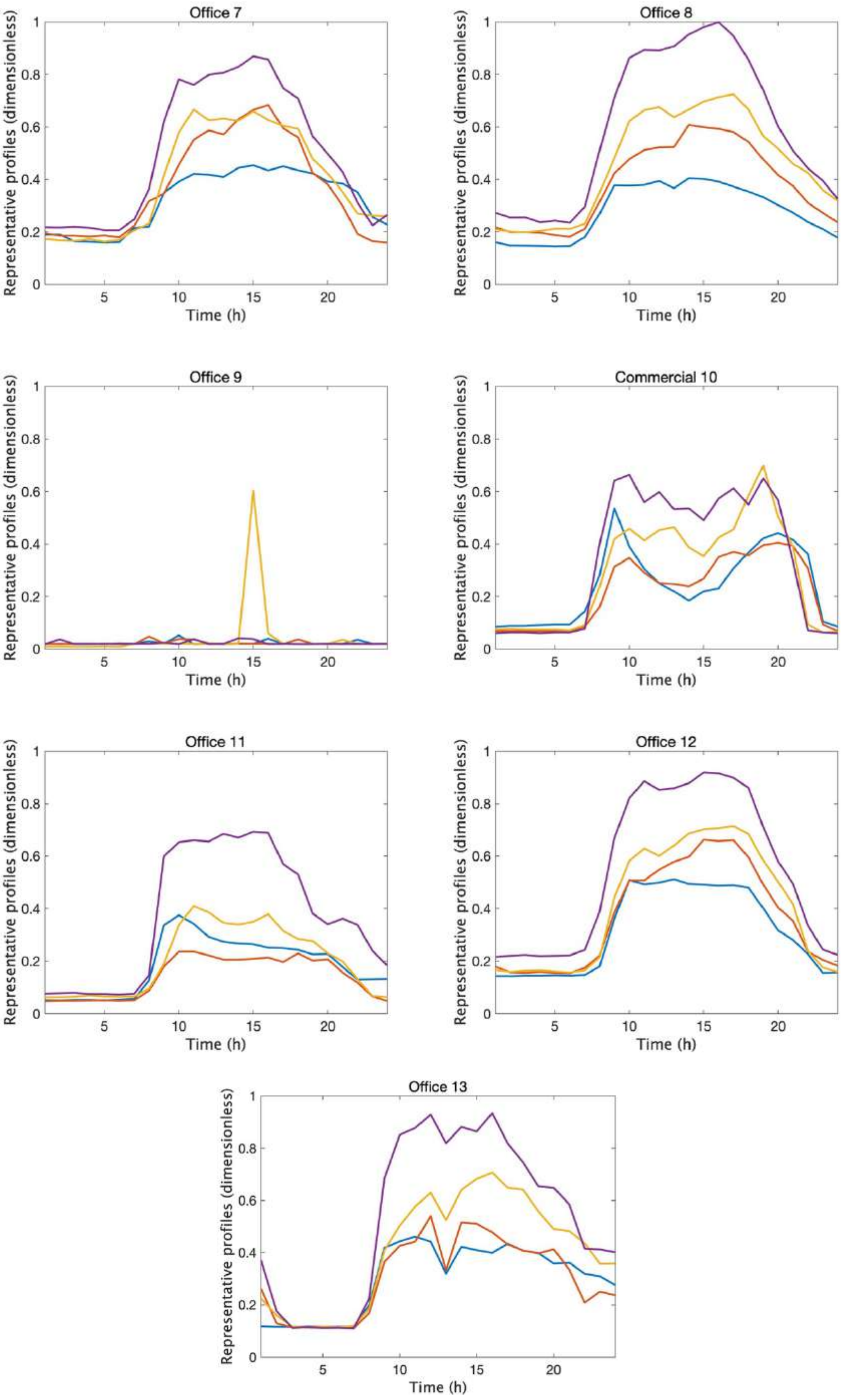


Fig 4. 36 Dimensionless representative load curve of office buildings

✧ Case study of Total Graphic Arts Creation Company (Office 13)

Aikouen residential has peak and valley electric charges, the price 8:00-22:00 is 21.21 JPY, and 22:00-8:00 is 10.15 JPY. It has roof area of 780 m². So, we can calculate that capacity of PV system is 62 kW. Because there is price difference, the SB system can get profit from price difference, so Aikouen residential can install SB system. Table 4.7 is the basic information of Aikouen residential. And Fig 4.29 shows the roof of Aikouen residential.

Table 4.7 Information of Total Graphic Arts Creation Company

Name	Roof area (m²)	PV capacity (kW)	Type	Electricity price (JPY)
Total Graphic Arts Creation Company	986	79	Office	8:00~22:00 17.82
				22:00~8:00 10.49

Fig 4. 37 Roof of Total Graphic Arts Creation Company

We select a typical day from each season to analyze the power load characteristics. As shown in Fig 4. 37, the load curve has obvious fluctuation characteristics. It can be seen from the typical daily load curves of the four seasons that the load curve is similar in different season. As an office building, Peak electricity consumption mainly occurs between 11:00~16:00. The largest electricity consumption appears in summer. And in the noon, there is obvious electricity consumption trough. This phenomenon is mainly related to its working hours.

Fig 4. 39 shows the load proportion of Total Graphic Arts Creation Company, blue line shows the original situation, and red line means the load proportion after adding PV system, the energy saving effect of PV system is obvious. And there is PV curtailment phenomenon.

Then the energy saving potential and economic benefit characteristics of Total Graphic Arts Creation Company of introducing PV and SB system was analyzed.

For Total Graphic Arts Creation Company, introduce PV system and SB system is feasible. Both PV system and SB system can generate revenue. The PV system can recover the cost within 10 years. The SB can recover the cost within 9 years.

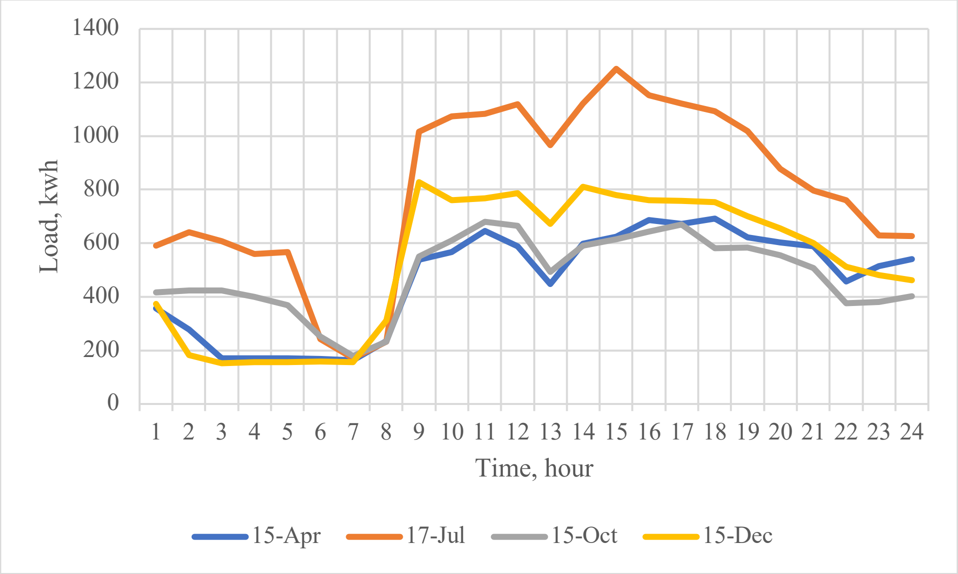


Fig 4. 38 Load characteristics of Total Graphic Arts Creation Company

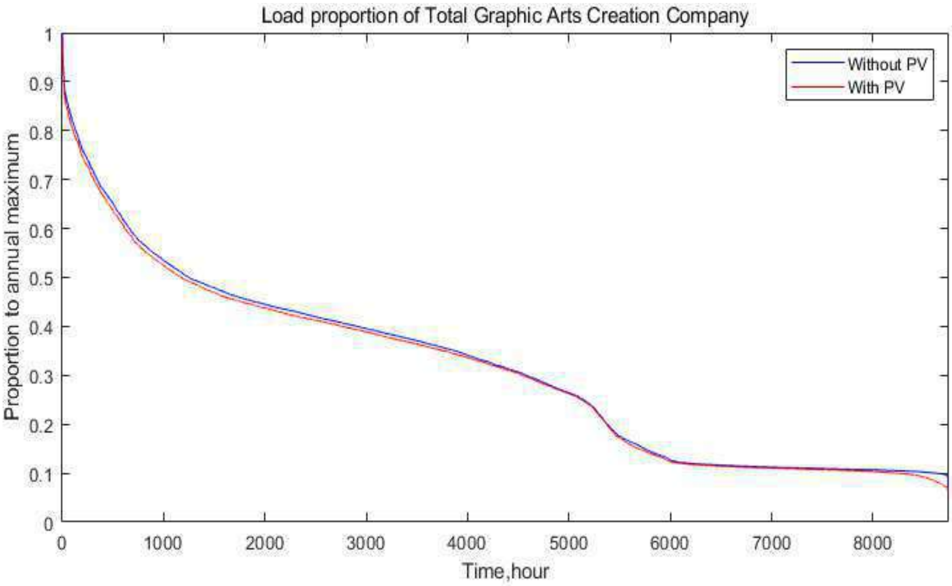


Fig 4. 39 Load proportion of Total Graphic Arts Creation Company

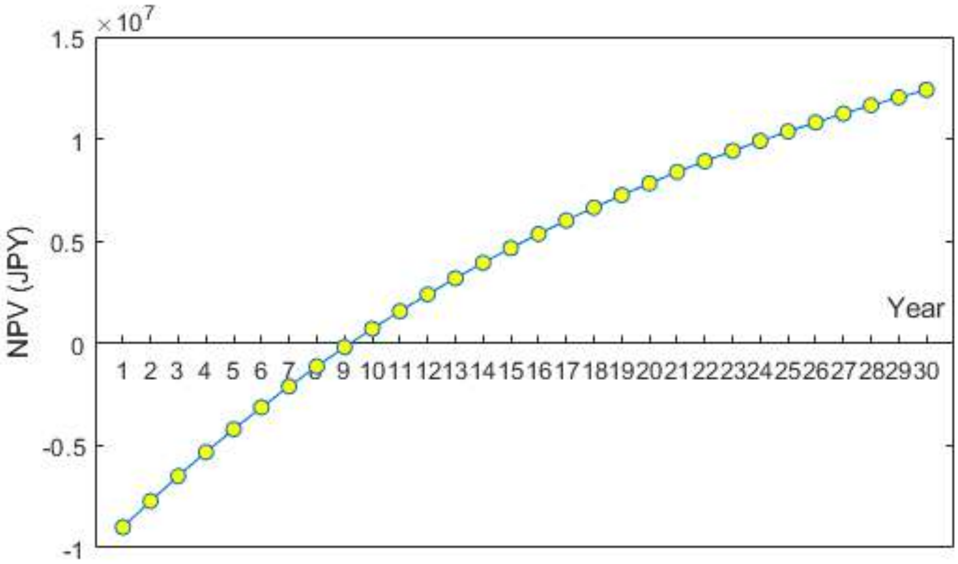


Fig 4. 40 NPV of PV system of Total Graphic Arts Creation Company

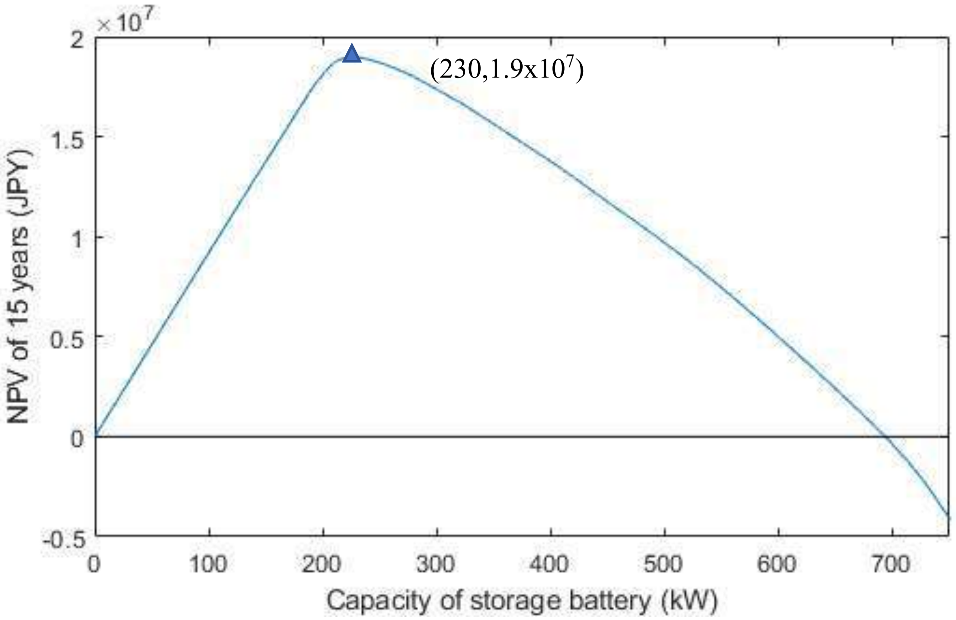


Fig 4. 41 15 year’s NPV of different capacity of SB system of Total Graphic Arts Creation Company

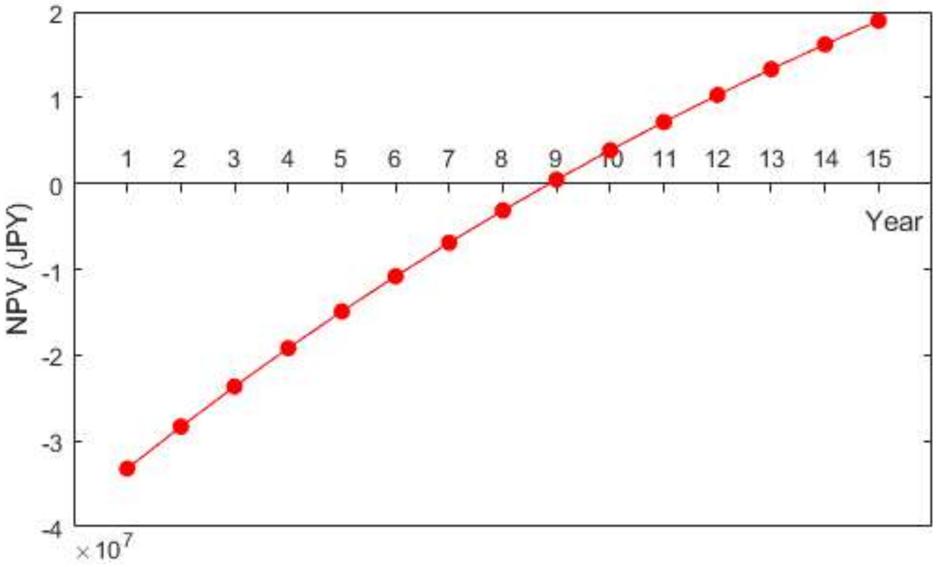


Fig 4. 42 NPV of SB system of Total Graphic Arts Creation Company

4.3 Summary

The load curve shape of the same type of buildings in four seasons is similar. The spring and autumn typical load curves are the most similar. Summer and winter load curves are similar, with similar load levels. The impact of climate on the load is mainly reflected in the air-conditioning cooling load in summer and the heating load in winter. Buildings such as museums and shopping malls have basically a stable power load during business hours. For factories and office buildings, there are obvious load troughs during lunch breaks. Load peaks of hospital typically occur at noon. For residential building, peak electricity usage usually occurs in the early morning and evening.

The payback period of the PV system is related to the electricity price, the higher the electricity price, the shorter the payback period; and the profit is related to the PV capacity and electricity price.

The payback period of SB is related to the electricity price difference and the amount of PV curtailment. The larger the electricity price difference, the shorter the payback period.

Chapter 5

FEASIBILITY, EFFICIENCY AND ECONOMIC ANALYSIS OF VPPS

CHAPTER 5: FEASIBILITY, EFFICIENCY AND ECONOMIC ANALYSIS OF VPPS

5.1 Content

Energy such as electricity, gas and petrol, being indispensable for human life, is supporting our society. Japan, as a country that lacks resources such as oil and liquefied natural gas (LNG), needs various measures to secure a stable supply of energy. The energy self-efficiency ratio of Japan in 2019 was 12.1% [1]. Since the 311 Eastern Japan Earthquake, electricity price had risen several times. This is due to increased utilization of thermal power generation to mitigate the impact of nuclear power plant shutdowns. This is also attributable to the fuel prices rising until 2014. Compared with the price before the 311 Eastern Japan Earthquake, household electricity price increased by about 16% in 2017, and industrial electricity price rose by about 21%. It is necessary for us to take measures to change the energy structure in terms of energy saving. With the gradual popular of various types of renewable energy, such as solar energy, wind energy and geothermal energy, a new concept called VPP has been proposed. There are increasing interests in accessing the potential to develop urban VPPs.

The purpose of this research is to explore the feasibility of VPPs in Higashida area. After that energy efficiency and economic benefits of VPPs were analyzed. A sustainable power supply framework should be suitable for the situation in the region. Increasing power self-sufficiency through multiple power flows and management strategies. At present, the most common energy saving technologies were used are storage battery (SB) and photovoltaic (PV), owing to its convenience and policy support.

5.2 Motivation

Firstly, government has a demand for energy self-sufficiency in the Higashida area. At present, Higashida co-generation is insufficient to meet the entire area demand needs of electricity. Therefore, it is necessary to expand production capacity. Secondly, in order to promote the construction of an environmentally friendly society, the Japanese government is vigorously promoting renewable energy and subsidizing users who install renewable energy equipment. The last one, imbalance of peak and valley power consumption on the demand side leads to the power plant side need to adjust its own power generation according to external demand, result in uneconomical power plant operation. These three reasons make the three parties seek a more efficient and low-pollution power supply method together.

The introduction of the VPP can bring the electricity saving for the demand side and greenhouse gas emission reduction benefits to the society, replacing the expansion construction of conventional power plant to meet the electricity demand. However, because of the introduction of VPPs, power plant will supply less electricity to the demand side, which will influence its electricity sold income in long run.

Therefore, based on the electricity market, a proper payment mechanism art between power and demand sides is essential to encourage the form of the VPPs. Energy Performance Contracting is introduced here. Energy Performance Contracting (EPC) is an energy saving investment method to pay for the full cost of energy saving projects by saving energy costs; this energy saving investment method allows users to use future energy saving gains to upgrade plants and equipment, reduce current operating costs and improve energy efficiency. The successful implementation of the project is the common goal of both the power plant and the demand side. The demand side benefit is to obtain excellent energy-saving equipment and long-term energy-saving and environmental benefits without or with little investment.

In this study, the power plant side is responsible for the energy management part. The power plant has to make a profit from the success of the project. (Here we average the profit of the power plant to the profit per kWh and return it to the power plant).

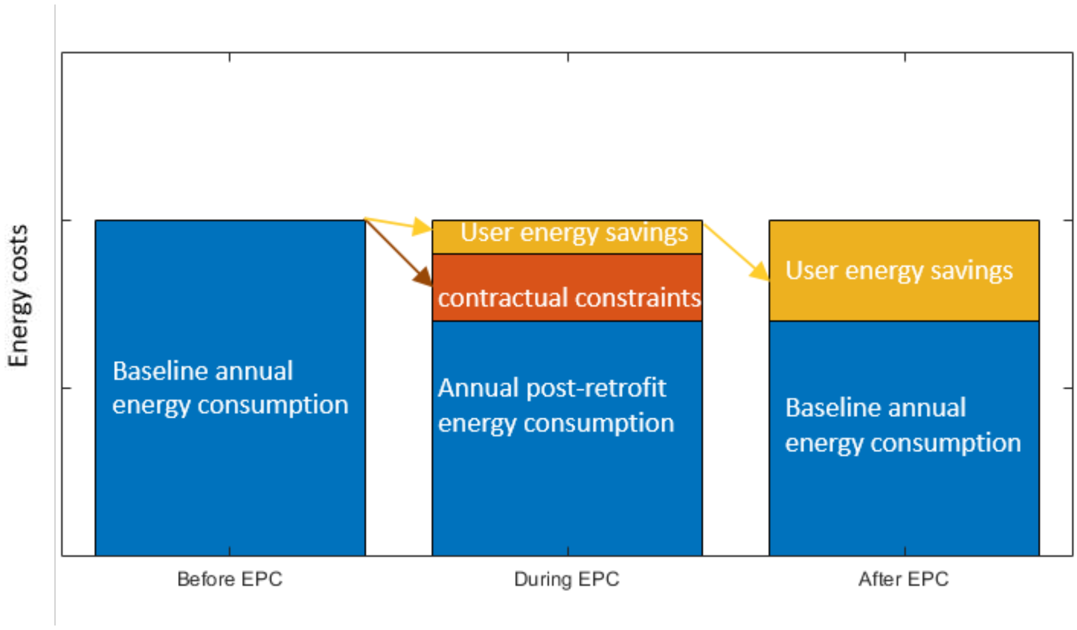


Fig 5. 1 Operating mechanism of EPC

In order to analyze the economic profit balance properly and develop commercial incentive agreement between both demand and plant sides, following part analyzed the performances of built VPP in different scenarios via changing the feed-in tariffs for plant side and corresponding electricity fee for demand side.

The composition of VPP in this article mainly includes PV system and SB system. Compared with large-scale PV power generation systems, we consider installing PV on the roof of buildings, which will not restrict the location and cause too much economic burden, it is also can reduce the initial investment. (Due to the shortage of land resources in Japan, rooftop PV is the best promoted in Japan.) The reason why we do not consider the backup system for the interruptible solar energy is that solar energy is a renewable energy source, and we hope to be able to fully utilize the electricity generated by photovoltaics. Also, we have equipped storage battery system, the battery has two functions here: 1. Store the electricity generated by PV not consumed by the demand side; 2. Store electricity when the grid's power demand is low and discharge at the peak of grid demand to stabilize the load curve. As for we did not consider gas turbines. On the one hand, currently PV and SB systems are the most popular distributed energy system with the best effect in Japan. On the other hand, gas prices in Japan are relatively expensive, the overall economic benefits of gas turbine not so good, thus, it is rarely used on the demand side currently. Today, due to global warming, the usage of clean fuels in power systems get more importance. Regarding Japan's current GHG emission reduction goals, gas turbines use gas as fuel, cannot contribute to reducing GHG emissions, and solar energy as renewable energy source can reduce GHG emissions. Considering the above reasons, we used a combination of PV system and SB system in this paper.

Before analyzing the effect and economic of VPPs, we can make a comparison between investing in VPPs and investing in conventional power plants. Table 5. 1and Table 5. 2 shows the cost of two investment plan.

The operating cycle of the PV system is set to 30 years, the operating cycle of the SB system is set to 15 years, and the operating cycle of the conventional (LNG) thermal power plant is set to 30 years, so 30 years is used as the equipment investment cycle to calculate its profit. The SB system requires two rounds of investment. Considering that battery investment costs will be lower, so the second round of investment will be lower.

5.3 Feasibility evaluation

The Higashida area is a demonstration of the planned smart community, with the goal of achieving self-sufficiency of electricity. It will also reduce the burden on the grid, so the Higashida Area has two investment options to cover the entire region.

1) Invest in conventional LNG-fired power plant
2) Invest in Virtual Power Plants (VPPs) & a small LNG-fired power plant

In the following, analysis model mainly includes the installation, operative and maintenance costs of the PV system and SB system, as well as incentive strategies by the local laws and regulations to build economic driver for the implementation of efficiency VPPs. The payback period of each component in the VPPs is calculated by setting to zero the NPV (net present value) of the total investment.

Table 5. 1 Cost of LNG power plant (source: https://www.enecho.meti.go.jp/)

Capital cost	Construction Investment	120000
	Residual value	5% of construction investment
Operating expenses	Staff salary (JPY/kW)	450
	Repair fee	1.2% of construction investment
	Other fee	0.76% of construction
	Management fee	14.3% of other operating
Fuel costs	Main fuel cost (JPY/T)	92,667
	Power generation efficiency	52%
	Heat production efficiency	28%
	Calorific value (MJ/KG)	55.01

Power Transmission and Distribution	Power Transmission and Distribution Prices	825
Self-use fee	Electricity self-use rate	10%

Table 5. 2 Cost of VPPs

Photovoltaic system		Storage battery system	
Brand	Panasonic HIT N250	Brand	NAS storage
Life expectancy	30 years	Life expectancy	15 years
Initial cost (JPY/kW)	250,000	Initial cost (JPY/kWh)	25,000
Module capacity	250w	Charge time	23:00~9:00
Module Dimension	1.58m×0.798m	Discharge time	9:00~23:00
Investment (JPY)	4,069,550,196	Investment (JPY)	5,783,531,644

5.3.1 Invest in conventional LNG-fired power plant

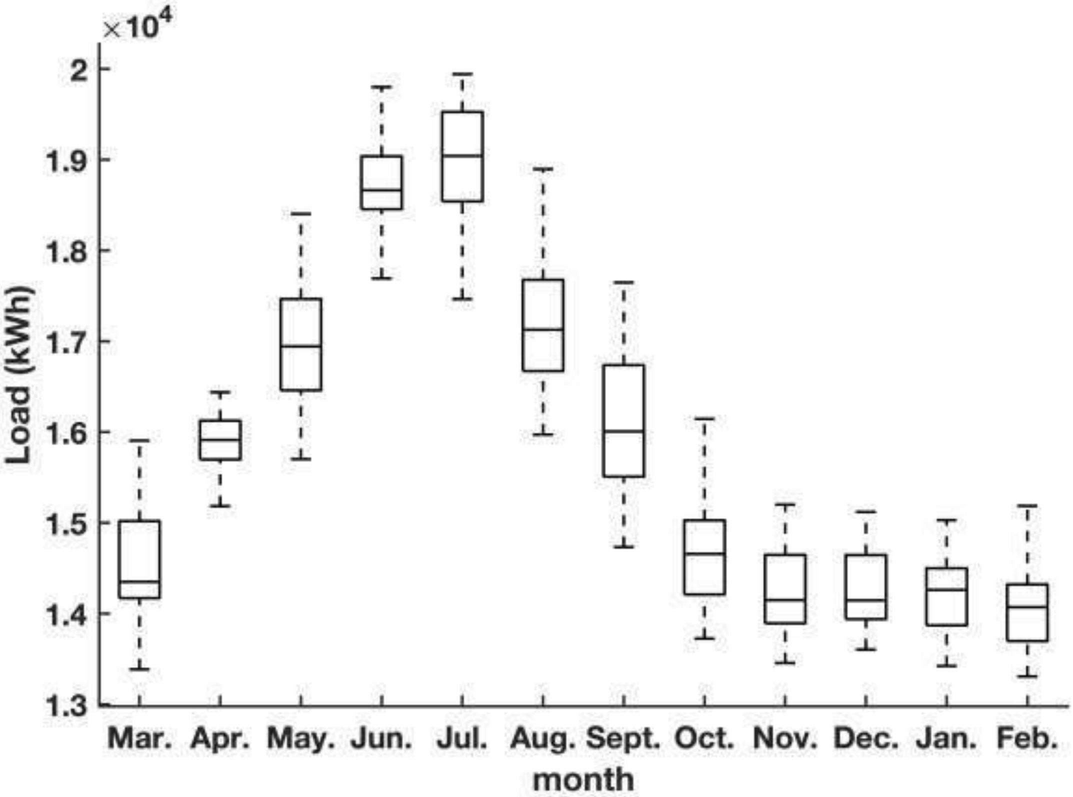


Fig 5. 2 Annual energy consumption of Higashida District

We analyze the plan of invest in conventional LNG-fired power plant first. The power plant needs to cover the entire area of electricity demand, and the capacity need to be increased to

52,830 kW. Picture shows the blank rate of the area below the red line increases. The annual profit is related to effective use hours and electricity price. The annual effective use hours of 33000kW power plant are 270,600,000 kWh / 33,000 kW=8,200 h. The annual effective use hours of 52830kW power plant are 341,113,408 kWh / 52,830 kW=6,456 h.

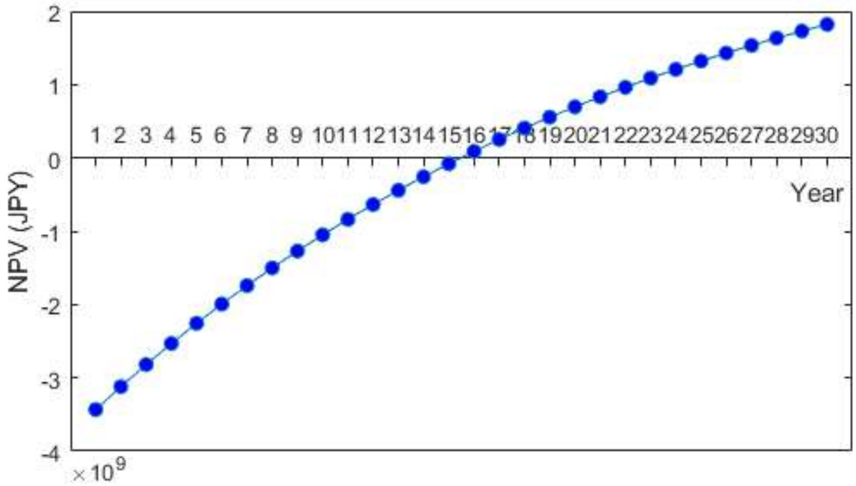
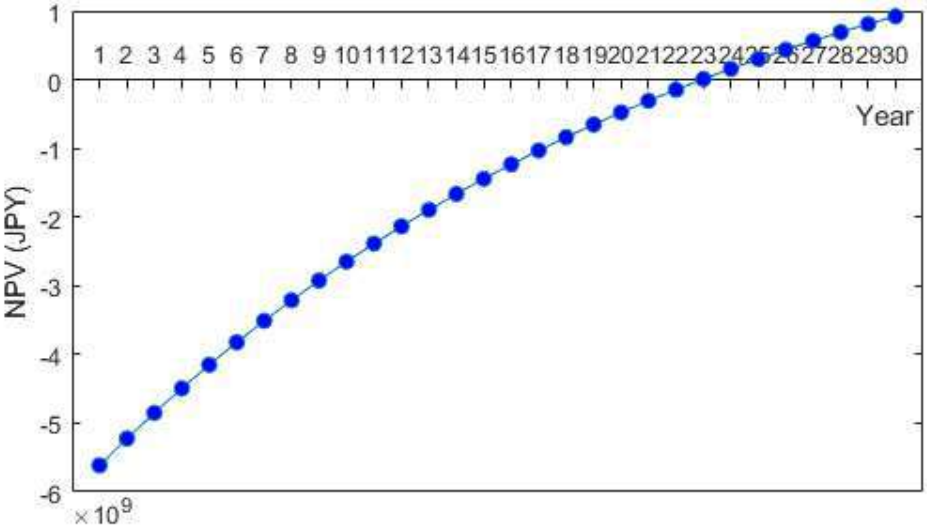


Fig 5. 3 NPV of 33,000 kW power plant



shows the NPV of 33,000 kW power plant under the current situation, the payback period of the current Higashida co-generation is within 16 years. And as show in Fig 5. 4, if the capacity expands to 55,754 kW, indicated that due to the reduction of the annual effective use hours, if the electricity price remains unchanged, the power plant profit will decrease, and the payback period will become longer.

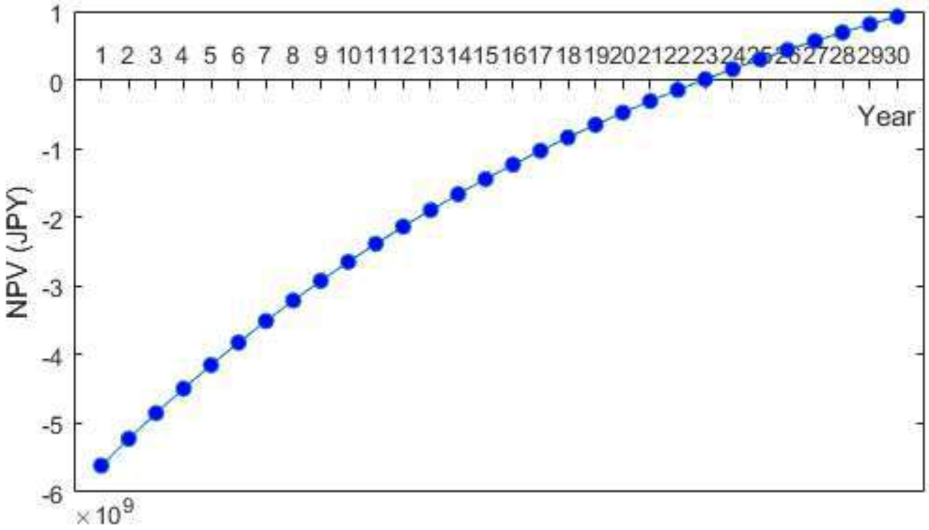


Fig 5. 4 NPV of 55,784 kW power plant

Further calculations show that in this case, the average electricity price increase 0.34~0.44 yen, which can maintain the payback period at 15-16 years. But at the same time, the increase in greenhouse gas emission will increase the possibility of environmental pollution.

This is a result that side, power plant side, and government are unwilling to see. Therefore, the three parties can jointly consider introducing VPP to solve the conflict.

5.3.2 Invest in VPPs

Second option is invested in VPPs & a small LNG-fired power plant, Fig 5-6 shows the electricity consumption after adding VPPs. After investing in VPP, the electricity consumption in the Higashida area is relatively stable, and the total power plant capacity only needs to be expanded to 39059kW. If the electricity price remains unchanged, because of the profit rate of the expanded part of the power plant is lower than the original 33000kW power plant, the payback period will also become longer. Further calculations show that in this case, the average electricity price need increase 1~1.1 yen, which can maintain the payback period of 15 to 16 years.

And Fig 5.5 analyzed the NPV of invest the VPP system, it can be seen that the VPP cannot cover its investment within 30 years by itself. It can be seen that although VPPs have benefits, due to the high initial investment, the system itself cannot pay back its costs in the life cycle.

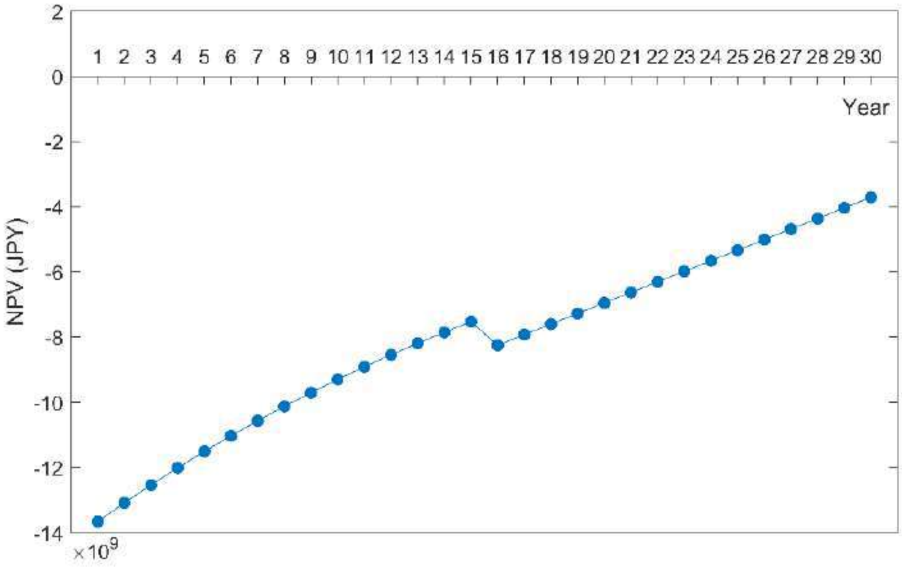


Fig 5. 5 NPV of VPP without subsidies and incentives

On the other hand, with the construction of VPPs, power plant side supply less electricity to the demand side. Furthermore, because of the SB’s energy arbitrage operation mode, the average purchase price of electricity on the demand side will decrease, leading to a significant reduction in the plant side's profit in long run. Under this circumstance, the plant side's electricity sold income will fall by 3.7 billion JPY within 30 years. As a result, the plant side will soon achieve profit growth by increasing the electricity price, which will harm the demand side’s profit. In order to analyze the influence of electricity price changes on both the plant and demand side, we calculated the profit variations under different electricity price increase. As shown in Fig 5.6, with the rise in electricity price, the demand side’s profit will decrease, and the plant side’s gain will increase. Obviously, the two parties cannot achieve a balance of interests.

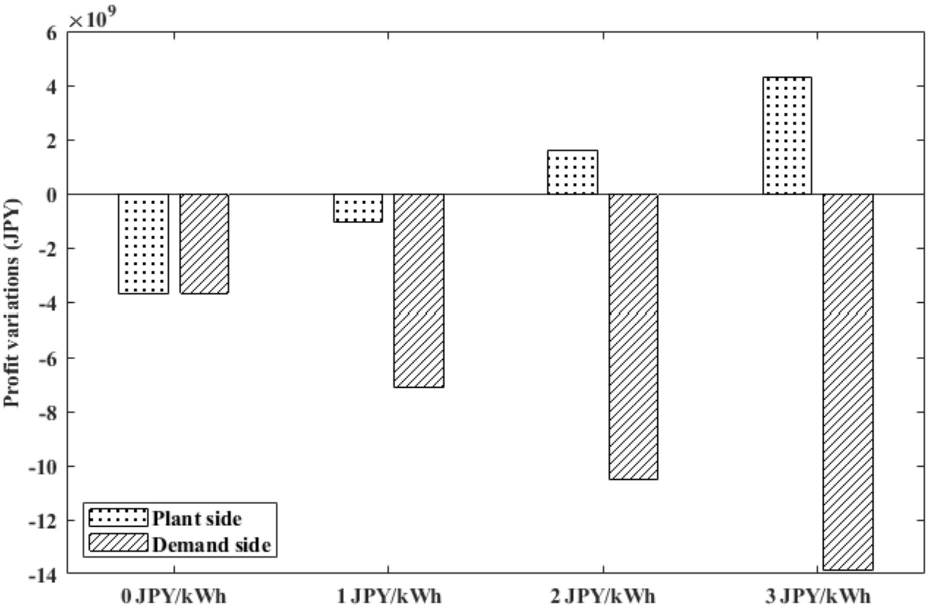


Fig 5. 6 Profit variations under different electricity price increase

Therefore, the following analysis was based on the assumptions:

1) Demand side consider the subsidy from government.

2) There is no renewable energy power generation in the Higashida area, that is, the electricity is supplied by the Higashida co-generation first, and the insufficient part is provided by Kyushu Electric Power.

3) The buildings in the Higashida area adopt the peak and valley electricity prices of the corresponding industries. Adopts the electricity price of Kyushu Electric Power corresponding to the buildings.

Table 5. 3 Annual electricity consumption of different buildings in Higashida Area

Type	Residential	Industry	Commercial	Office	Public	Total
Roof area (m²)	4,170	5,926	61,709	13,151	29,307	114,263
Electricity data (kWh)	21,516,748	7,978,896	59,256,962	69,824,292	6,3470,290	222,047,188
Total Area (m²)	18,129	12,535	91,944	23,546	39,594	185,748
Total electricity consumption (kWh)	93,543,675	16,877,398	88,290,559	125,015,799	85,748,888	341,113,408

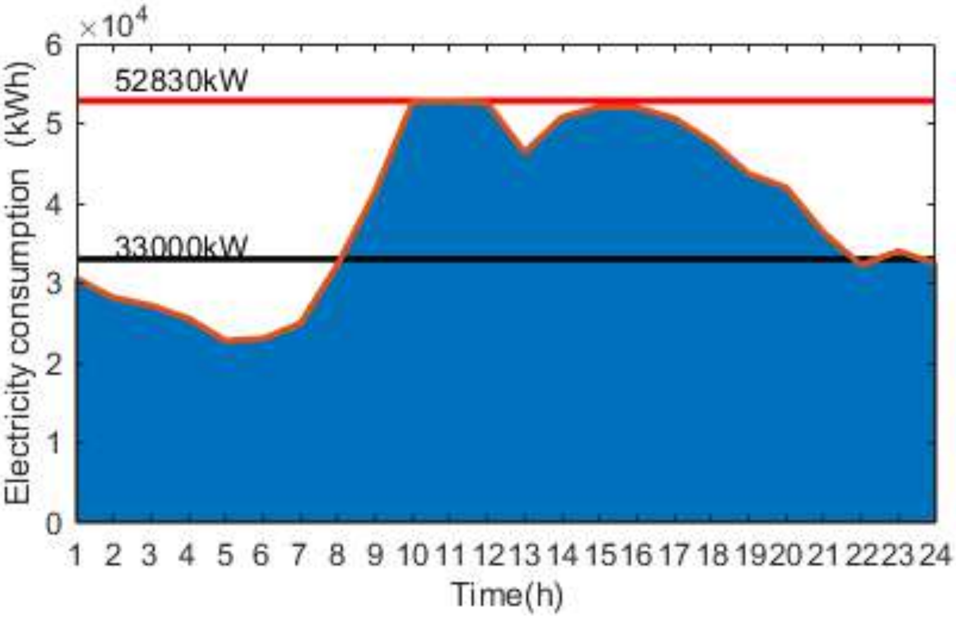


Fig 5. 7 Average daily electricity consumption in Higashida Area

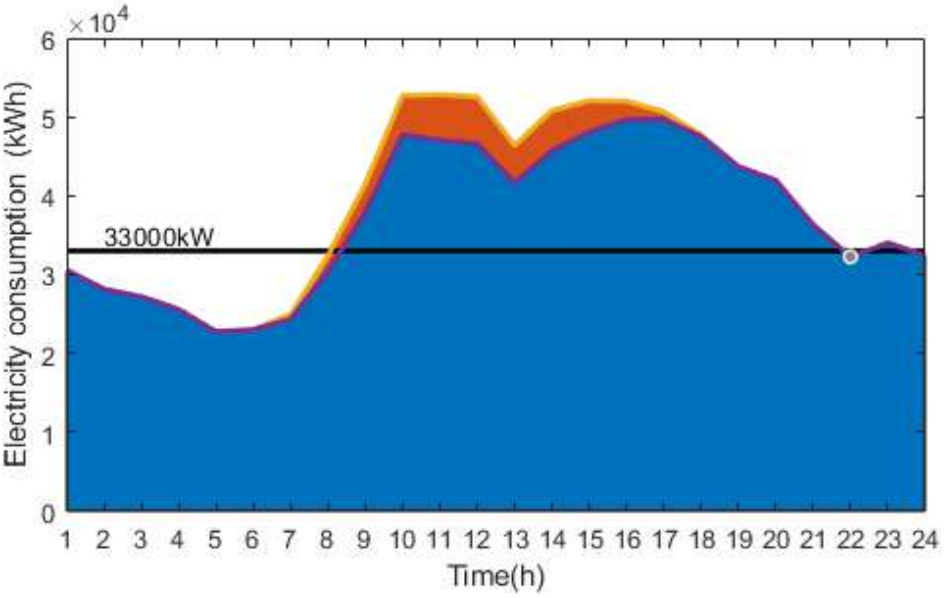


Fig 5. 8 Daily electricity consumption after adding PV system in Higashida Area

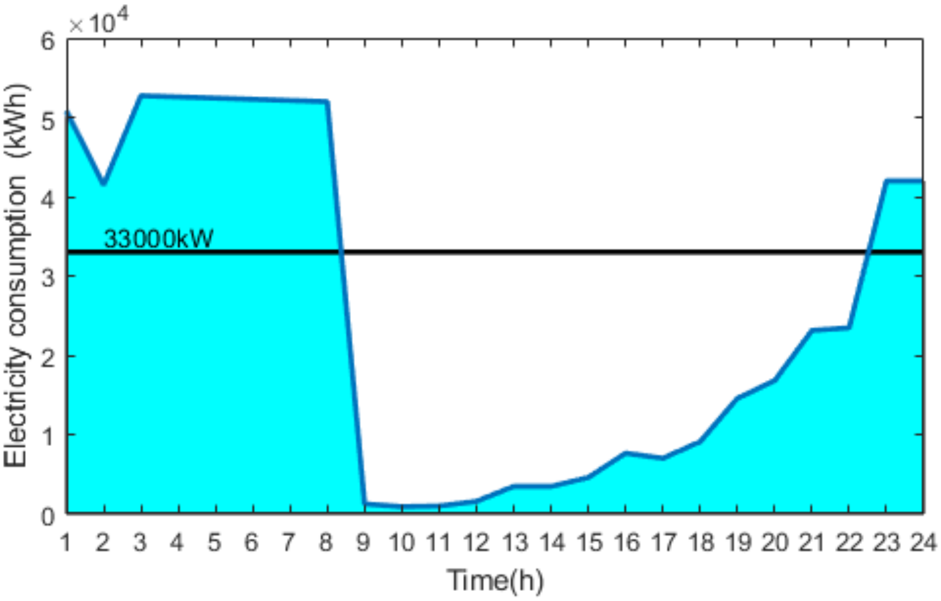


Fig 5. 9 Daily electricity consumption after adding SB system in Higashida Area

Therefore, considering the effect of peak cut on the power plant side, the capacity of SB system on the demand side can be appropriately reduced, so the installed capacity of the SB system can be limited to the difference between the average power consumption during the storage battery charge and discharge period to ensure that the battery has peak cut and valley filling effect. According to the study of the relationship between storage battery capacity and profit in the previous chapter, within this interval, capacity and profit are directly proportional. From this, the optimal capacity of the SB system can be determined (Fig 5. 10). In addition, optimizing the storage battery charge-discharge mode can further optimize the peak-shaving and valley-filling effects. (Fig 5. 11)

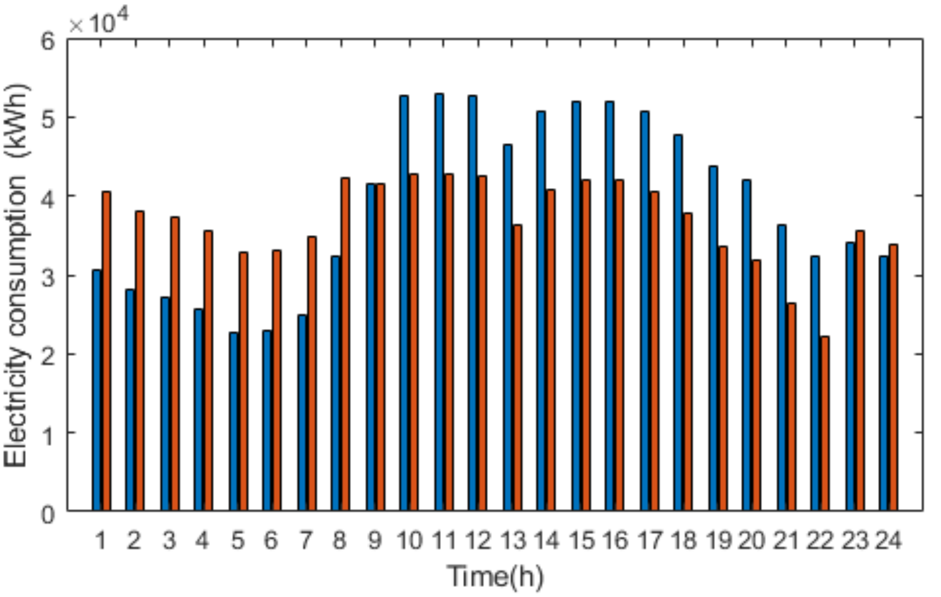


Fig 5. 10 SB system with same charge-discharge capacity

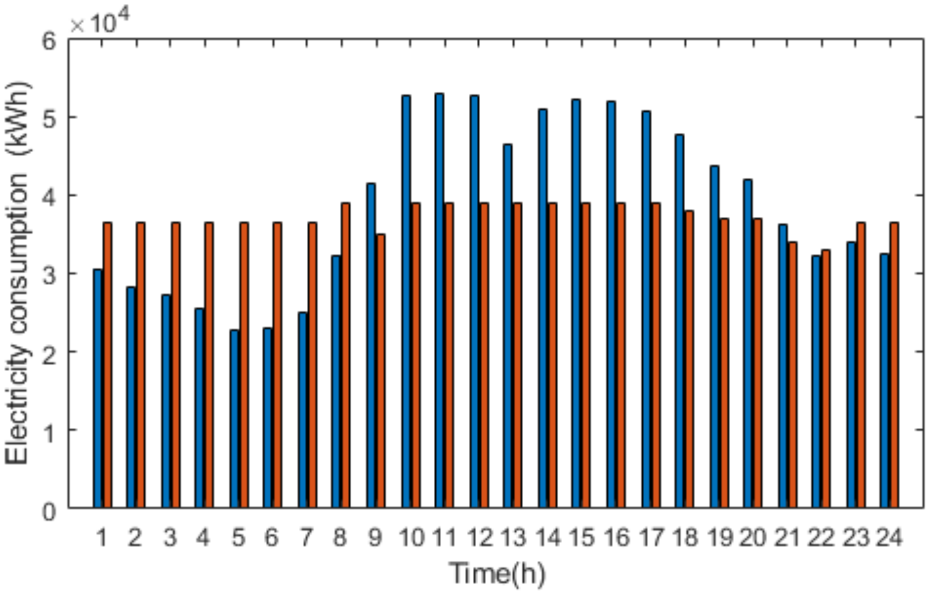


Fig 5. 11 Adjust the SB system charge-discharge capacity

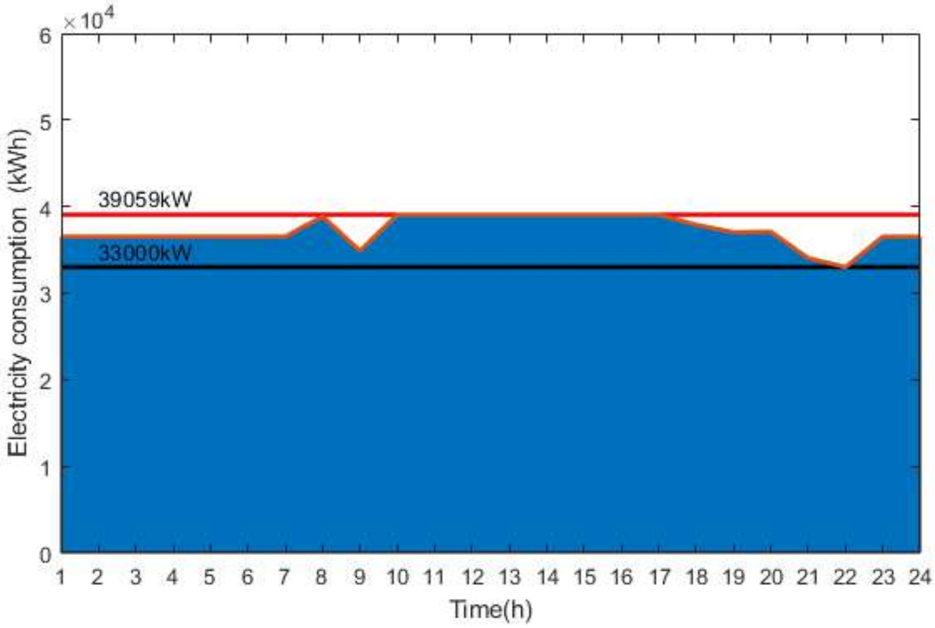


Fig 5. 12 Energy consumption after adding VPPs in Higashida area

After considering the effect of PV system and the optimized capacity of SB system, the final installation of VPP is shown in Fig 5. 12. Compared with the original state of Fig 5. 7, the maximum load is 39,059KW, and it can be concluded that the VPP capacity is equivalent to a 13,771 kW power plant.

As shown in Fig 5. 9 only consider the demand side can get highest profit, without considering the peak cut effect and profit on the power plant side. This causes the electricity consumption of demand side concentrate in the night and morning, and there is no essential change for the power grid. Considering the effect of peak cut on the power plant side, the capacity of SB on the demand side should be reduced appropriately.

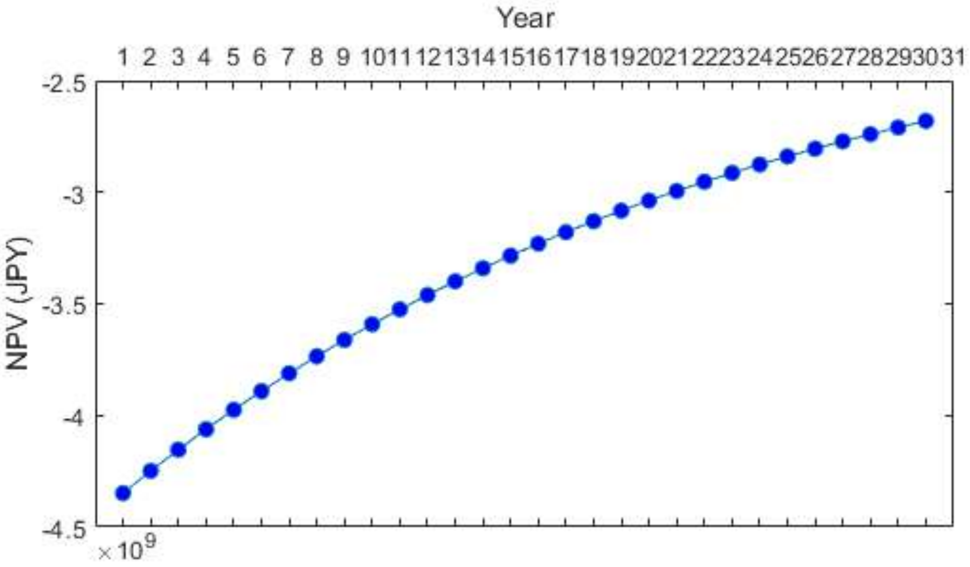


Fig 5. 13 NPV of 39,509kW power plant with electricity price remains

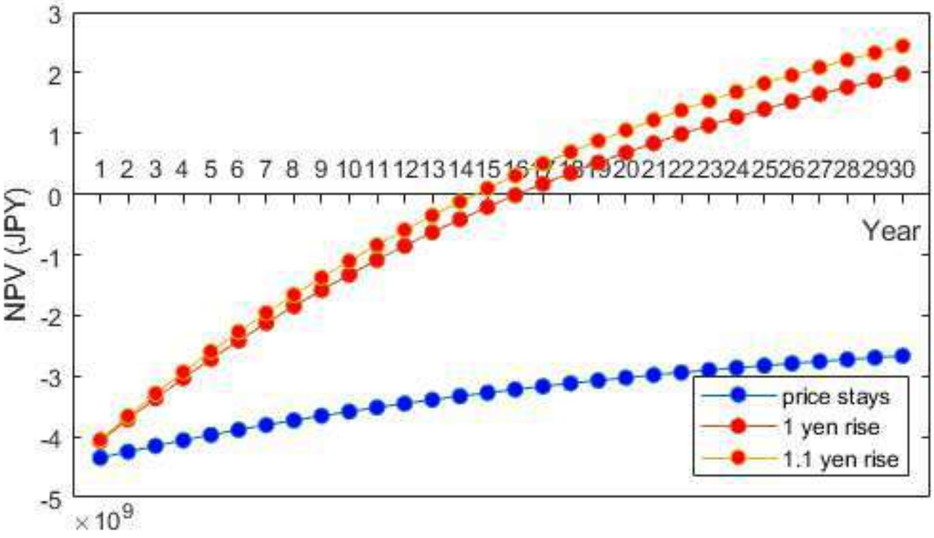


Fig 5. 14 NPV of 39509kW power plant with different electricity price

5.3.3 Comparison

Combining the analysis of the two options, if we consider maintaining the payback period in 15 to 16 years as the same with original Higashida power plant, it is inevitable for the power plant to increase the electricity price to make up for the gains. However, increasing the electricity price will damage the profit of the demand side, and it is necessary for the power plant to cooperate with raising the electricity price and undertake part of the VPP construction investment to balance the economic benefit of the power plant side and the demand side.

Through the introduction of VPPs, electricity consumption in Higashida area should be reduced. Of course, if electricity price remains, the annual electricity price that demand side need to pay will decrease. This is more economical for demand side, but for power plant side, the profit is reduced, and the relative profit is negative compared to invest in conventional LNG-fired power plant.

For power plant side, invest in VPP can reduce the power supply pressure of the power plant, and the utilization rate of equipment will increase. However, because of the introduction of VPPs, power plant will supply less electricity to the demand side, which will influence its electricity sold income in long run. As shown in the Fig 5. 15, invest in a new conventional power plant and maintaining the same electricity price will result in a 48% reduction in the profit of the power plant relative to the current situation. If the demand side imports VPP and the power plant side does not consider investment on it, the relative profit of the power plant side will be reduced by 245%.

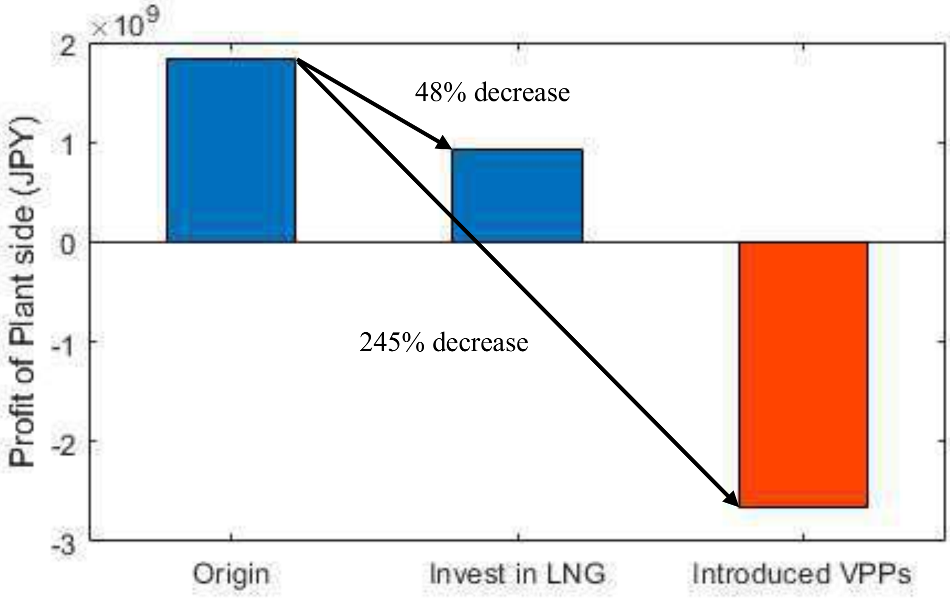


Fig 5. 15 Profit of plant side under different circumstance in 30 years

For demand side, after introducing VPPs, when the electricity price remains, demand side can save 8.8% of electricity fee in 30 years. If the power plant invests in conventional power plants, the demand side can only accept the price increase passively, the result must be unfavorable. If there are VPPs, even the electricity price is increased, first of all, the PV and SB system have intuitive benefits for the demand side. In addition, demand side can balance the increase electricity price and investment through signing EPC with the power plant.

The introduction of the VPP can bring the electricity saving for the demand side and greenhouse gas emission reduction benefits to the society, replacing the expansion construction of conventional power plant to meet the electricity demand. Above all, it is better for Higashida area to invest in VPPs.

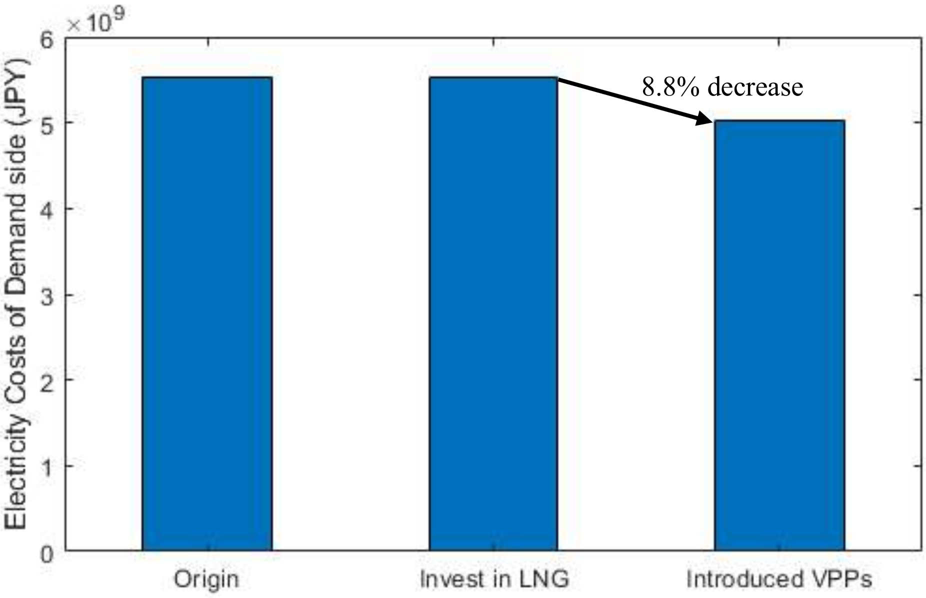


Fig 5. 16 Profit of demand side under different circumstance in 30 years

5.4 Economic analysis of invest in VPPs

On the basis of economic profit balance properly and develop commercial incentive agreement between both demand and plant sides, following part analyzed the performances of built VPP in different scenarios changing the feed-in tariffs for plant side and corresponding electricity fee for demand side.

In the following section, the return on investment of the PV power generation and SB system in buildings will be discussed by using payback period analysis and life cycle cost analysis respectively, thus the VPPs implemented feasibility will be carried out mainly considering the economic benefits brought to both of the plant and demand sides.

Because VPPs has energy-saving effects while satisfying demand sides' electricity needs, so it should receive government subsidies. In order to seek the maximum economic efficiency of VPP, preliminary calculations will take up to 1/3 as a government subsidy. Here we study the changes in the profits of power plants and demand side with the increase in electricity prices when the power plants invest 1/3 and 1/6 of the VPP construction.

5.4.1 Power plant side undertake 1/3 of VPPs construction fee

This section studies the changes in the profit of power plants side and demand side as electricity prices increase when the power plant undertakes 1/3 VPPs' construction investment. Combined with the 1/3 VPP construction subsidies from the government, the investment of demand side is 1/3 VPP construction fee, too.

As show in Fig 5.17, solid line shows the profit of plant side, dotted line shows the profit of demand side. After the introduction of VPPs, for the power plant side, if the electricity cost increases by 1.28 yen/kWh or higher, it is beneficial to the power plant side, and the implementation of VPP means economic benefits. On the other hand, for demand side, when the increase in electricity price is less than 1.68 yen/kWh, the profit is positive, indicating that it is beneficial to demand side. In other words, if the increase in electricity rates is between 1.28JPY-1.68 JPY, through the introduction of VPPs, both power plant side and demand side can obtain economic benefits and can implement VPP. From Fig 5. 17 we can know that when the electricity price increase 1.48 JPY, both the demand side and plant side can get best profit.

Table 5. 4 Investment ratio of three party

Government	Power plant side	Demand side
1/3	1/3	1/3

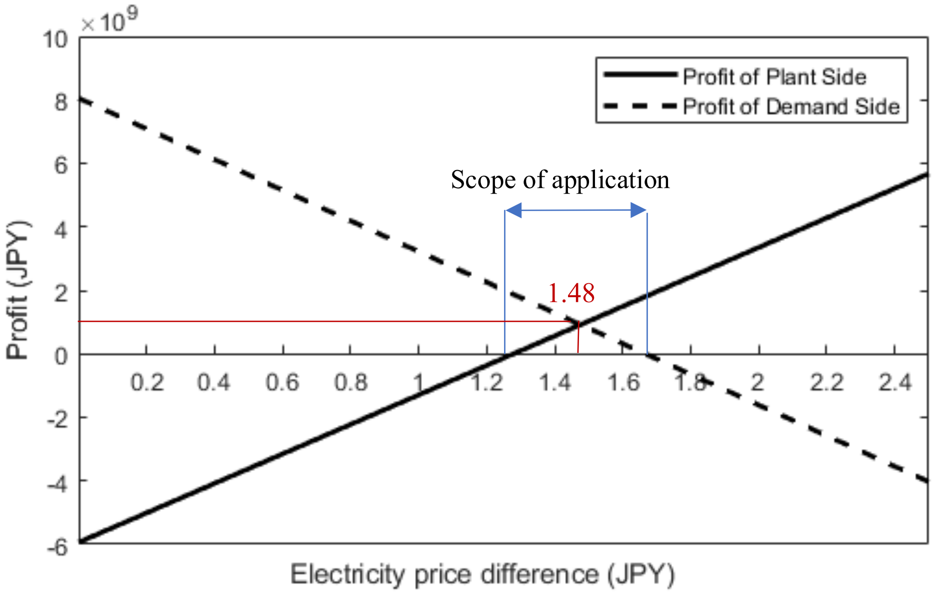


Fig 5. 17 Economic analysis of VPPs undertake 1/3 investment by plant side

✧ Plant side analysis

Fig 5. 18 shows the NPV of plant side when electricity price increase 1.48JPY/kW, from the picture, the payback period of power plant invest in VPP is within 24 years. Fig 5. 19 shows the profit of plant side when electricity price increase 1.48 JPY/kWh for 30 years. In 30 years, compared with the expansion of 52,830 kW conventional LNG-fired power plant, the profit after the introduction of VPPs increase about 1.6% that of conventional LNG-fired power plant. The total increase profit of power plant side t in 30 years is 14,762,081 JPY.

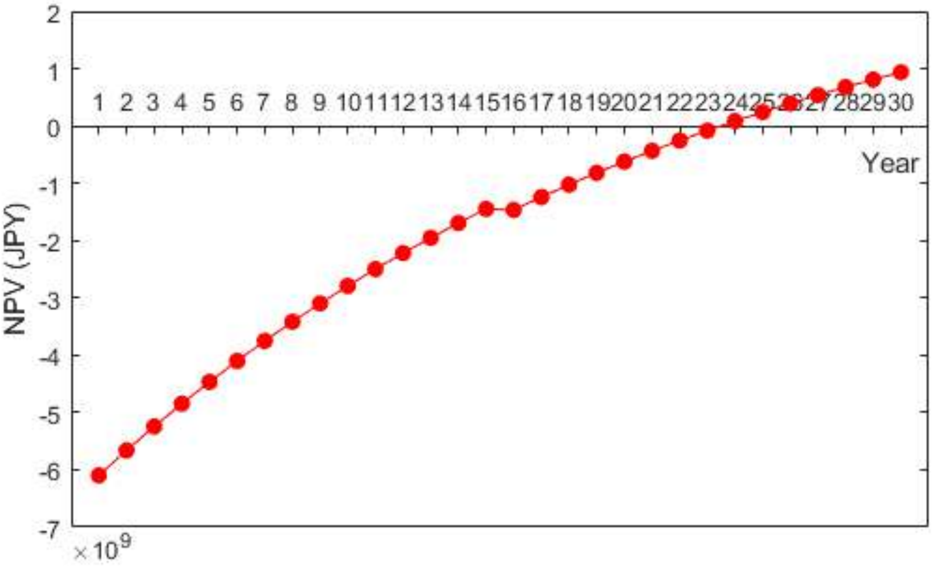


Fig 5. 18 NPV of plant side when electricity price increase 1.48 JPY/kWh in 30 years

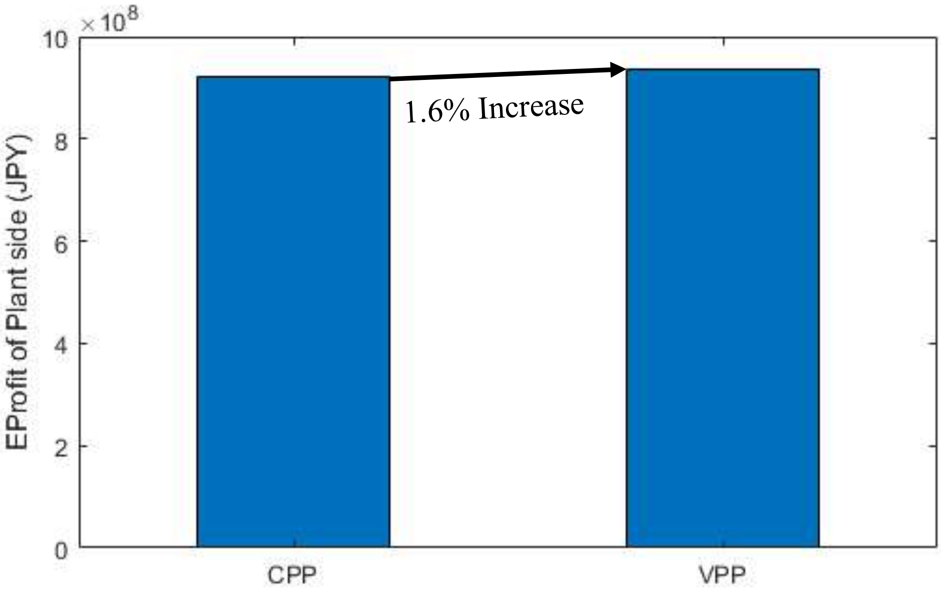


Fig 5. 19 Profit of plant side when electricity price increase 1.48 JPY/kWh in 30 years

- ✧ Demand side analysis

Fig 5. 20 shows the NPV of demand side in invest in VPP, the payback period is within 20 years. Fig 5. 21 shows the profit of demand side when electricity price increase 1.48JPY/kWh for 30 years. In 30 years, compared with the expansion of 52830 kW conventional LNG-fired power plant, after the introduction of VPPs, the electricity fee that users need to pay decreased 3.1% in 30 years. The total amount of electricity fee decreased 5,277,748,983 JPY.

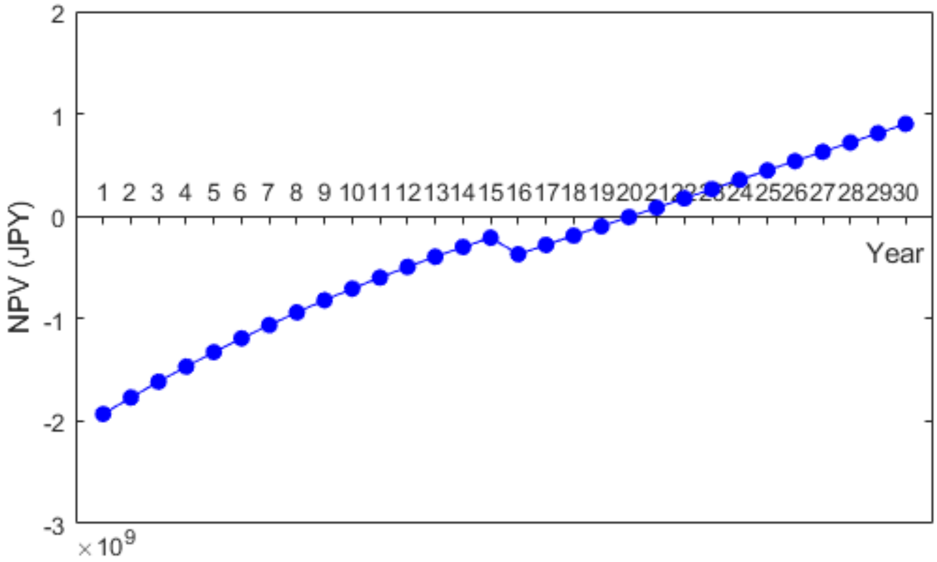


Fig 5. 20 NPV of demand side when electricity price increase 1.48 JPY/kWh in 30 years

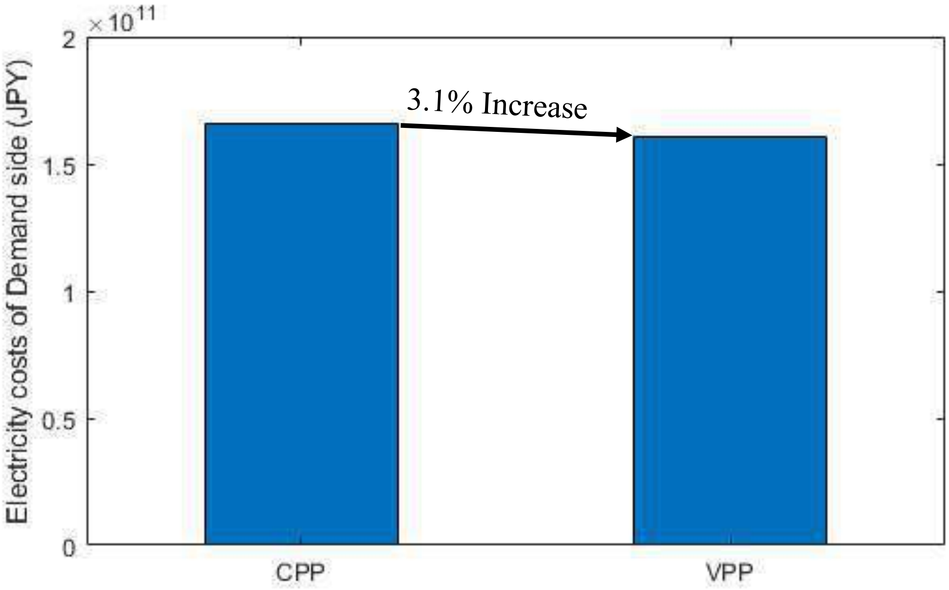


Fig 5. 21 Profit of demand side when electricity price increase 1.48 JPY/kWh in 30 years

5.4.2 Power plant side undertake 1/6 of VPPs construction fee

Table 5. 5 Investment ratio of three party

Government	Power plant side	Demand side
1/3	1/6	1/2

This section studies the changes in the profit of power plants side and demand side as electricity prices increase when the power plant undertakes 1/6VPP construction investment. Combined with the 1/3 VPP construction subsidies from the government, the investment of demand side is 1/2 VPP construction fee.

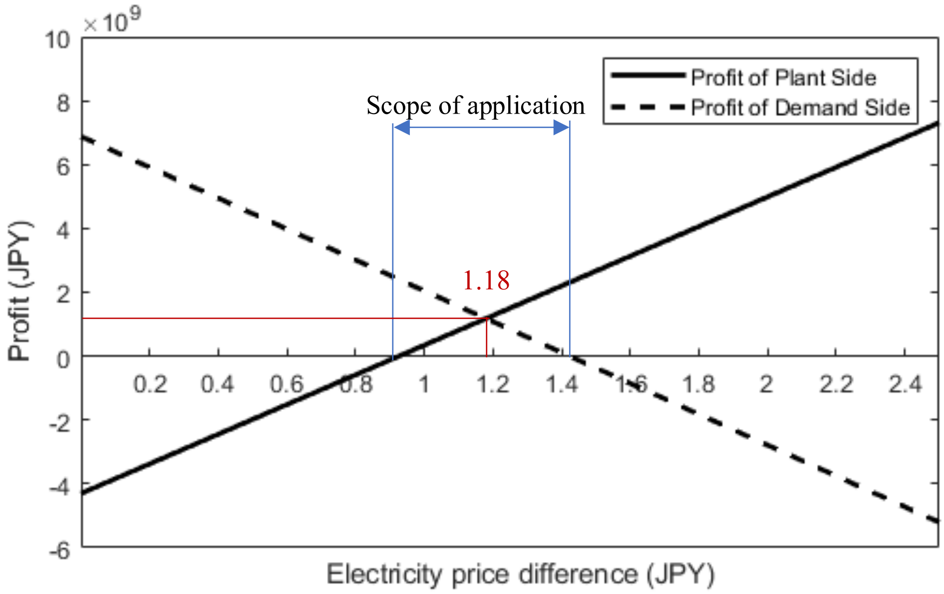


Fig 5. 22 Economic analysis of VPPs undertake 1/6 investment by plant side

As show in Fig 5. 22, solid line shows the profit of plant side, dotted line shows the profit of demand side. After the introduction of VPPs, for the power plant side, if the electricity cost increases by 0.92 yen/kWh or higher, it is beneficial to the power plant side, and the implementation of VPP means economic benefits. On the other hand, for demand side, when the increase in electricity price is less than 1.44 yen/kWh, the profit is positive, indicating that it is beneficial to demand side. In other words, if the increase in electricity rates is between 0.92 JPY-1.44 JPY, through the introduction of VPPs, both power plant side and demand side can obtain economic benefits and can implement VPP. From Fig 5-18 we can know that when the electricity price increase 1.18 JPY, both the demand side and plant side can get best profit.

Then we will analyze the economic for both demand side and power plant side when the plant side undertake the 1/3 construction fee and electricity price increase 1.18 JPY.

✧ Plant side analysis

Fig 5. 23 shows the NPV of plant side when electricity price increase 1.18JPY/kW, from the picture, the payback period of power plant invest in VPP is within 21 years. Fig 5-20 shows the profit of plant side when electricity price increase 1.18JPY/kWh for 30 years. In 30 years, compared with the expansion of conventional LNG-fired power plant, the profit after the introduction of VPPs increase about 27.8% that of conventional LNG-fired power plant. The total increase profit of power plant side t in 30 years is 256,616,005 JPY.

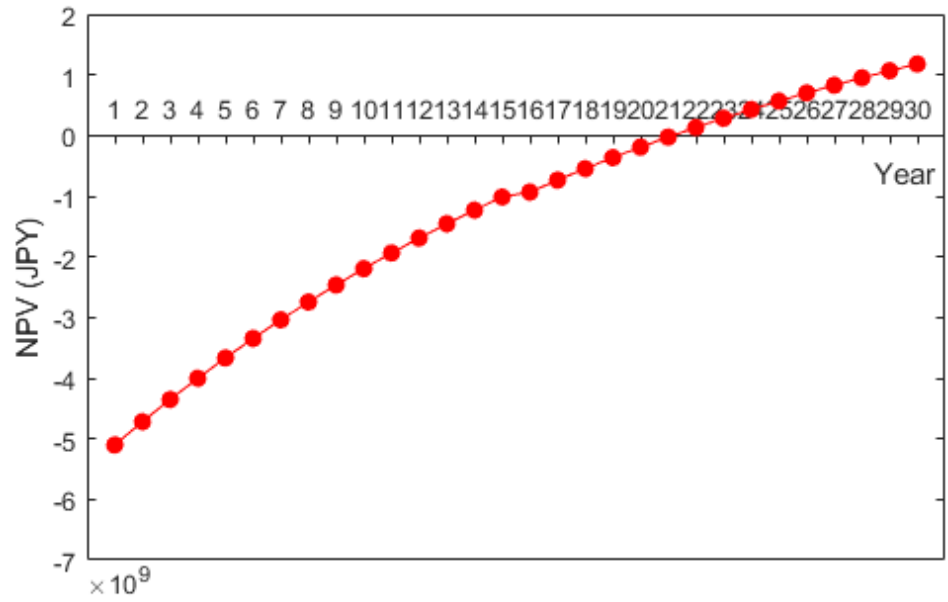


Fig 5. 23 NPV of plant side when electricity price increase 1.18JPY/kW

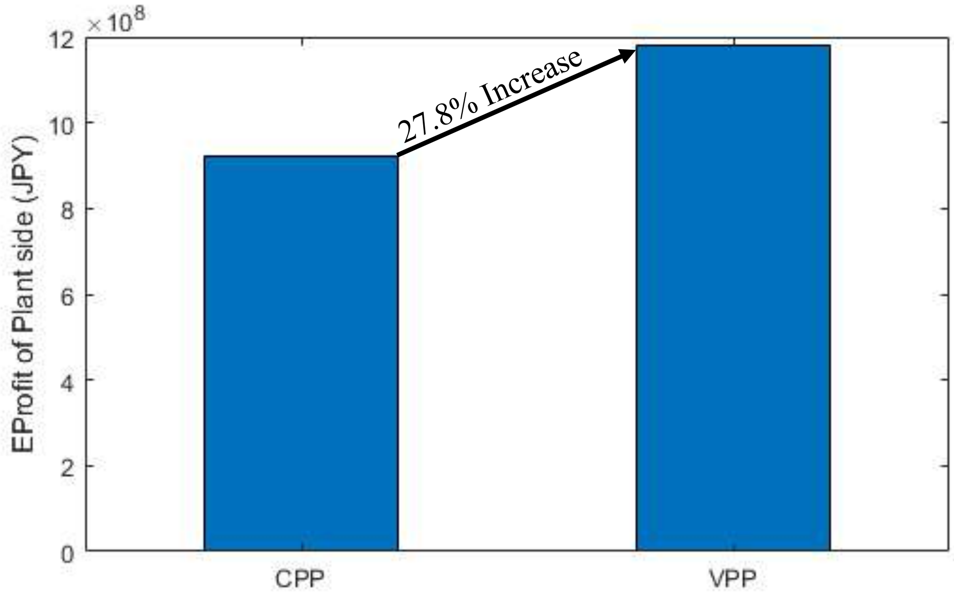


Fig 5. 24 Profit of plant side when electricity price increase 1.18 JPY/kWh

✧ Demand side analysis

Fig 5. 25 shows the NPV of demand side in invest in VPP, the payback period is within 21 years. Fig 5-22 shows the profit of demand side when electricity price increase 1.18JPY/kWh for 30 years. In 30 years, compared with the expansion of 52830 kW conventional LNG-fired power plant, after the introduction of VPPs, the electricity fee that users need to pay decreased 4.8% in 30 years. The total amount of electricity fee decreased 7,629,904,422 JPY.

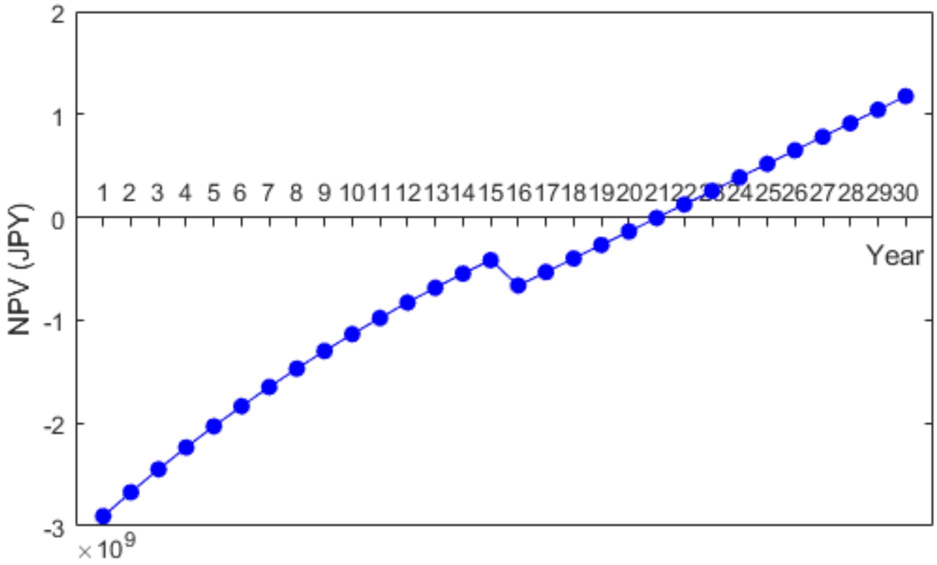


Fig 5. 25 NPV of demand side when electricity price increase 1.18 JPY/kWh

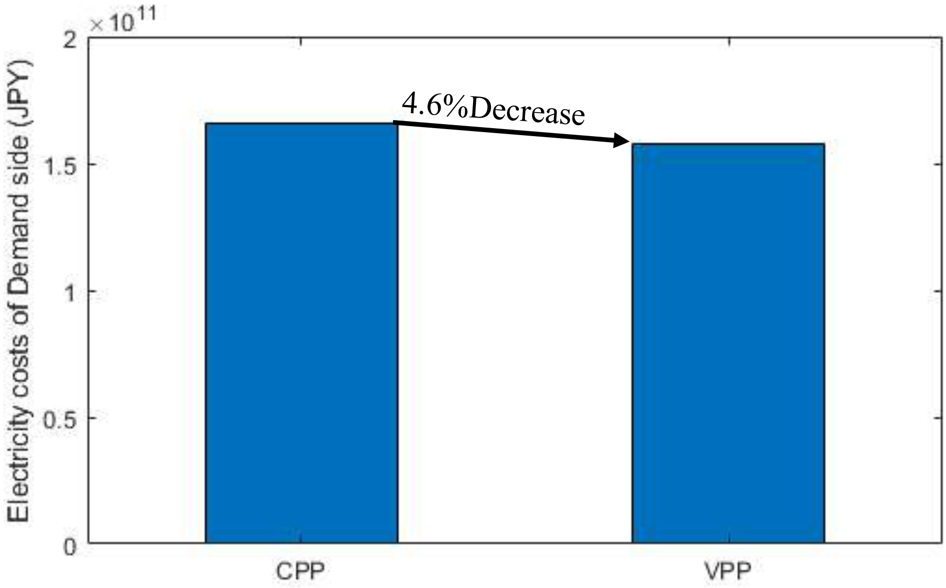


Fig 5. 26 Profit of demand side when electricity price increase 1.18 JPY/kWh

5.5 Sensitive analysis of plant side’s investment

Based on the economic profit balance properly between both demand and plant sides, the following part analyzed VPP’s performances by changing the investment from the plant side and corresponding electricity price for the demand side under different government subsidies. Therefore, economic benefits to both the plant side and the demand side will be mainly considered to discuss the feasibility of VPP.

Three factors are mainly analyzed to explore the feasibility of VPPs, including changes in government subsidies, the difference in power plant investment, and the variety in electricity prices. Results were shown in fig.11. The red plane represents the power plant side, and the blue plane represents the demand side. The Z-axis is the net present value of the 30th year. Analysis shows:

- Government subsidies play a vital role in the construction of VPPs. The common interests of the plant and demand sides increase with the increase of government subsidies. When the interests of the supply and demand sides reach a balance, the more government subsidies, the more electricity prices need to be raised.
- The profit of the power plant side will not change with changes in government subsidies. When the power plant side does not invest, and the demand side introduces VPPs, the electricity sold price increase at least 0.45JPY to maintain benefit.
- The profit of demand side will increase with the increase of government subsidies.

According to the previous section that the power plant side's investment in VPP should be recovered through the profit brought by the increase in electricity prices. This part considers the relationship between the plant side's investment ratio and the corresponding change in electricity price when the power plant participates in the construction of the VPP, and the interests of the power plant and the demand side reach a balance on the basis of government investment.

Fig 5.27 shows electricity price has been a steady rise with the increase of government subsidy; the reason was revealed in Fig 5.28. When the demand side receives more government subsidies, the plant and demand side can obtain more excellent benefits. When the plant side participates in the construction of VPP, the more the power plant investment, the more the electricity price will rise. Different plant side's investment has the same trend of increasing electricity prices. When the government subsidy remains unchanged, both parties' profits decreased with the increase of the plant side's investment.

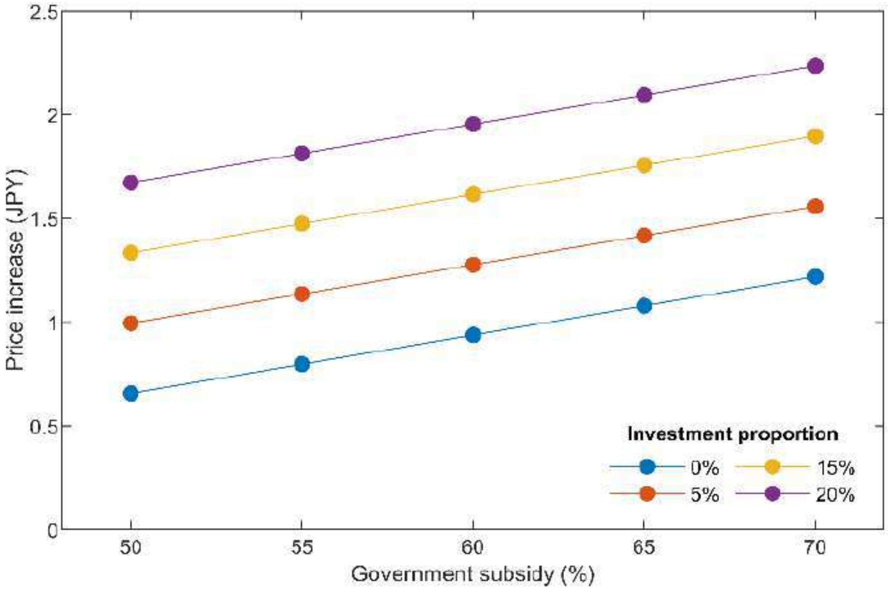


Fig 5. 27 Electricity price changes on demand side under different investment from plant side and government subsidy

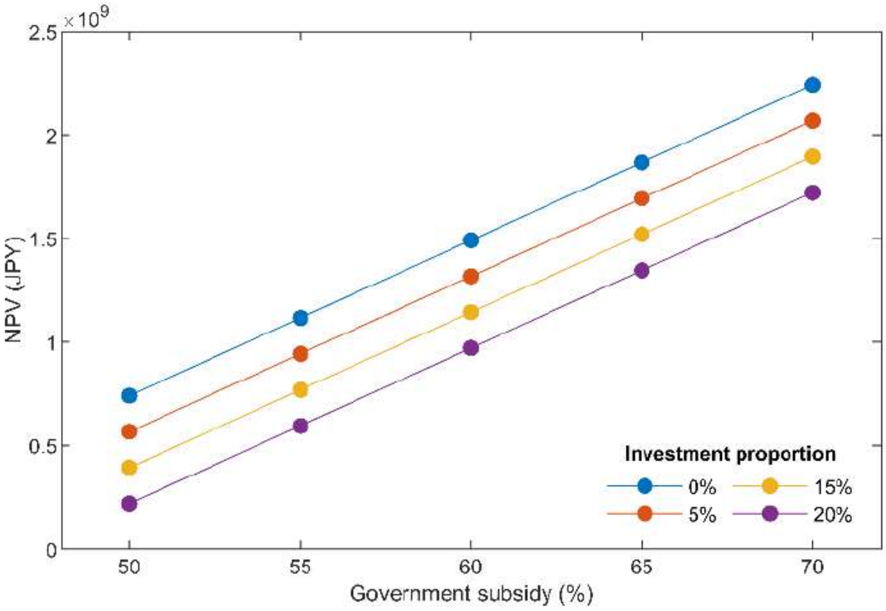


Fig 5. 28 NPV of the plant and demand side under different government subsidy

Next, the impact of government subsidies, power plant side's investment and the corresponding increase in electricity prices on the payback period of both the plant and demand side were considered.

The payback period of the demand side was shown in Fig 5.29. On the demand side, the payback period is shortened with the increase in government subsidies. What is curious about this result is that when the government subsidy is less than 60%, the payback period will become longer as the proportion of the plant side's investment increases. On the contrary, when the government subsidy is greater than 60%, the payback period decreases with the rise of power plant's investment. For the plant side, with the rise of investment proportion the payback period become longer.

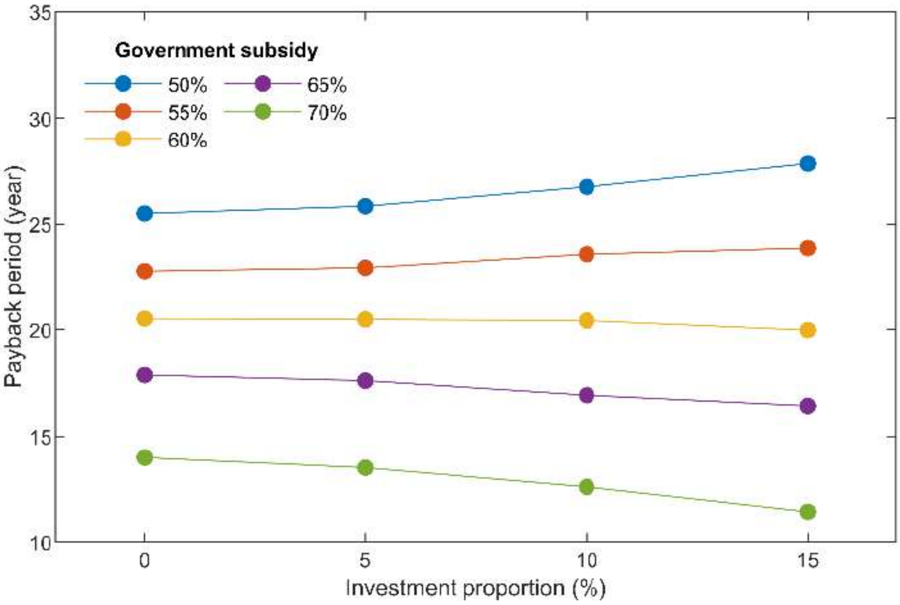


Fig 5. 29 Payback period of demand side under different government subsidy

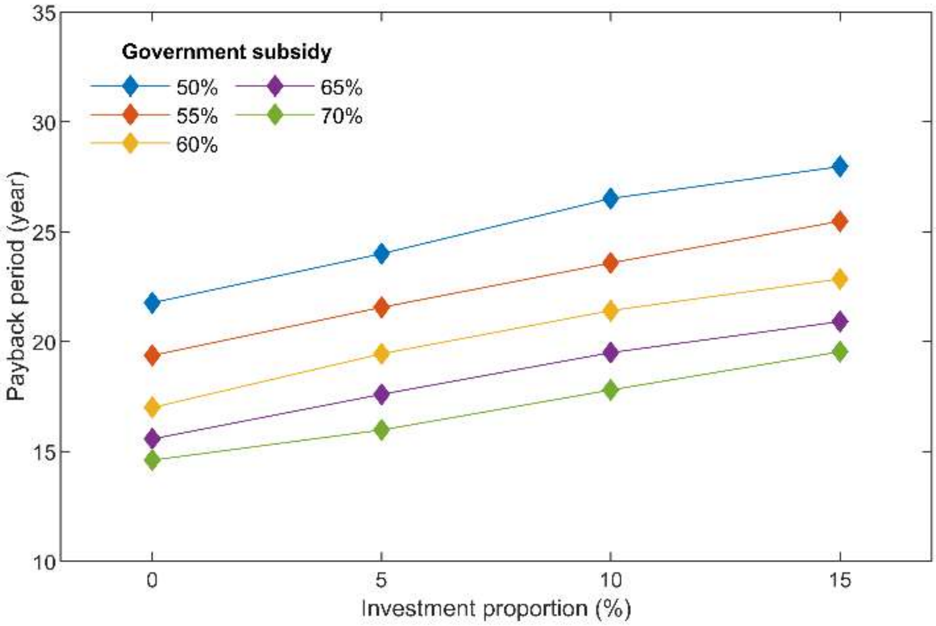


Fig 5. 30 Payback period of plant side under different government subsidy

Based on the present policy of the government provides 1/2 subsidy for VPP equipment, this chapter selects four cooperation plans between the plant and demand side to analyze the impact of VPP's construction on CPP's profit. Scenario settings are shown in Table 5. Finally, compare economic performance of four cases with the expansion of 22784kW CPP.

Table 5. 6 Investment proportion from plant side and demand side's electricity price increase for each scenario

	Scenario1	Scenario2	Scenario 3	Scenario 4
Electricity price increase (JPY/kWh)	0.656	0.9948	1.3337	1.6725
Plant side investment proportion (%)	0	5	10	15
Government subsidy (%)	50	50	50	50

Figure 5.31 shows the 30 years net present value and payback period of VPP on the demand side in four cases. It can be seen that the four scenarios can be recovered within 30 years. When the government subsidies are the same, with the increase of plant side's investment, the initial investment of the demand side is reduced, and the corresponding profit is also reduced. Fig 5.32 shows the annual electricity purchase of the demand side under different scenarios. After installing VPP, the demand side can reduce electricity bills every year.

Fig 5.33 shows the 30 years net present value and payback period of the plant side's investment in four cases. Obviously, the payback period on the plant side has been prolonged as the investment increases, and profits have also decreased.

Another plan to meet the regional electricity demand is the plant side invest a conventional power plant (CPP) with capacity of 22784kW. Under these circumstances, the initial investment of CPP is 2,597milion, and if electricity price remains, the plant side will not recover its cost. The initial investment of building CPP has increased greatly compared with VPP.

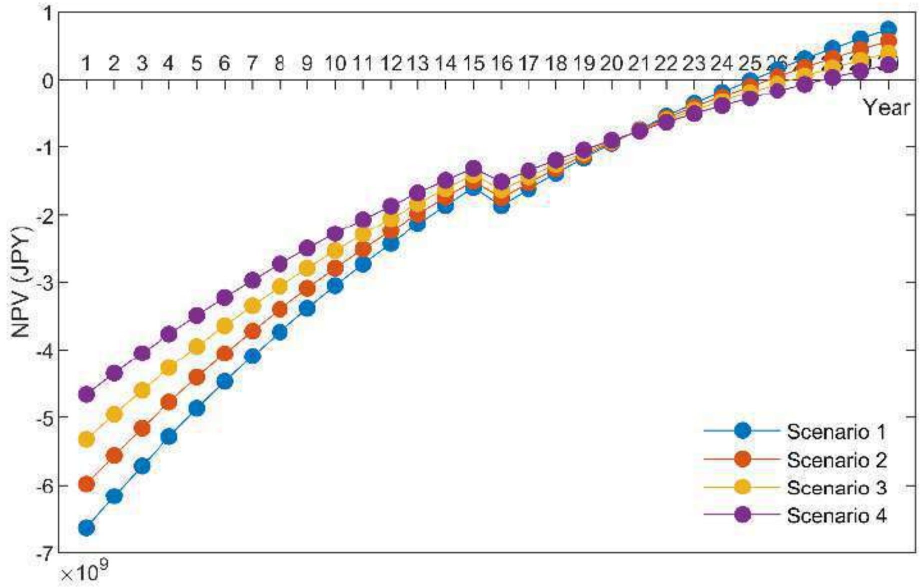


Fig 5. 31 Demand side's NPV and payback period of each scenario

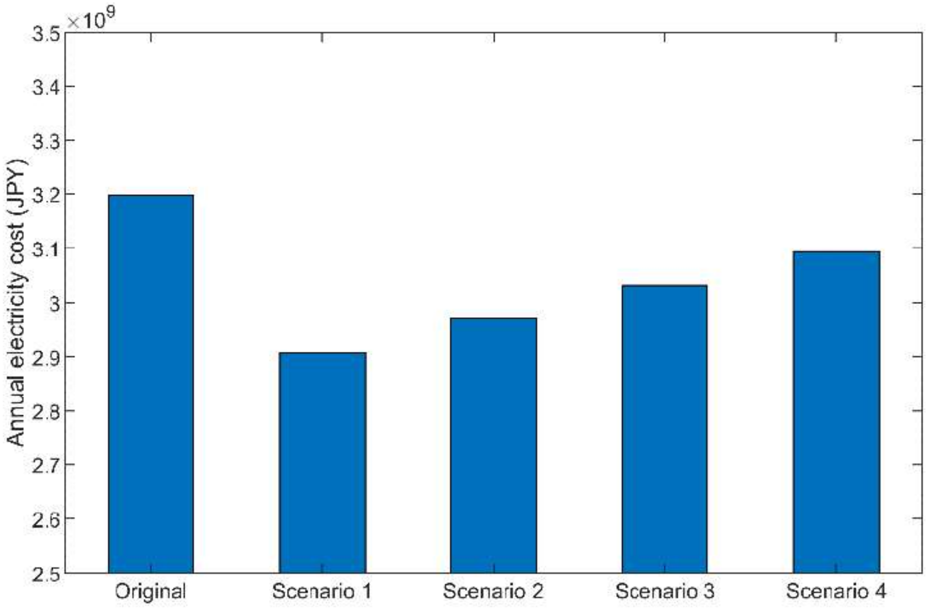


Fig 5. 32 Annual electricity cost of the demand side

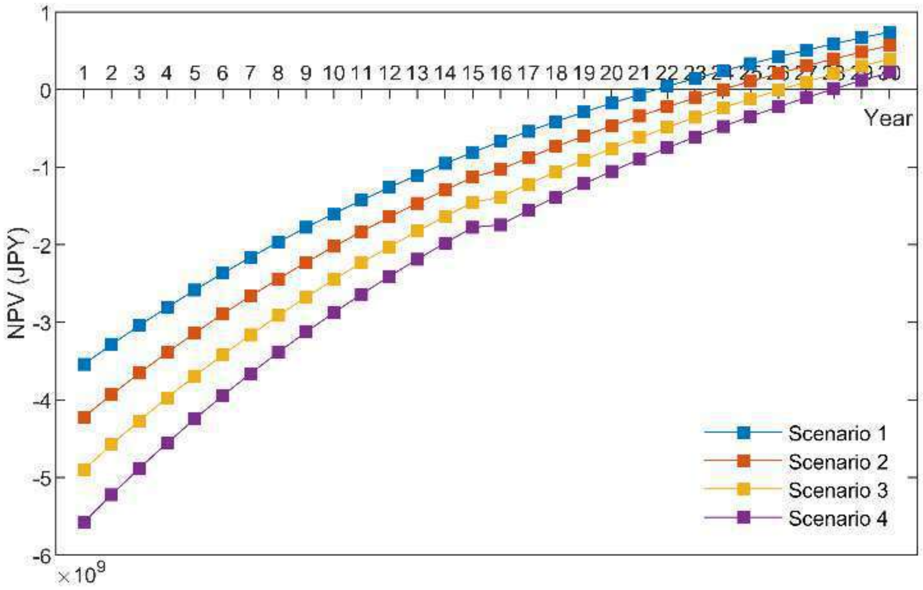


Fig 5. 33 Plant side's NPV and payback period of each scenario

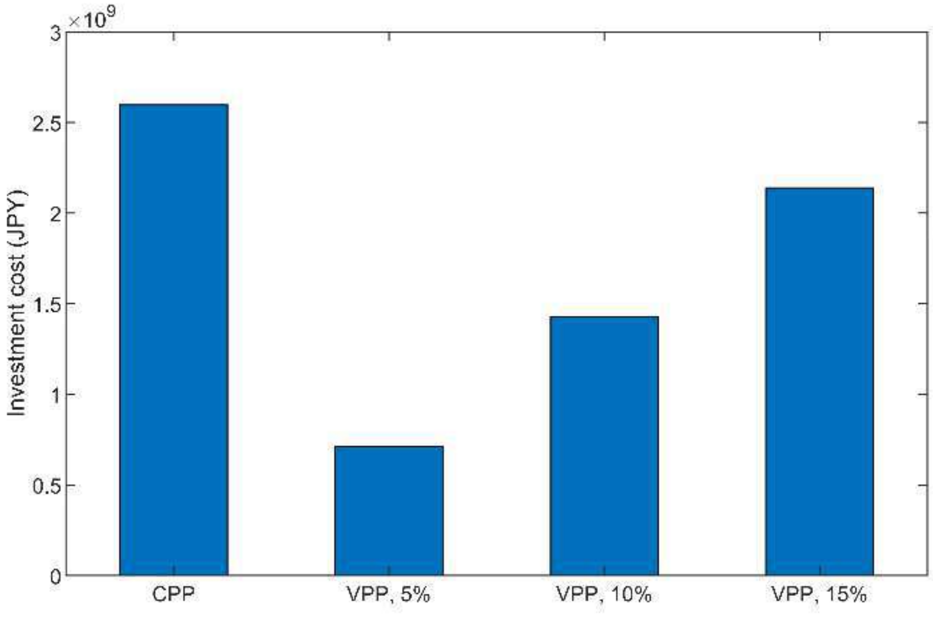


Fig 5. 34 Initial cost of plant side for each scenario

5.6 Summary

For power plant side, the plan of power plant side invests 1/3 of VPP construction has longer payback period than invest 1/6 of VPP construction. And the profit of 1/6 plan is higher.

For demand side, the plan of power plant side invest 1/3 of VPP construction has shorter payback period than 1/6 plan, because when power plant side invest 1/3 of VPP construction, the initial investment of demand side is lower.

Compared with the two-investment plan of the power plant, when the power plant invests 1/6, the adjustable range of the electricity price is larger, and the profit of plant side is higher, the electricity fee that customers saved higher too. When profit of both parties is maximized, the price difference at this time is 1.18 JPY. And the profit of power plant side is 256,616,005 JPY. Electricity price that demand side saved is 7,629,904,422 JPY.

This research proposed the concept of the virtual power plants (VPPs) to increase the local power self-support in the Higashida area. The economic performance and utilization potential of PV system and SB system were analyzed based on NPV indictor and lifecycle cost analysis. In addition, feasibility analysis of power supply-demand management, considering both supply and demand side was done.

Firstly, we master the basic performance of photovoltaic and storage battery and establish the best control and placement method.

Then we select the typical building as origin unit to investigate the energy saving potential of PV system and SB system, as well as economic characteristics. Result shows that optimal combination of PV system and SB system is a favorable option due to its shorter payback period compared with conventional power plant. And the decline in the price of renewable energy power generation equipment may make the power plant more economical and environmentally friendly in the future.

Secondly, introduced the selected origin unit to Higashida area. The analysis results found that the combination of PV and SB systems has a good potential for peak shaving and valley filling. AS well as verify the effectiveness of VPP concept based on cooperation between power plant side and demand side.

The third part of this research mainly considers the economic factors to implement the feasibility of VPPs. After the economic analysis of the demand side and the power plant side, the plan to introduce VPP in the Higashida area is feasible. However, VPPs will reduce the average electricity price purchased by demand side, which may influence the plant's profits in long run. After introducing the concept of EPC, power plants can also participate in the VPP investment and get profit.

Then compare the two options of investing in expand conventional LNG-fired power plant to 52830 kW and invest in VPP plus a small conventional power plant. Investigate the changes in the profits of power plant side and demand side with the increase in electricity prices when the power plants invest 1/3 and 1/6 of the VPP construction.

Analysis shows when the power plant side undertakes 1/6 of the construction investment and the electricity price increases by 1.18 JPY, both the plant side and the demand side can get the most excellent returns. For power plant side, compared with the expansion of conventional LNG-fired power plant, the profit after the introduction of VPPs increase about 28.7% that of conventional LNG-fired power plant. The total increase profit of power plant side t in 30 years is 256,616,005 JPY. For demand side, compared with the expansion of 52830 kW conventional

LNG-fired power plant, after the introduction of VPPs, the electricity fee that users need to pay decreased 4.8% in 30 years. The total amount of electricity fee decreased 7,629,904,422 JPY.

The VPPs can not only bring better benefits than new conventional power plant but will also reduce the greenhouse gas emission. What's more, VPPs also improve the self-sufficiency rate and dependence of electricity in the Higashida area.

This paper proposes an optimized VPP model comprised of HEA, PV and ESS, with the goal of energy self-sufficiency. Then the effectiveness of the VPP in reducing electricity demand from the power grid is verified based on real-world case study. The techno-economic feasibility and the adaptability performance of VPP in different buildings are evaluated. And the environmental benefits of VPP is confirmed. Based on this study, the following conclusions can be derived:

Government subsidies play a vital role in the construction of VPP. The balanced interests of the plant and demand sides increase with the increase of government subsidies. When the interests of the supply and demand sides reach a balance, the more government subsidies, the more electricity prices need to be raised.

The profit of the power plant side will not change with changes in government subsidies. When the power plant side does not invest, and the demand side introduces VPP, the electricity sold price increase at least 0.45JPY to maintain benefit.

The profit of demand side will increase with the increase of government subsidies.

VPP can not only bring better benefits than new conventional power plant, but also improve the self-sufficiency rate and dependence of electricity in the Higashida District. In addition, the construction of VPP will reduce the greenhouse gas emission.

Reference

[1] METI. Agency for Natural Resorces and Energy. 2022.

Chapter 6

TECHNO-ECONOMIC ANALYSIS OF THE TRANSITION TOWARDS THE ENERGY SELF-SUFFICIENCY COMMUNITY BASED ON VIRTUAL POWER PLANT

CHAPTER 6: TECHNO-ECONOMIC ANALYSIS OF THE TRANSITION TOWARDS THE ENERGY SELF-SUFFICIENCY COMMUNITY BASED ON VIRTUAL POWER PLANT

6.1 Content

Distributed energy resources are important measures in increasing energy self-sufficiency and overcome global carbon reduction problem. However, the individual planned renewable energy generation poses a significant threat to the power grid. Therefore, virtual power plant (VPP) is attracting more and more attention as a means of aggregating distributed energy in urban areas. In this study, a VPP model consisted of updating high efficiency appliances, photovoltaic and energy storage systems was proposed. A comprehensive analysis for assessing the technical, economic and environmental benefits deriving from the VPP was presented, indicated the feasibility of a smart community to achieve power self-sufficiency with the support of the VPP.

A smart community in Japan was selected as the research object, with a peak power demand of 57,350 kW. Analysis of the VPP's load leveling performance, return on investment and CO2 emission reduction are performed. In addition, external factors such as electricity price changes and FiT policies are considered to assess the impact on the economics of the VPP. The results show that the introduction of the VPP system in the community can effectively stabilize the grid load with a peak shaving rate reaching up to 42.55% and improve the energy self-sufficiency rate of the region reached to 100%, while also providing superior economic and environmental benefits (16.26% CO2 emission reduction) on the demand side. Furthermore, the economic performance of VPP shows a good prospect with the fall of equipment price and the future trend of carbon tax growth. This paper provides important insights into the development of VPP at other countries, especially for low energy self-sufficiency regions.

6.1.1 Background

Nowadays, the development and construction of cities still rely on energy. Consumption of fossil fuels has an increasing trend because of high growth rate of energy demand, which increases the global greenhouse gas (GHG) emissions. Since the Fukushima Crisis in 2011, Japan increased its use of fossil fuels, resulting in a rapid increase in GHG emissions in the energy sector, and in 2013 it emitted a record 1.4 billion tons of GHG. Our over-reliance on traditional energy sources and strategies has caused environmental degradation, climate change, and various geopolitical issues.

Global warming, as an important environmental issue, diverts governments attention towards energy systems with low carbon emissions. Japan has made a commitment to reduce its GHG emissions at least 46% by 2030 and achieving net zero emissions by 2050, which is one of the world's most laudable climate goals given the unique challenges the country faces [1]. In addition, the building sector account for more than 50% of the electricity usage in different countries, leading to a significant GHG emissions [2, 3]. Consequently, all countries worldwide are in a progressive of transforming their energy systems for building sector to accomplish the Paris Agreement goals.

6.1.2 Motivation

Development and construction can be achieved by optimizing energy demand and changing energy supply. Japanese government has been promoting the concept of energy conservation for a long time. [4] indicates that electricity consumption in the residential sector could be reduced by introducing energy savings technologies in Japan. Energy-efficient technologies help reduce total electricity use and maintain the reduction level over time by replacing inefficient technologies with high-efficiency devices [5]. Meanwhile, the penetration of renewable energy resources such as solar and wind also allows Japan to reduce dependence on energy imports and realize the decarbonization goal. According to [6], Japan will generate 50% - 60% of its electricity from renewable sources by 2050. In particular, solar and wind energy will play an important role in the future in countries with low energy self-sufficiency rate. However, as renewable energy increases, and its intermittent output puts management pressure on the public grid and system.

Under this circumstance, the vulnerability of the energy system has become more obvious. Therefore, energy storage is essential to balance the renewable power system. As a solution to resolve those problems mentioned above, a new concept called virtual power plant (VPP) has been proposed.

6.1.3 Literature review

A Virtual Power Plant (VPP) is a practical concept that aggregates various Renewable Energy Sources (RESs) to enhance energy management efficiency and promote energy trading [7]. The VPP is receiving increasing attention as a means of integrating distributed energy systems (DESs) to provide stable electricity. Compared with conventional power plants, the VPP allows for higher energy efficiency and better flexibility. Essentially, VPPs are clusters of distributed generation resources, energy storage systems, and controllable loads connected to a centralized entity that superintends the energy flow within the aggregation [8]. VPP can be divided into commercial VPP (CVPP) and technical VPP (TVPP) [9]. The main objective of CVPP is financial efficiency. However, TVPP always relates complex computations and analysis, as well as technological applications.

The financial efficiency of CVPP participates in energy market has been widely discussed in many studies. [10] discussed strategies for the provision of VPP for participation in energy and reserve power markets. [11, 12] proposed the modeling of a cooperation system among neighboring commercial VPPs to maximize the opportunities for power commercialization. [13] designed a novel concept of power-to-gas based VPP, as well as considering the variability of VPP profits when risk management participates in competitive markets. [14] provided a stochastic optimization evaluates the optimal bidding strategy of a VPP considering combined heat and power and intermittent renewables. [15] considered a VPP composed by an intermittent source, a storage facility, and a dispatchable power plant, which sells and purchases electricity in both the day-ahead and the balancing markets seeking to maximize its profit. [16] maximized the profit of the VPP and minimized the cost of self-consumption of the VPP by the method of iterative process using CPLEX solver. [17] took the Lankao Rural Energy Revolution Pilot program as an example proposed a benefit allocation strategy based on Nash negotiations, considering the following factors of risks, benefits, and carbon emission reduction into account. [18] addresses the participation of VPPs in different electricity markets. Studies mentioned above have well demonstrated the economic feasibility of CVPPs in the aspect of for power commercialization. CVPP can be seen as an aggregator between DERs and the energy market, as it can trade energy on behalf of smaller DERs that are unable to participate in the electricity market. As CVPP only performs commercial aggregation, thus the network limitations and the impact to power load are always not taken into account in its operation.

In the aspect of TVPP, there is a large amount of literature focused on the energy management and dispatching of various distributed energy sources (DESs). In view of energy management, [19] developed an optimization meta-heuristic algorithm to determine optimal energy management of a VPP with RESs, energy storage and load control in a case study. [20] presents energy management of industrial VPPs using both demand response loads and available electric vehicles in car parks to improve grid reliability under peak load conditions. [21] developed a blockchain-based energy management platform for a VPP. As for optimal scheduling, [22] proposed a multiple regions VPP optimal scheduling method for multi energy complementarity and low-carbon, which solves the threat of high-permeability renewable energy power generation and grid connection faced by the VPP. [23] modeled a stochastic scheduling problem for a VPP, while considering network security constraints and uncertainties in power and thermal loads, wind speed, solar radiation, and market prices to satisfy thermal and electrical loads. [24] proposed a hierarchical model for simultaneous modeling of an microgrids scheduling and VPPs energy management problems. Technologies for integrating different DESs also a hot spot all over the world. [25] proposed a VPP model containing carbon capture devices, and explored the cooperative operation mode of a carbon capture system and power-to-gas, and develops a comprehensive demand response mechanism for the VPP. [26] present a VPP combining large and small-scale distributed renewable energy generation technologies, and its practical application in the operation of irrigation systems is introduced. [27] aggregated various controllable loads in a commercial office building, including air conditioning, lighting, and elevators, into heterogeneous and reliable components of a VPP, described the substantial flexibility that exists in commercial office buildings. The studies reviewed generally present models that include control variables of different types of DESs and have well discussed the optimization of power flow, network architectures within VPPs and operational specifications solutions. However, few of these models involve a combination of distributed rooftop PV self-consumption facilities, energy storage devices and the management of building-side efficient appliances (This combination of VPP model always has great application potential in urban areas).

In the current academic field of VPP, the practice of integrating VPP with communities to achieve energy self-sufficiency is still exist limitation. A simulation case study select a coastal site in Hong Kong which comprises 8 high-rise residential buildings and 2 mid-rise office buildings to evaluate the technical and economic feasibility of a zero energy community using a hybrid offshore wind and tidal stream energy generation [28], and the carbon emission reduction potential also be identified. Another simulation case study in Cairo, Egypt has carried out to explore different RESs and uses different building materials to reduce energy consumption and carbon emissions in a community [29]. A recent study proposes the concept of Building-VPP [30], they have discussed building design and support technologies for aggregating buildings into VPP. However, these case studies are based on simulation data and are rarely supported by real-world data. In the real-world cases, different building types (e.g. residential, office, commercial and industrial), different geographical location, different technologies combination will lead to different energy consumption patterns.

6.1.4 Scientific gaps and objectives

Diversification of power loads and uncertainty of renewable energy generation pose challenges to conventional power system operation. According to the studies mentioned above, much uncertainty still exists:

1) Because of the maturity of technology, most of the current studies focus on directly connected to public grid after integrating distributed energy sources. While relatively little attention has been paid to the potential, benefits, and feasibility of coupled small scale PV-ESS and building efficient appliances.
2) Most studies on VPP are based on idealized software simulations and lack of variation in building types. There is limited knowledge on the VPP design with the goal of regional energy self-sufficiency, and the corresponding grid load matching performance of VPP systems deeply integrated into communities, which is affected by demand side's electricity usage characteristics.

To address the above knowledge gaps, the novelty of this research is:

1) A VPP model which consist of renewable energy sources, ESSs and update high efficient appliances was proposed for realization of energy self-sufficiency. The effects of each technology applicated into different type buildings are investigated, and the sensitivity analysis between different technologies of VPP are evaluated.
2) Based on real-world cases, combine the management of co-generation power plant (33,000 kW) in community with VPP. The load characteristics of the community and the corresponding load matching performance after formation the VPP is investigated. Comprehensively compare the technical, economic and environmental performance based on demand side.

The remainder of the chapter is structured as follows: Section 2 introduce the comprehensive methodology includes optimization and analysis approach of VPP. Section 3 briefly describe the research area and data source, as well as data pre-processing. Section 4 present a case study of VPP based on real-world data. Section 5 provides a sensitivity analysis of VPP. Finally, Section 6 summarized the paper.

6.2 System formulation

6.2.1 System description

Although distributed energy is already widely used around the world, there is still concern about how to efficiently aggregate and integrate various resources within a community. Against this background, the VPP in this research is comprised power saving technology, distributed photovoltaic (PV) and energy storage systems (ESSs). Reducing energy demand is the most important and cost-effective strategy. Energy efficiency can be increased by using appliances with lower energy requirements. As price advantages become increasingly prominent and technology continues to develop, cities and regions can turn their attention to alternative energy sources such as renewable energy to meet their own energy needs. Fig.6.1 briefly described the main components of proposed VPP system, as well as energy, cash and information flow. The system boundary is set at the interface with the public grid. The community-owned co-generation power plant and rooftop PV are the main power generators for self-sufficient. Considering the limited capacity of co-generation power plant and the intermittence of the PV generation, the community energy system is also connected with the public grid to guarantee a reliable power supply. All buildings are consumers. In terms of electricity demand reduction, the power saving technologies (e.g., lighting and AC) are responsible for energy saving to directly reduce the power demand. In addition, the surplus and shortage of renewable energy can cause communities to export or import power from the public grid at any time of the year. Consequently, energy storage system is essential to control the instantaneous system load matching at 100%. It is worth noting that the technologies we mentioned above (including energy saving technologies, rooftop PV, and energy storage system) are all distributed rather than centrally deployed. Therefore, the building sector is no longer a mere consumer, but has been converted to a prosumer. The ability to perform energy arbitrage is the biggest motivation for individual users to install distributed technologies. Improving the economic benefits of distributed application technologies on the demand side will facilitate negotiations and profit allocation among upstream stakeholders (government as well as power contractors), meanwhile this is the keystone of the realization of VPP. In proposed system, energy saving technologies, rooftop PV directly reduce electricity bills by reducing electricity demand or by self-supply. The individual EESs are aggregated into a large portfolio to provide community-scale ancillary services (load leveling), thus, ESS can gain revenue based on optimal market management. Therefore, an overview analysis of the introduction of VPP in the Community from the perspectives of “energy production”, “energy storage” and “energy saving” will be proposed. The three aspects mentioned above will also determine the capacity of the VPP.

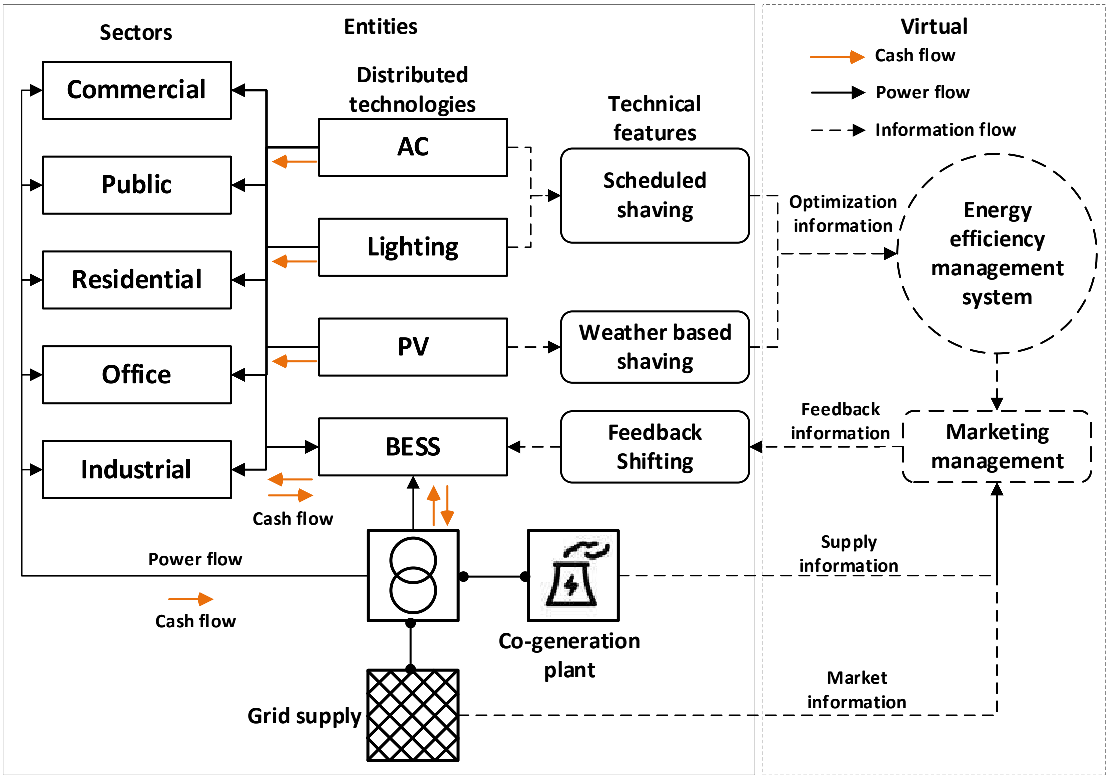


Fig. 6.1 System description of proposed VPP model

6.2.1.1 Power saving technology

According to the decomposition of carbon emission change factors from 2006 to 2019 by the Ministry of the Environment of [31], energy conservation measures contributed more emission reductions until 2011, but electricity saving measures were not significant (and even increased carbon emissions in 2007 and 2010). The demand side can reduce energy consumption by upgrading the building with advanced high efficiency appliances (HEA), such as lighting, air conditioner, etc., which responsible for a large amount of energy consumption in buildings. Load shedding potential through updating HEA in the building sector will be modelled in this part. According to the Agency for Natural Resources and energy, compared with 10 years ago, high efficiency lighting can save 20~86% of electricity and high efficiency air-conditioning can save 17% of electricity [32]. Through investigation, fluorescent lamps were mainly popular in the market 10 years ago, so in this article we plan to replace fluorescent lamps with LED, with an estimated energy saving rate of 21% [33]. Update HEA can provide persistent power demand reduction regardless of time. And the energy saved by HEA can be described as follows:

$$E_{save,ac} = E_{ac} \times r_{ac} \tag{6.1}$$

In the above, E_{ac} represent the electricity demand of AC, r_{ac} is the electricity saving ratio of updating AC, and the $E_{save,ac}$ is the electricity saving potential of updating AC.

$$E_{save,light} = E_{light} \times r_{light} \tag{6.2}$$

Here, E_{light} represent the electricity demand of lighting, r_{light} is the electricity saving ratio of updating AC, and the $E_{save,light}$ is the electricity saving potential of updating lighting. Based on the above conditions, we can calculate the VPP capacity of updating high efficiency appliance by Eq. (6.3):

$$\boldsymbol{Cap_{VPP,HEA} = Cap_{origin,ac} \times r_{ac} + Cap_{origin,light} \times r_{light}} \tag{6.3}$$

6.2.1.2 Power generation technology

There are many distributed generation technologies. Currently, gas turbine units, wind turbines and PV are relatively mature distributed generation technology [34]. Tidal stream energy, offshore wind energy also attract the attention of many researchers [35, 36]. The development of renewable and clean energy sources offers a great prescription to ease the increasingly serious energy crisis and environmental issues. PV systems are an essential substitution energy source with a wide range of applications [37]. The maturity of PV technology has been well studied by many researchers [38, 39]. There have been numerous studies showing that widespread urban rooftop PV deployments can cover a significant portion of electricity consumption [40, 41]. [42] has proposed a integrated system of cities' roof-top PV and EVs provide affordable and dispatchable electricity to urban research without CO2 emission. In the "2050 Carbon Neutral and Green Growth Strategy", the plan for the PV industry is included in the "Home and Office" section. This reflects the close integration between Japanese PV power generation and building. Due to terrain constraints, Japan lacks large-scale centralized PV power generation sites, so distributed building attached PV is the main direction of PV development. Building attached PV, also known as "installed" solar PV buildings. Its main function is to generate electricity, which does not conflict with the function of the building, nor does it destroy or weaken the function of the original building and not restricted by the site. While renewable energy is widely believed to reduce carbon emissions, challenge such as the intermittency of renewables will pose an increasing pressure to the stability of the main grid. Consume the renewable energy locally instead of interacting with main grid can be one of the solutions. As the FiT price of PV power is declining year by year which has dropped to 10 JPY/kWh in 2022, the self-consumed PV gains increasingly popular.

Table 6. 1. Weather data in Kitakyushu [43]

Feature	Solar radiation	Hours
Data	4500 MJ/m^2	1860

The life expectancy of PV system used in this research is 20 years. In this research, we adopt the Panasonic's PV module with unit price of 250,000 JPY/kW (1US dollar=108JPY, this price already includes the PV panel fee, construction fee, invertor fee, and other fee), the module dimension is 1.26 m2 with capacity of 250 W [44]. And the weather data in Kitakyushu was shown in Table 6. 1. The PV power generation can be described as:

$$\boldsymbol{p_{pv}(t) = P_R \times \left(\frac{R}{R_{ref}}\right) \times \left[1 + N_T + \left(T_c - T_{ref}\right)\right]} \tag{6.4}$$

Here, $p_{pv(t)}$ represents PV panel generated electricity at time (t), P_R refers to the rated power of the PV module, and R refers the region solar radiation which is equal to 4500 MJ/m2. The R_{ref} is 1000 W/m2, and the T_{ref} is equivalent to 25 ℃. N_T represents module temperature coefficient equals to $-3.7 \times 10^{-3}\ (1/°\mathrm{C})$. The module temperature can be calculated by Eq. (5), as follows:

$$\boldsymbol{T_C = T_{\mathrm{air}} + \left[\left(\frac{NOCT-20}{800}\right) \times R\right]} \tag{6.5}$$

Here, T_{air} is ambient temperature (°C), T_C refers to normal operating temperature (°C). $NOCT$ refers to a specification stated by PV module manufacturers, respectively. And w refers to the quantity of modules. Therefore, we can calculate the PV power generation by Eq. (6.6):

$$\boldsymbol{Gen_{pv} = w \times p_{pv}(t)} \tag{6.6}$$

6.2.1.3 Power storage technology

Because the instability of renewable energy power generation poses a risk to the safety and reliability of the power grid, in regard to provide high-quality power, the renewable energy generation system should be incorporated with other power sources to ensure a steady supply of electricity and increase the local utilization of renewable energy. [45] has demonstrated that networked microgrids with rooftop solar PV and battery storage system can improve distribution grid resilience to natural disasters. ESS as an attractive option can significantly increase the availability of loads while not being sufficient to provide long-term energy demand [46, 47]. In this research, we select the sodium-sulfur (NAS) battery with a life expectancy of 15 years or approximately 4,500 charge/discharge cycles [48]. The charge-discharge efficiency of NAS battery is 0.9, and there is no self-discharge [49, 50]. And the unit price of this NAS energy storage system (ESS) is 25,000 JPY/kWh. In this research, the ESS is restricted to work within an allowable range.

An important characteristic of the ESS is the time coupling characteristic in relation to charge/discharge status (SOC). The SOC (%) dynamics can be defined by Eq. (6.7) and Eq. (6.8),

$$\boldsymbol{SOC(t+1) = SOC(t) + \frac{\eta_{cha} \cdot \sum E_{cha}(t) \times \Delta T}{Cap_{ESS}}} \tag{6.7}$$

$$\boldsymbol{SOC(t+1) = SOC(t) - \frac{\sum E_{dis}(t) \times \Delta T}{Cap_{ESS} \cdot \eta_{dis}}} \tag{6.8}$$

Here, $SOC(t)$ indicates the charge status of ESS at time t, η indicates the efficiency, and Cap_{sb} represents the capacity of ESS. T refers a one-day time series with a time step of ΔT, and is characterized as T = {1,2,3,..24}.

6.2.1.4 Energy flow modeling

There always a balance between PV generation, energy saved by high efficiency appliance, grid, and the actual demand. This can be calculated by the following equation:

$$\boldsymbol{E_{net}(t) = E_{load}(t) - E_{PV}(t) - E_{HEA}(t)} \tag{6.9}$$

Here $E_{net}(t)$ is the net energy demand and $E_{load}(t)$ is the energy demand, $E_{PV}(t)$ is the PV generation at time t, and $E_{HEA}(t)$ represents the energy saved by high efficiency appliance. The relationship between net energy demand and ESS charge/ discharge state can be described by Eq. (6.10):

$$|\boldsymbol{E_{net}(t)}| = \begin{cases} \sum \boldsymbol{E_{cha}(t)} / \boldsymbol{\eta_{cha}}, & (\boldsymbol{E_{net}(t)} < \boldsymbol{0}) \\ \boldsymbol{0}, & (\boldsymbol{E_{net}(t)} = \boldsymbol{0}) \\ \sum \boldsymbol{E_{dis}(t)} \cdot \boldsymbol{\eta_{dis}} + \sum \boldsymbol{E_{load}(t)}, & (\boldsymbol{E_{net}(t)} > \boldsymbol{0}) \end{cases} \tag{6.10}$$

Where $E_{cha}(t)$ represents the charge energy at time t, and $E_{dis}(t)$ is the discharge energy at time t. η_{cha} and η_{dis} are the efficiency rate in charging/discharging process. pw is the power rating, and j represent the building sectors. The individual ESSs can be aggregated into a large portfolio through VPP to provide community-scale ancillary services (such as load leveling). The relationship between the community level distribution network and individual ESS can be developed so that individual ESS management systems can adjust charge and discharge power with peak information from the distribution network based on intelligent communication system to achieve better load leveling performance. The battery charge and discharge states can be described as:

$$\boldsymbol{E_{cha}(t)} = \begin{bmatrix} \boldsymbol{E_{cha}^{1,1}(t)} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{E_{cha}^{2,2}(t)} & \cdots & \boldsymbol{0} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{E_{cha}^{j,j}(t)} \end{bmatrix} \tag{6.11}$$

$$\boldsymbol{E_{dis}(t)} = \begin{bmatrix} \boldsymbol{E_{dis}^{1,1}(t)} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{E_{dis}^{2,2}(t)} & \cdots & \boldsymbol{0} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{E_{dis}^{j,j}(t)} \end{bmatrix} \tag{6.12}$$

And there are two stages for ESS, ESS cannot be charged and discharged at the same time. First is charging state: When there are surplus PV power generation, for example, when $\sum \mathrm{E_{net}(t)} < 0$, the ESS is in a charging stage.

$$\boldsymbol{E_{cha}^{j}} = \sum \boldsymbol{E_{cha}^{j,j}(t)} = \begin{cases} |\sum \boldsymbol{E_{net}(t)}| \cdot \boldsymbol{\eta_{cha}}, & \boldsymbol{if}\ |\sum \boldsymbol{E_{net}(t)}| \le \boldsymbol{pw} \\ \boldsymbol{pw}, & \boldsymbol{if}\ |\sum \boldsymbol{E_{net}(t)}| > \boldsymbol{pw} \end{cases} \tag{6.13}$$

Another is discharging state: When there is insufficient PV power generation, for example, when $\sum \mathrm{E_{net}(t)} > 0$, ESS is in a discharging stage.

$$\boldsymbol{E_{dis}^{j}} = \sum \boldsymbol{E_{dis}^{j,j}(t)} = \begin{cases} |\sum \boldsymbol{E_{net}(t)}| / \boldsymbol{\eta_{dis}}, & \boldsymbol{if}\ |\sum \boldsymbol{E_{net}(t)}| \le \boldsymbol{pw} \\ \boldsymbol{pw}, & \boldsymbol{if}\ |\sum \boldsymbol{E_{net}(t)}| > \boldsymbol{pw} \end{cases} \tag{6.14}$$

6.2.1.5 Optimization method

This research adopts a genetic algorithm (GA) as optimization algorithm to find the fittest ESS capacity. It is a search heuristic that is inspired by Charles Darwin's theory of natural evolution [51]. Li Y. et al. [52] proposed a method using GA that optimally deployed BESS and determined their capacities in an energy sharing framework. The optimization flow was shown in Fig.6.2, which described the design and optimization methods of distributed ESS under a VPP framework.

1). Input the data such as original load profiles, update high efficiency appliance, PV system capacity and solar radiation as well as GA parameters. The values of the genetic parameters in this study were as follows. the maximum generations were 100 generations, the population size was 20, the crossover rate was 0.8, the mutation probability was 0.05, the mutation rate was 0.5, and the elitism was 0.5.

2). Calculate the net load of each building.

3). Initialize the battery matrix that needs to be optimized.

4). Calculate the energy exchange between buildings and ESS.

5). Optimize each building's ESS capacity aim at minimizing the peak demand for electricity in the area (with the goal of less than 33000kW) and maximizing the profit. The objective function of this step can be described as:

$$\boldsymbol{MP = Max(Load(t))} \tag{6.15}$$

Where MP is the max load in the time t.

$$\boldsymbol{J_{fitness}} = \begin{cases} \boldsymbol{min\ (MP)} \\ \boldsymbol{max\ (NPV_{ESS})} \end{cases} \tag{6.16}$$

In the above, NPV_{ESS} is the net present value of ESS.

Last step is output the optimal solution.

The optimization process is implemented in Matlab, while the programming models are also built using GA in Matlab. Moreover, the entire process is conducted on a computer with Intel Core i7-8700 processor, 16GB RAM and 3.2GHz Clock Speed. The elapsed time for the process is found to be 493.2 seconds.

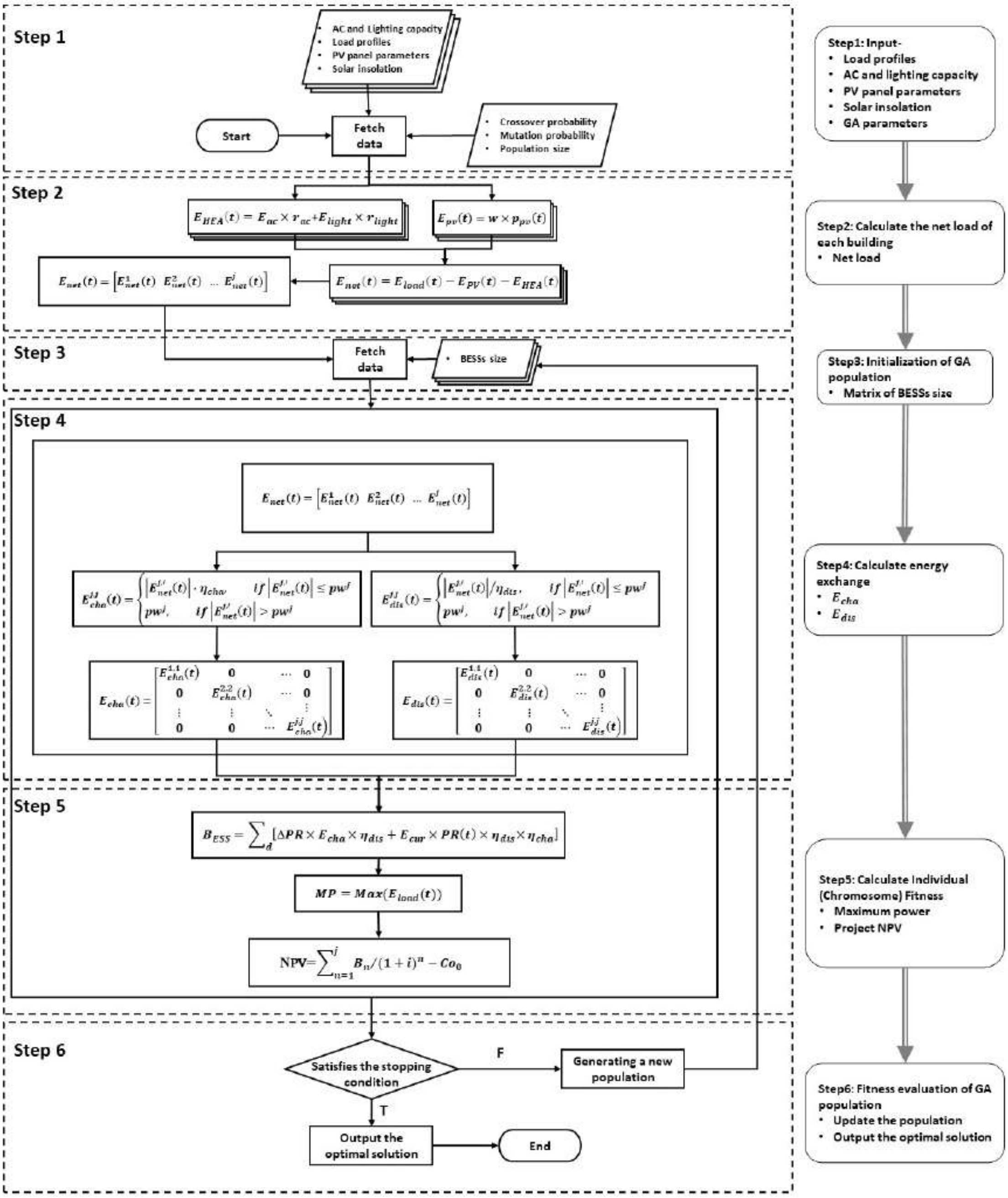


Fig. 6.2 Optimization flow of ESS

6.2.2 Establishment of economic model

In this research, the economic benefit of VPP comprises the electricity cost saved by update HEA, PV system and ESS. Therefore, economic benefit of the VPP can be determined by Eq. (6.17), as follows:

$$\boldsymbol{B_{total} = B_{HEA} + B_{PV} + B_{ESS}} \tag{6.17}$$

In the above, B_{HEA} is the benefit of the updating high efficiency appliance and can be calculated using Eq. (6.18). B_{PV} refers to PV system's benefit which can be determined by Eq. (6.19). B_{ESS} the ESS system's benefit and can be computed by Eq. (6.20).

$$\boldsymbol{B_{HEA}} = \sum_d \sum_t [\boldsymbol{E_{save,ac}} \times \boldsymbol{PR(t)}] + \sum_d \sum_t [\boldsymbol{E_{save,light}} \times \boldsymbol{PR(t)}], \forall \boldsymbol{d} \in \boldsymbol{\vartheta}; \boldsymbol{t} \in \boldsymbol{T} \qquad (6.18)$$

Here, $PR(t)$ refers to the electricity price at time t, ϑ represents day collection $\vartheta = \{1, 2, 3, \ldots 365\}$.

$$\boldsymbol{B_{PV}} = \sum_d \sum_t [\boldsymbol{PR(t)} \times \boldsymbol{E_{PV}(t)}] \qquad (6.19)$$

Here, $E_{PV}(t)$ refers to the PV power generation at the time t.

$$\boldsymbol{B_{ESS}} = \sum_d [\Delta \boldsymbol{PR} \times \boldsymbol{E_{cha}} \times \boldsymbol{\eta_{dis}} + \boldsymbol{E_{cur}} \times \boldsymbol{PR(t)} \times \boldsymbol{\eta_{dis}} \times \boldsymbol{\eta_{cha}}] \qquad (6.20)$$

In the above, ΔPR refers to electricity prices difference caused by the peak-to-valley electricity plans, different electricity consumers will choose different plans. E_{cha} refers to the electricity stored by the ESS, E_{cur} represents the surplus PV power generation stored by ESS.

The overall investment of the VPP can be described by Eq. (6.21), as follows:

$$\boldsymbol{Invest_{total}} = \boldsymbol{Cap_{VPP,HEA}} \times \boldsymbol{MP_{HEA}} + \boldsymbol{Cap_{PV}} \times \boldsymbol{MP_{PV}} + \boldsymbol{Cap_{ESS}} \times \boldsymbol{MP_{ESS}} \qquad (6.21)$$

Here, $Cap_{VPP,HEA}$ is the installed capacity of the HEA, Cap_{PV} is the PV system's capacity, and Cap_{ESS} is the ESS system's capacity, MP_{HEA} is the unit prices of HEA, MP_{PV} is the unit prices of PV and MP_{ESS} is the unit prices of ESS system, respectively.

In 2012, the Japanese government launched the new Feed-in Tariff Act (FiT) [53]. This study also adopts different export feed-in tariff (FiT) schemes to evaluate the economic.

$$\boldsymbol{B_{FiT}} = \sum_d \sum_t [\boldsymbol{FiT} \times \boldsymbol{E_{PV}}] \qquad (6.22)$$

In the above, $\boldsymbol{B_{FiT}}$ is the benefit of export PV generation to public grid, and $\boldsymbol{FiT}$ is the price of FiT policy.

6.2.3 Economic evaluation indicator

This study adopts net present value and return on investment to forecast the economy of VPP's life cycle. The expense of installing and maintaining the equipment and the energy loss from the depreciation of the equipment are ignored, and only the expense of the equipment is taken as the investment of construct VPP.

6.2.3.1 Net Present Value (NPV)

Net present value (NPV) is normally used in capital budgeting and investment planning to analyze the profitability of a projected investment or project. Ignore the operation and maintenance cost, the NPV of demand side can be presented as:

$$\text{NPV} = \sum_{\boldsymbol{n=1}}^{\boldsymbol{j}} \boldsymbol{B_n}/(\boldsymbol{1} + \boldsymbol{i})^{\boldsymbol{n}} - \boldsymbol{Co_0} \qquad (6.23)$$

where B_n is the annual benefit of the system, initial investment and generic year n= [1,2,3,...], i is discount rate generally refer to bank rate. This research uses the Fukuoka Bank's annual interest rate: 4.5%.

6.2.3.2 Return on investment (ROI)

Return on investment (ROI) is a performance measure used to evaluate the efficiency or profitability of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost. To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment. The result is expressed as a percentage or a ratio.

$$\boldsymbol{ROI}(\boldsymbol{x}) = \frac{\boldsymbol{B}(\boldsymbol{x})}{\boldsymbol{Invest}(\boldsymbol{x})} \tag{6.24}$$

where $B(x)$ is the annual benefit of the x, $x = [Lighting,\ AC,\ PV,\ ESS, VPP]$.

6.3 Research object and data source

6.3.1 Introduction of research object

To investigate the techno-economic viability of the proposed VPP model, the Higashida Area Smart Community (H Community) is selected for case study. Which is a model project for "Environmentally Symbiotic Town Development" and is a part of the national urban renewal project. Took the geographical advantages of Kitakyushu, the Imperial Steel Works were established in Yahata in 1901, centered around Higashida. After that, companies and factories sprung up in rapid succession, and Kitakyushu City supported the industrial development of Japan as one of the country's four major industrial zones. Due to energy advancements following World War 2, coal mines in the Chikuho region were shuttered and steel plants were streamlined. The industrial economy of Kitakyushu slid into decline, and this situation was called "tetsubie" (economic slowdown caused by decreased steel production). The rainbow-colored smoke, which had been seen as a symbol of development as an industrial city, became known as the chief source of air pollution, and pollution became a severe social problem. However, Kitakyushu City went on to overcome the pollution problem and promoted recycling industries. Now the city has a unique presence as an "environmental future city", in addition to being a city of manufacturing. The H Community is positively promoting numerous low-carbon techniques to achieve energy self-sufficiency and realize advanced zero-carbon areas early. And it covers an area of 1.2 km2 which is in Yahata Higashi, Kitakyushu, Fukuoka, as shown in Fig. 6.3.

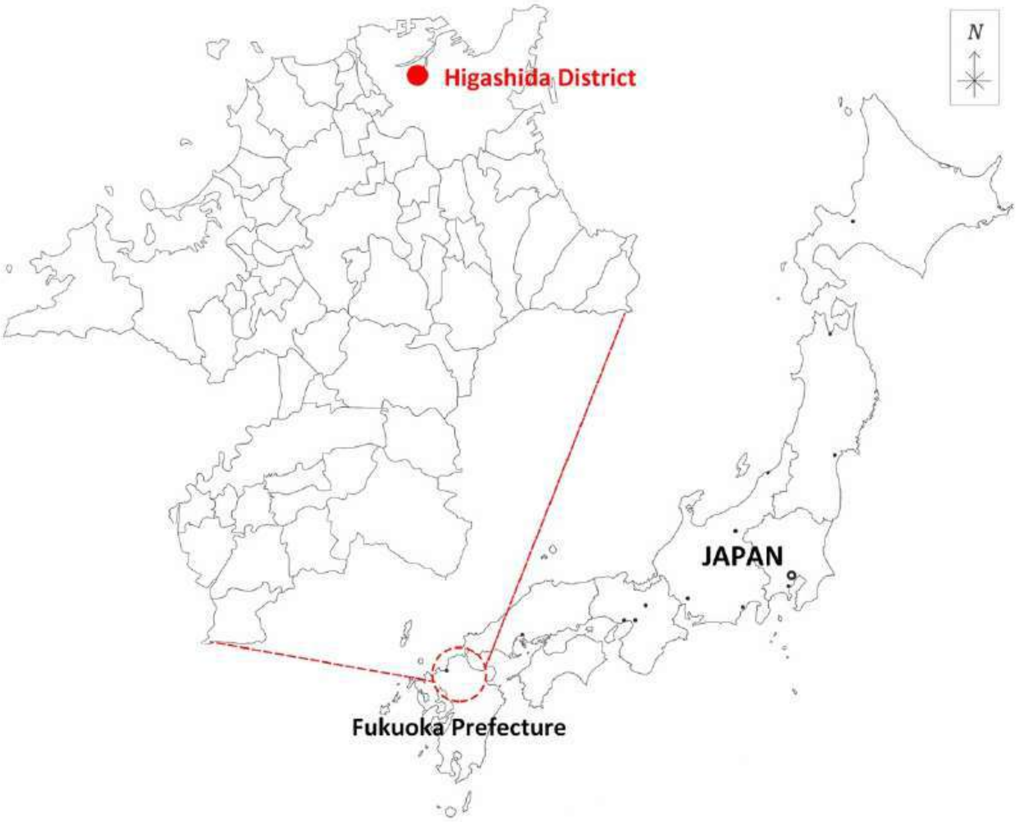


Fig. 6.3 Location of Higashida Smart Community in Japan

6.3.1 Current energy situation

Currently, the regional electricity demand is firstly provided by the Higashida co-generation (capacity is 33,000 kW), then the Kyushu Electric Power provided the shortfall of electricity requirements. This study collected the hourly electricity usage between April 2013 and March 2014 in H Community. There are five types of buildings in the H Community: residential, commercial, office, public and industrial. Each type of buildings has different activity schedules. Office buildings are usually closed on weekends. Public buildings always have rest on Sunday. Commercial and industry buildings open all year round.

The structure of electricity consumption of different building sectors in H Community as follows: the commercial sector account for 36.4% of regional energy consumption, and the office is 30.4%, public is 16.3%, residential is 11.5%, industry is 5.4%. We mainly collected the total energy consumption as well as the electric light and heating and cooling loads expect industry buildings. Electricity consumption by lighting in residential buildings accounted for 33% of total electricity consumption; the electricity heating load accounted for 26% and the cooling load account for 10% of total electricity consumption. In commercial buildings, the cooling load accounts for 28% of the total electricity load, and the heat load accounts for 18%, and lighting accounts for 22%. In office buildings, the cooling load accounts for 21% of the total electricity load, and the heat load accounts for 10%, lighting accounts for 24%. In public buildings, the cooling load accounts for 19% of the total electricity load, and the heat load accounts for 14%, and lighting accounts for 22%. Due to the relatively complicated electricity consumption of the industry buildings, we can collect the total electricity load only. And we summarize the heating and cooling schedule of different types of buildings: In commercial and public buildings, the cooling season is from April to November and the heating season is from December to March, in office and residential buildings, cooling season is from June to September, and heating season is from December to March.

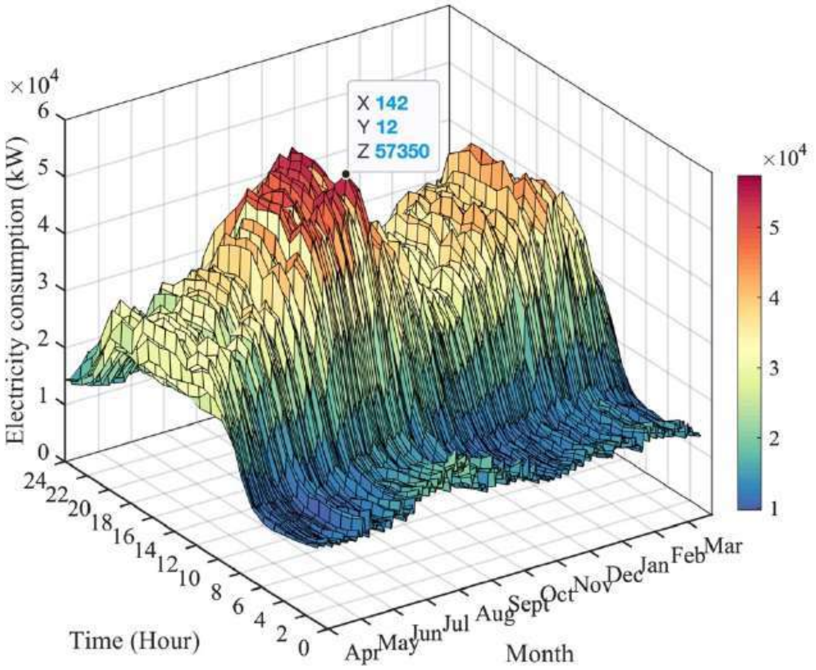


Fig. 6.4 Energy consumption of H Community in one year

The yearly energy consumption of H community was shown in Fig. 6.4. The color from blue to red represents the electricity load from low to high. It is clearly that the change of seasons has an obvious impact on the electrical load, and in the same season, the daily energy consumption trend is similar. It also can be seen that the trends of the electricity load have exhibits evident peak-valley changes, the peak electricity consumption in the area is usually concentrated at 10-18 o'clock. The electricity consumption is much more in summer than winter; the peak electricity consumption reached 57,350 kW in a year.

6.4 Effect analysis of VPP

6.4.1 Electricity saving potential of different building sectors

Table 6.2. Original installed capacity of lighting and AC

	Residential	Commercial	Office	Public	Industry
Original installed capacity of Lighting (kW)	1946	16781	13555	6287	---

Original installed capacity of AC (kW)	2423	7821	7855	2728	---

Table 6.3. Installed capacity of PV and ESS

	Residential	Commercial	Office	Public	Industry
Roof area (m^2)	36258	91944	23546	39594	12535
Installed capacity of PV (kW)	2317	5910	1517	2544	797
Installed capacity of ESS (kWh)	19000	30800	19000	6000	1400

The Table 6.2 shows the original installed capacity of lighting and AC in different type buildings. Due to the complex power structure of different types of industry buildings, we do not consider the update of high-efficiency electrical appliances in industry buildings. The installation capacity of the PV system is related to the roof area that can be installed.

Commonly, part of the roof area is designed for chimneys and ventilation pipes or sheltered by surrounding buildings. In addition, the PV system also needs to reserve maintenance channels. Therefore, we assumed that the maximum installation ratio of the area on the roof where PV modules can be installed is 50%. According to the statics, in Japan, when install 10kW PV module on the roof, the minimum area of PV module is 49 m2; 10 kW PV module with an inclination angle of 35° on a flat roof is 100 m2; 10kW PV module with an inclination angle of 20° on a flat roof is 85 m2 [54]. Thus, we can calculate the maximum capacity of PV system. The calculation results were shown in Table 6.3.

As the integration of renewable energy into the grid will affect the stability of the grid, it is unrealistic to sell the remaining PV power generation to the grid. Therefore, energy storage needs to store surplus PV power first. The capacity of ESS can be simulated by the proposed optimization flow in section 2, and the results are shown in Table 6.3.

Based on the obtained installed PV capacity, original installed capacity of Lighting and AC, and ESS capacity. We simulated the energy-saving potential of different technologies in different types of buildings.

Fig. 6.5 ~ Fig. 6.9 shows the energy-saving potential of the five types of buildings in a year. Due to the difference in electricity consumption in different departments, to be able to perform more prominently, we have done dimensionless processing of the data. The monthly energy consumption data is divided by the total annual energy consumption to obtain a ratio (monthly consumption rate).

In the figures, the columns represent the monthly electricity consumption of each type of building. And the blue represents the final electricity demand from conventional power plant. The effect of the ESS is not shown in the figure because the ESS is only used as a carrier for charge/discharge electricity, and it does not produce energy by itself. The polyline in the figures shows the electricity saving rate.

The figures show that the commercial, office and public buildings have the same characteristics in that the electricity consumption in July and August is higher than other months in the whole year. The electricity consumption of residential buildings in December and January is higher than other months.

PV generation is higher in summer than in winter, this is because of the longer daylight hours and higher intensity of sunlight in summer.

Among the five types of buildings, residential buildings have the highest energy saving rate after introducing VPP, and the highest energy saving rate is 35.11% in June, it can be observed that the electricity demand of the building is low at this time, but the power generation of PV is highest in the year. And in January, the electricity saving rate in residential is smallest of 17.53%. The energy saving potential of PV is significant except for office buildings because the office has a high demand for electricity but a low PV installation capacity.

The electricity saving rate of commercial buildings after the introduction of VPP is relatively stable, although AC saves a lot of electricity and PV systems also generate large amount electricity, because of its origin large electricity consumption, the energy saving rate is between 14.61% and 27.29%.

In office buildings, the energy saving rate during the summer from June to September is higher than other months due to the higher space cooling consumption.

Public buildings show similar characteristics to commercial buildings in terms of the trend of electricity saving rate; both commercial and public sectors’ energy saving rates show two peaks in June and November.

In industry buildings, only PV system was introduced, and the installed capacity is small, so the energy saving rate is lower than other buildings.

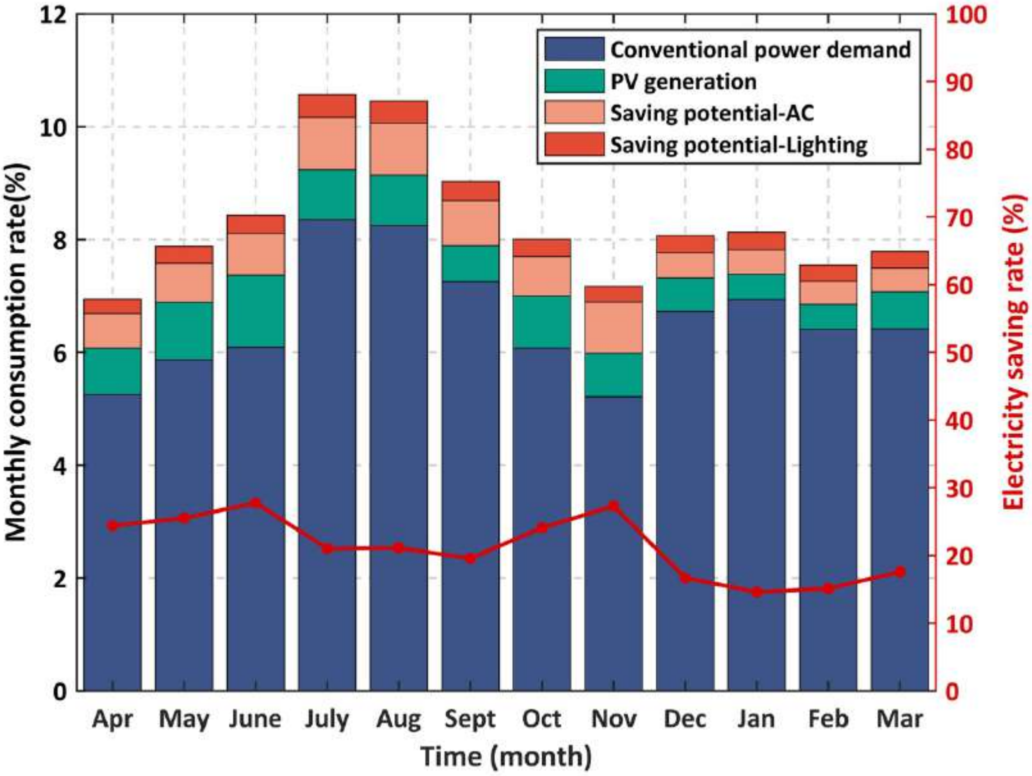


Fig. 6.5 Energy saving potential in commercial buildings

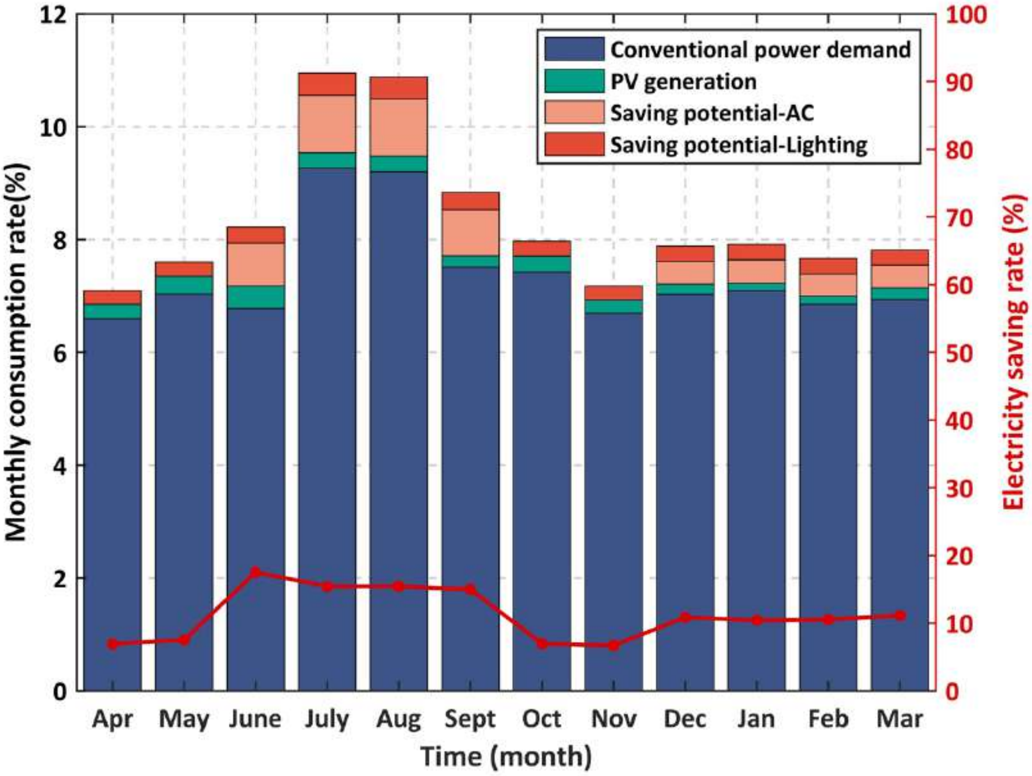


Fig. 6.6 Energy saving potential in office buildings

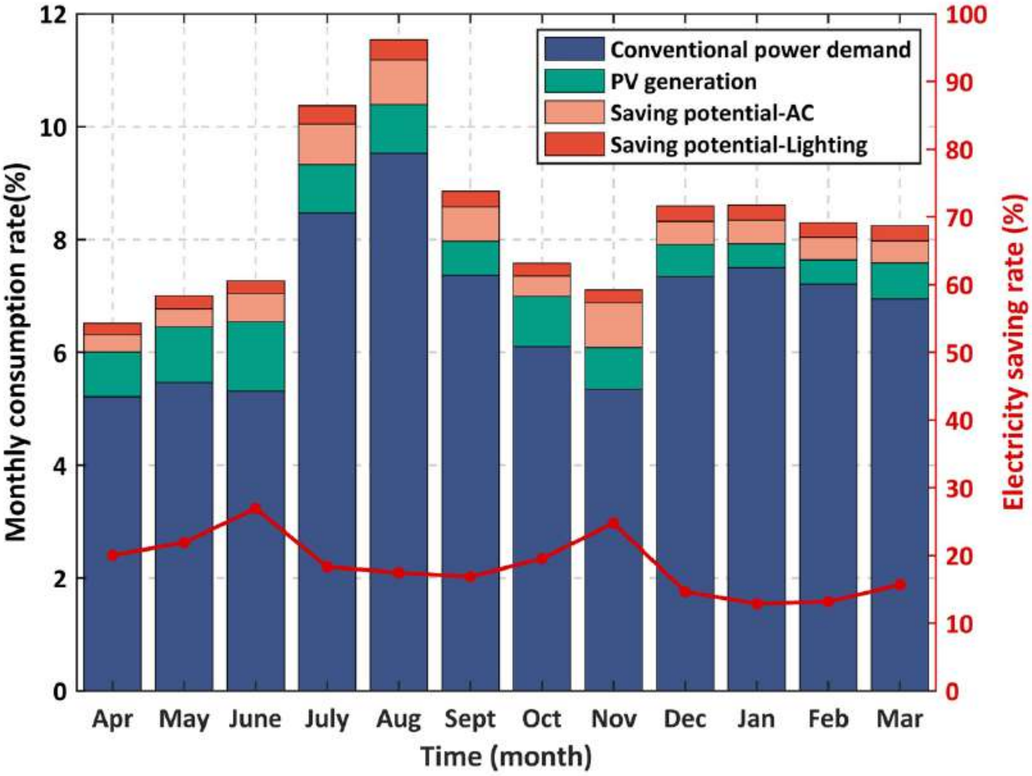


Fig. 6.7 Energy saving potential in public buildings

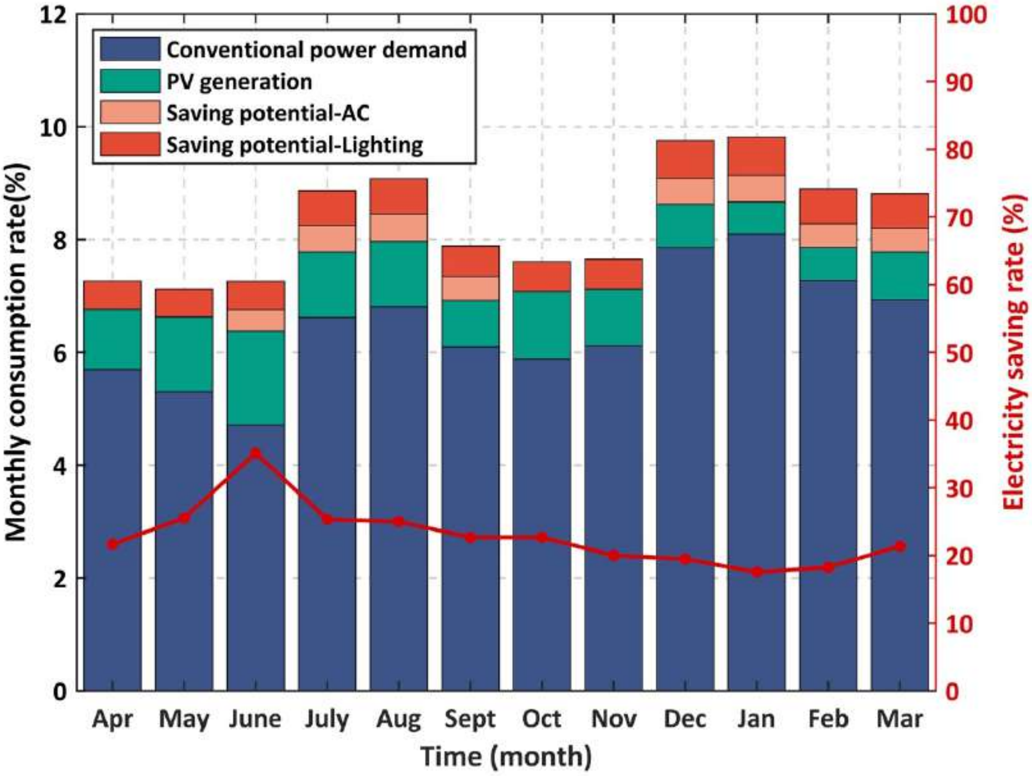


Fig. 6.8 Energy saving potential in residential buildings

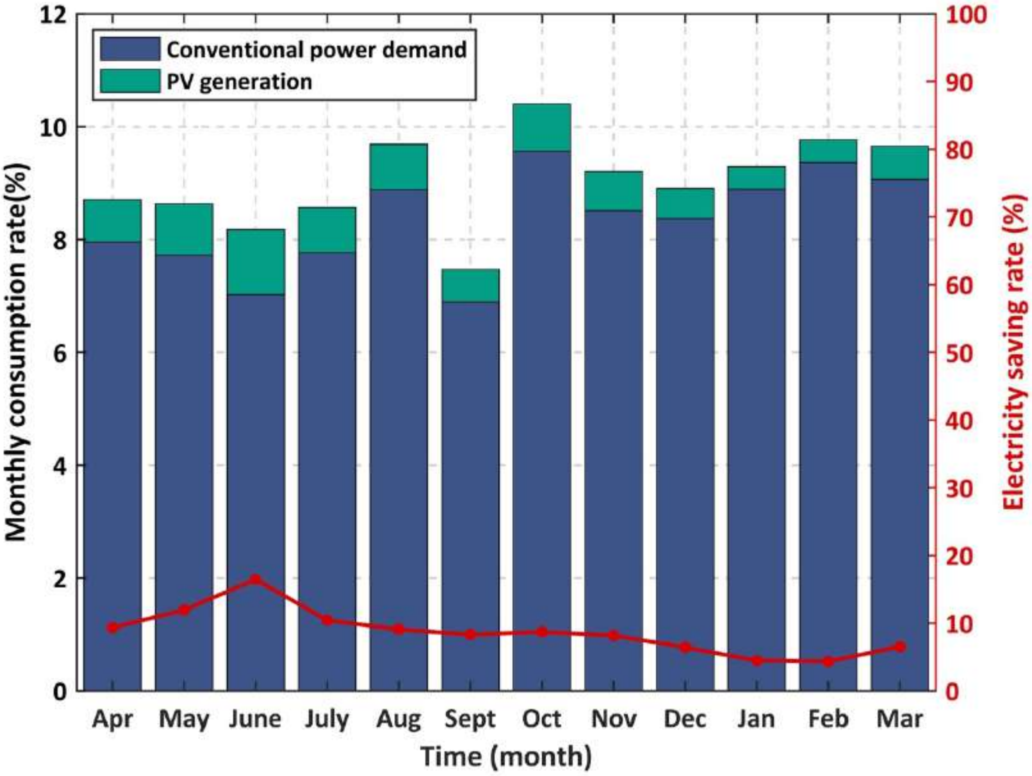


Fig. 6.9 Energy saving potential in industry buildings

6.4.2 Load leveling performance

We selected a typical day in each season to simulate the effect of peak load shaving after the introduction of VPP to H community, results are demonstrated in Fig. 6.10. The blue line represents the original electricity load. The red line represents the load leveling effect of the VPP which shows the final electricity demand load, the electricity load after applying different technologies is also shown in the figure. The original electricity load presents “double peaks” in summer and winter, and “double peaks” in the morning and afternoon throughout the day. In summer and winter, the effect of updating high-efficiency appliances is more pronounced than in spring and autumn. This is due to the seasonality of AC use. The part where the green line exceeds the red line means that the ESS is discharging, otherwise, the energy storage system is charging. It can be observed that the electricity consumption is higher in summer than the other seasons, the peak electricity consumption in summer reached up to 57,350 kW at 12 o’clock, and the difference between peak and valley load of electricity reached up to 41,050 kW. At the same time, it can be noticed that after the introduction of the VPP, the peak-to-valley difference between day and night is significantly reduced (from 41,050 kW to 9,610 kW), the VPP contributes a peak shaving ratio of 42.55% at that day. The capacity of the VPP on that day is equivalent to 24,400 kW. Electricity demand is lowest in Spring, and the load after introducing the VPP in spring is smoothest, the peak-to-valley difference of power load is only 4,450 kW after the introduction of the VPP. The peak of electricity consumption in spring usually occurs in the afternoon, and the peak shaving ratio reaches up to 42.31%. Electricity loads in the fall are similar to the spring, however, the peak of electricity consumption always occurs around 12 o'clock. In winter, the VPP can achieve a peak shaving rate of 34.81%. In summary, after the introduction of VPP, the uncertainty of renewable energy generation is compensated by the energy diversity of VPP. Please note that the capacity of VPP is not constant, its capacity will be changed by factors such as weather, demand side's electricity usage habits, etc. The following analysis is based on the results obtained from our proposed VPP.

6.4.3 Economic performance analysis

Under the premise of ensuring the stable operation of the power grid, the technical and economic viability of VPP in the transition to energy self-sufficiency in communities should be taken seriously. As the equipment that the demand side can import spontaneously, economic benefits are often the most concerned factor on the demand side and can even affect the demand side's willingness to install it. Thus, after the establishment of VPP model, this section mainly discusses the economic performance of VPP in different building sectors and external network factors that can affect the economic performance of VPP. First, the primary purpose of demand sides installing VPP is to save electricity, and the intuitive economic performance of electricity saving is the electricity bills that demands can save.

The electricity price model in the H community is the peak-valley price model as shown in Table 6.4, the corresponding electricity price model can be found on the Kyushu Electric Power official website. Another important parameter for calculating profit is the initial investment. We list the price of the equipment and its lifetime in Table 6.5.

Fig. 6.11 shows the result of annual electricity bill saving of different type buildings and different technologies. It can be observed from the figure that electricity bill saving provided by ESS in residential buildings (about 69 million JPY) is the highest than other technologies, this is because the profit model of ESS is energy arbitrage, that is, charging electricity from the grid when the electricity demand is lower than electricity supply, and discharging to the demand side when the electricity demand is insufficient. Another factor is residential buildings have the highest peak-to-valley price difference, so the bill saving is largest.

In addition, this is also related to the electricity consumption habits of the household sector. The PV system contributes bill saving of 58 million JPY, and about 15 million JPY saving of updating AC for residential. In commercial buildings, PV system contributes the highest electricity bill saving (about 118 million JPY), because it has installed the most PV panels.

In addition, there are considerable benefits to upgrading high-efficiency appliances in commercial buildings, as AC in commercial buildings are operated all year-round, resulting in higher electricity savings. Similarly, the electricity savings from upgrading high-efficiency appliances are higher in office building. Totally, the PV system saves 275 million JPY within a year and saving 313 million JPY by updating HEA. And the ESS contributes 237 million JPY electricity bill saving within one year.

The results show that the VPP formed by the various technical technologies introduced in H community has significant economic potential.

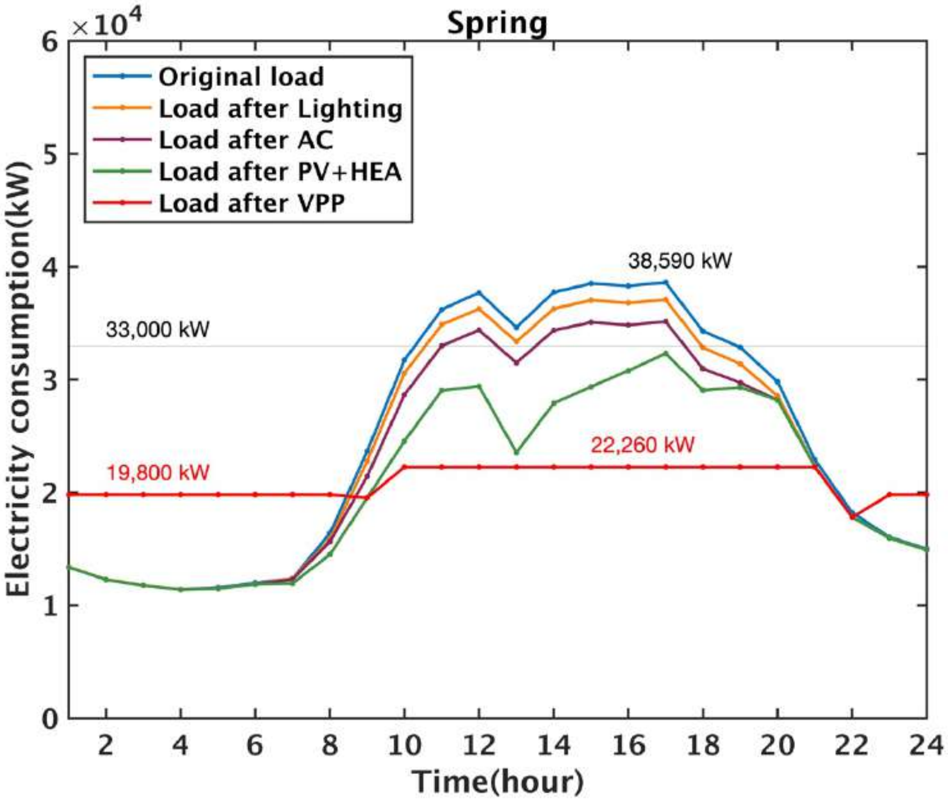


Fig. 6.10 Peak-shaving effect of virtual power plant in a typical day of each season (Spring)

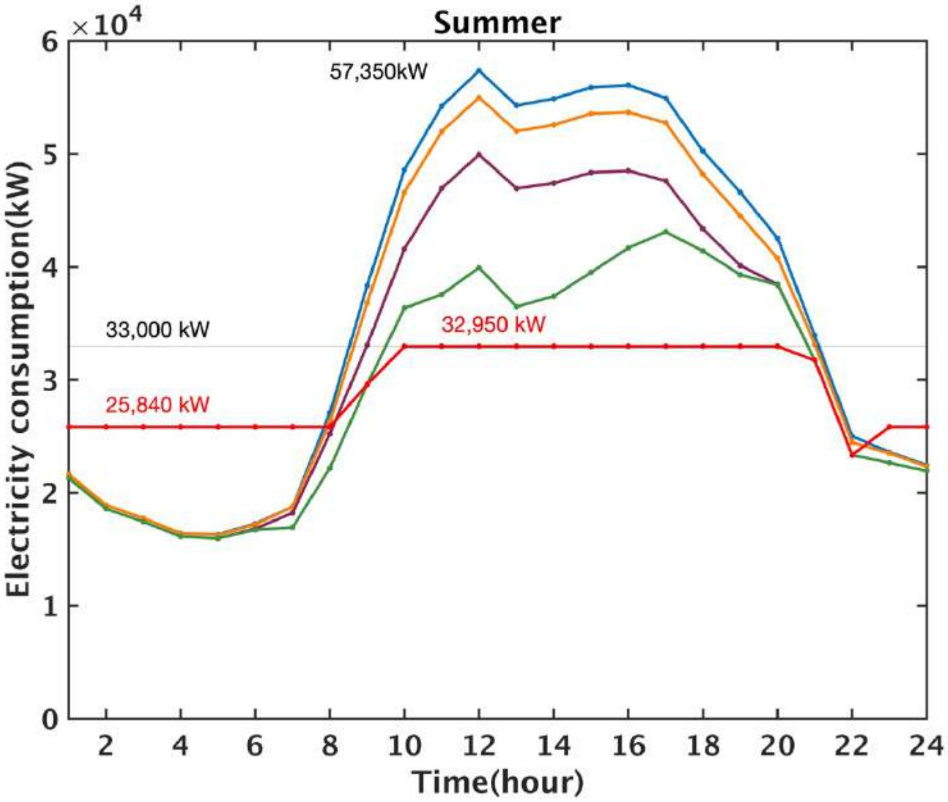


Fig. 6.10 Peak-shaving effect of virtual power plant in a typical day of each season (Summer)

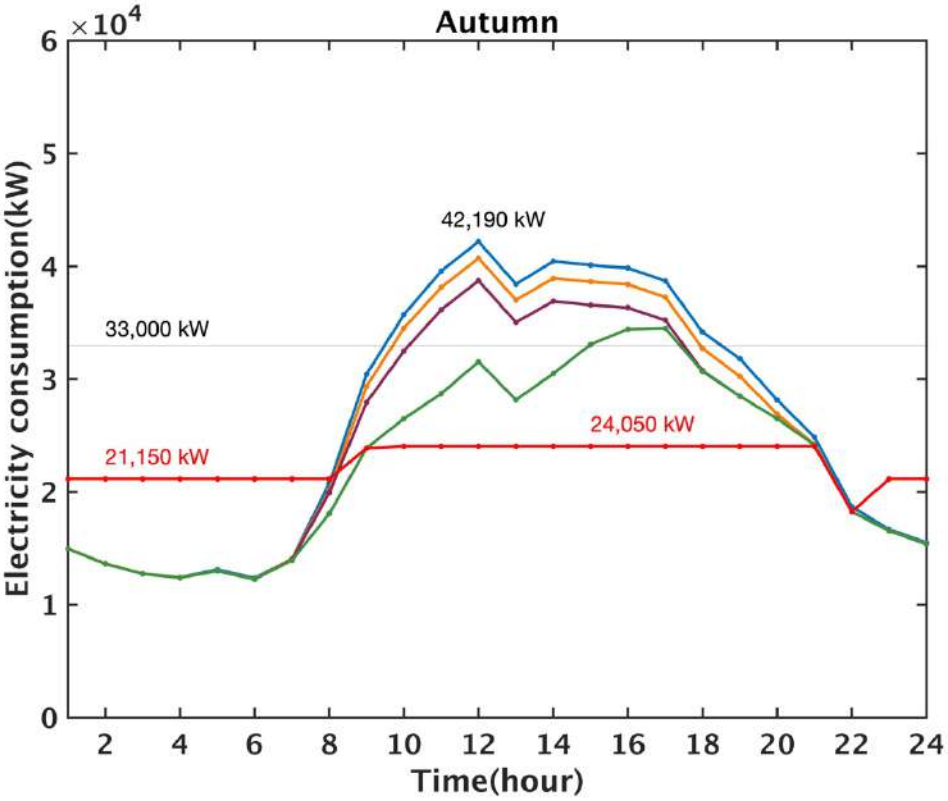


Fig. 6.10 Peak-shaving effect of virtual power plant in a typical day of each season (Autumn)

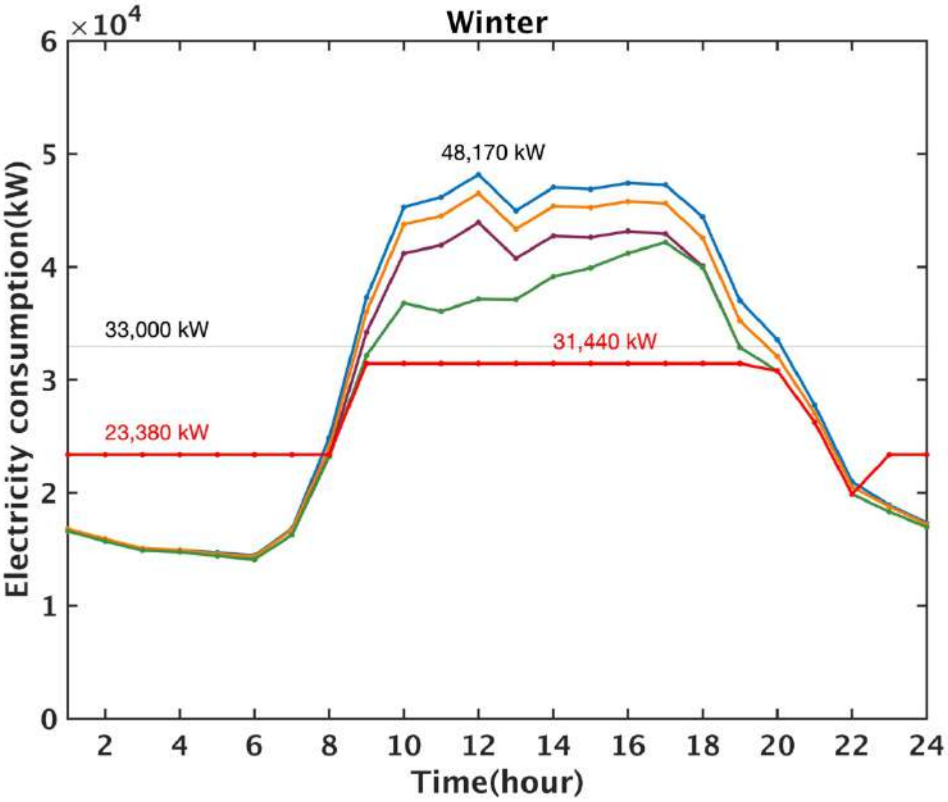


Fig. 6.10 Peak-shaving effect of virtual power plant in a typical day of each season (Winter)

Table 6.4. Electricity price model of different type buildings

	Time period	Commercial	Residential	Office	Industry	Public
Electricity price (JPY/kWh)	9:00-22:00	16.95	21.21	17.82	15.32	17.82
	22:00-9:00	9.06	10.15	10.49	8.59	11.89

Table 6.5. Equipment price and lifetime

	Lighting	AC	PV	ESS
Investment	100,000 JPY /kW	40,000 JPY /kW	250,000 JPY /kW	25,000 JPY/kWh
Lifetime (Year)	10	10	20	15

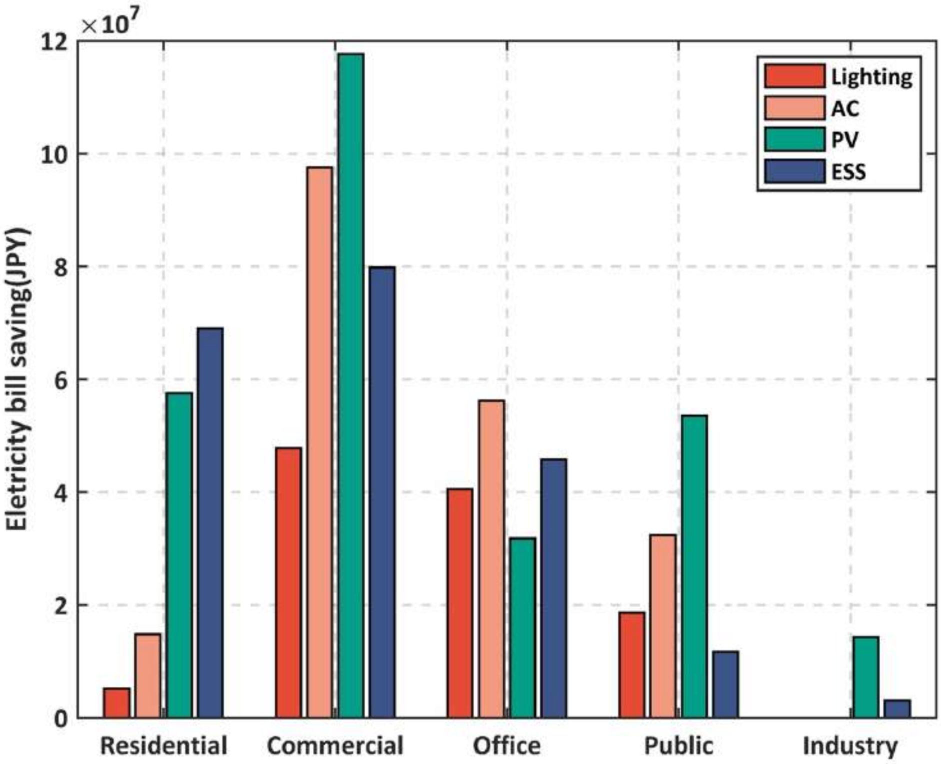


Fig. 6.11 Annual electricity bill saving of different technologies

For the economic analysis, this study also discussed different FiT schemes and renewable energy self-consumption for community. The different FiT price can be found on METI [55]. The analysis compares economic performance of four FiT scenarios and the renewable energy self-consumption scenario, results shown in Table.6.6. In all scenarios, with the FiT price decreases, the revenue of buildings receives from selling PV power to the grid also decreased. When the FiT is less than the building's corresponding time's electricity price, it will no longer be profitable to sell PV power to the grid. Under the current FiT policy, the VPP system investment cannot be compensated through renewable energy export FiT incentives and electricity bill savings, which indicated it is more cost effective of PV generation self-consumption than selling to the grid. Therefore, the subsequent analysis of this paper is based on the scenario of PV self-consumption.

Table 6.6. Summary of the VPP annual electricity bill saving considering different FiT

	Self-consumption	2014	2017	2019	2021
		FiT=32 (JPY)	FiT=21(JPY)	FiT=14 (JPY)	FiT=11 (JPY)
residential	146,612,838	177,770,404	147,270,361	127,861,243	119,543,049
commercial	342,840,778	451,536,959	373,740,129	324,233,056	303,015,739
office	174,350,741	200,630,787	180,661,618	167,953,964	162,507,827
public	116,217,067	160,116,236	126,628,058	105,317,399	96,184,259
industry	17,447,259	33,615,514	23,124,131	16,447,796	13,586,510

Another important issue that can affect the VPP's economic performance is electricity price. The increased use of fossil fuels in thermal power generation after the Fukushima Crisis leading to the rise of electricity price. Therefore, the economic performance considering different electricity price scenario was evaluated, results shown in Table 6.7. With the rise of electricity price, although the demand side's electricity bill increased, the electricity bill saving rate increased. With the rising price of electricity in Japan, VPP have a good future and can bring better benefits to the demand side.

Table 6.7. Summary of the VPP annual electricity bill saving considering different electricity price

	Original electricity price			electricity price 10% rise			electricity price 20% rise		
	bill (JPY)	bill saving (JPY)	saving rate (%)	bill (JPY)	bill saving (JPY)	saving rate (%)	bill (JPY)	bill saving (JPY)	saving rate (%)
residential	388,701,062	146,612,838	37.72	418,935,866	167,125,864	39.89	449,170,669	187,638,893	41.77
commercial	1,158,783,084	342,840,778	29.59	1,260,921,550	385,850,274	30.60	1,363,060,016	428,859,769	31.46
office	992,229,334	174,350,741	17.57	1,073,502,325	197,834,129	18.43	1,154,775,316	221,317,517	19.17
public	538,186,241	116,217,067	21.59	579,442,634	129,765,385	22.39	620,699,027	143,313,704	23.09
industry	163,472,771	17,447,259	10.67	178,677,890	19,553,917	10.94	193,883,009	21,660,574	11.17

6.4.4 Environmental performance analysis

The reduction in CO2 emissions during a year after the formation of VPP was simulated in this section to explore the environmental impact of the introduction of VPP. Currently, the CO2 emission by electricity generation is 0.488 kg/kWh in the Kitakyushu [56], this is proximity to the maximum value of current CO2 emission price in Japan. And the carbon tax price is about 2.18 JPY/kWh. Based on the simulation of VPP's load leveling effect, the carbon emission reduction result was shown in Fig. 6.12. After the introduction of the VPP system, CO2 emissions have been significantly reduced. Originally, the highest CO2 emissions appeared in August, with 10.49×106 kg of emissions, after the introduction of the VPP system, CO2 emissions have been reduced to 8.75×106 kg. And Table 6.8 lists the CO2 emissions reduction rate of 12 months. In November, the CO2 emission rate decreased the most, with a decrease of 23.69%. The rate of carbon emission reduction is closely related to the rate of energy saving.

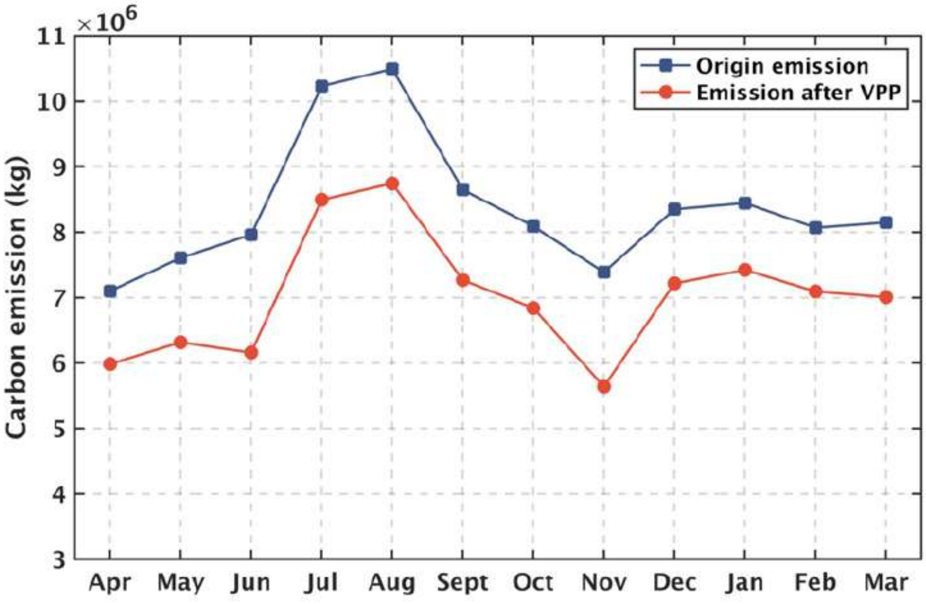


Fig. 6.12 Carbon emission reduction

Table 6.8. CO_2 emission reduction rate

	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Reduction rate (%)	15.68	17.00	22.65	16.95	16.63	15.95	15.46	23.69	13.57	12.08	12.11	14.00

6.5 Sensitivity analysis

It is clear from previous economic and environmental analysis that VPP has certain advantages not only in the economic aspects, but also in the environmental aspect. This section provides analysis and forecasts on the return on investment (ROI) of VPP and capability of carbon emission reduction based on the influence of changes in equipment installation capacities, as well as carbon tax prices equipment prices.

6.5.1 Installation ratio

System size may be an important factor in the economic performance of the system. Combined with the load characteristics of different buildings, the economic adaptability and environmental performance of VPP in different type buildings is studied in this section. The ROI was adopted to evaluate how well the different VPP technologies has performed in different buildings, and the control variates was used to explore the effect of installation capacity of different technologies on ROI in different buildings. The result shows in Fig. 6.13. The overall ROI for the community was 8.31%. Firstly, when all technologies are installed 100%, the ROI of residential buildings is highest (10.89%), ROI of commercial building is 8.29%, public building is 7.63%, industry building is 7.49%, and office building is lowest 6.78%. This shows that VPP bring the highest economic benefits and the best adaptability to residential buildings. The green line shows the relationship between ROI and PV installation ratio while the other technologies' installation ratio is 100%. It can be observed that when the installation rate of PV increases, the ROI of commercial, public, and office increased. The purple line shows the relationship between updating rate of lighting and ROI when other technologies unchanged, and the orange line represents the ROI change of AC update ratio. ROI of residential buildings decreases as the increase of update ratio for Lighting. Updating AC gains increasing ROI in public, office, residential, and commercial buildings. The blue line demonstrates the change of ROI with different ESS installation ratio. In all five building types, the ROI of ESS tends to increase as the installation rate increases. In residential buildings, ESS has the most significant ROI ups and downs trend, however, the ROI is relatively stable in public, commercial and industry buildings, this is mainly influenced by the electricity price difference. And in the industry buildings, with the increase of PV installation ratio, the ROI decreased significantly. In summary, updating AC has a good adaptability and more profitable in the community, as the renewable energy generation technology with high initial investment, PV has poor economic adaptability to buildings.

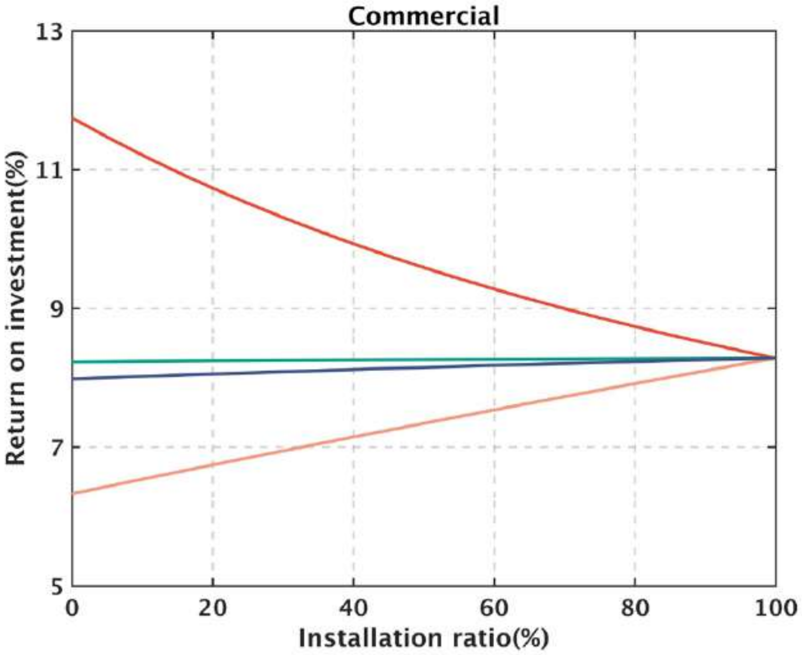


Fig. 6.13 Relationship between return on investment and equipment installation ratio (Commercial)

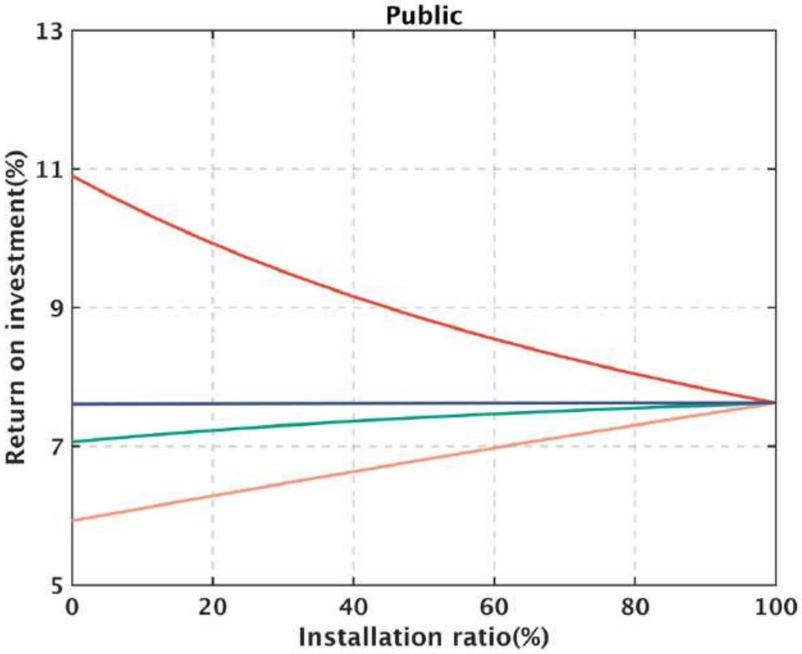


Fig. 6.13 Relationship between return on investment and equipment installation ratio (Public)

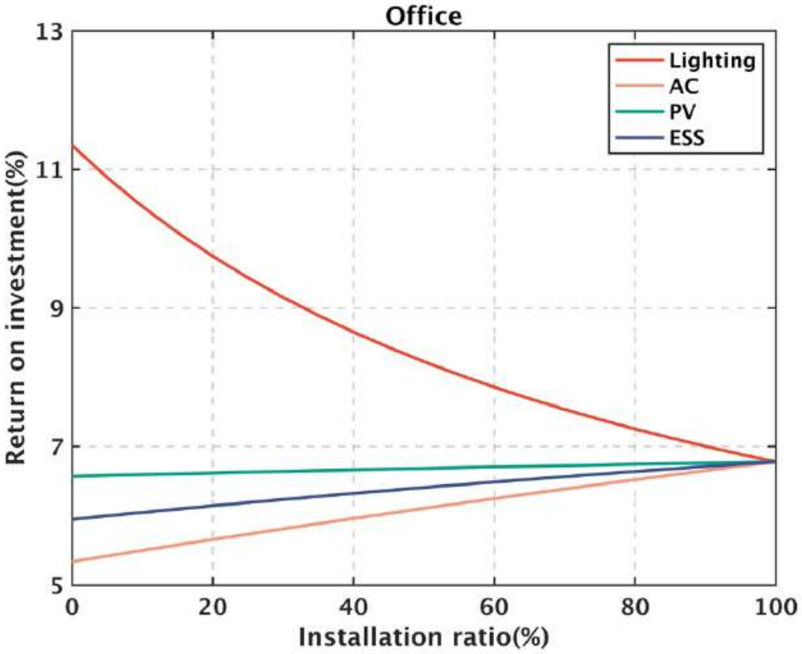


Fig. 6.13 Relationship between return on investment and equipment installation ratio (Office)

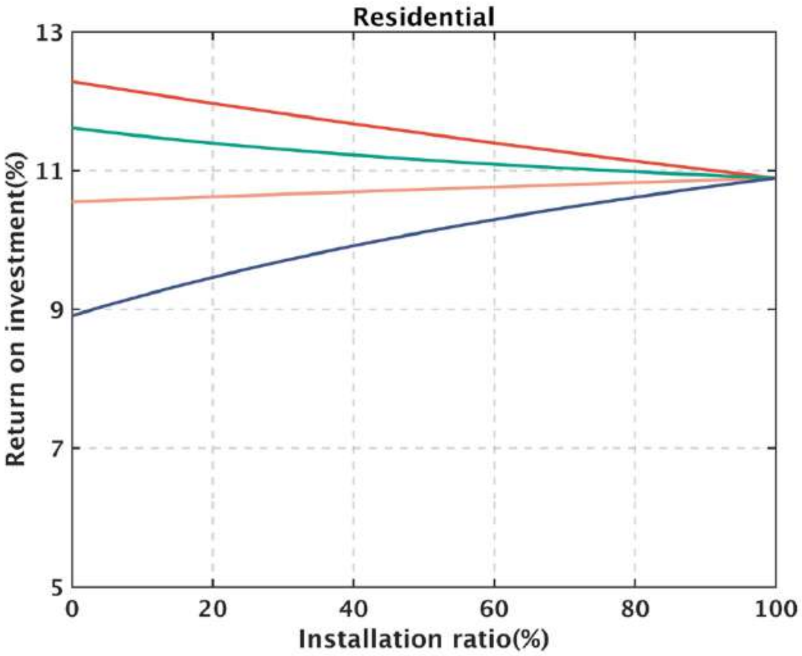


Fig. 6.13 Relationship between return on investment and equipment installation ratio (Residential)

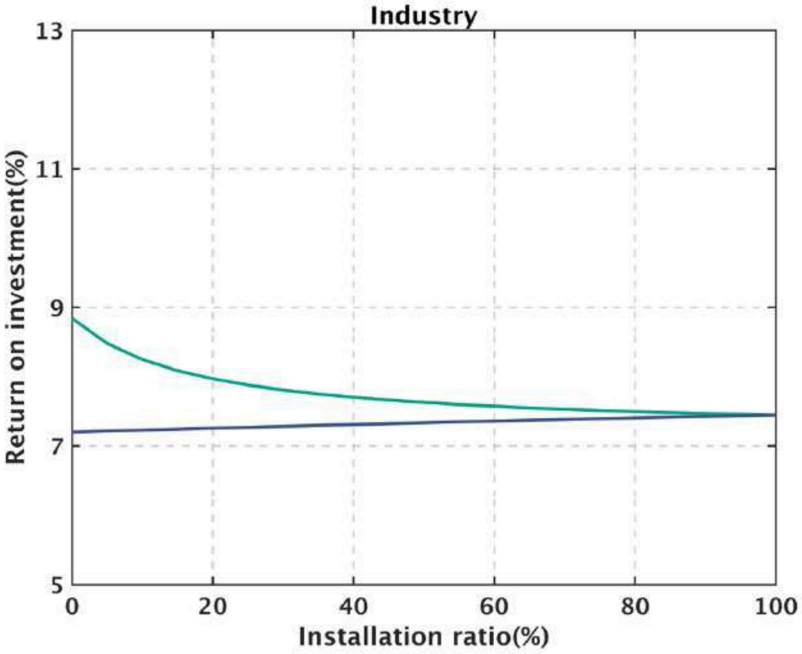


Fig. 6.13 Relationship between return on investment and equipment installation ratio (Industry)

Carbon emission is an important factor leading to global warming, as it accounts for 80% of GHG. With the development of society, population and energy demand increased, CO_2 emissions are progressively increased. This part, the relationship between carbon emission reduction and equipment installation capacity was studied. Results were shown in Fig. 6.14. It can be observed that with the increase of equipment installation ratio, the VPP’s capability of carbon emission reduction also increased. The purple line shows the relationship between carbon emission reduction capability and lighting updating ratio. The orange line represents the relationship between carbon emission reduction capability and AC updating ratio, and green line represents the influence of the PV installation ratio. The installed capacity of ESS has no effect on carbon emission reduction, as ESS does not generate electricity. PV is the most effective approach to reduce the carbon emission in all sectors except in office buildings, because the installed capacity of PV is small in office. Commercial buildings have the biggest emission reductions because they have the largest HEA replacement capacity and PV installation capacity. In summary, updating high-efficiency appliances and installing PV both provide good environmental benefits.

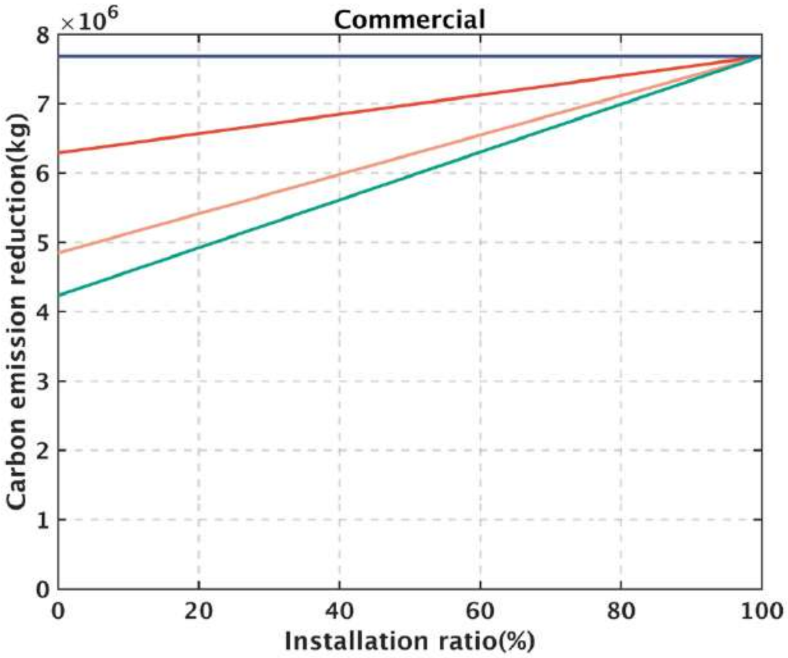


Fig. 6.14 Relationship between carbon emission reduction and equipment installation ratio (Commercial)

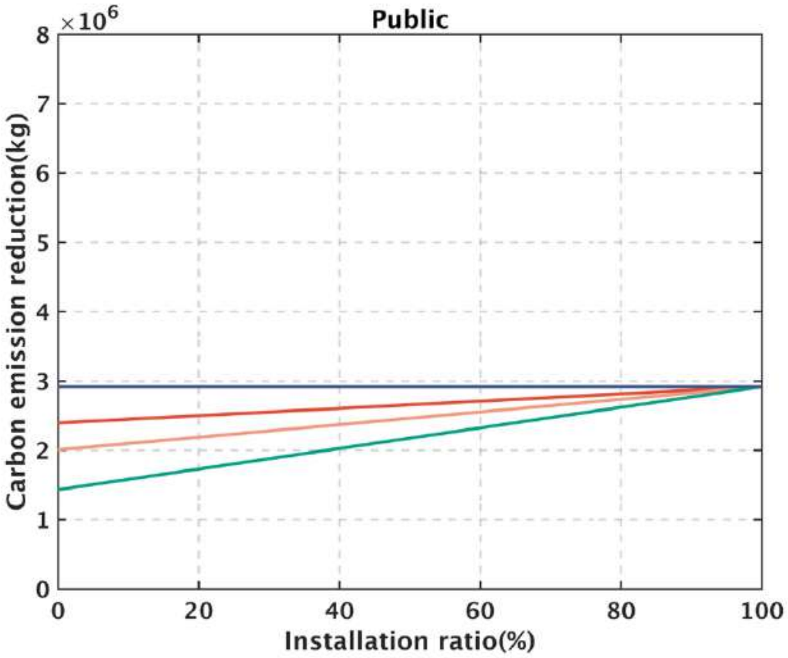


Fig. 6.14 Relationship between carbon emission reduction and equipment installation ratio (Public)

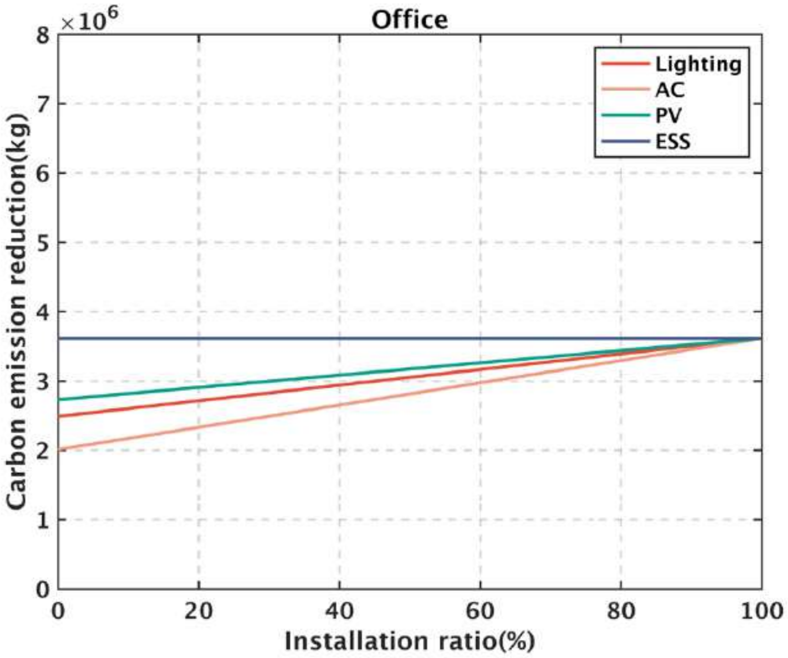


Fig. 6.14 Relationship between carbon emission reduction and equipment installation ratio (Office)

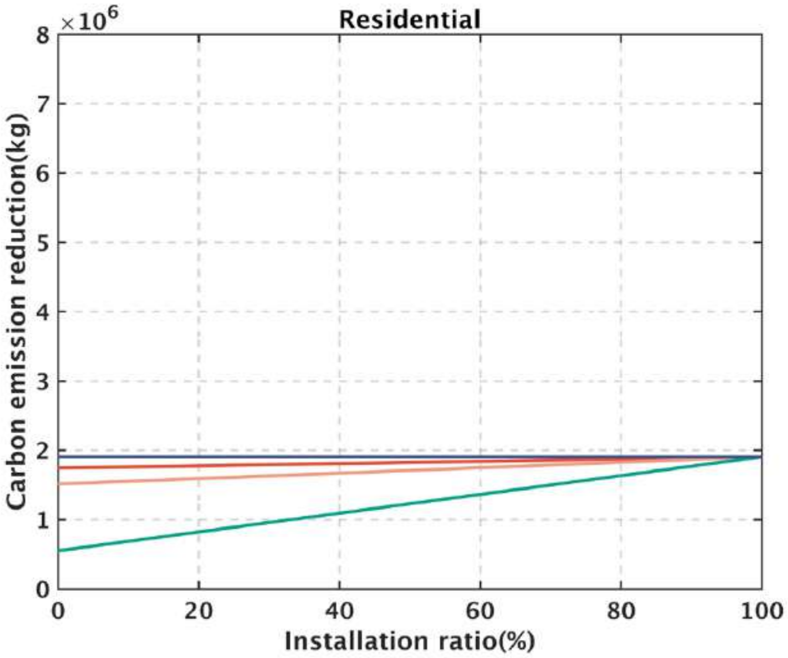


Fig. 6.14 Relationship between carbon emission reduction and equipment installation ratio (Residential)

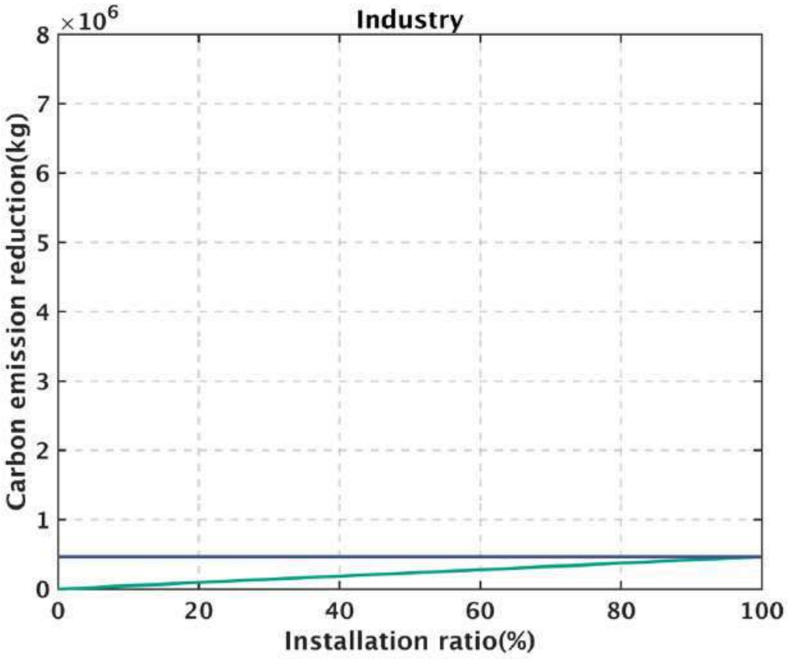


Fig. 6.14 Relationship between carbon emission reduction and equipment installation ratio (Industry)

6.5.2 Carbon tax

Research on carbon pricing is becoming a hot topic as an essential intervention for global energy conservation and GHG emission reduction [57, 58]. There have been some studies showing the contribution of VPP in energy saving as well as GHG emission reduction [59, 60]. Carbon trading mechanism is introduced to VPP system with the goal of achieving low-carbon operation [61]. Compared with conventional power plants, VPPs mainly aggregates the renewable energy and various energy-saving technologies, which can reduce carbon emissions. Therefore, when considering the benefits of VPPs, it is necessary to consider the effects of carbon emission price on holistic benefits. Currently, carbon emission prices are commonly used to compare technologies and building life cycle analysis [62]. Since 2010, Japan has begun promoting the application of carbon tax. Carbon emitters need to refer to the original carbon footprint and reduce their emissions year by year according to a fixed target (first stage from 2010 to 2014, the second stage from 2015 to 2019). The World Energy Outlook (WEO) has present the prediction of future carbon tax changes, the carbon tax shows an upward trend from 2020 to 2040, and three case of carbon tax were shown in Table 6.9. Keep the equipment prices steady and introduce the carbon tax as the only variable into the system to calculate the economic performance, the change in the NPV of the VPP after introducing carbon tax are presented in Fig. 15. The life cycle of VPP system was set 30 years, it need invest 3 times of HEA, and 2 times of ESS system. When the NPV is greater than 0, it means the VPP system starts to generate revenue. With the increase in the price of carbon tax, the payback period shows a trend of shortening year by year. This is because after the introduction of the VPP system on the demand side, CO_2 emissions have been reduced, leading to an increase in operating profit and shorten the payback period. When carbon tax is 2.18, the payback period of VPP is reduced from 18 years to 9 years. And it shows When the price of carbon tax reaches 15.23 JPY, the payback period is reduced more than half (about 5 years) compared to the original situation (14 years).

Table 6.9. Carbon tax

	Case1	Case 2	Case 3
Carbon tax (JPY/kWh)	2.18	10.88	15.23

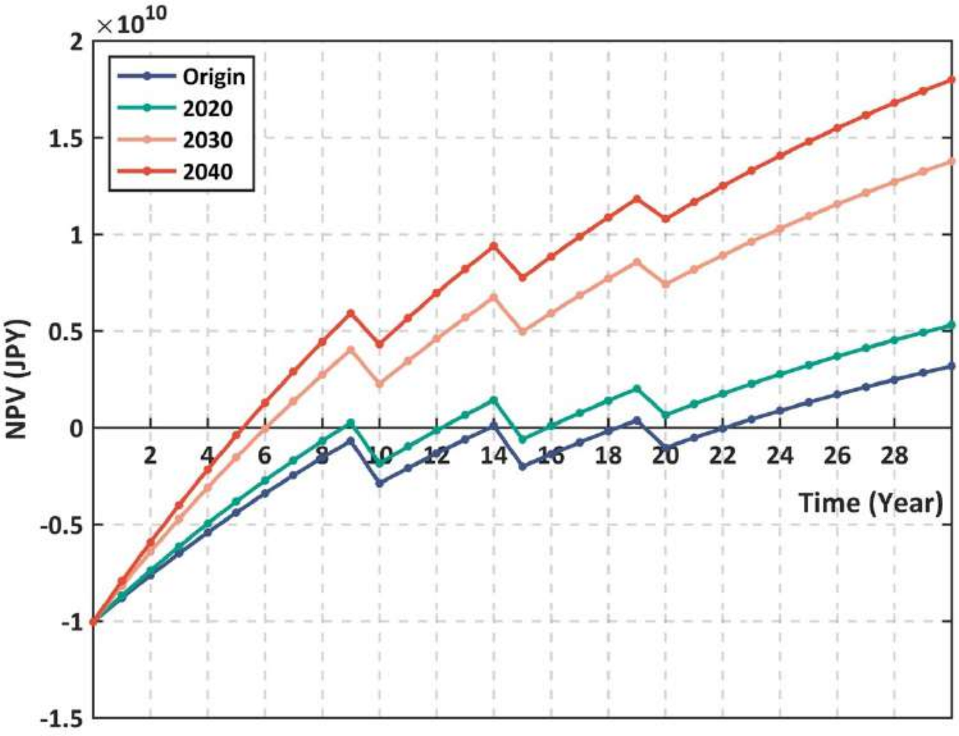


Fig. 6.15 Net present value of VPP with different carbon tax

6.5.3 Equipment price

The equipment price plays an essential role in the formation of the VPP. There is a great deal of uncertainty in the costs chosen for economic evaluation, especially the cost of capital investment. This uncertainty can significantly affect the economic performance of the system and potentially alter the economic advantages between them. Currently, the price of PV and ESS equipment is relatively high. In recent years, in order to promote the DES to more buildings, the prices of PV and ESS have also been declining year by year with the efforts of the Japanese government. The price of PV is expected to drop to 150,000 JPY/KW within 10 years, and the price of ESS will drop 5,000 JPY/kWh [63]. On the basis of this situation, the ROI of VPP regarding the initial cost decrease in the lighting, AC, PV and ESS is calculated, and the result were shown in Fig. 6.16. When the price of equipment decreased, the ROI of the entire VPP system was increased. The lines show the change of ROI with the different technologies' price decrease while other equipment price remains unchanged, the price of lighting has the most significant impact on ROI, with the decrease of lighting price, the ROI of lighting increases rapidly. And the green line shows the ROI of PV also increased with the price decreased. Good returns from falling equipment prices show a bright future for VPP.

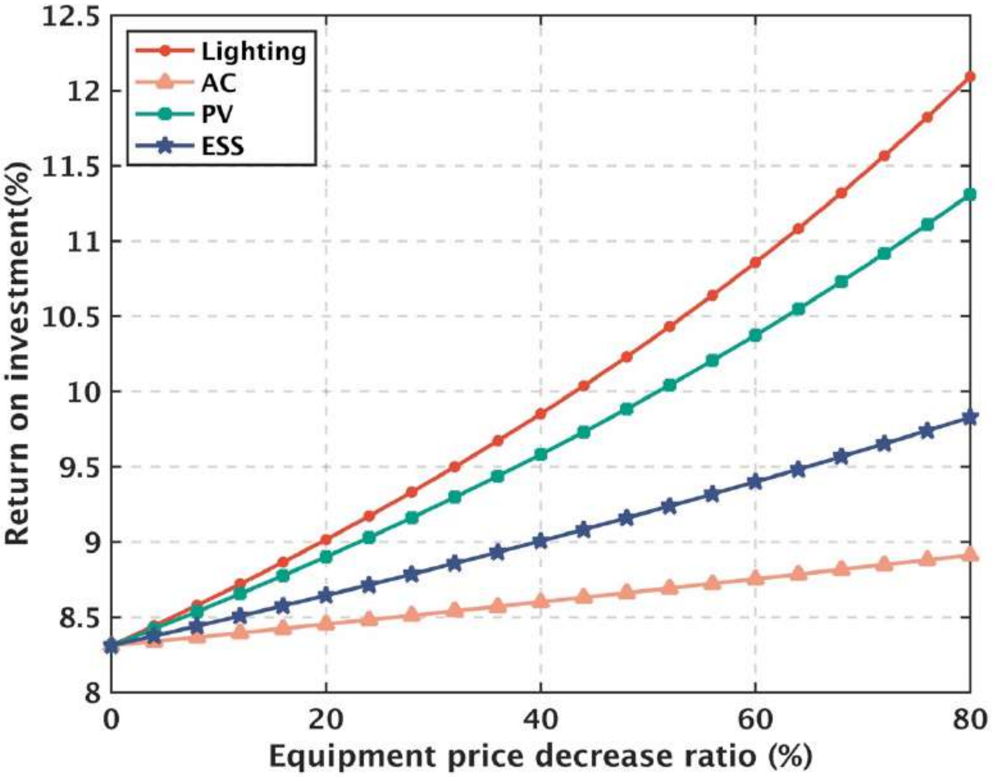


Fig. 6.16 ROI of VPP with different equipment price

6.6 Conclusion

This paper proposes an optimized VPP model comprised of HEA, PV and ESS, with the goal of energy self-sufficiency. Then the effectiveness of the VPP in reducing electricity demand from the power grid is verified based on real-world case study. The techno-economic feasibility and the adaptability performance of VPP in different buildings are evaluated. And the environmental benefits of VPP is confirmed. Based on this study, the following conclusions can be derived:

1) The proposed VPP model in this research promotes the realization of regional energy self-sufficiency and the peak shaving rate can up to 42.55%. The economic evaluation shows that VPP can bring electricity bill saving of 825 million JPY/Year for Higashida area smart community. Compared with a conventional power plant, VPP can contribute 16.26% annual carbon emission reduction for the community.
2) In different building sectors, VPP brings the highest economic benefits and the best adaptability to residential buildings. In general, upgrading high efficiency AC has better economic benefits than lighting. Install PV in commercial, office and public buildings are more beneficial than other buildings. The installation ratio of PV system has a greater impact on ROI than other technologies.
3) The introduction of carbon tax could significantly increase the economic benefits of VPP. As the price of FiT continues to drop, it is better to self-consumption than sell PV power to the grid. With continuous increase of electricity price in Japan, the future operation of

VPP will be more economical. Moreover, the main obstacle to more widespread implementation of VPP remains the expensive investment costs. When the costs of these key components fall in the future, the market competitiveness of the proposed VPP system can be enhanced.

The findings of this research have high practical reference value. This is particularly important in the context of the decarbonization revolution of the power system.

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Chapter 7

EVALUATION OF ECONOMIC BENEFITS OF VIRTUAL POWER PLANT BETWEEN DEMAND AND PLANT SIDES BASED ON COOPERATIVE GAME THEORY

CHAPTER 7: EVALUATION OF ECONOMIC BENEFITS OF VIRTUAL POWER PLANT BETWEEN DEMAND AND PLANT SIDES BASED ON COOPERATIVE GAME THEORY

7.1 Content

As most distributed energy resources (DERs) are accessible in urban areas, interest has increased in regard to evaluating the potential advantages from introducing virtual power plants (VPPs) comprised of DERs into such areas. A VPP provides a solution for improving an energy self-sufficiency rate, as an alternative to expanding the capacity of a conventional power plant (CPP). This research proposed a comprehensive method for analyzing the feasibility of using a VPP to benefit both the plant and demand sides. First, the energy-saving potential of a VPP composed of a photovoltaic (PV) and energy storage system (ESS) was explored, based on historical monitoring data in a Japanese smart community called Higashida District (with a size of approximately 1.2 km2). Second, the economic performance of the VPP was evaluated based on a payback period and total life cycle cost analysis. Then, considering the imbalance of the benefits between the demand and plant sides, cooperative game theory was applied to explore the cooperation potential. The influence of government subsidy policies on both the plant and demand sides was a simultaneous concern. Finally, the profit of the alliance, comprising both the demand and plant sides was allocated, based on the Shapley value. This study highlights the excellent energy-saving potential from implementing a VPP. The results show that there is substantial economic cooperation potential between the demand and plant sides. In addition, both the plant and demand sides have better profits in cooperative games than with non-cooperation. This research provides policy guidance for the Japanese government to promote VPPs in the future and provides a solution for coordinating the profit allocations of the plant and demand sides.

7.1.1 Background

The current energy crisis is one of the main problems facing humankind [1]. Energy, such that from electricity, gas, and petrol, is indispensable for human life, and supports our societies. Achieving sustainable energy and a low-carbon supply are currently concerns for all countries worldwide. Distributed renewable energy systems in homes, commercial buildings, and industry are expected to flourish, bringing significant changes to power systems. These changes are particularly driven by the increasing availability of renewable energy, advances in digitalization, and growing opportunities for electrification [2]. The rapid rises in consumers' abilities to generate their own electricity presents new opportunities and challenges for electricity providers and policymakers worldwide.

Japan, as a country that lacks resources such as oil and liquefied natural gas, requires various measures to secure a stable supply of energy. The energy self-efficiency ratio of Japan in 2017 was 9.6%. Since the Fukushima crisis, electricity prices have risen several times, owing to the increased utilization of thermal power generation to mitigate the impact of nuclear power plant shutdowns. This situation is also attributable to rise in fuel prices (until 2014). Compared with the prices before the Fukushima crisis, household electricity prices increased by approximately 16% in 2017, and industrial electricity prices rose by approximately 21% [3]. With the Fukushima crisis as the turning point, the restriction of the electricity supply is becoming increasingly evident, and the importance of countermeasures such as energy saving and peak reduction on the demand side is also increasing. With the gradual increase in popularity of various types of renewable energy, such as solar energy, wind energy, and geothermal energy, a new concept, called the virtual power plant (VPP), has been proposed. As an alternative to a conventional power plant (CPP), a VPP provides an avenue for resolving the problems in achieving energy self-sufficiency in regional areas.

7.1.2 Previous research

The VPP will play an important role in the development of smart grids in the future. At present, the concept of the VPP is still relatively new. The concept of a VPP was firstly introduced by V. K. Dielmann. et al. [4], aiming to overcome the issues regarding the participation of distributed energy resources (DERs) in system operation. The VPP also was defined as an effective option for aggregating and operating DERs so as to allow them to participate in wholesale energy markets, and to provide the flexibility and associated grid services required in a renewable-rich energy system [5]. K. Mahmud.et al. [6] defined a VPP as an advanced automated power plant that combines variously distributed generators, battery storage units, and prosumers with a demand response capability, thereby forming an exceptional power plant. VPPs can be classified into two types: commercial VPP and technical VPP [7].

A considerable number of studies have primarily focused on technical perspectives, such as smart grid control [8-10], the structure of the VPP[11, 12], and power quality and load support based on distributed energy storage (DES)[13, 14]. S.M. Nosratabadi. et al. [15] presented a comparative study of VPPs and microgrids considering various DES systems. S. Monie. et al. [16] explored how a VPP in a local residential area with single-family houses could provide power balancing services to a power system with large shares of variable renewable electricity generation sources. W. Guo. et al. [17] proposed a new optimal dispatching method for electric-thermal interconnected VPPs considering market transaction problems. L. Ju. et al. [18] applied a stochastic chance-constrained planning method to build a multi-objective optimization model for VPP scheduling, considering the uncertainties and demand response. However, in these studies, the financial implications have mostly been ignored. In fact, without economic profits, a VPP cannot deploy its technical flexibilities. In terms of economic analyses of the VPP, most studies have been conducted with an aim to maximize the profits of the VPPs participating in the energy market. Z. Li. et al. [19] discussed the feasibility of introducing a VPP in China based on technological and economic aspects. M. Loßner. et al. [20] discussed the economic performance of a VPP in the German energy market. In [21], a transactive energy framework was modeled to manage and schedule DERs, so as to maximize the overall benefit of a VPP in day-ahead and real-time energy markets. Y. Liu. et al. [22] combined interval and deterministic methods to design a scheduling model for maximizing the operating profits of VPPs. L.F.M. van Summeren. et al. [23] adopted a multiple-methods approach to explore the community-based VPPs as a novel model for energy provision. F. Fang. et al. [24] developed a novel method of profit allocation for multiple DERs co-existing in a combined heat and power-virtual power plant. S. Hadayeghparast. et al. [25] proposed a model for managing the energy of a VPP, focusing on maximizing the expected day-ahead profit of the VPP and minimizing the expected day-ahead emissions. Y. Li. et al. [26] analyzed the economic feasibility of a VPP by constructing a renewable energy power plant and updating high efficiency appliances located on the demand side. Many researchers have also focused on bidding strategies for VPPs. X.Kong et al. [27] focused on the optimal scheduling for a multi-operator VPP considering the fluctuation costs and penalties in the bidding mechanism. H.T. Nguyen. et al. [28] presented a mathematical model for an energy bidding problem of a VPP participating in a regular electricity market and intraday demand response exchange market. J. Zapata Riveros. et al. [29] focused on developing a bidding strategy for a VPP composed of a combined heat and power plant with district heating and renewable energy source (RES) generation to maximize the profit and cover the heat demand, as well as to compensate for possible forecast errors in the RES-based generation.

Based on the aforementioned studies, the economic performance and cooperation potential of a VPP may be underestimated on the demand side. There is a lack of studies on how to achieve win-win cooperation between the power plant side and demand side after the introduction of the VPP. To address the knowledge gaps identified above, we propose a comprehensive method for analyzing the feasibility of a VPP for both the plant and demand sides. The key and novel contributions of this study are as follows.

- A real-world urban VPP feasibility study is conducted based on the Higashida District under development in Japan, with the goal of energy self-sufficiency.
- The energy-saving and economic potential for the demand side when introducing the VPP are identified.
- Shapley value-based cooperative game theory is applied, aiming to benefit both the plant and demand sides.
- Policy and financial references are provided for promoting VPP development under similar structures for markets/regimes.

The remainder of this chapter is organized as follows. Section 2 briefly describes the research objectives. Section 3 introduces the methodology used in this study. Section 4 explores the energy-saving potential of the VPP and investigates its economic performance. A cooperative analysis is presented in Section 5. Finally, Section 6 concludes the paper.

7.2 Research Object

The following section is a brief description of Higashida District, mainly in regard to the geographical scope and power supply and demand situation.

7.2.1 Introduction of Higashida District

Higashida District is located in Yahata Higashi, Kitakyushu City, Fukuoka Prefecture, Japan. It covers an area of 1.2 km2. As of 2012, there were 1000 residents, 6000 employees and 10 million visitors per year. Fig.7.1 shows the location of Higashida District. Higashida District was selected as the implementation site for the Kitakyushu Smart Community Creation Project from 2010 to 2014. This project was aimed at energy self-sufficiency and preventing global warming, along with building a low-carbon society. Now, it is transforming from the birthplace of modern industry to the origin of the green revolution. The Higashida District is characterized by a combination of factories and streets, and regional energy supply centered on co-generation. In addition, local residents and organizations are committed to realizing the transformation from consumers who only uses energy to consumers who produce energy.

Fig.7.1 Geographical scope of Higashida District

7.2.2 Power supply and demand situation

As shown in Fig. 7.2, household users account for 39% of the region's total energy consumption. Office users account for 34% of energy consumption. The electricity demand in Higashida District in 2013 is shown in Fig.7.3. It is clearly that the power load has exhibits evident peak-valley changes. Through correlation analysis, it can be seen that the trends of the daily energy consumption are similar. The peak of electricity consumption mainly occurs in summer; in 2013, the annual peak electricity consumption reached 55,784kW, with a self-production power 33,000kW.

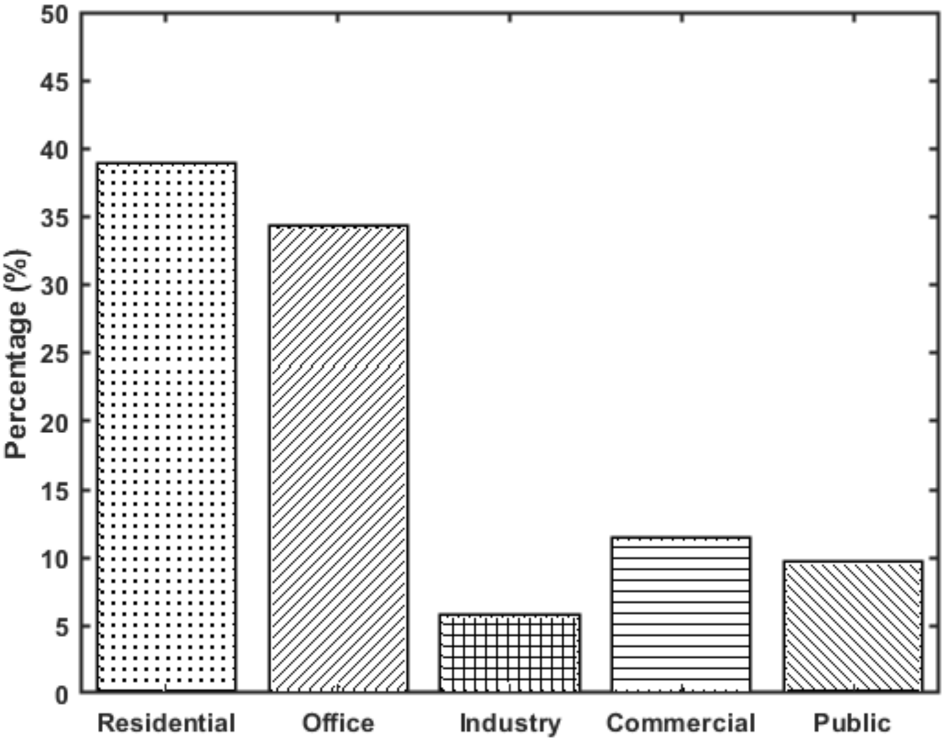

Fig.7. 2. Energy consumption of different sectors

Thus, based on 2013, a new power plant with a capacity of 22,784 kW would need to be built to meet the requirements for regional power self-sufficiency. However, according to the energy consumption prediction for Kitakyushu [30], the energy consumption in 2050 will be reduced by 17% relative to 2012. The main reasons for this are population decline and the spread of energy-saving appliances. It is believed that the main reason is the population decline and the spread of energy-saving appliances. In addition, in October 2020, the new Prime Minister of Japan declared that Japan will aim to reduce greenhouse gas (GHG) emissions to net-zero by 2050, and to realize a carbon-neutral, decarbonized society [31].

The long-term target of Kitakyushu city is to reduce GHG emissions within the city by eight million tons from the 2005 level (a 50% reduction) by 2050 [32]. Long-term planning strategies for energy supply options are essential for achieving energy self-sufficiency. Reaching carbon neutrality by 2050 requires steep emission reductions as early as possible and latest from 2030 onwards, and the quick implementation of a wide set of policies and measures. To achieve the desired GHG emission reduction goal, the new power supply sector should pay more attention to renewable energy.

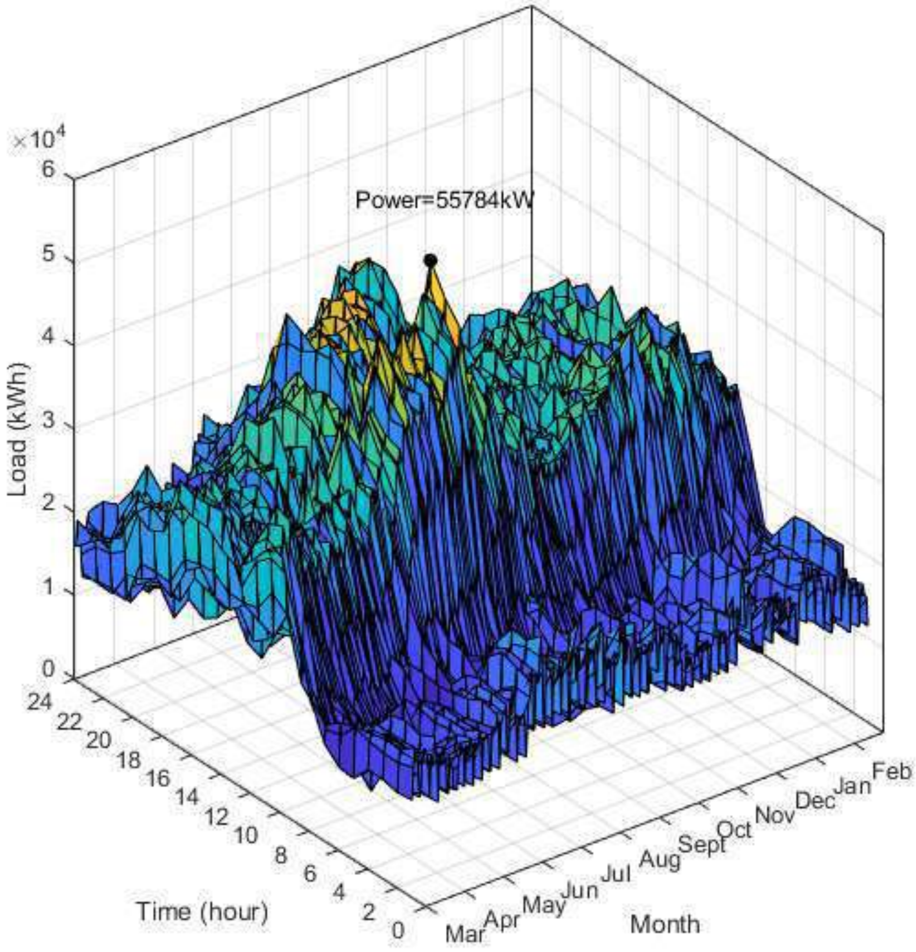

Fig.7. 3. Energy demand in Higashida District in 2013

7.3 Methodology

7.3.1 Data sources

In terms of data collection, the power load data was based on approximately 200 residential households and corporate users in Higashida District between April 2013 and March 2014. The local climate information was obtained from the Japan Meteorological Agency [33]. The research object was located in Kitakyushu City, Japan, which belongs to the power supply range of the Kyushu power grid. Therefore, we selected the corresponding electric price from the official website of Kyushu Electric Power [34]. The electricity price model we chose in the research area was the peak-valley price. The specific prices are shown in Table 7.1.

Table 7.1. Electricity price model

	Time	Commercial	Residential	Office	Industry	Public
Electricity price (Yen/kWh)	9:00-22:00	16.95	21.21	17.82	15.32	17.82
	22:00-9:00	9.06	10.15	10.49	8.59	11.89

7.3.2 Technology Method

A sustainable power supply framework should be suitable for the situation in the region. Currently, renewable energy utilization still accounts for a small proportion of the total electricity demand in Higashida District. By aggregating distributed energy generation and energy storage systems, a VPP would provide multi-facade flexibility, e.g., to accommodate the intermittence in renewable energy generation and improve the reliability of the power supply. The composition of VPP in this article mainly includes PV system and SB system. Compared with large-scale PV power generation systems, we consider installing PV on the roof of buildings, which will not restrict the location and cause too much economic burden, it is also can reduce the initial investment (Due to the shortage of land resources in Japan, rooftop PV is the best promoted in Japan.). Also, the VPP is equipped with storage battery system, the battery has two functions here: 1. Store the electricity generated by PV not consumed by the demand side; 2. Store electricity when the grid's power demand is low and discharge at the peak of grid demand to stabilize the load curve. As for we did not consider gas turbines. On the one hand, currently PV and SB systems are the most popular distributed energy system with the best effect in Japan. On the other hand, gas prices in Japan are relatively expensive, the overall economic benefits of gas turbine not so good, thus, it is rarely used on the demand side currently. Today, due to global warming, the usage of clean fuels in power systems get more importance. Regarding Japan's current GHG emission reduction goals, gas turbines use gas as fuel, cannot contribute to reducing GHG emissions, and solar energy as renewable energy source can reduce GHG emissions. Considering the above reasons, we used a combination of PV system and SB system in this paper.

7.3.2.1 Solar

At present, photovoltaic (PV) technology is the most common renewable energy generation technology. PV power generation has attracted increased attention, as it lowers the costs for introducing power generation equipment and preparing for disasters, and contributes to energy security and the resilience of energy systems [35]. Some countries (such as Jordan) have enhanced the durability, stability, robustness, and resilience of their energy sector by increasing the use of renewable energy [36]. Owing to the growing demand for RESs, the manufacturing of solar cells and PV arrays has advanced considerably in recent years, and the costs have also decreased. The solar radiation is abundant in Kitakyushu, with an annual average utilization time of approximately 1860 hours, and an average annual solar radiation of 4500 MJ/m2. The introduction of solar power generation facilities on the roofs of buildings allows for energy-saving. Table 7.2 shows the basic information of the PV used in this study. The unit price of the PV system is the average price, and includes the PV module fee, invertor fee, construction fee, and other fees.

The power generated by the PV module can be calculated using Eq. (7.1), as follows:

$$p_{pv}(t) = P_R \times \left(\frac{R}{R_{ref}}\right) \times \left[1 + N_T + \left(T_c - T_{ref}\right)\right] \tag{7.1}$$

In the above, $p_{pv(t)}$ refers to the power produced by a PV module at time (t), P_R is the rated power of the panel, and R is the solar radiation. The reference solar radiation is 1000 W/m2(R_{ref}), and the reference temperature is 25℃ (T_{ref}). The panel temperature coefficient is represented by N_T, and is equal to -3.7×10^{-3} $(1/°\mathrm{C})$ for mono and polycrystalline silicon cells. The temperature of the cell was determined using Eq. (7.2), as follows:

$$T_C = T_{\mathrm{air}} + \left[\left(\frac{NOCT-20}{800}\right) \times R\right] \tag{7.2}$$

Here T_{air}, T_C are the ambient temperature (°C) and normal operating cell temperature (°C), respectively. $NOCT$ is a specification of the cell and is declared by the cell producer. Considering the number of panels as n, the total generated power was determined using Eq. (7.3), as follows:

$$Gen_{pv} = n \times p_{pv}(t) \tag{7.3}$$

7.3.2.2 Power storage technology

Electricity cannot be stored without storage battery (SB), and for the purpose of supplying high-quality electricity, it is necessary to maintain a balance between supply and demand. The SB usually be charged in the case of a low peak load or during (reduced) electricity consumption at night, and then the energy is used in the on-peak period of the day. Owing to its unique characteristics, a SB is suitable for us solving the contradiction between the improvement of the whole grid and the economic benefit of the demand side. Likewise, the strategic charging and discharging of SBs based on energy prices and peak load demand can provide a cost-effective solution to energy needs.

In this study, we chose a sodium-sulfur (NAS) battery as a power storage technology. The

NAS battery has a large capacity and low self-discharge, and because it does not use toxic metals, it is very safe. In addition, it has a high charge and discharge tolerance, with an expected life of 15 years or approximately 4,500 charge and discharge cycles. The application range is quite large, from 600kW to tens of thousands of kW. Table 7.2 shows the basic information of the SB used in this study. In this study, the SB is constrained to work within a permissible range. The maximum possible rate of battery charge is calculated regarding SB system's capacity, and the maximum possible rate of battery discharge is computed regarding the amount of energy available within the capacity.

A crucial feature of the SB system is the time coupling characteristic related to state of charge (SOC). During the charging and discharging process, the SOC (%) dynamics are defined by Eq. (7.4) and Eq. (7.5),

$$SOC(t+1) = SOC(t) + \frac{\eta \cdot \sum_{v=1}^{u} PW(v,t) \times \Delta T}{Cap_{sb}} \tag{7.4}$$

$$SOC(t+1) = SOC(t) - \frac{\sum_{v=1}^{u} PW(v,t) \times \Delta T}{Cap_{sb} \cdot \eta} \tag{7.5}$$

Here, $SOC(t)$ denotes the state of charge of SB at time period t, η and Cap_{sb} denote the efficiency and capacity of SB, respectively. T is a time series for a day with a time-step of ΔT, and is represented as T={1,2,...,24}. v is the number of consumers. u is the set of all consumers, which is represented as u ={1,2,…,5}.

Table 7.2. Features of photovoltaic (PV) and storage battery (SB) [37-39]

PV		SB	
Life expectancy	30 years	Type	NAS
Unit price (Yen/kW)	180000	Life expectancy	15 years
Module capacity	250 w	Unit price (Yen/kWh)	25000
Module dimension	1.26 m^2	η (Charge-Discharge efficiency)	0.9

7.3.2.3 Economic descriptions of virtual power plant (VPP)

This research assumed that the life cycle of the PV system was 30 years. The life cycle of the SB system was 15 years, and it was assumed that it requires two rounds of investment. The costs and benefits from constructing the VPP were also calculated.

The benefit of the VPP comprises the electricity cost saved by the PV system and the SB system, described in Eq. (7.6), as follows:

$$BD_{total} = B_{pv} + B_{sb} \tag{7.6}$$

In the above, B_{pv} is the benefit of the PV system and can be calculated using Eq. (7). B_{sb} is the benefit of the SB system and can be calculated using Eq. (7.8).

$$B_{pv} = \sum_d \sum_t \left[PR(t) \times Gen_{pv}(t)\right] \ , \forall d \in \vartheta \, ; t \in T \tag{7.7}$$

Here, $PR(t)$ refers to the electricity price at the time t, and $Gen_{pv}(t)$ is the power generation at the time t. ϑ is the set of days $\vartheta = \{1,2,3,...365\}$, and $T = \{1,2,3,..24\}$.

$$B_{sb} = \sum_d [\Delta PR \times E_{trans} + E_{cur} \times PR(t)] \tag{7.8}$$

In the above, ΔPR refers to the peak-to-valley difference in electricity prices and is determined based on the choices of electricity plans for different types of demands. E_{trans} is the power stored by the SB, and E_{cur} is the PV curtailment based on the SB storage.

The total cost of the VPP system consists of the PV and SB construction fees, described in Eq. (7.9), as follows:

$$CD_{total} = Cap_{pv} \times MP_{pv} + Cap_{sb} \times MP_{sb} \tag{7.9}$$

Here, Cap_{pv} is the installed capacity of the PV system, and Cap_{sb} is the installed capacity of the SB system, MP_{pv} and MP_{sb} are the unit prices of PV and SB systems, respectively, and are given in Table 7.2.

7.3.2.4 Evaluation indicators

1) Net present value (NPV)

The net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is always used in capital budgeting and investment planning to evaluate the profitability of a projected investment or project. NPV accounts for the time value of money. It provides a method for evaluating and comparing capital projects or financial products with cash flows spread over time. By ignoring the operation and maintenance costs, the NPV can be determined as follows:

$$\text{NPV} = \sum_{n=1}^{j} B_n / (1+i)^n - Co_0 \tag{7.10}$$

In the above, B_n is the net cash inflow-outflow during a single period n, $n = \{1,2,3,...j\}$, and i is the discount rate. This study adopts Fukuoka Bank's annual interest rate of: 4.5% [40]. Co_0 is the initial capital cost.

2) Payback period (PBP)

The payback period (PBP) is an acknowledged indicator for evaluating the economic performance of a project and considers both the cost and revenue of the entire system. It is crucial for conducting a comprehensive life-cycle analysis of the VPP system. The annual revenue equals the sum of the revenues caused by the saved electricity cost from the direct-use PV electricity, as well as the revenue of electricity sold back to the grid. The PBP (years) can be expressed as follows:

$$PBP = (Co_{intial} + \sum_{n=1}^{m} [\frac{C_{annual}(n)}{(1+i)^n}]) / [\sum_{n=1}^{m} \frac{B_{annual}}{(1+i)^n} / m] \tag{7.11}$$

Here, m is the number of minimum years by which the total revenue of the system is larger than the total cost.

7.3.2.4 Cooperative game theory

Game theory is a mathematical tool for analyzing strategies of competitive situations in which the actions of participants influence each other's results [41]. A cooperative game is a game with competition between combinations of players (stakeholders), stress that each player should obey the agreement made by the combinations and obtain the maximum benefit of the combination through reciprocal cooperation [24].A cooperative game focuses on how to provide incentives for independent decision-makers so that they act together as entities to improve their respective status (or utility) in the game [42]. Cooperative games are also widely used in the energy market [43].

1) Parameters and experiments setting

In this research, two players were considered to participate in the game. The first is the demand side, denoted by D, and the second is the plant side, denoted by P. The set $N = \{D, P\}$ constitutes the set of players in the model, each player in the set is an independent interest individual.

The profit of different players in cooperation game can be expressed by the characteristic function $\omega(\bullet)$. When the alliance has no participants, the set is an empty set, can be defined as $\omega(\emptyset) = 0$.

When there is no cooperation, the profit of the demand side can be described as:

$$\omega(D) = \sum_{n=1}^{30} \frac{BD_{total}}{(1+i)^n} - CD_{total} \times (1 - SU) \tag{7.12}$$

In the above, SU is the subsidy rate from government.

The profit of the plant side can be described as follows:

$$\omega(P) = \sum_{n=1}^{30} \frac{Gen_{plant} \times PR_{sold} \times (1-\varepsilon) - CP_{annual}}{(1+i)^n} - CP_{total} \tag{7.13}$$

Here CP_{annual} is the power generation cost, CP_{total} is the total cost of power plant construction.

2) Profit allocation in cooperative game based on Shapley value

The Shapley value is a solution for profit allocation problems based on cooperative game theory, and is widely used in the energy field [24]. In the process of profit allocation, the allocation is made according to the increase in the marginal profit of the combination that the players participate in, so that the players who raise more revenue for the combination will be allocated additional profit. When players participate in the cooperation game, the plant side needs to provide investment for the VPP. The investment proportion of the plant side can be defined as IP, simultaneously, the power plant can coordinate the electricity price with the demand side to realize the return on investment. The rising electricity price (bargain price) is represented by BP , where ε represents the self-use rate of the plant side. The profit of the demand side can be described as follows:

$$\omega(D)' = \sum_{n=1}^{30} \frac{BD_{total}+\sum_d \sum_t [BP\times Gen_{pv}(t)]-E_{com}\times BP}{(1+i)^n} - CD_{total} \times (1 - SU - IP) \qquad (7.14)$$

The profit of the plant side can be described as:

$$\omega(P)' = \sum_{n=1}^{30} \frac{Gen_{plant}\times(\sum_t^T PR(t)+BP)\times(1-\varepsilon)-CP_{annual}}{(1+i)^n} - CP_{total} - CD_{total} \times IP \qquad (7.15)$$

The total profit of the alliance is equal to the sum of the players' profits, defined as $\omega(\{D,P\})$.

$$\omega(\{D,P\}) = \omega(D)' + \omega(P)' \qquad (7.16)$$

After participating in the cooperative game, players allocate the total profit of the alliance according to the Shapley value:

$$\omega(D)' = \frac{1}{2}\omega(\{D,P\}) + \frac{1}{2}\omega(D) \qquad (7.17)$$

$$\omega(P)' = \frac{1}{2}\omega(\{D,P\}) + \frac{1}{2}\omega(P) \qquad (7.18)$$

7.4 Preliminary

7.4.1 Energy-saving potential of VPP

The VPP in this study comprised distributed PV and SB systems installed on demand sides. In the VPP, the PV system was responsible for power generation, and the SB system was responsible for balancing the power demand and storing unused electricity based on solar power. Solar power is renewable and clean energy, so it should be used as much as possible within its capacity. We also set the SB system to store the part of the electricity left unused by the PV power generation, so the selling-to-grid power price of the PV power was not considered. The capacity of the VPP was determined based on the installed capacity of the PV system and that of the SB system. The regional power demand was supplied by the Higashida co-generation first, and any insufficiency was compensated for by Kyushu Electric Power. There was no renewable energy power generation in the Higashida District.

The configuration capacity of the PV system was related to the roof area for installation. Most of the buildings in Higashida District have flat roofs. Table 7.3 shows the roof areas of different types of buildings. It was assumed that 15% of the roof areas were occupied by chimneys and ventilation ducts or were shadowed from surrounding buildings, and that 35% of the roof area were considered as maintenance access. Therefore, the maximum installation ratio of the area on the roof where the PV panels could be installed was 50%. Therefore, the maximum installed capacity of the PV system was calculated as 13085 kW. The profit of the PV system could be considered as equivalent to the electricity cost saved during the working period of the PV system.

Then, we studied how to match the SB after PV installation to achieve the maximum economic benefit. To explore the best combination of the PV and SB systems, we calculated the potential peak shaving effect when the PV installation was 25%, 50%, 75% and 100%, respectively, as matched with SBs with different capacities. The results are shown in Fig. 7.4. First, it can be seen that the peak shaving effect of the PV is determined by the installed capacity. The peak shaving effect increases with an increase in the PV capacity. Therefore, we chose to install a 13085 kW PV system. With a 100% installation capacity of the PV system, as the SB capacity increased, the peak power value first decreased, and then increased. When the peak shaving ratio reached a maximum, the capacity of SB under this condition was 123,000 kWh. Table 7.3 shows the final installed capacities of the PV system and the SB system.

We chose a winter week and a summer week to explore the effect of the VPP peak shaving effect. The results are shown in Fig. 7.6. It can be seen from the blue line that the demand is mostly concentrated during the daytime from 9 am to 7 pm, from Monday to Friday, and the peak demand is likely to be experienced in the summer, owing to the high space cooling requirements. The winter months have a lower electricity demand. And the demand load after the PV generation is shown in black solid line in Fig. 7.6. According to solar irradiation in Fig. 7.5, solar energy production in summer is higher than that in winter, owing to the longer duration of total sunshine in summer, and the higher sunshine intensity. And the effect of the SB system is plotted in the red line in Fig. 7.6 which shows the final demand load after the introduction of the VPP. In this study, SB performance is implemented in MATLAB by using Eq. (7.4) and Eq. (7.5), based on the principle of load levelling. For more details of the principles, please refer to Ref. [44]. Therefore, the demand side can save more energy in summer than in winter. The maximum peak shaving rate can reach up to 40.1%. As a result, the capacity of the VPP is 22,382 kW. The following study was based on the simulation result of the VPP that we have proposed.

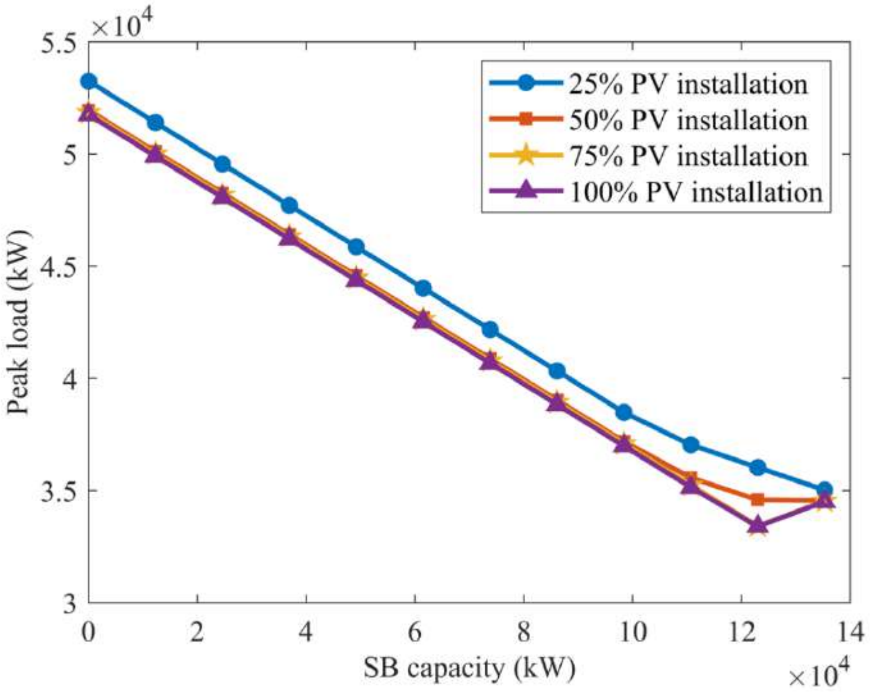

Fig.7. 4. Influence of the installed capacity of photovoltaic (PV) and storage battery (SB) on the peak shaving effect

Table 7.3. Roof area, PV capacity, and SB capacity of different types of demands

	Roof area (m^2)	PV (kW)	SB (kWh)
Residential	36258	2317	86493
Office	23546	1517	18251
Industry	12535	797	0
Commercial	91944	5910	20478
Public	39594	2544	0
Total	203877	13085	123000

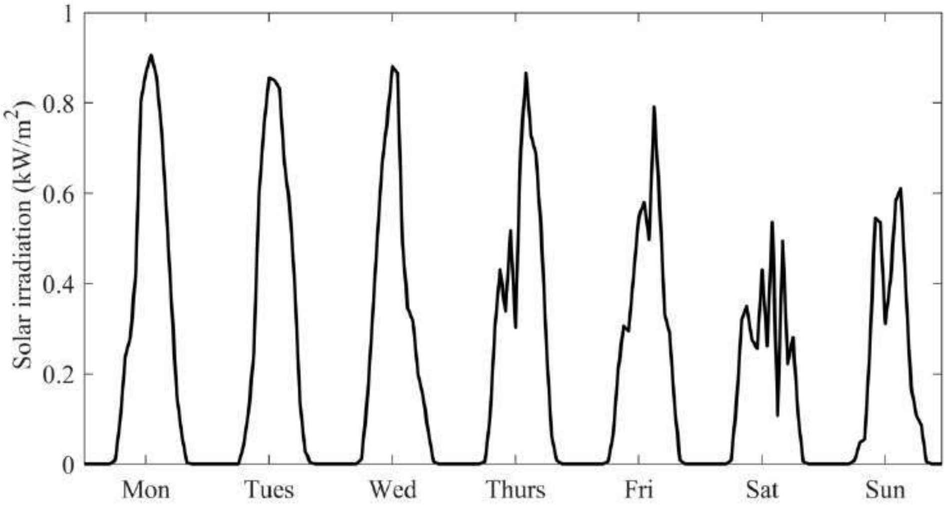

Fig. 7.5. Solar irradiation of typical weeks: (a) a summer week.

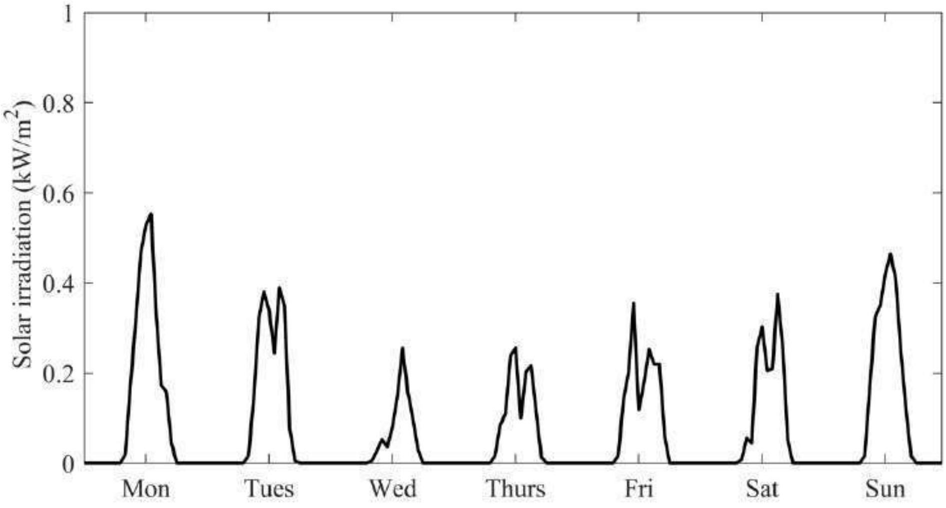

Fig. 7.5. Solar irradiation of typical weeks: (b) a winter week.

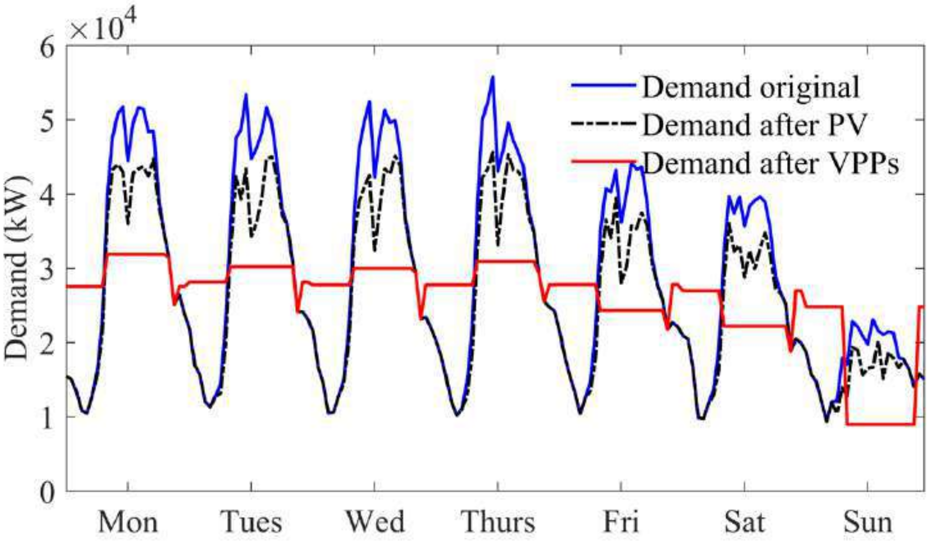

Fig. 7.6. Peak-shaving effect of virtual power plant (VPP): (a) a summer week.

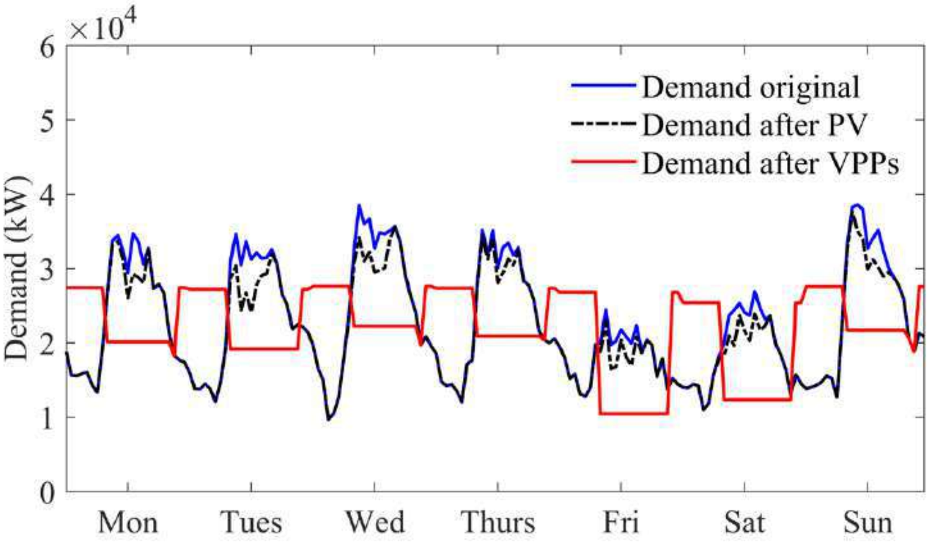

Fig. 7.6. Peak-shaving effect of virtual power plant (VPP): (b) a winter week

7.4.2 Economic performance analysis of VPP and CPP

In an actual project, equipment investment is often a major concern. Therefore, after the formation of the VPP, we will compare economic performance of the VPP and CPP based on total life cycle cost analysis. Fig. 7.7 shows the NPV of the VPP and CPP within 30 years. In terms of the price of the VPP system, we chose the current equipment price and the lowest price forecast (reduced by half) for the future market. As illustrated in Fig. 7.7, the blue line is the original state of the VPP, indicating that although VPP has benefits, owing to the high initial investment, the system itself cannot payback its costs in its life cycle; the PBP for the VPP is much longer than that for the CPP. However, when the VPP system price is reduced to half of the original price, as the red line shows, the VPP has a fast PBP of 15 years. Thus, price decreases in the PV and SB systems will make this VPP more economical and environmentally attractive. As the green line shows in Fig. 7.7, under the assumption the electricity price remains the same, the construction of a new CPP will reduce the effective use hours of the plant side, the power plant's profit will decrease, and the PBP will become longer.

However, with the construction of the VPP, the power plant side supplies less electricity to the demand side. Furthermore, because of the SB system's energy arbitrage operation mode, the average purchase price of electricity on the demand side decreases. In the long run, this will lead to a significant reduction in the plant side's profit. Under these circumstance, the plant side's electricity sold income fall will by 3.7 billion Yen (approximately 34 million $, 1 U.S. dollar = 108 Yen) within 30 years. As a result, the plant side will achieve profit growth by increasing the electricity price, which will harm the demand side's profit. Evidently, the two parties cannot achieve a balance of profits.

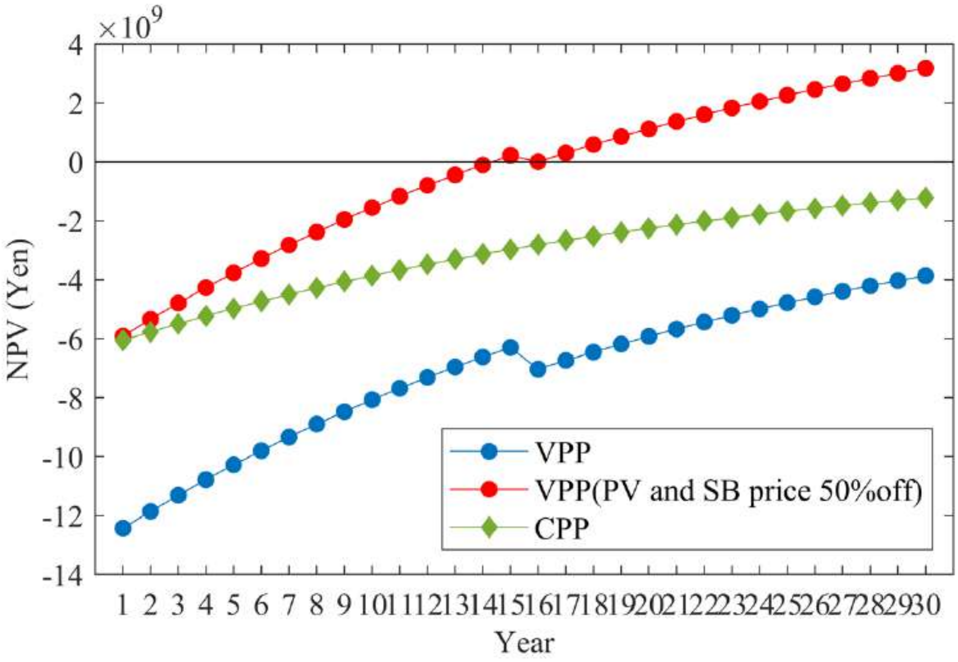

Fig. 7.7. Net present value (NPV) of VPP and CPP

7.4.3 PBP Analysis of subsidy effect and equipment price

Previous research on the economic performance of the VPP has shown that both the equipment price and financial support play essential roles in the construction of the VPP. Thus, the influence of the subsidy on PBP is analyzed in the following section. The blue line in Fig. 7.8 reveals that there is a gradual decrease in the VPP's PBP with an increase in subsidies. To recover the cost within 30 years, the subsidy needs to reach at least 26.01%. What can be clearly seen in this figure is the sharp decrease in the PBP when the subsidy rate is within 30%~60%The PBP when the subsidy is between 60~100% is drop more stable than 0~30%. However, if the equipment price is reduced by half, as shown by the red line, even if there is no subsidy, the VPP can be paid back within 16 years.

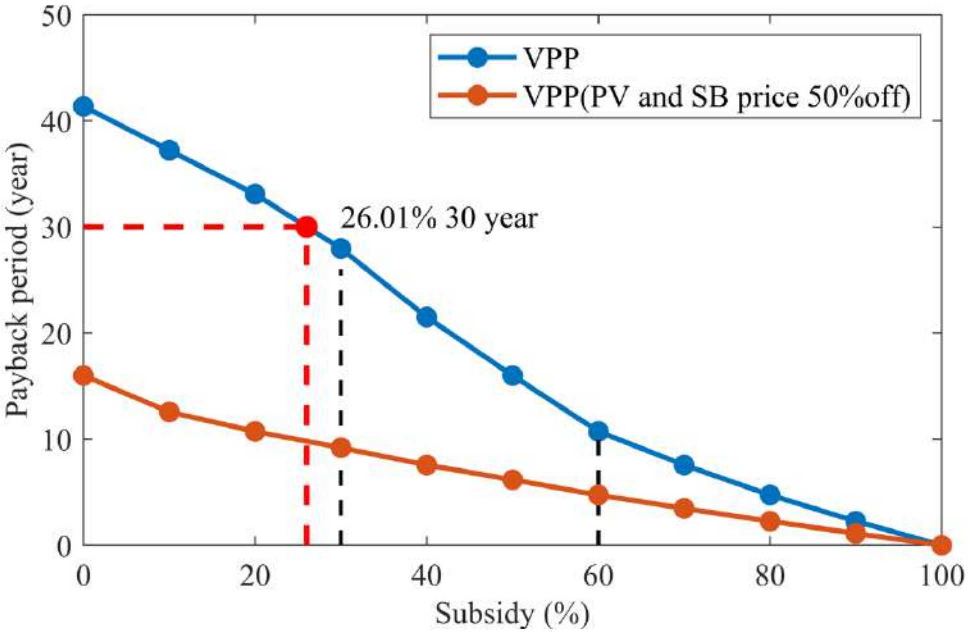

Fig. 7.8. Payback period performance of VPP under different financial subsidies and different equipment prices

7.4.4 Cooperative game

Fig. 7.9 shows the relationship structure of the VPP between the demand side, plant side, and government. The government plays an essential role in VPP construction. The government makes laws into effect and regulates rules, impacting both the demand side and plant side willingness to build the VPP. First, the government has a demand for energy self-sufficiency in Higashida District. At present, the Higashida co-generation is insufficient for meeting the demand for electricity for the entire area. Therefore, it is necessary to expand the capacity of the power plant. Second, to promote the construction of an environmentally friendly society, the Japanese government is vigorously promoting renewable energy, and subsidizing users who install renewable energy equipment. Finally, the imbalance of peak and valley power consumption on the demand side leads to the power plant side adjusting its power generation according to external demand, resulting in uneconomical power plant operation. These three reasons make the three parties seek a more efficient and low-pollution power supply method. The introduction of the VPP can save electricity purchases on the demand side and reduce GHG emissions, while replacing the expansion (or construction) of CPPs as an option for meeting the regional electricity demand.

To make both the plant side and the demand side profitable, based on the electricity market, an appropriate payment mechanism between the plant side and demand side is essential for encouraging the formation of the VPP. We adopted the cooperative game theory to analyze the cooperation potential, and to ensure the fairness of the profit allocation of each player. The players in the game are no longer in purely competitive relationships, avoiding the overall inefficiency of players owing to mutual competition in non-cooperative games. In terms of profit allocation, we adopted the Shapley value method, which is widely used in profit allocation.

Based on balancing the economic profit properly between both the demand and plant sides, the following part analyzes the VPP's performances by changing the investment from the plant side and corresponding bargain electricity price for the demand side under different government subsidy policies. Cooperative games always focus only on the cooperation result, without considering the details of the negotiation between players. In this cooperative game model, we considered two players participating in the game. The first was the demand side, and the second was the power plant side. The set $N = \{D, P\}$ constituted the set of players in the model, and each player in the set was an independent-interest individual. The primary question was how to distribute profits among players in a fair and consensus-based approach.

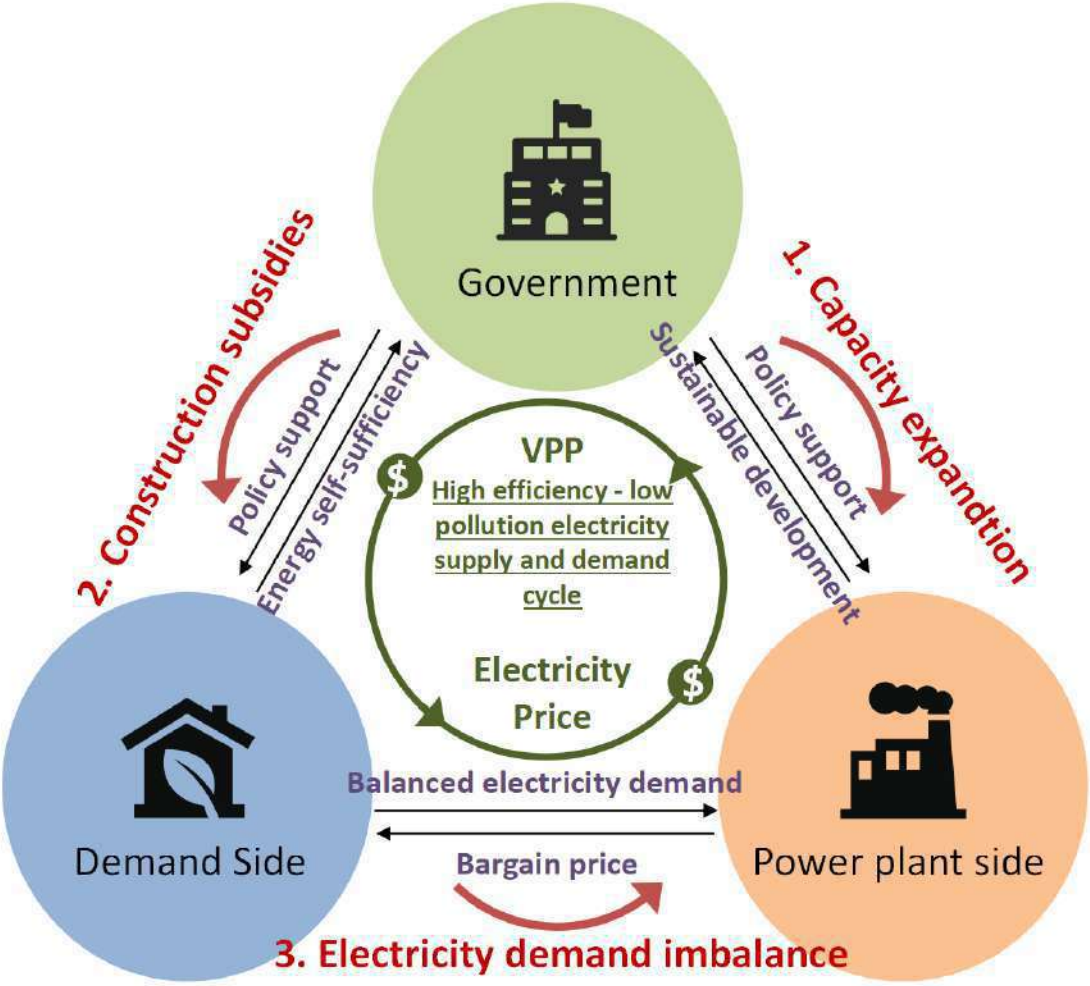

Fig. 7.9. Relationship of VPP construction between government, demand side and plant side

7.4.4.1 Influence factors of cooperative game

There were several factors that influencing the game, as follows.

1). Bargain price (BP)

We defined the BP based on the premise of cooperation between the two parties. The power plant could negotiate with the demand side to increase the electricity price (Yen/kWh). The research interval for this study is 0Yen/kWh -3Yen/kWh.

2). Investment proportion (IP)

The IP represented the power plant side's proportion of investment in VPP construction.

3). Subsidy reduction rate (SRR)

$$SRR = (Su_{max} - Su_{act})/IP, \tag{7.19}$$

In the above, SU_{max} is the maximum government subsidy for the demand side, SU_{act} is the actual subsidy received from the government, and SRR represents the ratio of the subsidies that the government can save to the proportion of plant-side investment. The increase in SRR will be accompanied by a decrease in SU_{act} or a decrease in IP.

4). GIP to IP Ratio (GIR)

$$GIR = \frac{\sum_d \sum_t [GIP \times Gen(t)]}{CD_{total} \times IP} \tag{7.20}$$

Here, GIR represents the ratio of the government's incentive cost for the plant side to the plant side's investment in the VPP. GIP (Yen/kWh) represents the government incentive price on the plant side. $Gen(t)$ represents the electricity generated by the plant side in time t. CD_{total} represents the total cost of the VPP, and IP represents the plant side's investment proportion for the VPP. The increase in GIR will be accompanied by a increase in GIP or a decrease in IP.

Therefore, the BP and IP mainly constitute the negotiable factors in the cooperation between the demand side and plant sides. To maintain profitability, the plant side limits the IP, and the demand side limits the BP. GIR and SRR constitute the factors based on government policy in the cooperative game. The government can adjust the GIR and SRR to promote cooperation between the two parties. The above factors influence each other and play a decisive role in the final cooperation.

7.4.4.2 Game rules

The profits resulting from the coalition and how to dispatch these profits fairly to the players were considered. In the game, to encourage the plant side to join the cooperation game, prerequisites were set as follows:

We adopted the maximum of Japan's current 50% subsidy policy for the VPP construction fee.

In addition, to achieve fairness in the allocation, we financially encouraged the plant side to make concessions to the cooperative. The subsidy to the power plant side was the GIP, and the GIP increased with an increase in the plant side's IP.

The profit of the plant side arose from the increase of the electricity price.

The conditions for determining the feasibility of the alliance scheme were as follows:

a. The two parties' total income after participating in the cooperative game was not less than the income in non-cooperation: $\omega(\{D,P\}) > \omega(D) + \omega(P)$.

b. The respective income of both parties participating in the game was higher than that with non-cooperation for the allocation of the profits based on the participants' contributions to the alliance: $\omega(D)' > \omega(D)$ & $\omega(P)' > \omega(P)$.

7.5 Results and Discussions

Fig. 7.10 (a) shows the influence of the government's subsidy policies on both the plant and demand sides on the feasible cooperation rate of the game. It can be seen that when the SRR is constant, with an increase in the GIR, the feasible rate of the cooperative game increases. When GIR=0, the government does not subsidize the power plant side, and regardless of how the SRR changes, the feasible rate of the game is very low. The feasible rate decreases with an increase in the SRR, because the government subsidies to the demand side decrease. The feasible rate is more sensitive to the GIR than to the SRR. Therefore, the government subsidy to the power plant side has a greater impact on the feasible rate of the game than the subsidy to the demand side. This provides a reference for the government's subsidy policy.

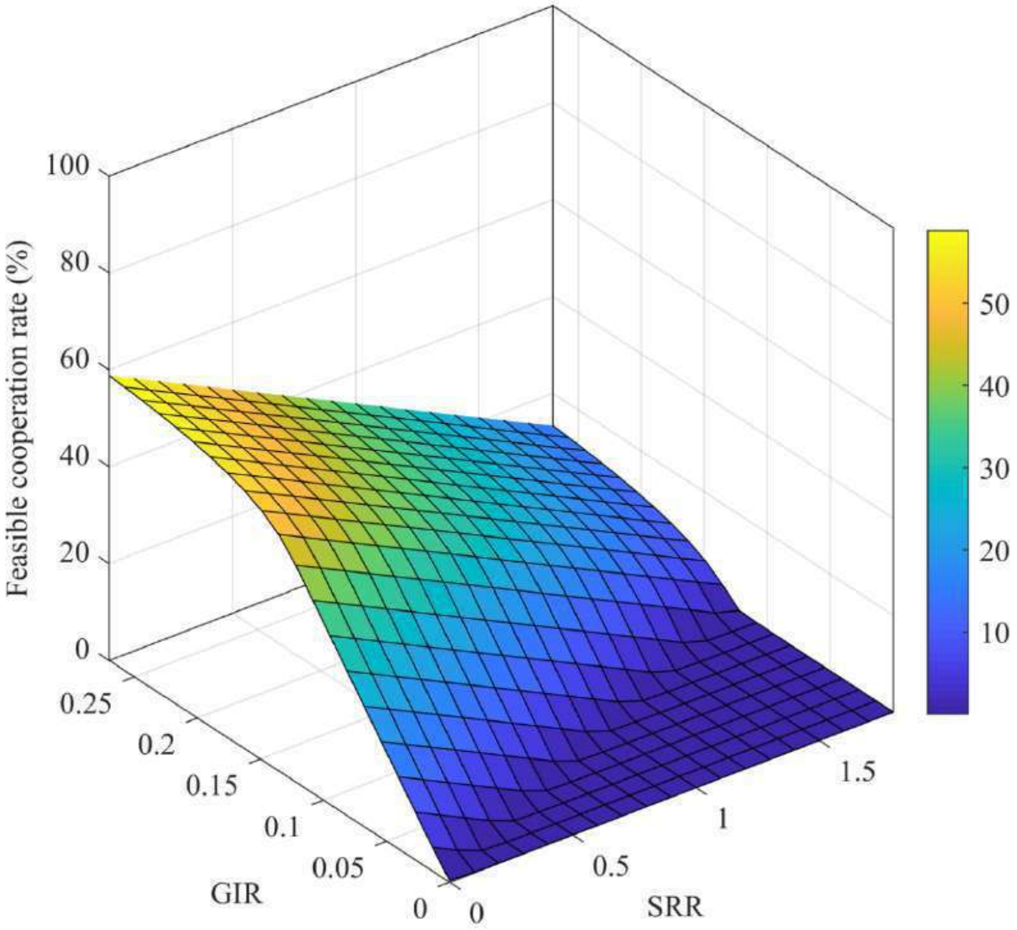

Fig. 7.10. (a) Feasible cooperation rate under different GIR and SRR

Fig. 7.10 (b) shows the feasible rate of the cooperative game between different power plant investment proportions and bargain prices, based on the different policies. In the dark blue interval, the game always fails, regardless of how the two participants coordinate. With increases in the IP and BP, the feasible rate increases. When the IP remains unchanged, with an increase in the BP, the feasible cooperative rate first increases and then decreases. However, when the BP remains unchanged, the feasible cooperative rate increases with an increase in the IP.

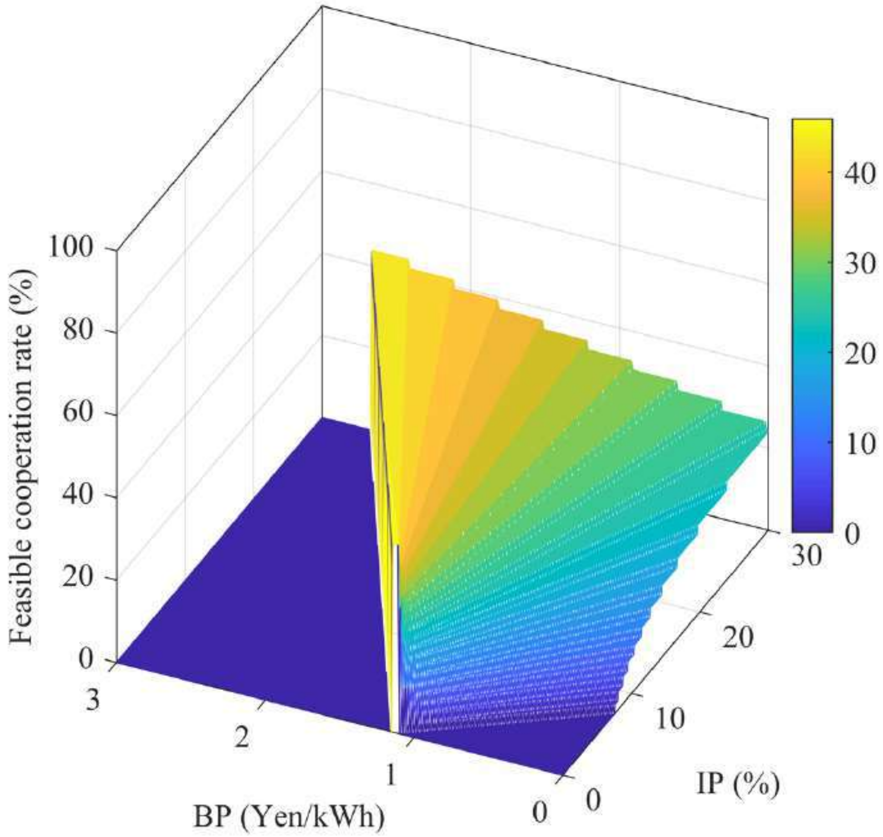

Fig. 7.10. (b) Feasible cooperation rate under different BP and IP

7.5.1 Scenario analysis

To show the proposed method more intuitively, nine scenarios are selected for discussing the profits of both the plant and demand sides under different subsidy policies. Based on the feasible rate of cooperation, three scenarios are selected, i.e., when the GIR is 0.014, 0.095, and 0.136, respectively. $GIR = 0.014$ indicates that the ratio of the government's incentive cost for the plant side to the plant side's investment in the VPP is 0.014. To observe the economic impact of the government subsidy received by the demand side, three scenarios with SRR value of 0, 0.835, and 1.67, are selected. Therefore, nine combinations are generated. Table 7.4 lists the scenarios. It is stipulated that the value increases with the lighter color, so the distribution of the data can be quickly distinguished. The black area indicates that there are no feasible cases.

Table 7.4. Scenario settings

Scenario	A	B	C	D	E	F	G	H	I
Government incentive ratio (GIR)	0.014	0.014	0.014	0.095	0.095	0.095	0.136	0.136	0.136
Subsidy reduction rate (SRR)	0	0.835	1.67	0	0.835	1.67	0	0.835	1.67

Fig. 7.11 shows the relationship between the demand side's total profit,IP, and BP under various scenarios. Under the same GIR, with the increase in the SRR, the feasible cooperative game schemes are reduced, and the profits of the demand side also decrease. Under the same SRR, with an increase in the GIR, the feasible cooperative game schemes are increased. Fig. 7.12 illustrates the relationship between the plant side's total profit in 30 years and the IP and BP under various scenarios. It can be seen that with the increase in the SRR, under the same GIR, the feasible cooperative game schemes are reduced. It means that the government subsidies to the demand side is reduced, and the feasible cooperative game schemes are reduced, and the profits of the plant side are increased. Under the same SRR, with an increase in the GIR, the feasible cooperative game schemes are increased.

The comparison between the different scenarios indicates that with the increase in the GIR, the feasible plan for both players shows a trend of increasing first and then decreasing. With the increase in the SRR, the feasible plans for both players increase. Observing a given scenario, i.e. scenario E, it can be found that under the same BP, with an increase in the IP, the profits of both sides also increase. Under the same IP, the profit on the demand side decreases with an increase in the BP. In contrast, the profit on the plant side increases with an increase in the BP. In the scenarios B and C, there is no feasible plan for players, because the GIP is too low, regardless of the subsidy received by the demand side; thus, it is impossible to realize benefits for both parties. The results from these scenarios suggest that a policy providing an incentive to the power plant side is more conductive to balancing the profits of both players.

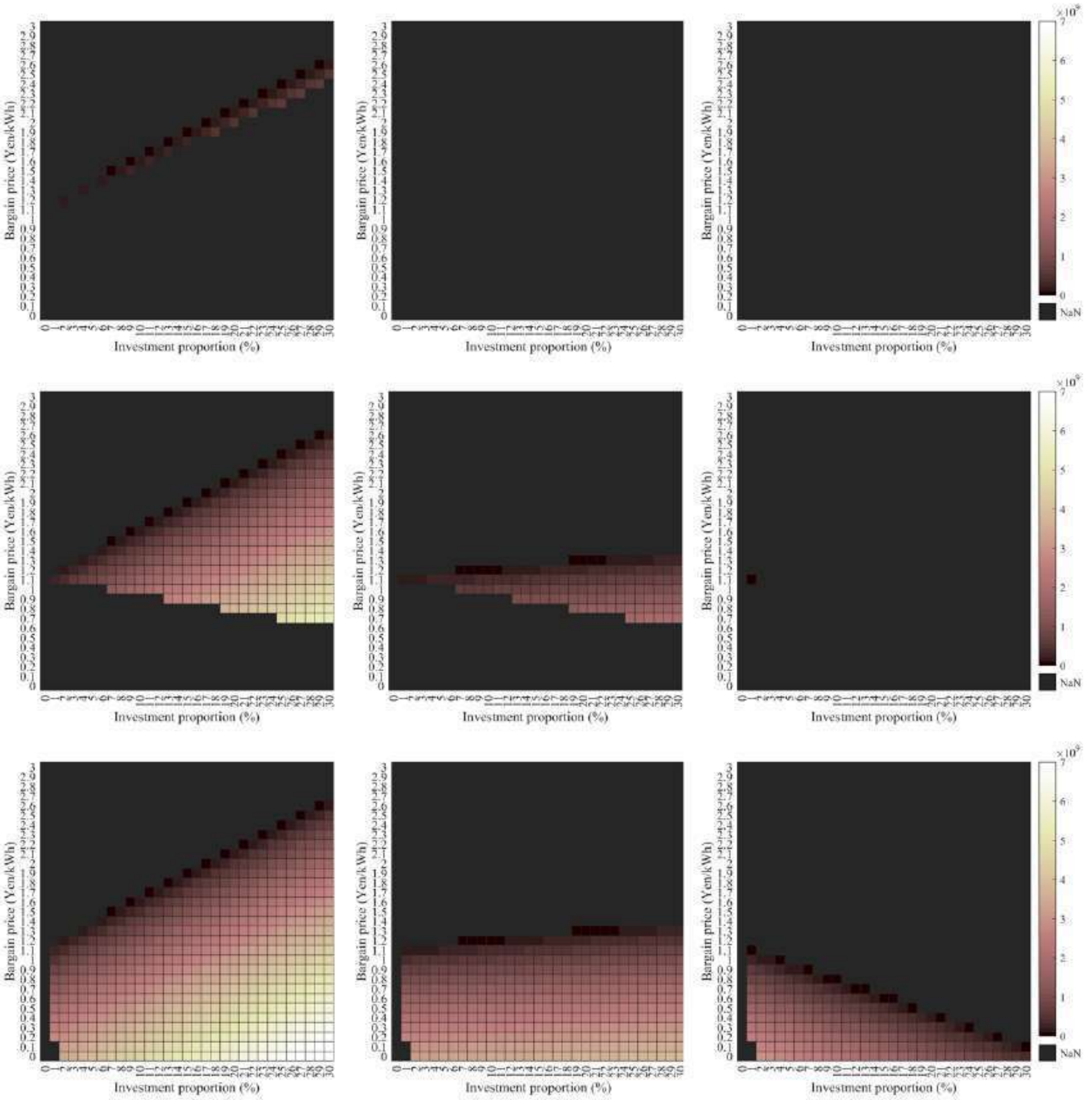

Fig. 7.11. Profit of demand side, with different BP, under different plant side’s IP.

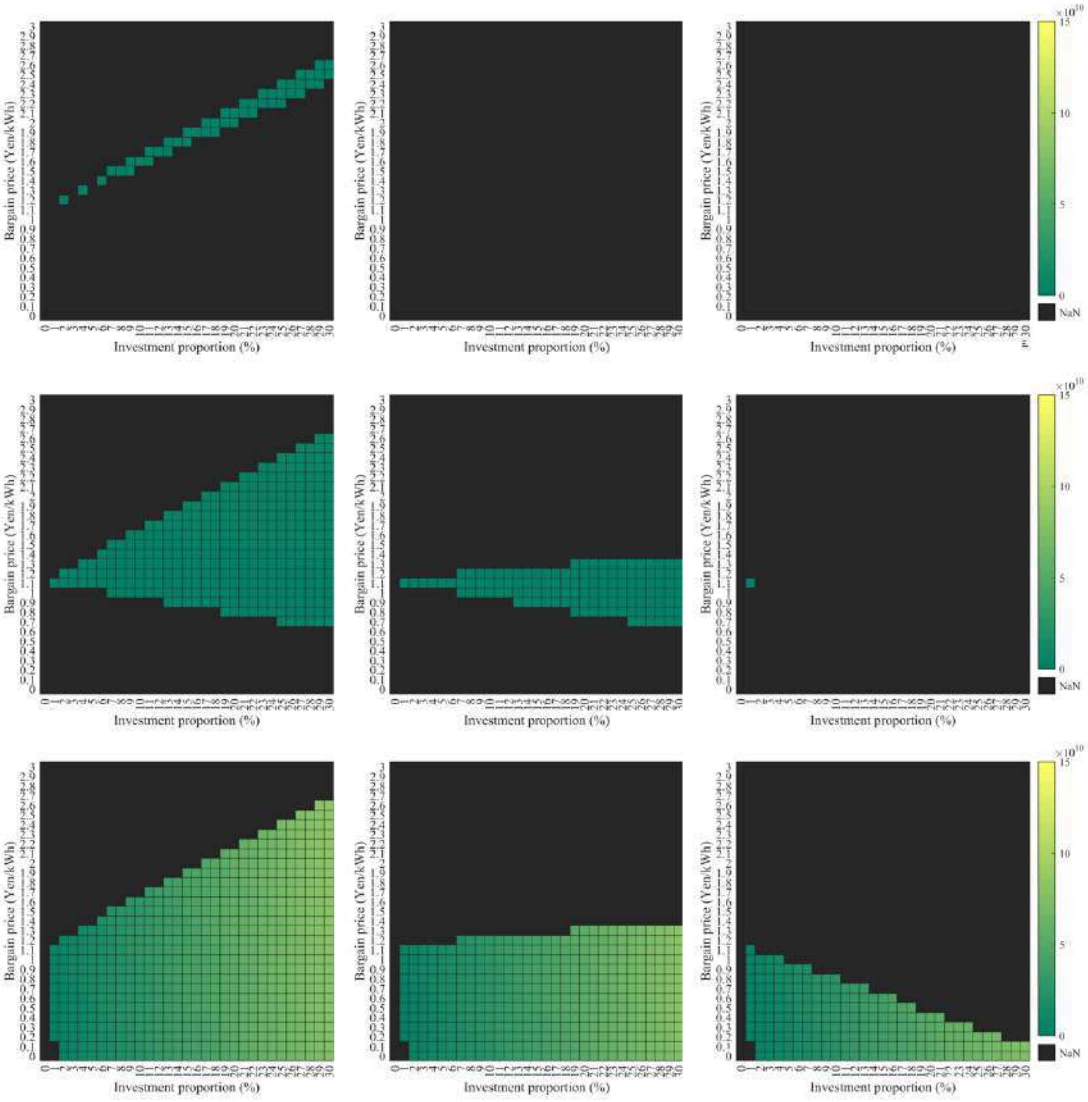

Fig.7. 12. Profit of plant side, with different BP, under different plant side's IP.

7.5.2 Profit allocation

Fig. 7.13. shows the distribution of the optimal profit allocation cases based on the Shapley value. As the SRR increases, the optimal profit distribution decreases. If the SRR exceeds 1.6, there are no cooperative plans. Fig. 7.13 also reveals that when IP is 30% from the power plant, a government subsidy of at least 2% is required for both parties to have an optimal profit allocation plan. When the SRR=0 and the GIR increases, there is also optimal profit allocation plans.

In the non-cooperative mode, without the construction of the VPP, the demand side's profit is 0, and the profit of the plant side in 30 years is 2.71 billion Yen. We choose three cooperative games from Fig. 7.13 for the case studies listed in Table 7.5. A critical value when SRR=0 is chosen as Cooperative-1. A middle value when SRR=0.8, is chosen as Cooperative-2. A critical value when SRR=1.6 is chosen as Cooperative-3. It can be readily observed that when all players cooperate, and both sides achieve their own optimal profits based on the Shapley value, the total profit increases. In fact, the plant side makes concessions to the profits of the alliance, and the plant side provides greater profits for the VPP on the demand side, under the premise of guaranteed profits. Therefore, based on the cooperative game between the power plant side and demand side, a fair profit allocation can be made based on the Shapley value.

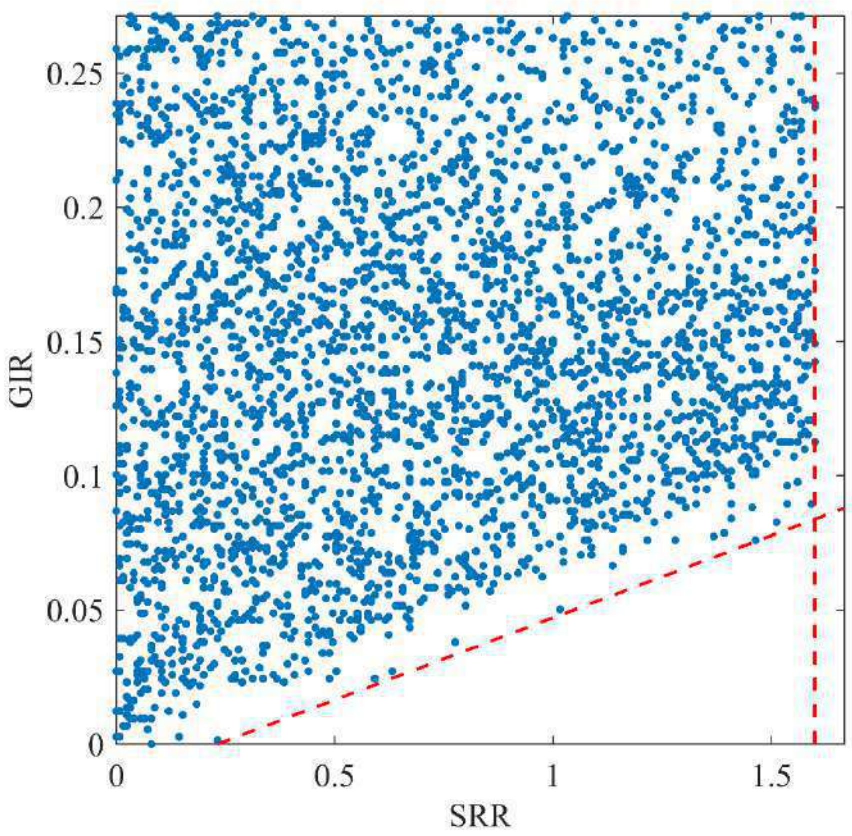

Fig. 7.13. Distribution of optimal profit allocation cases under different incentive policies

Table 7.5. Profit of the plant side and the demand side by participate in cooperative game, compared to non-cooperative

	SU (%)	GIP (Yen/kWh)	IP (%)	BP (Yen/kWh)	Profit of demand side (Yen)	Profit of plant side (Yen)
Non-cooperative	-	-	-	-	0	2.71×10^9
Cooperative-1	50	0.09	10	1.6	14.7×10^7	2.84×10^9
Cooperative-2	45.2	0.23	6	1.2	1.72×10^7	2.72×10^9
Cooperative-3	16.4	1.74	21	0.5	1.46×10^7	2.74×10^9

7.6 Conclusion

The goal of this study was to analyze the feasibility of a VPP and assess its economic benefits in Higashida District, Kyushu, Japan. First, the capacities of the PV system and SB system that could be installed on the demand side were evaluated. Then, we proposed a VPP composed of DERs on the demand side. A total life cycle cost analysis was used to analyze the economic performance of the VPP. The economic analysis showed that owing to the high initial investment required for the VPP, it would not be paid back within its lifespan. In addition, the formation of the VPP would reduce the electricity consumption of the demand side, potentially affecting the plant side's profits in the long run. Accordingly, a Shapley value-based cooperative game was used to benefit both parties. After applying the concept of cooperative game theory, it was found that the plant side could also invest in the VPP and obtain profits. Through the cooperative game, the influences of government subsidy policies on both supply and demand were deeply studied. Based on the study, the following conclusions can be drawn:

1) The technical analysis demonstrates that the total capacity of the VPP is 22,382 kW, and the peak shaving potential can reach up to 40.1%. This proves that the introduction of the VPP can effectively reduce the electricity demand of Higashida District.

2) Through cooperative game theory, two parties with conflicting interests can mutually benefit. The profits of the alliance can be fairly allocated based on the Shapley value. The profits of both the demand and plant sides increase, which verifies the economic feasibility of the VPP, and provides blueprints for promoting VPP development under similar structures in markets/regimes worldwide.

3) The government subsidy policy plays a vital role in the construction of the VPP. The results indicate that government subsidies for the plant side are more conducive to the cooperative game between the two parties. With incentive policies for the plant side, the government can reduce the initial subsidies on the demand side. This provides a reference for government subsidy policies.

4) At present, although the PBP of the VPP is longer than that of the CPP, with the expected declines in equipment prices in the future and the government's vigorous promotion of renewable energy, the PBP of the VPP will gradually be shortened. The VPP is expected to be more economical considering future trends, and VPPs have more development prospects.

The formation of the VPP promotes the use of renewable energy, making power plant operation more economical. In addition, the energy self-sufficiency rate of Higashida District will improve. Besides, the construction of the VPP will reduce GHG emissions. The results we obtained can contribute to the accelerated promotion of VPPs and provide a solution for coordinating the profit allocation for both the plant and demand sides.

Nomenclature

Abbreviations	
VPP	virtual power plant
DER	Distributed Energy Resource
CPP	conventional power plant
PV	photovoltaic
SB	storage battery
ESS	energy storage system
DES	distributed energy storages
RES	renewable-energy sources
NPV	Net present value
PBP	payback period
GHG	green house gas
Set	
t	index for time
n	index for number, n = {1,2,3,...j}
Variable	
$p_{pv(t)}$	produced power by a PV module at time t
R	solar radiation
P_R	rated power of the utilized panel
R_{ref}	reference solar radiation
T_{ref}	reference temperature
N_T	panel temperature coefficient
T_{air}	ambient temperature (°C)
$\mathrm{T_C}$	normal operating cell temperature (°C)
$NOCT$	specification of the cell
Gen_{pv}	total generated power by PV
$SOC(t)$	the state of charge of SB at time t
η	efficiency

u	the set of all consumers, u ={1,2,…,5}
BD_{total}	total electricity cost saved by PV and SB
B_{pv}	electricity cost saved by PV
B_{sb}	electricity cost saved by SB
$PR(t)$	electricity price at time t
ΔPR	peak-to-valley difference in electricity price
E_{trans}	power stored by SB
E_{cur}	PV curtailment stored by SB
CD_{total}	total cost of PV and SB
Cap_{pv}	installed capacity of PV
Cap_{sb}	installed capacity of SB
MP_{pv}	unit price of PV
MP_{sb}	unit price of SB
B_n	net cash inflow-outflows during a single period n
i	discount rate
Co_0	initial capital cost
D	demand side
P	power plant side
SU	subsidy rate from the government
IP	plant side's investment proportion for VPP
BP	Bargain price
$\omega(\bullet)$	profit of $\bullet$ in function $\omega(\ )$
SRR	Subsidy reduction rate
GIP	Government incentive price to plant side
GIR	GIP to IP ratio

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Chapter 8

CONCLUSIONS AND PROSPECTS

CHAPTER 8: CONCLUSIONS AND PROSPECTS

8.1 Conclusions

Against the background of energy shortage and secure supply requirements, renewable energy has developed 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 energy self-sufficiency rate. After the implementation of the feed-in tariff system in 2011, renewable energy ushered in explosive growth. However, the large-scale introduction of renewable energy will affect the stability of the grid, so this study is devoted to studying the interaction between community renewable energy, electricity demand, grid and energy storage system to maximize the utilization of renewable energy.

The main work and achievements can be summarized as follows:

In Chapter 1, Research Background and Purpose of the Study. Under the demand of energy shortage and safe supply, it is imperative to develop renewable energy sources. This chapter analyzes the international as well as Japan's energy situation, bottlenecks, and historical evolution. These factors lead to the necessity of developing renewable energy sources. Secondly, the development trend of renewable energy in the international and Japanese regions is summarized. The international level combines the energy structure evolution and renewable energy promotion strategies of typical countries such as the United States, Germany, Japan, and China. The Japan region details how renewable energy is entering the grid and analyzes the evolution of the energy mix in detail combining the industrial sector, the household sector, and the transportation sector. This demonstrates the importance of the power system in stabilizing energy supply and reducing greenhouse gas emissions. And it is urgent for us to find an optimal method to aggregate those renewable energy sources.

In Chapter 2, Literature Review of Virtual Power Plant. This Chapter provides a detailed review of the application of Virtual Power Plants in this research. Section 2.1 reviews the application of VPP around the world and introduced the principle of. Section 2.2 mainly summarize the previous study of VPPs, especially difference between Technical VPP and economic VPP, etc. Section 2.3 gives a detailed description and summary of the barriers and challenges of VPP. In general, the review in this section focuses on the application of VPP in the power sector.

In Chapter 3, Virtual Power Plant Model Establishment and Methodology. This Chapter describes the research methods used in this research. Firstly, introduced the technology approach involved in this research. And then, the VPP system model was established. Includes the calculation of indicators to evaluate the impact of VPP. Section 3.1 shows the technical technology used in this research. In terms of economy, the dynamic payback period of VPP system is adopted. Compared with the static payback period, the dynamic investment payback period adds a time cost.

In Chapter 4, Energy Consumption Characteristic Analysis in Higashida Smart Community. The load curve shape of the same type of buildings in four seasons is similar. The spring and autumn typical load curves are the most similar. Summer and winter load curves are similar, with similar load levels. The impact of climate on the load is mainly reflected in the air-conditioning cooling load in summer and the heating load in winter. Buildings such as museums and shopping malls have basically a stable power load during business hours. For factories and office buildings, there are obvious load troughs during lunch breaks. Load peaks of hospital typically occur at noon. For residential building, peak electricity usage usually occurs in the early morning and evening. The payback period of the PV system is related to the electricity price, the higher the electricity price, the shorter the payback period; and the profit is related to the PV capacity and electricity price. The payback period of SB is related to the electricity price difference and the amount of PV curtailment. The larger the electricity price difference, the shorter the payback period.

In Chapter 5, Feasibility, Efficiency and Economic Analysis of VPPs. As most of the distributed energy resources are available in urban areas, there are increasing interests in assessing the potential to develop urban Virtual Power Plant (VPP). This chapter aims to analyze the feasibility of VPPs through the construction of local renewable energy and energy storage technology in Higashida area. The return on investment was carried out through payback period and life cycle cost analysis. The economic performance of the power plant side and the demand side by changing the investment from power plant side and the corresponding electricity price on the demand side were analyzed. Two investment proposal were compared in the aspect of economic analysis. For power plant side, the plan of power plant side invests 1/3 of VPP construction has longer payback period than invest 1/6 of VPP construction. And the profit of 1/6 plan is higher. For demand side, the plan of power plant side invest 1/3 of VPP construction has shorter payback period than 1/6 plan, because when power plant side invest 1/3 of VPP construction, the initial investment of demand side is lower. Compared with the two-investment plan of the power plant, when the power plant invests 1/6, the adjustable range of the electricity price is larger, and the profit of plant side is higher, the electricity fee that customers saved higher too. When profit of both parties is maximized, the price difference at this time is 1.18 JPY. And the profit of power plant side is 256,616,005 JPY. Electricity price that demand side saved is 7,629,904,422 JPY. This research proposed the concept of the virtual power plants (VPPs) to increase the local power self-support in the Higashida area. The economic performance and utilization potential of PV system and SB system were analyzed based on NPV indictor and lifecycle cost analysis. In addition, feasibility analysis of power supply-demand management, considering both supply and demand side was done. Then compare the two options of investing in expand conventional LNG-fired power plant to 52830 kW and invest in VPP plus a small conventional power plant. Investigate the changes in the profits of power plant side and demand side with the increase in electricity prices when the power plants invest 1/3 and 1/6 of the VPP construction. Analysis shows when the power plant side undertakes 1/6 of the construction investment and the electricity price increases by 1.18 JPY, both the plant side and the demand side can get the most excellent returns. For power plant side, compared with the expansion of conventional LNG-fired power plant, the profit after the introduction of VPPs increase about 28.7% that of conventional LNG-fired power plant. The total increase profit of power plant side t in 30 years is 256,616,005 JPY. For demand side, compared with the expansion of 52830 kW conventional LNG-fired power plant, after the introduction of VPPs, the electricity fee that users need to pay decreased 4.8% in 30 years. The total amount of electricity fee decreased 7,629,904,422 JPY.

In Chapter 6, Techno-economic Analysis of the Transition towards the energy self-sufficiency community based on VPP. Distributed energy resources are important measures in increasing energy self-sufficiency and overcome global carbon reduction problem. However, the individual planned renewable energy generation poses a significant threat to the power grid. Therefore, virtual power plant (VPP) is attracting more and more attention as a means of aggregating distributed energy in urban areas. In this study, a VPP model consisted of updating high efficiency appliances, photovoltaic and energy storage systems was proposed. A comprehensive analysis for assessing the technical, economic and environmental benefits deriving from the VPP was presented, indicated the feasibility of a smart community to achieve power self-sufficiency with the support of the VPP. A smart community in Japan was selected as the research object, with a peak power demand of 57,350 kW. Analysis of the VPP's load leveling performance, return on investment and CO2 emission reduction are performed. In addition, external factors such as electricity price changes and FiT policies are considered to assess the impact on the economics of the VPP. This paper proposes an optimized VPP model comprised of HEA, PV and ESS, with the goal of energy self-sufficiency. Then the effectiveness of the VPP in reducing electricity demand from the power grid is verified based on real-world case study. The techno-economic feasibility and the adaptability performance of VPP in different buildings are evaluated. And the environmental benefits of VPP is confirmed. The proposed VPP model in this research promotes the realization of regional energy self-sufficiency and the peak shaving rate can up to 42.55%. The economic evaluation shows that VPP can bring electricity bill saving of 825 million JPY/Year for Higashida area smart community. Compared with a conventional power plant, VPP can contribute 16.26% annual carbon emission reduction for the community. In different building sectors, VPP brings the highest economic benefits and the best adaptability to residential buildings. In general, upgrading high efficiency AC has better economic benefits than lighting. Install PV in commercial, office and public buildings are more beneficial than other buildings. The installation ratio of PV system has a greater impact on ROI than other technologies. The introduction of carbon tax could significantly increase the economic benefits of VPP. As the price of FiT continues to drop, it is better to self-consumption than sell PV power to the grid. With continuous increase of electricity price in Japan, the future operation of VPP will be more economical. Moreover, the main obstacle to more widespread implementation of VPP remains the expensive investment costs. When the costs of these key components fall in the future, the market competitiveness of the proposed VPP system can be enhanced.

In Chapter 7, Evaluation of Economic Benefits of VPP between Demand and Plant Sides Based on Cooperative Game Theory. As most distributed energy resources (DERs) are accessible in urban areas, interest has increased in regard to evaluating the potential advantages from introducing virtual power plants (VPPs) comprised of DERs into such areas. A VPP provides a solution for improving an energy self-sufficiency rate, as an alternative to expanding the capacity of a conventional power plant (CPP). This research proposed a comprehensive method for analyzing the feasibility of using a VPP to benefit both the plant and demand sides. First, the energy-saving potential of a VPP composed of a photovoltaic (PV) and energy storage system (ESS) was explored, based on historical monitoring data in a Japanese smart community called Higashida District (with a size of approximately 1.2 km2). Second, the economic performance of the VPP was evaluated based on a payback period and total life cycle cost analysis. Then, considering the imbalance of the benefits between the demand and plant sides, cooperative game theory was applied to explore the cooperation potential. The influence of government subsidy policies on both the plant and demand sides was a simultaneous concern. Finally, the profit of the alliance, comprising both the demand and plant sides was allocated, based on the Shapley value. This study highlights the excellent energy-saving potential from implementing a VPP. The results show that there is substantial economic cooperation potential between the demand and plant sides. In addition, both the plant and demand sides have better profits in cooperative games than with non-cooperation.

The goal of this study was to analyze the feasibility of a VPP and assess its economic benefits in Higashida District, Kyushu, Japan. First, the capacities of the PV system and SB system that could be installed on the demand side were evaluated. Then, we proposed a VPP composed of DERs on the demand side. A total life cycle cost analysis was used to analyze the economic performance of the VPP. The economic analysis showed that owing to the high initial investment required for the VPP, it would not be paid back within its lifespan. In addition, the formation of the VPP would reduce the electricity consumption of the demand side, potentially affecting the plant side's profits in the long run. Accordingly, a Shapley value-based cooperative game was used to benefit both parties. After applying the concept of cooperative game theory, it was found that the plant side could also invest in the VPP and obtain profits. Through the cooperative game, the influences of government subsidy policies on both supply and demand were deeply studied. Based on the study, the following conclusions can be drawn: The technical analysis demonstrates that the total capacity of the VPP is 22,382 kW, and the peak shaving potential can reach up to 40.1%. This proves that the introduction of the VPP can effectively reduce the electricity demand of Higashida District. Through cooperative game theory, two parties with conflicting interests can mutually benefit. The profits of the alliance can be fairly allocated based on the Shapley value. The profits of both the demand and plant sides increase, which verifies the economic feasibility of the VPP, and provides blueprints for promoting VPP development under similar structures in markets/regimes worldwide. The government subsidy policy plays a vital role in the construction of the VPP. The results indicate that government subsidies for the plant side are more conducive to the cooperative game between the two parties. With incentive policies for the plant side, the government can reduce the initial subsidies on the demand side. This provides a reference for government subsidy policies. At present, although the PBP of the VPP is longer than that of the CPP, with the expected declines in equipment prices in the future and the government's vigorous promotion of renewable energy, the PBP of the VPP will gradually be shortened. The VPP is expected to be more economical considering future trends, and VPPs have more development prospects. The formation of the VPP promotes the use of renewable energy, making power plant operation more economical. In addition, the energy self-sufficiency rate of Higashida District will improve. Besides, the construction of the VPP will reduce GHG emissions. The results we obtained can contribute to the accelerated promotion of VPPs and provide a solution for coordinating the profit allocation for both the plant and demand sides.

8.2 Prospects

Japan is focus on the new development of the energy efforts through innovative energy strategy. Paradigm shift of the energy efficiency and conservation policies. Creating low-carbon power-source market and reestablishing renewable energy industries. Innovation of energy industries utilizing IoT. Establishing a strategy for creating hydrogen society toward the post-2030 era. And realization of the Fukushima plan for a new energy society.

The idea of VPP is still being promoted in Japan. The government and power plant and other related agencies are necessary to understand it. This study takes Higashida area, Kitakyushu as the research object, and the results shows a bright future of VPP.

In order to achieve the goal of building a sustainability, resilience and accessibility power plant. Changing energy to renewable energy will reduce carbon dioxide emissions and reduce climate change. Building a power network that supplements construction, storage and usage capabilities, even in the event of a disaster, it will not interrupt the energy supply. And realizing an energy platform mainly based on renewable energy and energy storage system to increase the energy self-sufficiency rate, the risk of cost fluctuations caused by changes in the international situation and rising resource prices can be minimized.

The findings of this research have high practical reference value. This is particularly important in the context of the decarbonization revolution of the power system. This research provides policy guidance for the Japanese government to promote VPPs in the future and provides a solution for coordinating the profit allocations of the plant and demand sides.