博士論文

COMPARISON AND ECONOMIC OPTIMIZATION OF DIFFERENT ENERGY SYSTEM IN SMART HOUSE

スマートハウスにおける異なるエネルギーシステムの比較と経済的最適化に関する研究

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Comparison and Economic Optimization of Different Energy System in Smart House

ABSTRACT

In recent years, with the improvement of people's living standards and the popularization of smart appliances, household power consumption shows an upward trend. Reasonable energy management combined with efficient and energy-saving equipment is an effective way to achieve energy conservation and emission reduction in the household sector. Smart house is an energy-saving residence combining renewable energy utilization and efficient energy supply equipment. At the same time, home energy management system (HEMS) in smart house has the characteristics of real-time monitoring and energy consumption intelligent management, and can realize two-way communication between users and power companies. Meanwhile, the combination of different equipment in the smart house energy system can also produce different energy-saving and emission reduction effects for various types of users.

Based on the characteristics and advantages of smart house, this study analyzes and compares the economy and environment of different energy systems in smart house, and optimizes the economy from the three sides of users, equipment, and power market.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. Firstly, introduced the energy background of the world and Japan. Then through the analysis of the characteristics of energy background, it shown the energy consumption of the household sector is increasing year by year. After that, the development and application of smart house and the significance and purpose of application was explained. Finally, introduced the energy supply equipment and energy storage equipment in the smart house energy system, and highlights the advantages of smart house through the utilization of renewable energy, real-time monitoring, high efficiency, and energy saving.

In Chapter 2, LITERATURE REVIEW OF SMART HOUSE. Firstly, through the review of the research on the advantages and application of smart house in various countries, the current status and trends of the smart house promotion were explained. Combined with the current research and popularization of smart house, it is pointed out that there are still some problems in smart house, such as high investment cost and complex operation. Then it shown that the current research focus on smart house is economic optimization. Next, different optimization methods of smart house energy system was reviewed, such as combined with energy storage equipment, combined with renewable energy utilization, and selection of different electricity price schemes. Finally, the

incentive policies implemented by various countries in order to popularize smart house were carried out.

In Chapter 3, MODEL ESTABLISHMENT AND FORECASTING METHOD RESEARCH. Firstly, the software TRNSYS for energy system energy consumption simulation was expounded. Based on TRNSYS, a smart house energy system with different combinations of energy supply equipment is established, and the annual energy consumption of the system is simulated. The economy and environment of different systems are compared. Then, based on MATLAB, a double-layer optimization model is established to double optimize the energy storage equipment capacity and annual output of the smart house energy system with energy storage equipment as the goal of cost minimization. Combined with the characteristics of two-way communication in smart house, a short-term load forecasting model is established to predict the power load of users the next day according to the measured data. At the same time, combined with the development of power market, a real-time electricity price model is established to reduce power cost.

In Chapter 4, INVESTIGATE AND ANALYZE THE CHARACTERISTICS OF ENERGY CONSUMPTION IN SMART HOUSE AREA. Firstly, the research object is introduced, and the completion of Jono smart house area, surrounding facilities and energy system application information are explained. Next, the questionnaire results of users living in Jono area are sorted out. The questionnaire includes family member composition, energy equipment use, energy conservation and environmental protection awareness and so on. The results of the questionnaire show that living in smart house is conducive to improve users' awareness of energy conservation and environmental protection. At the same time, the application of smart house energy system can also save users' power cost. After that, this part utilizes the monitored history data to analyze the energy consumption characteristics and influencing factors of the residential customers, which feature with heat pump heat supply system in smart house.

In Chapter 5, PERFORMANCE COMPARISON OF MULTI-ENERGY SUPPLY SYSTEM IN SMART HOUSE. Firstly, the energy consumption and performance of energy supply equipment is analyzed based on one year's monitor data. The results show that HFPS has a better environmental performance than HHPS, but in terms of economic analysis, HHPS presented an economic advantage over HFPS. In addition, this part also lists five kinds of electricity price schemes of electric company. The electricity costs of HFPS and HHPS were calculated based on five cases.

In Chapter 6, ECONOMIC OPTIMIZATION OF COMPOSITE ENERGY STORAGE SYSTEM IN SMART HOUSE. Firstly, the application and existing problems of residential distributed energy system are introduced, which leads to the concept of microgrid. Then, based on the research status of microgrid, it is proposed that the combination with energy storage equipment can realize economic optimization. After that, an independent smart house in "Jono smart house area" in Japan is selected as the research object. Relies on one year measured data, four cases are designed according to the introduction of different energy storage equipment. A double-level optimization model is established based on adaptive particle swarm optimization algorithm to optimize the size of energy storage equipment and system annual equipment output. The upper model optimizes the optimal size of energy storage equipment, and the lower model simulates the annual optimal equipment output according to the upper results. In addition, the system performance of the four cases is compared and analyzed from three aspects of energy, environment and economy based on the comprehensive comparison model.

In Chapter 7, INFLUENCE OF POWER MARKET FLUCTUATION ON SMART HOUSE ELECTRIITY COST AND FUTURE DEVELOPMENT SUGGESTIONS. Firstly, the research object of this study is a two-story detached smart house integrated with HEMS in the "Jono smart house area" in Japan. Next, to predict the energy consumed on the next day based on historical data, a short-term household load forecasting model based on the particle swarm optimization regression vector machine algorithm was developed. Then a dynamic pricing model was developed to guide the users' electricity consumption behavior and adjust the grid load. According to the prediction results obtained by the load forecasting model, the annual electricity charges of users under the three pricing schemes of multistep electricity pricing (MEP), time-of-use pricing (TOU), and real-time pricing (RTP) were calculated and compared.

In Chapter 8, CONCLUSION AND PROSPECT. The conclusion of whole thesis is deduced and the future work of smart house has been discussed.

赵　雪园 博士論文の構成

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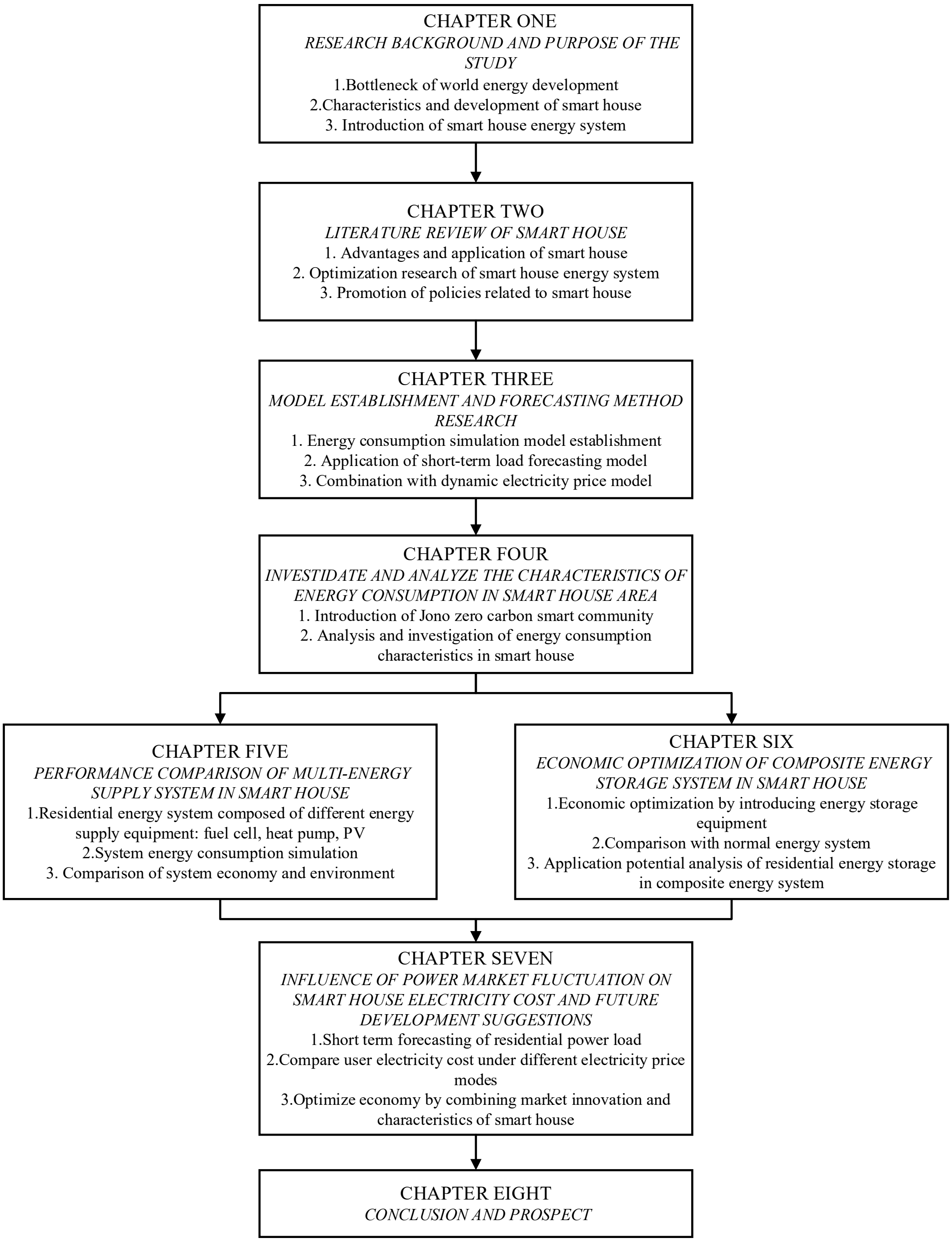

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Chapter 1

RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

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1.1 Background

Energy is an important basic resource for the development of human society. The progress and development of human society must be based on the full supply of energy. With the development of the world economy, the sharp increase of the world population and the continuous improvement of people's living standards, the world energy demand continues to increase[1].

1.1.1 Current status and bottleneck of international energy development

At present, the types of primary energy include coal, oil, natural gas, nuclear energy, hydropower and renewable energy. In the world primary energy consumption structure in 2014, coal, oil, natural gas, nuclear energy, hydropower, renewable energy and geothermal accounted for 30.03%, 32.57%, 23.71%, 4.44%, 6.80%, 2.11% and 0.89% respectively[2]. Among them, the coal and petroleum industries have a history of 246 years and 156 years respectively[3]. The natural gas industry is in the early stage of rapid development, the nuclear power industry is in the recovery period after the Fukushima incident in 2011, and renewable energy is being vigorously developed by countries based on the goal of energy conservation and emission reduction. In order to adapt to the sustained growth of the world's primary energy consumption, the world energy system structure must be constantly adjusted[4].

With the steady growth of GDP and sustained economic development, the world's energy demand continues to grow, but the growth rate of energy demand decreases. According to the type of energy, the growth rate of world oil consumption is 1.6%, it is about $7.5*10^7$ t oil equivalent[5]. In 2014, the world's oil consumption was $4.211*10^9$t, accounting for 32.57% of the world's total primary energy. In 2016, the world's oil consumption was $4.418*10^9$ t, a year-on-year increase of 1.8%, which has been higher than the ten-year average growth rate for the second consecutive year (1.2%). The distribution of world oil consumption in 2016 is shown in Fig 1-1[6]. From the perspective of resource potential, the annual new oil reserves in the world reached their peak as early as the 1960s, and have been declining for half a century. It is expected that the year-on-year growth of world oil production in the future will decrease from 2.3% in 2015 to 0.04% in 2040. After reaching the peak in 2044 ($52.88*10^8$t), the output will slowly drop to $52.4*10^8$t in 2050. Accordingly, the proportion of oil consumption in the world's primary energy consumption in 2035 and 2050 will be 27.74% and 25% respectively[7][8].

Natural gas is the most important and realistic low-carbon energy to replace oil, but the international natural gas market has shown a structural oversupply since 2009. The proportion of natural gas in the world energy structure has hovered around 23.75% for five consecutive years. By the end of 2016, the world's proven natural gas reserves were $1.86*10^{14}$ m^3, an increase of only 0.6% compared with 2015, which is sufficient to ensure the supply demand of 52.5 years[9]. In 2016, the world's natural gas production reached $3.55*10^{12}m^3$, an increase of only 0.3%, which is the lowest increase in natural gas production in 34 years except for the financial crisis. Due to the excess supply of natural gas, the total world natural gas consumption in 2016 was $3.54*10^9m^3$, an increase of 1.5%, lower than the 10-year average growth rate of 2.3%[10]. The distribution of world natural gas consumption in 2016 is shown in Fig 1-2. In fact, the contrarian rise in world coal consumption since 1999, the sharp decline in international oil prices since June 2014, the five-year high hovering of natural gas and the surge in renewable energy are all abnormal responses of the energy market to the high international oil and gas prices in the past 15 years[11]. In the future, the competition between conventional and unconventional oil and gas, oil and natural gas, clean coal and non-fossil energy will become increasingly fierce. Only after the price of world natural gas returns to rationality can it enter a new stage of development. According to BP's "Energy Outlook 2019" forecast for the future energy development trend, in the 20 years after 2018, the consumption and output of the world natural gas market may develop at an average annual growth rate of 2.43%[12]. After 2035, due to the development of nuclear energy and other factors, the growth rate may slow down. It is estimated that natural gas will account for 26.09% and 27.53% of the world's energy structure in 2035 and 2050 respectively. It may surpass oil as the world's leading energy around 2038[13].

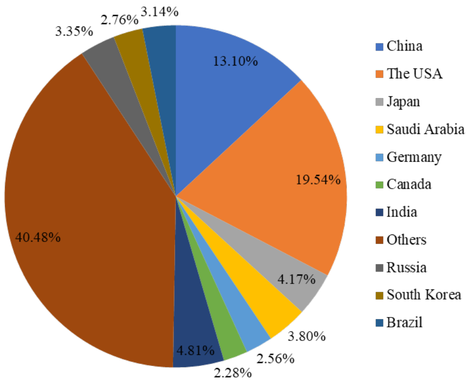

Fig 1-1 Distribution of world oil consumption in 2016 [6]

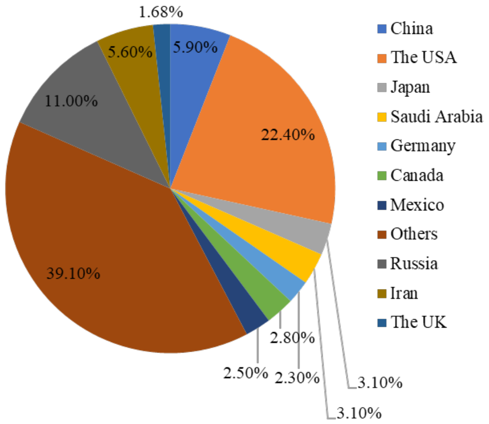

Fig 1-2 Distribution of world natural gas consumption in 2016 [1]

In 2016, the world's proven coal reserves were $1.14*10^{12}$t, enough to meet the demand in 153 years, about three times the ratio of oil and gas reserves. The distribution of world coal consumption in 2016 is shown in Fig 1-3[14].

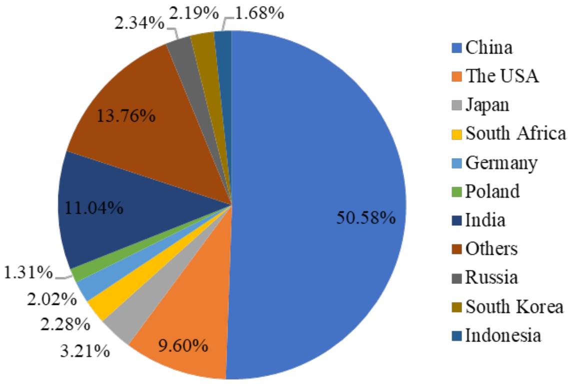

Fig 1-3 Distribution of world coal consumption in 2016[14]

As a low-carbon green energy, fast-growing renewable energy (including wind energy, solar energy, geothermal energy, biomass and biofuels) will quickly penetrate into the world's energy system and become the main direction of the world's energy transformation. It takes about 25 years for renewable energy to increase from 1% to 10% of primary energy, and the penetration rate is faster than any energy in the past (oil has been used for 45 years and natural gas has been used for more than 50 years)[15]. 2017 renewable energy demand $5.71*10^{8}$t oil equivalent, accounting for 4% of the world's total demand for primary energy, and the demand for renewable energy will be 2.75% by 2040 × 109 t oil equivalent, accounting for 15% of the primary energy demand, with an average annual growth rate of 7.1%, growing rapidly (Fig1-4)[16].

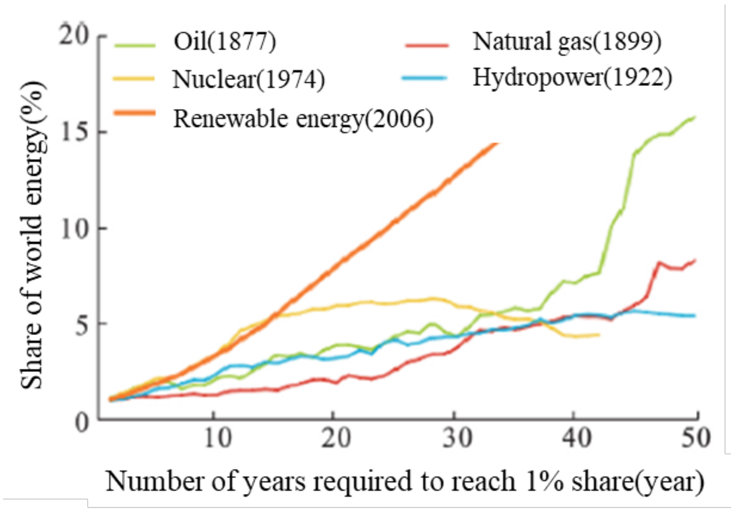

Fig 1-4 Share of renewable energy in world energy [16]

As a clean energy, renewable energy investment, production capacity and consumption have gradually increased in recent years due to factors such as technological innovation and cost reduction. According to the statistics of the International Renewable Energy Agency (IRENA), the demand for renewable energy in 2018 still maintained a strong growth trend for a decade, with a global year-on-year increase of 8%, an increase of 171 GW, accounting for almost one quarter of the growth of global energy demand [17]. According to the statistics, the investment in clean energy exceeded US $300 billion for five consecutive years and US $333.1 billion in 2018. Since 2010, the cost of onshore wind power, solar photovoltaic and offshore wind power has decreased by 49%, 84% and 56% respectively. Since 2012, the cost of lithium-ion battery has decreased by 76%. Governments and enterprises of various countries have formulated decarbonization plans and renewable energy development goals[18]. So far, 57 countries have formulated plans to completely decarbonize the power sector, 179 countries have formulated national or state renewable energy targets, and some oil producing countries have also put forward the goal of increasing the proportion of renewable energy.

1.1.2 World energy demand trend forecast

At present, the types of primary energy include coal, oil, natural gas, nuclear energy, hydropower and renewable energy. With the steady growth of GDP and sustained economic development, the world's energy demand continues to grow, but the growth rate of energy demand decreases[19]. From the regional primary energy consumption, the countries with the fastest increase in energy demand are China and India. In the energy structure, coal accounts for a relatively high proportion. The consumption proportion of China and India is expected to reach 22% and 11% respectively in 2040, and the average annual growth is 1.1% and 4.2% respectively from 2017 to 2040[20]. The energy structure of the United States and the European Union has been diversified, and the consumption is expected to account for 8% and 12% respectively in 2040. They are compiled in table 1-1 below.

Table 1-1 Prospect of primary energy consumption in major regions of the world from 2017 to 2040

Region	Total consumption in 2040(10^4t oil equivalent)	Proportion (%)	Consumption increment (10^4t oil equivalent)	Incremental change(%)	Annual change rate(%)
China	4,017	22	885	28	1.1
India	1,928	11	1,174	156	4.2
The USA	2,223	12	-12	-1	0.0
The EU	1,475	8	-215	-13	-0.6
The	1,391	8	494	55	1.9

Middle East					
Russia	750	4	52	7	0.3
Brazil	485	3	191	65	2.2
The world	17,866	100	4,355	32	1.2

In terms of energy types: compared with coal and oil, renewable energy and natural gas are becoming more and more important and will continue to change to a green and low-carbon energy system, as shown in table 1-2[21]. It is estimated that by 2040, renewable energy and natural gas will account for 85% of the increment of primary energy, among which renewable energy will grow the fastest (7.1% per year), accounting for 15% of the proportion of primary energy. Natural gas grows faster than coal and oil, with an average annual growth of 1.7%, -0.1% and 0.3% respectively. Looking forward to the end of the period, the proportion of natural gas in primary energy (accounting for 26%) will exceed that of coal (accounting for 20%) and approach that of oil (accounting for 27%).

Table 1-2 Prospect of energy consumption in 2017-2040[21]

Types of energy	Total consumption in 2040(10^4t oil equivalent)	Proportion (%)	Consumption increment (10^4t oil equivalent)	Incremental change(%)	Annual change rate(%)
Oil	4,860	27	323	7	0.3
Natural gas	4,617	26	1,461	46	1.7
Coal	3,625	20	-106	-3	-0.1
Nuclear energy	770	4	173	29	1.1
Hydropower	1,245	7	327	36	1.3
Renewable energy	2,748	15	2,177	381	7.1

It is predicted that by 2040, electricity will account for 40% of the world's energy consumption. Renewable energy will account for 30% of the world's total power generation and about 66% of the world's new power generation. With the sharp growth of the world power market share, renewable energy will be the main power source in the world in the future. Wind and solar power generation increased significantly (5 and 10 times, respectively). Since the Organization for Economic Co-operation and development(OECD) prohibits traditional coal power generation from 2030, the main power source will be wind power after 2030, as shown in Fig 1-5. According to statistics, renewable energy accounted for 24.5% of the world's total power generation in 2017, accounting for nearly 2/3 of the total new net power generation. Solar photovoltaic power generation increased by 32% and wind power increased by 10%. Due to cost reduction, power generation in the world power market will double by 2040[22].

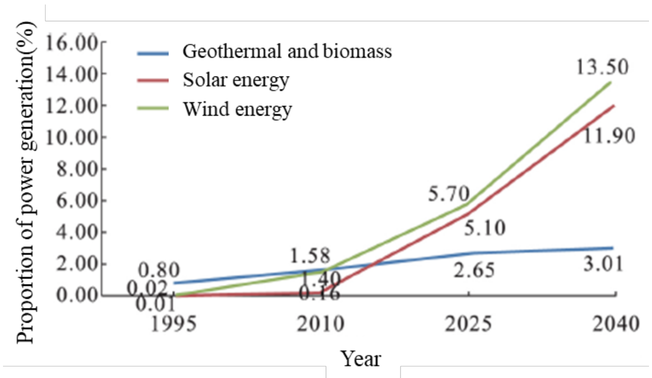

Fig 1-5 Proportion forecast of renewable energy power generation [1]

By Region: the EU renewable energy is growing rapidly. By 2040, more than half of the EU electricity market will come from renewable energy power generation, as shown in Fig 1-6. Developing countries have led the growth of renewable energy. China has the fastest growth of renewable energy, and India will be the second fastest growing country by 2030. Asian countries such as China and India account for nearly 50% of the increment of renewable energy power generation in the world.

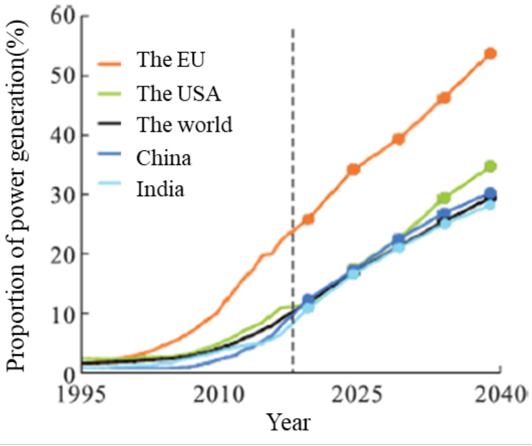

Fig 1-6 Forecast of proportion of renewable energy power generation by region [1]

During the outlook period, although the total amount of nuclear power and hydropower continues to grow, it is still slow compared with the total power generation, so their proportion in the power structure continues to decline[23]. In 2017, nuclear energy accounted for 4% of the world's total primary energy consumption, but it is still lower than the 6% in the peak period in 1995. At present, the USA and the EU account for the highest proportion of nuclear power in the world, the EU has decreased slightly, and Japan's nuclear power is growing at a high speed.

It is estimated that in 2040, the total demand for hydropower in the world will be 1.245*10^9t oil equivalent, accounting for 7%. During the forecast period, the average annual growth of hydropower is 1.3%, which is significantly lower than that in the past 20 years (2.2%). The specific trend is shown in Fig 1-7.

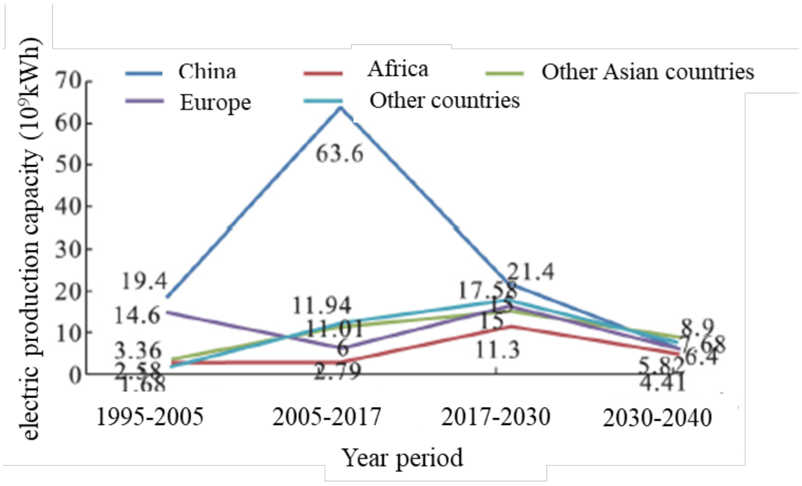

Fig 1-7 Forecast of annual average hydropower generation growth by region [1]

According to the development forecast of various energy situations, generally speaking, with the growth of production level and the prosperity of economic development, the world's energy demand continues to grow, but the energy intensity accelerates to decrease. It is estimated that by 2040, the main characteristics of the world's energy development are as follows:

(1) the growth rate of the world's primary energy demand gradually slows down and changes to a lower carbon energy system.

(2) Fossil energy is still the leading energy in the world from now to 2040. Among them, the growth of tight oil in the United States is strong and the oil demand is generally stable. The growth of natural gas in the world is strong, and the demand market for natural gas is broad.

(3) The demand for coal has slowed down significantly, and the peak of world coal will appear around 2020. The fastest growing energy is renewable energy, accounting for 15% of the total energy demand in 2040, nuclear energy (accounting for 4%) and hydropower (accounting for 7%).

1.1.3 Current status and bottleneck of Japan energy development

As a developed industrialized country, coal, oil, natural gas and nuclear energy are the four major energy sources that support Japan's economic growth. Since the first oil crisis, the Japanese government has made a long-term planning[24]. At present, the supply and demand of major energy sources in Japan are as follows:

Since the industrial revolution, coal has become one of Japan's major sources of energy. During the wars of the 1930s and 40s and the post-war economic recovery, the Japanese government implemented a unified national management of the coal industry, and coal provides 3/4 of the energy for Japan. After the Second World War, the Japanese coal industry gradually declined as the national energy development policy gradually shifted from a coal-based energy structure to an oil-based energy structure. After the oil crisis, Japan re-recognized the importance of coal and began to vigorously import coal from other countries. In 2007, Japan imported 182 million tons of coal, ranking first in the world.

Japan is the world's third-largest oil consumer, and its oil supply is largely dependent on imports. Figure 1.1 shows the production and consumption of oil in Japan over the years. From the overall trend, the difference between Japan's oil production and consumption reached its peak in 2000. After entering the 21st century, with the continuous improvement of energy efficiency, Japan's oil consumption has been declining year by year, and the production volume has remained stable and has risen slightly. The gap between the two has been shrinking.

After the war, in the context of rapid economic growth, the scale of Japan's power market expanded and the demand for oil increased. In the 1970s and 1980s, under the impact of two oil crises, in order to get rid of its dependence on oil, Japan took the opportunity of the establishment of the Department of resources and energy to take measures such as expanding oil reserves, promoting energy conservation and promoting the use of natural gas and nuclear energy. After the 1990s, affected by global climate change and the signing of the Kyoto Protocol, the environmental value of low carbon has attracted attention, and renewable energy has gradually become an important part of energy in Japan[25]. In the above process, Japan has formulated and implemented a number of development and utilization strategies and plans in the energy field, such as "sunshine plan", "Moonlight plan", "New sunshine plan", "3E (Energy supply stability, Economic efficiency and Environmental adaptability) balanced energy plan" and many basic energy plans, which have promoted the evolution of its energy structure. After the East Japan earthquake in 2011 and the accident of Tokyo Electric Power's Fukushima Daiichi nuclear power plant, the utilization of nuclear energy fluctuated and shrank, and the safety of energy development and utilization also attracted extensive attention. How to ensure the security of energy development and utilization while ensuring the stability of energy supply, economic efficiency and environmental adaptability has become an important topic.

In terms of transportation, hydrogen is the most promising decarbonization option for trucks, buses, large cars, and commercial vehicles. Among them, lower energy density (hence lower range), higher initial cost, and slow battery charging performance are the main disadvantage. Compared with batteries and internal combustion engines, fuel cells require less raw materials. Since the transportation sector accounts for nearly a quarter of global carbon dioxide emissions, decarbonization is a key factor in achieving energy transformation. In addition, hydrogen fuel replenishment facilities have a significant advantage: compared to fast charging, it only requires about one tenth of the city and highway space. Similarly, suppliers can flexibly supply hydrogen, and large-scale deployment of fast charging facilities requires major upgrades to the grid. Finally, once the smallest scale of promotion is achieved, hydrogen provides operators with an attractive business case. In addition to road transportation, in the longer term, hydrogen may also promote decarbonization in the fields of railway transportation, shipping, and aviation. In the aviation industry, hydrogen and hydrogen-based synthetic fuels are the only options for large-scale decarbonization.

(1) Basic energy structure of Japan

After the war, Japan's basic energy structure was in the process of continuous adjustment, from coal and oil to energy diversification. Although the development and utilization of new energy are increasing, its basic structure remains roughly unchanged, and fossil energy still occupies an important position.

First, from the perspective of primary energy, oil, coal and natural gas are still the most important components of Japan's energy supply. In 2017, the three accounted for 39.1%, 25.2% and 23.4% respectively, and renewable energy accounted for 4.6%. If large-scale hydropower is calculated, the proportion of clean energy in Japan's energy in 2017 can reach 8%. As shown in table 1-3.

In addition, renewable energy has achieved substantial growth, and its proportion in the primary energy structure has been improved to a certain extent; The improvement of nuclear power is due to the shutdown of all nuclear power plants in the early stage and the re operation of some nuclear power plants at the present stage.

Table 1-3 Primary energy supply in Japan in 2017

Energy resource	Crude oil conversion(10^4kl)	Constituent ratio	Previous year ratio
Coal	13,024	25.2%	0.0%
Oil	20,239	39.1%	-0.5%
Natural gas	12,128	23.4%	-0.7%
Renewable energy	2,379	4.6%	14.7%
Hydropower	1,743	3.4%	4.1%
Others	1,543	3.0%	2.8%
Nuclear energy	685	1.3%	80.0%
Total	51,741	100%	1.0%

From the perspective of energy consumption, as shown in table 1-4, oil, electricity and coal are the most important components, accounting for 48.2%, 25.6% and 10.2% of the total final energy consumption respectively, and heating accounts for a large proportion of 7.1%. In particular, renewable energy accounts for 4.6% of the supply structure, but it accounts for a small proportion in final consumption.

Table 1-4 Japan's final energy consumption in 2017 (energy category)

Energy resource	Crude oil conversion(10^4kl)	Constituent ratio	Previous year ratio
Coal	3,519	10.2%	-0.6%
Oil	16,667	48.2%	0.1%
Natural gas	2,976	8.6%	4.2%
Renewable energy	35	0.1%	-5.3%
Electricity	8,830	25.6%	0.0%
Thermal	2,459	7.1%	1.1%
Others	73	0.2%	3.3%
Total	34,560	100%	0.4%

From the perspective of power sector, as shown in table 1-5, natural gas and coal are the main sources of power in Japan, followed by oil and hydropower. In the field of new energy power generation, photovoltaic power generation accounted for the highest proportion in 2017, reaching 5.2%, and achieved a year-on-year growth of more than 20%. Although Japan is also committed to the development and utilization of wind energy technology, the scale and proportion of wind power generation are small.

Table 1-5 Power source composition of Japan in 2017 (power generation)

Energy resource	(Billion kWh)	Constituent ratio	Previous year ratio
Nuclear energy	329	3.1%	82.2%
Coal	3,406	32.3%	-0.3%
Natural gas	4,201	39.8%	-3.3%
Oil	920	8.7%	-9.7%
Hydroelectric	849	8.0%	6.8%
PV	550	5.2%	20.3%
Wind power	65	0.6%	5.1%
Geothermal	25	0.2%	-1.8%
Biomass energy	215	2.0%	9.3%
Total	10,560	100%	0.6%
Zero emission power supply	2,033	19.3%	18.4%

(2) Changes in Japan's energy structure

In the face of changes in domestic and international environmental conditions, Japan's energy structure is also constantly changing. It can be divided into changes in energy structure before the oil crisis, changes in energy structure during the oil crisis, changes in energy structure after the oil crisis, and changes in energy structure after the East Japan earthquake. In different periods, Japan's energy composition is also different, mainly through the process of coal, oil, energy diversification and the change of energy structure to deal with the greenhouse effect.

In 2011, affected by the East Japan earthquake and the Fukushima Daiichi nuclear power plant accident, Japan's energy policy changed significantly. Under the strong demand of the people, nuclear power plants were gradually shut down, and the energy structure of nuclear power in Japan was interrupted and reduced. In particular, all nuclear power plants were shut down in 2014, and the nuclear power supply was reduced to 0, as shown in table 1-6. Since then, although a small number of nuclear power plants have been put back into operation after safety assessment, they still account for less than 1.5% of Japan's energy supply by the end of 2017. Affected by this, Japan's dependence on coal and oil supply has increased, and the vulnerability of its energy structure has further deepened. In order to deal with the structural problems of energy, when formulating the fourth basic energy plan in 2014, Japan emphasized the importance of "Security" under the basic viewpoint of "3E" (Energy security, Economic efficiency and Environment), and the development and utilization of new energy technologies has become the top priority. In the energy supply structure, the scale of renewable energy continues to rise, from 425 MJ in 2010 to 921 MJ in 2017, with an average annual growth of more than 10%. Under these conditions, by the end of 2017, the proportion of renewable energy in Japan's primary energy supply had reached 4.5%, becoming the most important energy composition except oil, coal and natural gas. In addition, due to the cessation of the use of nuclear energy, the proportion of coal in Japan's energy structure has increased by about 2 percentage points compared with that before the East Japan earthquake, which puts forward higher requirements for Japan to achieve the goal of reducing greenhouse gas emissions.

Table 1-6 Japan's primary energy supply structure from 2010 to 2017 (unit: PJ)

Year	2010	2011	2012	2013	2014	2015	2016	2017
Coal	4,997	4,672	4,883	5,303	5,097	5,154	5,041	5,043
Oil	8,858	9,097	9,220	9,001	8,351	8,138	7,879	7,837
Natural gas	3,995	4,681	4,871	4,898	4,961	4,657	4,729	4,696
Renewable energy	425	433,729	444	524	609	725	803	921
Hydroelectric	716	873	657	679	702	726	648	675
Nuclear energy	2,462	508	137	80	0	79	147	265
Others	530	20,994	511	545	538	535	581	597
Total	21,983	20,994	20,722	21,030	20,257	20,014	19,829	20,035

In the 1970s, Japan encountered the oil crisis originated in the Middle East. Not only the industry, business and family fields, but also the soaring energy prices. Later, while promoting energy management activities, the government vigorously carried out technology development and successfully developed equipment, technologies and systems with high energy efficiency. In the case of high energy prices, encouraging investment will soon be popularized in Japan. Therefore, in the 15 years since 1973, Japan has dramatically doubled its GDP without increasing energy consumption[27]. Later, Japan has been committed to the development and popularization of energy-saving technologies. Now, compared with 1973, GDP has increased by 2.4 times, while energy consumption is controlled at 1.3 times that in 1973. Especially in the industrial sector, energy consumption decreased by 0.9 times (Fig 1-8).

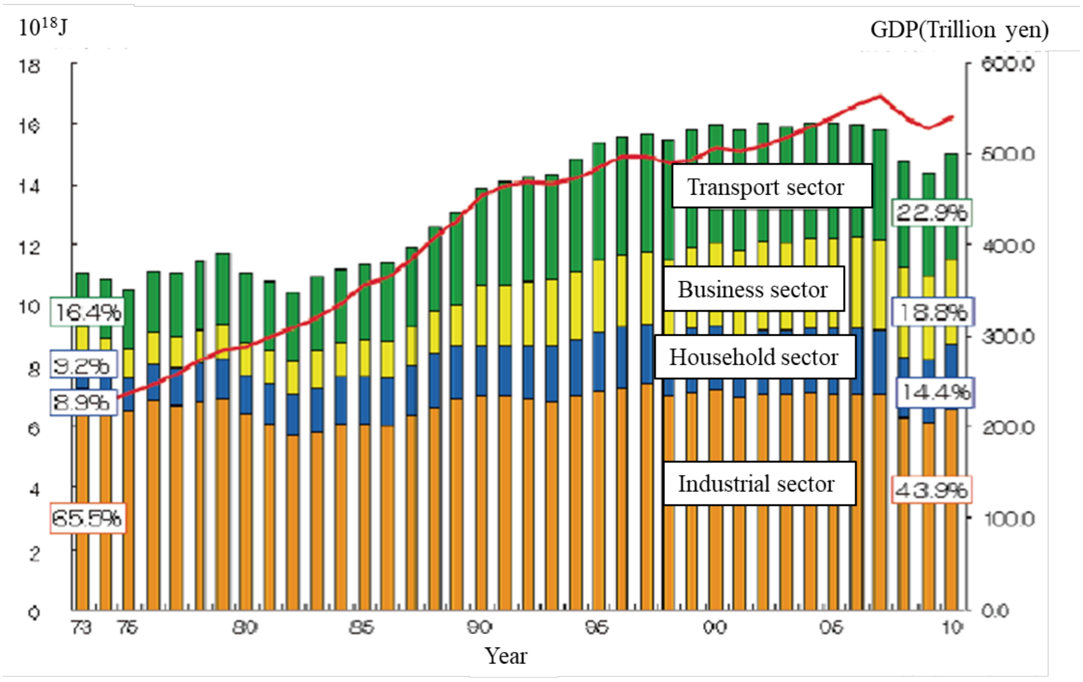

Fig 1-8 Changes in energy consumption in various fields in Japan

As can be seen from Fig 1-8, since the mid-1980s, with the improvement of national living standards and commercial activities in new fields, energy consumption in the household sector has increased significantly[28]. Due to the improvement of people's living standards and the large-scale and multi-functionalization of household appliances, electricity accounts for a large increase in the proportion of primary energy use. Currently, electricity accounts for more than 50% of primary energy use. As for the proportion of energy consumption by household applications. Power, lighting are increasing due to the spread and enlargement of home appliances and changes in lifestyles.

After the 2011 Great East Japan Earthquake, some power stations were shut down to ensure safety. The amount of electricity generated in Japan has been reduced. In 1960 Japan’s self-sufficiency rate was about 60% due to domestic resources such as coal and hydropower. However, due to the increase in energy demand during periods of high growth, the self-sufficiency rate has fallen sharply. Since 2011, the self-sufficiency rate has further declined due to the suspension of nuclear power plants. According to this situation, in order to better develop and utilize renewable energy, reduce the carbon dioxide emissions of residential energy systems, and improve energy efficiency, a variety of energy-efficient energy-supplied equipment are gradually being promoted. The emergence and development of intelligent housing, as a representative innovation case of technological breakthrough and industrial integration, has gradually been widely promoted and applied[29].

1.2 Smart house characteristics and development process

(1) Concept and composition of smart house

Smart house refers to a low-carbon residence through the effective utilization of energy without affecting the living comfort (Fig 1-9). Due to the decline of photovoltaic system cost and the implementation of Feed-in-Tariff(FiT), more families begin to install residential PV systems. With the rapid decline of the cost of fuel cell system, the number of houses using domestic fuel cell system also began to increase. Real estate developers have also begun to merge and sell residential photovoltaic systems, fuel cells and household battery systems. It can be predicted that the smart house with home energy management system (HEMS) will be the development trend of residence in the future.

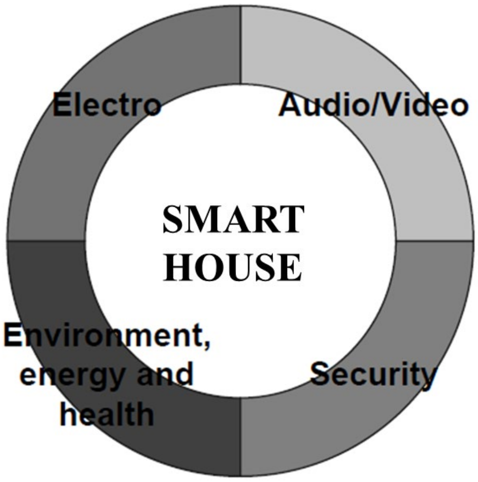

Fig 1-9 Function diagram of smart house

Energy management system(EMS) refers to the energy management system that uniformly manages the visualization of energy generation and consumption, power storage system and control energy consumption equipment. The design and installation of the management system are divided according to the scale of the region, including home energy management system(HEMS), building energy management system(BEMS), factory energy management system(FEMS) and community energy management system(CEMS). The house installed with HEMS is called smart house, the building installed with BEMS system is called smart building, and the area installed with CEMS system is called smart community (Fig 1-10).

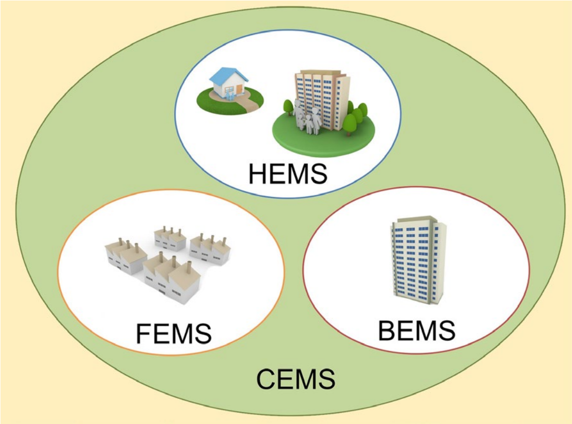

Fig 1-10 The composition of EMS

Specifically, the smart house effectively manages the energy used, manufactured and stored by household appliances, solar power generation system, residential energy supply system and residential energy storage system through HEMS, so as to realize the rational use of energy and residential comfort.

(2) Development process of smart house

In the 1980s, when promoting the concept of smart house, the Ministry of construction of Japan took the bus technology for residence as an opportunity to integrate the functions of household appliances, security equipment and communication equipment, and put forward a new concept of home bus concept and residential system automation. At the beginning of 1988, the housing informatization promotion association was established to mainly carry out the research on home bus technology. In September 1988, the home bus system standard (HBS) was formulated, and it was proposed to adopt HBS home bus technology for the information management of all houses in the residential area. In 1990, Japan established the first high-level demonstration smart house area in Makuhari. In recent years, in order to meet the needs of large residential areas, the concept of super home bus system is proposed.

Especially after the East Japan earthquake in 2011, with the improvement of people's awareness of power saving and environmental protection, smart house has attracted more and more attention. Japanese real estate enterprises are generally optimistic about the development prospect of smart house, so as to further improve various functions and services, and vigorously promote and promote the commercialization process of smart house. The typical case is that Japan built the first smart house community in June 2013. The residential area is located in Osaka, covering an area of about 17000m^2. There are 65 single family houses. Each house is equipped with solar power generation system and household information management system, which can realize power self-sufficiency and household goods operation automation.

Characteristic	
Safety	Introduce facilities to secure electricity and water in houses and public facilities.
Comfort	Preliminarily planned green landscape and underground utility lines.
Communication	Promote community activities among residents.
Sustainability	Administrative corporation realizing independent management.
Environmental	Utilization of energy by power generation, storage and HEMS.

Fig 1-11 The characteristics of Japan's first smart house community case

At present, the smart house promoted in Japan takes the residence as the platform and has construction equipment, network communication, information appliances and equipment automation. It has an efficient, comfortable, safe, convenient and environment-friendly living environment integrating system, structure, service and management. On the basis of maintaining the traditional living function, it gets rid of the passive mode and becomes a dynamic and intelligent modern tool. smart house not only provides all-round information exchange function, but also optimizes people's lifestyle and living environment, and helps people effectively arrange time and save all kinds of energy. At the same time, the functions of home appliance control, lighting control, indoor and outdoor remote control, curtain automatic control, anti-theft alarm, computer control, timing control and telephone remote control are realized. The Japanese government believes that smart house is bringing a lifestyle revolution to the Japanese people, which will become the main direction of building a new generation of housing and have a far-reaching impact on social development.

(3) Characteristics of smart house in Japan

Smart house can be understood as a house with intelligence. However, only with a correct understanding of smart house can plan and design excellent smart house. Therefore, the definition of smart house is developing[30].

Nowadays, the definition of smart house by the Japanese Intelligent Building Research

Association (IBRAJ) is a house that integrates the most advanced technologies in computer and information communication to coordinate the power supply, air conditioning, lighting, disaster prevention, anti-theft and household appliances in the house, and realize the combination of three automation functions of residence, communication and life.

In recent years, Japan Sustainable Building Development Association (JSBDA) has put forward another definition of smart house, which believes that smart house is designed and constructed according to the appropriate selection of intelligent environment modules. And by configuring appropriate residential equipment to obtain long-term architectural value and residential functions to meet the needs of residents. JSBDA proposes that the core of smart house is the following eight smart modules:

1) Environmental intelligence: including health and energy.
2) Spatial intelligence: including utilization and flexibility.
3) Life intelligence including construction cost, service life and maintenance.
4) Live intelligence including human comfort.
5) Residential intelligence including life and work efficiency.
6) Safety intelligence including fire, security and anti-theft.
7) Cultural intelligence including people-oriented image.
8) Scientific and technological intelligence including the degree of high and new technology.

Japan's smart house industry has advanced technology, and it is also one of the three largest smart house markets in the world. Therefore, the development of building intelligence in Japan has its own characteristics. It mainly includes the following aspects:

1) Japan is an energy deficient country, so it first requires smart houses to save energy. For example, the intelligent energy-saving indicators of water, electricity, gas and household appliances used in housing are better solved under the guidance of policies and regulations. Achieve the effect of reducing energy use, improving energy utilization efficiency and making full use of natural energy as much as possible.
2) Japan is a country with frequent natural disasters. Frequent earthquakes and typhoons require smart house to have the ability to solve the problem of coordination between human settlements and nature. For example, a smart house in Tokyo is very representative. There is a semi open courtyard in the building. The indoor sensing device can measure the temperature, humidity and wind force of the weather at any time, and transmit all kinds of data to the

underground computer system in time. Based on this, the computer system controls the switches of doors, windows and air conditioners to keep the room in the most comfortable state for residents. At the same time, under the computer control, various instruments in the house can also cooperate. For example, in windy and rainy weather, the doors and windows will be closed automatically, and the air conditioner controlling the indoor temperature will also start to operate automatically.

3) Japan advocates the spirit of environmental protection and low carbon emission, and requires that the equipment installed in smart houses must give full play to the maximum environmental efficiency.

Based on these characteristics, Japan has formed an energy-saving and efficient smart housing industry[31]. According to the latest report released by IBRAJ, through observation, analysis, investigation and research, it is predicted that in the decade from 2016 to 2025, smart housing will become the main direction of national industrial and economic development and have a far-reaching impact on social development.

1) In terms of lifestyle development prospects: according to the results of the "Civil housing statistical survey" of the Ministry of general affairs of Japan in 2015, 6.2% of the 46.863 million families in Japan decided to buy smart houses within one year, 18.8% planned to buy smart houses within three years, 28.8% planned to buy smart houses within five years, and 46.2% planned to buy smart houses within ten years.

2) In terms of market scale and development prospects: for many years, technology and price have been two difficult problems for the popularization of smart house. According to the Research Report of the real estate bureau of the Ministry of land, resources and transportation of Japan, in 2011, the market scale related to intelligent housing in Japan was 634.3 billion yen. Since then, it has increased by more than 20% every year, exceeding 1.28 trillion yen in 2020; It is predicted that it will reach 2 trillion yen in 2025.

3) In terms of the development prospect of housing industry: smart house will bring industrial revolution to Japan's housing construction industry and become a new starting point for economic revival. In recent years, not only many real estate companies have actively developed smart house, but other industries have also participated in relevant industries in the field of smart house. Some public utility companies have also introduced price schemes to cooperate with smart house. With the arrival of the era of smart house, the intelligent real estate industry has broad prospects.

4) In terms of energy conservation and environmental protection development prospects: an important sign of smart house is that solar cells will be installed on the roof. Solar cells can

fully absorb sunlight and store electricity. Houses store electricity through solar power generation in the daytime and can be used at night, so as to effectively reduce the burden of electricity consumption. At the same time, hems can monitor data such as solar power generation and power consumption at any time. When there is excess electricity, it can be sold to the public grid. Thus, the residence can basically realize zero electricity charge and zero carbon dioxide emission every year. Therefore, more households will participate in zero carbon emission trading. The non-clean energy consumed by society will also decline, and the negative impact on the environment will be minimized. Moreover, some smart house are also equipped with perfect water circulation system to reuse wastewater for many times, and water resources are greatly saved.

1.3 Technology and advantages of smart house

1.3.1 Introduction of smart house energy system

Smart house refers to the combination of traditional building engineering, emerging information technology and energy-saving technology. Through the home energy management system (HEMS), the smart house can effectively manage the energy used, manufactured and stored by household appliances and solar power generation system, so as to realize the rational use of energy and living comfort. The construction of smart house is essentially a process of system integration. In this integration process, relevant technologies, equipment and materials finally form a qualified smart system under the control of the integrator (Fig 1-12). The information flow connects the electric and gas suppliers and the demand side through the HEMS, to realize a two-way communication of the energy data[32]. Users can validate the usage and power consumption of home appliances through the HEMS. Meanwhile, the HEMS sends the collected energy consumption data to the power company, which in turn formulates the electricity price and incentive scheme according to the power load characteristics of the users and feeds the data back to the household. Finally, the users can adjust the energy consumption behavior and select an economical electricity price plan through the information displayed by the HEMS, for optimizing the power cost. The energy flow comprises electric and gas suppliers, a utility grid and the demand side. Power suppliers, public grids and other energy supply equipment imported from residential buildings provide electricity to users. A PV battery uses solar energy to provide electricity for residence during the day, and users can sell the remaining power back to the grid. The external equipment imported by users can be classified into two types: energy supply only and energy supply and storage simultaneously. Energy-only devices include heat pumps and fuel cells, which provide electricity and heat to the users during the operation time. Energy storage devices, including batteries and electric vehicles, have the function of charging and discharging. They maximize the advantages of HEMS by storing energy when the cost of power is low and releasing it to users when the cost is high. The following will introduce the equipment and system operation mode in the energy system of smart house.

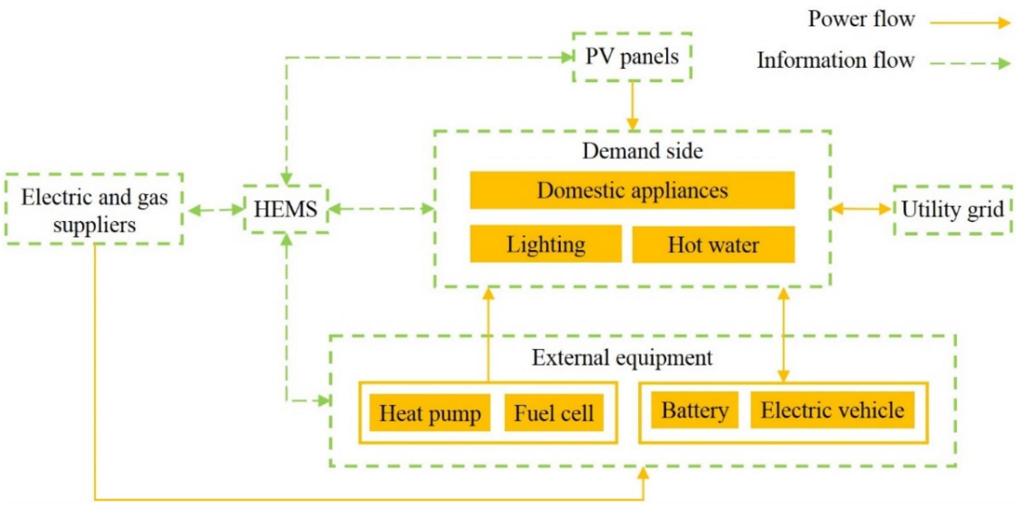

Fig 1-12 Basic framework of smart house energy system

(1) Home energy management system(HEMS)

The HEMS includes the most appropriate control system for the operation of household appliances. Lighting switch, solar power generation system and fuel cell system are always visible equipment for power generation. The specific functions include:

1) HEMS can accurately grasp the power consumption of air conditioning and lighting, and control the air conditioning and lighting through the comprehensive control and analysis of indoor temperature, humidity and lighting.

2) The power and heat generated by the installed solar energy equipment, urban liquefied gas and fuel cells shall be managed uniformly. Charge the battery with the remaining electric energy and heat the water heater to meet the consumption during peak hours

3) Based on the analysis of the actual situation of energy consumption in the past, HEMS comprehensively considers the changes of power generation caused by weather changes, so as to achieve the most reasonable control of household energy consumption.

Therefore, smart house is composed of HEMS, solar power generation system, battery system, energy-saving lighting system, solar energy utilization system, fuel cell system, heat pump system, electric vehicle charger, intelligent household appliances, etc. Smart housing industry is a new industry born under the premise of technological breakthrough and high technological integration and cross industry cooperation of enterprises (Fig 1-13).

In addition to household appliances, HEMS can also be connected with energy machines, residential equipment and instruments, electric vehicle, home gateway and electricity meter to realize household energy management. In addition, the system can also connect outdoor power system, information system and nearby community network.

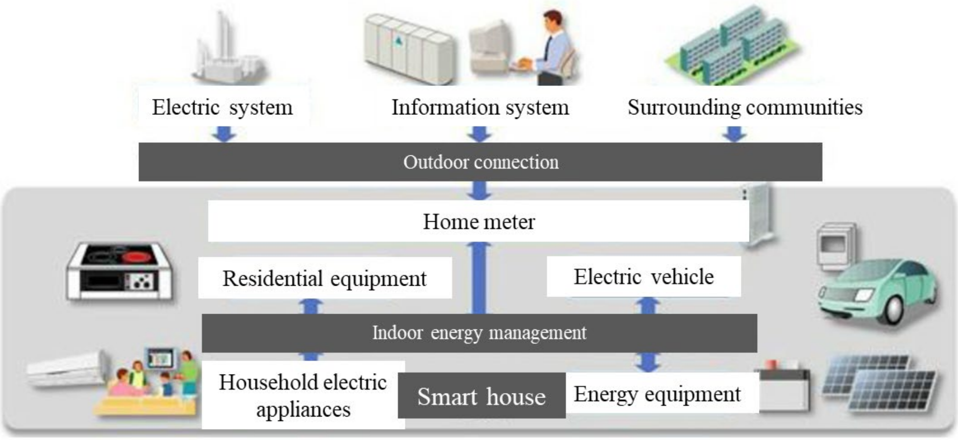

Fig 1-13 Panorama of HEMS

The key technologies of HEMS include the following parts:

1) Data acquisition technology:

- Smart appliances: used for automatic monitoring of their own faults, automatic measurement, automatic control, automatic adjustment and communication technology with remote control center. It has the characteristics of networking function, intelligence, openness, compatibility, energy saving, ease of use and so on. The equipment has the function of intelligent mode operation, can automatically control the operation based on the environment, realize the data collection of working conditions and energy consumption, and has the ability of fault self-diagnosis.

- Smart socket: it can directly reflect the operating power, current, voltage and other information of electrical appliances on the socket. Be able to find electrical abnormalities in time to avoid abnormal power consumption. At the same time, it has a communication interface, which can transmit the monitoring data to the monitoring platform. As a transitional product, when smart appliances are not mature and unified, smart sockets will exist for a long time. The main function is to realize the electric energy measurement of electric equipment, mainly focusing on the measurement of voltage, current, power and power factors.

- Electric energy meter: statistics the electric energy used by the equipment within the measurement range, so that the power supply department can charge according to the accumulated metering data, and has the function of data remote transmission. Smart meter technology is mainly driven by the marketing business needs of State Grid Corporation of China. Its function is mainly measurement and cost control, which is updated according to the standards formulated by the State Grid Corporation of China.

2) Communications technology

- Home communication network: a home network access platform integrating home control network and multimedia information network to realize the interconnection and management of information equipment within the scope (Fig 1-14).
- Home energy gateway: it has the information collection of all metering equipment in the home, and can realize the energy management technology of distributed energy access management and municipal power switching.

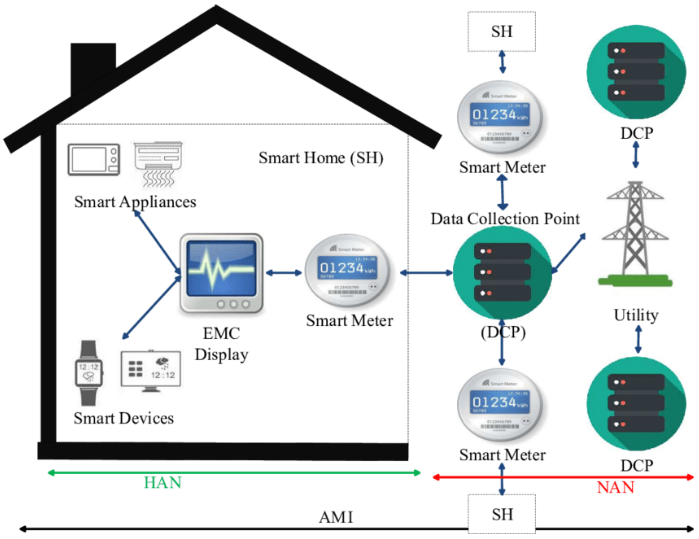

Fig 1-14 The key technologies of HEMS

3) Visualization technology

- HEMS display terminal includes home energy display, mobile client software and home interactive terminal. The display terminal can directly manage and manipulate all household equipment through wireless connection with HEMS and user interactive graphical interface.
- Display software: the open intelligent operating system control terminal design is adopted, and the application framework supporting component reuse and replacement is used.

4) Energy management technology

- Under the guidance and promotion of energy conservation and emission reduction policies, energy management technology will achieve rapid development. Including energy management software development and design, energy consumption monitoring and energy efficiency evaluation.

(2) Photovoltaics(PV)

PV is the conversion of light into electricity using semiconducting materials that exhibit the PV effect, a phenomenon studied in physics, photochemistry, and electrochemistry. PV system employs solar modules, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop mounted or wall mounted. Japan has reduced the FIT price of household PV year by year, and implemented subsidies for household energy storage installation in order to improve the spontaneous self-use rate and improve the power grid. This will also enable Japan to install about 130,000 household energy storage units in 2020. At the same time, as the equipment price decreases year by year and the fit expires, the number of energy storage installations will only increase. According to the survey statistics, the number of houses suitable for PV installation in Japan exceeds 25 million. By 2020, the number of installed PV and energy storage is close to 3 million and 500,000, accounting for about 10% and 2%. It can be seen that even in Japan, where the development of household PV has been relatively mature, there is still a lot of room for expansion in the future. In addition, a large number of distributed PV installations also bring potential for the future small energy storage market.(Fig 1-16, table 1-7)

Table 1-8 lists several main components of residential PV system. The mount may be fixed, or use a solar tracker to follow the sun across the sky. Japan began introducing solar power generation in the 1990s, and by the end of 2015, the cumulative installation volume had reached 32.8 million KW. Among them, 27% is for residential solar power (less than 10 kW) and 73% for non-residential one (more than 10 kW).

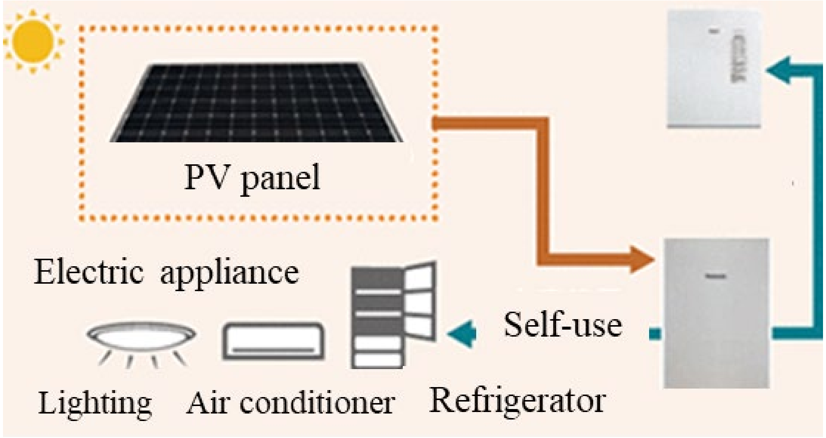

Fig 1-15 Composition diagram of residential PV system

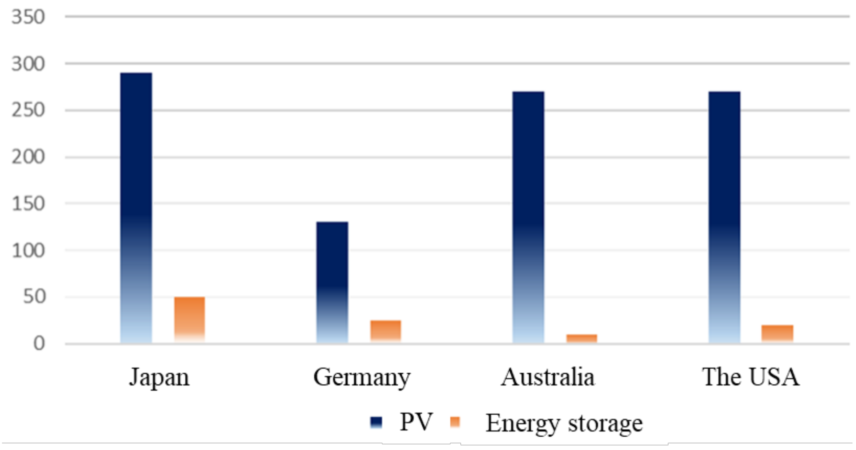

Fig 1-16 Residential PV and energy storage installations in Japan, Germany, Australia and the USA by 2020

Table 1-7 Comparison of residential PV penetration rates in Japan, Germany, Australia and the USA by 2020

	Japan	Germany	Australia	The USA
Installable residence(Ten thousand households)	>2,500	>1,000	>1,000	>8,000
PV installation quantity(Ten thousand households)	290	130	270	270
Cumulative proportion(%)	11	11	20	3

Table 1-8 The main components of residential PV system

Name	Function
Solar panels	It is a device installed on the roof to collect sunlight. The grid part of the solar panel is the module, and the smaller panel that makes up the module is the battery.
Power regulator	The utility model relates to a device for converting sunlight (direct current) collected by a solar panel into alternating current that can be used at home.
Distribution board	A device that distributes alternating current to each electrical device.
Watt-hour meter	A device that measures the amount of electricity flowing when connected to an external wire. The electricity sold from the household to the power company is recorded as the feed-in, and the electricity purchased by the household from the power company is recorded as the grid import.
Battery (not required)	The utility model relates to a power storage device, which can be used at night or in case of disasters. Users can choose whether to install or not.

Based on the main equipment in table 1-7, the brief working principle of residential PV system is as follows:

1) Collect sunlight from solar panels.

2) Use the power regulator to convert the collected sunlight (DC) into AC.

3) Use the distribution board to distribute AC power to electrical equipment for users.

The electricity generated by solar power generation is used by households, but the remaining electricity can be sold to power companies. FIT is a system that stipulates the fixed price of electricity sold to the power company within a certain period of time. For household solar power generation (below 10kW), the application in 2019 will be from 24 yen to 26 yen per 1kwh for 10 years. By fixing the selling price, we can simulate how many years it takes to recover the initial cost of solar power generation, so fit has played a great role in promoting the promotion of solar power generation.

The advantages of installing Residential PV system are as follows:

1) Selling electricity can earn extra income.

The first is the additional income from selling electricity, which can be said to be the biggest advantage of residential PV. After the introduction of residential PV, the initial investment cost can be recovered within ten years, and additional income can continue to be obtained for subsequent equipment maintenance.

2) It can save water and electricity.

Residential PV is also a great advantage for saving energy costs. Combined with the electricity price scheme with high electricity price during the day and low electricity price at night, the electricity generated by residential PV can be used during the day, so as to effectively reduce hydropower charges.

3) It can insulate the house

Installing solar panels on the roof can insulate the house. If there is nothing on the roof, it will be exposed to direct sunlight and the indoor temperature will rise, but the existence of solar panels will absorb light and heat. In addition, it can also play a thermal insulation role in winter, because solar panels can prevent the outflow of warm air in the room.

Residential PV also has the following disadvantages:

1) Frequent component replacement. The power flow direction in the distribution network will change in time, the reverse power flow will lead to additional loss, the relevant protection needs to be reset, and the transformer tap needs to be constantly changed.

2) Power control is difficult, voltage and reactive power regulation is difficult, there are technical

problems in power factor control after the access of high-capacity photovoltaic, and the short-circuit power will also increase.

3) It is more difficult to manage. The energy management system at the distribution network level is needed to uniformly manage the load in the case of large-scale photovoltaic access. It provides new requirements for secondary equipment and communication, and increases the complexity of the system.

(3) Fuel cell

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel and an oxidizing agent into electricity through a pair of redox reactions. Fuel cells are different from most batteries in requiring a continuous source of fuel and oxygen to sustain the chemical reaction, whereas in a battery the chemical energy usually comes from metals and their ions or oxides that are commonly already present in the battery. A residential fuel cell is a scaled down version of industrial stationary fuel cell for primary or backup power generation. These fuel cells are usually based on combined heat and power-CHP or micro combined heat and power Micro-CHP technology, generating both power and heated water or air. In May 2009, the world's first residential fuel cell sales began in Japan. In December 2018, the cumulative production of residential fuel cells exceeded 250,000 units (Fig 1-17).

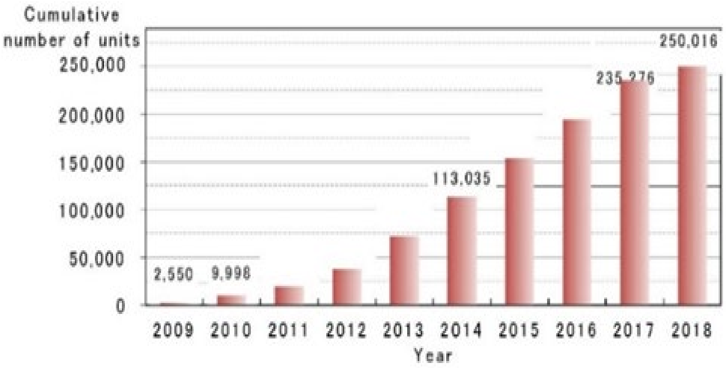

Fig 1-17 Cumulative number of domestic fuel cell

Japan is one of the countries with the fastest development of fuel cell industry in the world, which mainly benefits from the Ene-farm project of distributed hydrogen fuel cell for home use in Japan since 2005 (Fig 1-18). Ene-farm project is one of the successful fuel cell commercialization projects in the world. At present, the project has deployed more than 200,000 sets of household fuel cell equipment, realizing the commercialization of household fuel cells. These fuel cells are installed in apartments and ordinary houses, which are selected by apartment developers, and other accessory applications are available. The new fuel cell can operate independently without relying on the power grid, which is very important for Japan with frequent natural disasters.

Fig 1-18 Domestic fuel cell in Japan

Japan's interest in domestic fuel cells dates back to 1999, and its Millennium Project includes support for PEFC research. Japan's residential energy demand is large and has been growing. The Japanese government started a large-scale domestic fuel cell demonstration project in 2005. During the validation and pilot period from 2005 to 2009, nearly 5000 sets of distributed fuel cell systems were sold, reducing the system acquisition cost from 8 million yen in 2005 to 3.5 million Yen in 2009, a decrease of 56.25%.

The promotion and popularization period of products is from 2010 to 2020. The Japanese government has provided subsidies of 1.4 million Yen or half of the manufacturing cost to families installing fuel cell systems since 2010. In 2015, the price of the new generation of household fuel cell system launched by Panasonic, Toshiba and other enterprises has been as low as about 1.5 million Yen, down 81.25% and 57.14% respectively compared with 2005 and 2009. The efficiency of its thermoelectric system has increased from 70% to 95%. At the same time, the amount of government subsidies was also reduced to 500,000-600,000 Yen. Since 2012, sales have almost doubled. In 2015, the subsidy amount of Ene-farm reached 22.2 billion Yen.

As Japan continues to encourage families to purchase fuel cells and manufacturers' mass production effect is expanded, the price of residential fuel cells is gradually falling. As can be seen from Fig 1-19, 42,000 residential fuel cells were added in Japan from April 2016 to March 2017. The newly added quantity is about the same as that in 2015, and the cumulative number of installed units is 196,000, of which PEFC models with low price and short restart time account for a higher proportion.

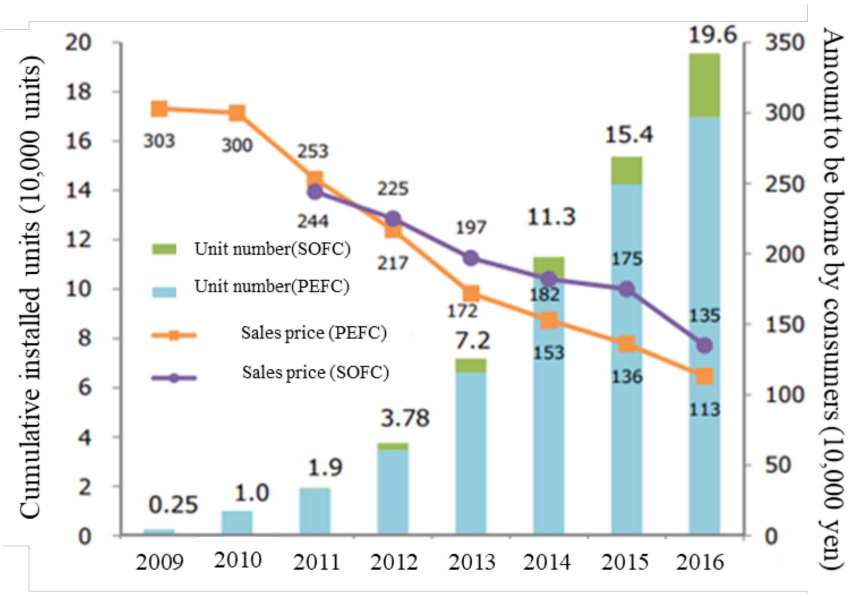

Fig 1-19 Annual installed number of residential fuel cells in Japan

(4) Heat pump

A heat pump is a device that transfers heat energy from a source of heat to what is called a heat sink. Heat pumps move thermal energy in the opposite direction of spontaneous heat transfer, by absorbing heat from a cold space and releasing it to a warmer one. In Japan, heat pump is an electronic air conditioner, which is widely used in families and commercial spaces, so it constitutes a huge market. In recent years, heat pump products for domestic hot water supply have increased rapidly. As people pay more and more attention to environmental problems, heat pumps using natural refrigerants instead of fluorocarbon refrigerants have attracted the attention of consumers. The ozone depletion potential (ODP) of carbon dioxide heat pump is zero and the global warming potential (GWP) is also very low.

The residential heat pump system was first introduced in Japan in April 2001 (Fig 1-20). In September 2007, the cumulative shipments of the entire market exceeded 1 million units, and in October 2009, it exceeded 2 million units. In January 2014, the sales volume reached 4 million units (Fig 1-21). Compared with other countries in the world, domestic air energy heat pump water heater is the most popular in Japan. Small size, exquisite structure, leading technology and excellent performance are the biggest characteristics of Japan's air energy heat pump water heater. "Eco cut" is the main model of air-water heat pump water heater using natural refrigerant (CO_2). The demand of eco-cut has increased steadily in recent years. CO_2 gas has the advantages of good safety, chemical stability, harmless to the environment, large latent heat of evaporation, high refrigerating capacity per unit volume, good transportation and heat transfer properties, etc. And it still maintains high thermal efficiency in the heat exchange process with large temperature rise on the water side.

The rated operating temperature can generally reach 600 °C and the maximum outlet water temperature can reach 900 °C.

Fig 1-20 Appearance style of eco-cut equipment in Japan

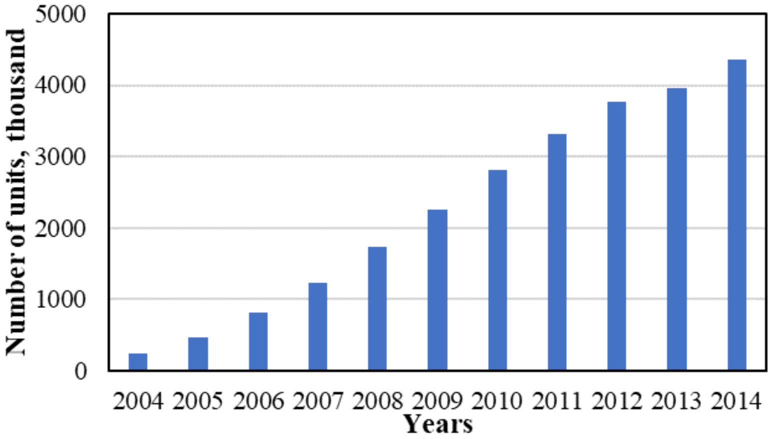

Fig 1-21 Cumulative number of residential heat pump

Eco-cute has gradually become a new product of great concern in the Japanese heat pump market. Many new residential and commercial buildings take the heat pump water heater as the preferred home heating center. Since entering the market in 2001, the sales volume has continued to rise, and the household penetration rate reached 10% in 2007. Affected by the economic crisis, the sales volume of eco-cute products in 2008 still exceeded 510,000 units, although there was a certain gap with the expectation. According to the market ownership, about 1.8 million domestic carbon dioxide heat pump water heaters were sold in the Japanese market in 2008. In 2010, the sales volume was about 800,000 units, and the cumulative sales volume will reach 3.2 million units. In 2011, the output reached 1 million units and the cumulative sales volume reached 5.2 million units.

As a rapidly growing market, heat pump water heater has attracted the attention of many manufacturers and promoted the development of relevant new products. It is certain that eco-cute will trigger significant changes in the central water heater market. In this market, gas water heater has occupied most of the share, and heat pump water heater has only accounted for about 6% for a long time. If the eco-cute market expands from now on and the total installed capacity can reach the expected 5.2 million units, the share of heat pump water heater in the central water heater market will rise to 30% or more.

(5) Battery

Battery is an electric storage equipment that can be repeatedly used by charging. The battery is from a small size portable material to a large size of electric installation, and the size is approximately proportional to the storage capacity.

Household batteries are mainly divided into two types:

1) One is the "system disconnected type", which is the power storage type purchased from the power company. Use the socket for charging, and connect the appliances you want to use directly to the household battery. According to different models, household appliances can also be wired and connected in electrical engineering. If the line is connected in advance, it will switch automatically in case of power failure, which has certain safety.

2) The second type is "system connected". Through the residential distribution panel, it is connected with the electrical system in the family to supply power to household appliances and lighting, and store the power produced by the solar power generation system. The stored electricity can also be used when using the electricity generated by sunlight. The system connection type is mainly used to store the power generated by solar power generation, and users with large power storage capacity.

In recent years, the installation of household batteries in Japan, which can store the electricity generated by household solar panels, has increased sharply (Fig 1-22). According to fit, during the ten-year contract period, the production company of household battery can buy the excess power of users' Households at a high price. However, there are now families whose ten-year contracts have expired. However, compared with selling electricity, more families choose to use their own electricity. At present, household batteries have attracted much attention. Household batteries can generate and store electricity during the day and use it at night when electricity consumption is high. According to Sharp, the market of household batteries is expected to increase from 42,000 in 2017 to 150,000 in 2021. At the same time, due to frequent natural disasters in Japan, the demand for domestic batteries as a solution to power failure has also increased.

Fig 1-22 Japanese household battery appearance

By 2030, Japan's new energy power generation is expected to account for 35% of the total power generation. It is estimated that Japan's energy storage market capacity will account for 50% of the world's total by 2020. In order to promote the installation and popularization of residential batteries, the Japanese government provides 66% cost subsidies for household and enterprise users who install lithium battery energy storage.

However, the price of household batteries is high. According to the capacity, the price ranges from hundreds of thousand Yen to millions of Yen. Moreover, the life of household battery is limited, and the cost may not be recovered. On the other hand, due to different regions, some local governments provide subsidies for residents to buy household batteries as disaster prevention countermeasures.

According to the market trend in 2017, there are two basic choices for solar power suppliers - reducing solar PV power generation or building battery energy storage equipment to absorb additional power generation. The number of PV power stations equipped with energy storage is increasing, and the power grid company is also investing in the installation of some large energy storage power stations to ensure the stability of the power grid. In the future, power grid companies can no longer invest in battery equipment, but purchase auxiliary services from suppliers. Real estate developers want their houses to have more added value. They also begin to choose to be equipped with power storage system, which can sell auxiliary services and battery power.

The advantages of installing household batteries are as follows:

1) It can reduce the electricity bill.

Household batteries can store electricity and use it when needed. By connecting the solar power generation system, users can save idle power generated during the day and use it at night to reduce electricity charges. Even if the solar power generation system is not connected, the electricity bill can be reduced by charging with cheap midnight electricity and using it during the day (Fig 1-23).

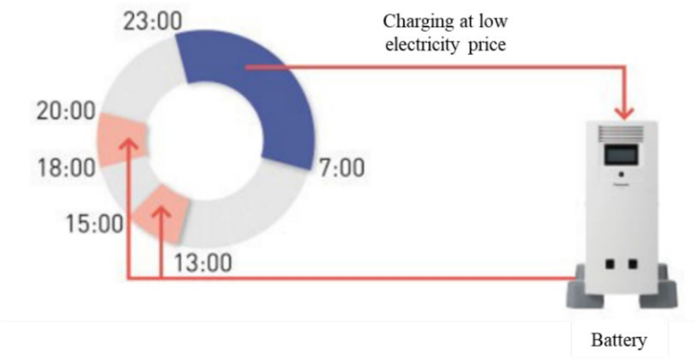

Fig 1-23 Schematic diagram of battery combined electricity price scheme

2) Emergency power

In Japan, where earthquakes, typhoons and other natural disasters frequently occur, the frequency of power outages is high. Household batteries can use stored electricity in an emergency. At the same time, it is linked with the solar power generation system. Even if the stored power is used up, it can be charged with solar energy during the day the next day.

3) Reduce carbon dioxide emissions

The main cause of global warming is the large amount of carbon dioxide produced when burning fossil fuels. Reducing household electricity consumption can reduce the use of fossil fuels and reduce carbon dioxide, thereby slowing global warming.

The disadvantages of installing household batteries are as follows:

1) The installation of household batteries takes up some space.

2) The equipment price of household battery is high, which requires high initial investment cost.

(6) Thermal storage tank

Water heater is a kind of equipment with very simple structure to provide hot water supply function. It is mainly divided into hot water storage type and instantaneous type.

The hot water storage type is characterized by the ability to store water, so the water heater is in the shape of a water tank. The advantages of using hot water storage type are low operation cost and small heater capacity. The disadvantage is that there must be a water tank to store sufficient hot water.

The main feature of instantaneous type is to supply heating hot water immediately when the hot water tap is opened. Therefore, there is no need to worry that the hot water supply pressure is almost the same as the hot water supply pressure or the hot water is exhausted. And different from the hot water storage type, it does not need a water tank, so it has the advantage of small occupation space. On the contrary, the disadvantage is that a large amount of electrical equipment capacity is required.

There are other water heaters with combustion systems, most of which are installed outdoors. Since the temperature can be changed and set through the remote control in the room, it is easy to provide hot water for the house.

The specific principle of heat storage is to convert other forms of energy into heat energy, and store the heat energy under good thermal insulation conditions through a specific heat storage medium. When it needs to be used, the stored heat is extracted and used through heat exchange. Heat storage can be divided into sensible heat storage and phase change storage according to the state of heat storage medium.

Phase change materials have greater energy storage density, so they have greater development potential. Due to the limitation of material cost and supporting equipment, sensible heat storage is still the main energy storage market at present. With the development and application of new heat storage materials and the improvement of supporting equipment manufacturing process, the cost of heat storage technology application has decreased year by year, and more and more commercial engineering applications have been promoted.

The addition of heat storage tank can improve the operation reliability of the energy supply system, and maintain the indoor temperature by prolonging the operation time of the system even in cold weather. In case of shutdown protection of heat pump unit, it can also supplement heat directly.

In addition, the heat storage tank can follow the randomness and fluctuation of the total heat load of the energy supply system, flexibly adjust the total amount of stored heat energy, reasonably control the heat exchange of stored heat energy, and make full use of the economic benefits of peak valley electricity price. Through heat storage, it can not only cut the peak and fill the valley, adjust the load balance of local power supply, improve energy utilization efficiency, but also reduce the electricity cost of the system.

(7) Electric vehicle

An electric car or battery electric car is an automobile that is propelled by one or more electric motors, using energy stored in batteries. Charging an electric car can be done at a variety of charging stations; these charging stations can be installed in both houses and public areas.

Out of all cars sold in 2020, 4.6% were plug-in electric, and by the end of that year there were more than 10 million plug-in electric cars on the world's roads, according to the International Energy

Agency. Despite rapid growth, only about 1% of cars on the world's roads were fully electric and plug-in hybrid cars by the end of 2020.Many countries have established government incentives for plug-in electric vehicles, tax credits, subsidies, and other non-monetary incentives while several countries have legislated to phase-out sales of fossil fuel cars to reduce air pollution and limit climate change.

Nowadays, electric vehicles can not only take the place of transportation, but also supply power to the home. The vehicle to home(V2H) function with this feature has been applied in electric vehicles, and this function of plug-in hybrid vehicle (PHV) and fuel cell vehicle (FCV) is also under development. This is unmatched by previous gasoline vehicles. In the future, the energy conversion between cars and families is likely to add new added value to cars.

At present, Japanese researchers have begun to explore the V2H system which is most suitable for popularizing electric vehicles to Volkswagen. Its advantage is that it can reduce the household electricity expenditure through "peak load shifting power consumption", and can be used as an emergency power supply in case of power failure.

At present, Japan has a variety of residential power generation equipment, such as solar power generation, household battery, household fuel cell and natural gas power generation. Since the East Japan earthquake, the planned power outage policy implemented in Japan has increased the number of power outages caused by natural disasters such as typhoons and storms. Nissan Motor Company pointed out that "the actual demand of consumers for V2H is increasing".

After automobile manufacturers add V2H function to electric vehicles, some manufacturers aim to simplify the existing household power generation system, while others combine with the existing system to make the use more flexible and diverse. All manufacturers still hope to improve the added value of electric vehicles through the practical application of V2H, so as to promote the further popularization of electric vehicles.

The world's first V2H system produced by Nissan has sold about 2000 units so far. This device can convert up to 6kW of power from the vehicle lithium battery for household use. Fig 1-24 shows the basic structure of V2H. The power conversion device (PCS) is used to convert DC power into AC power to supply power to the home. PCS configuration and automobile power output mode of different automobile manufacturers are different (Fig 1-25).

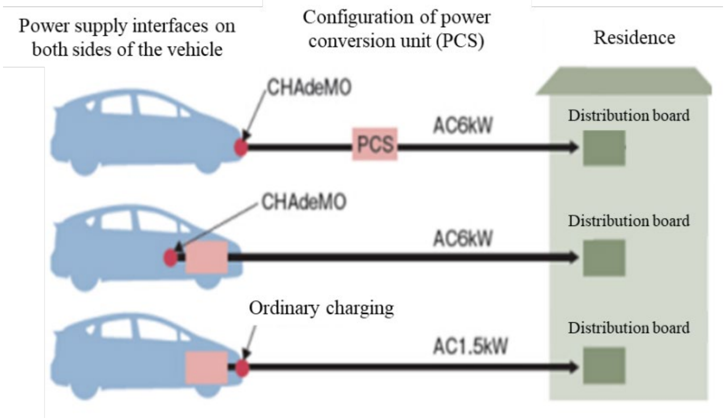

Fig 1-24 The basic structure of V2H

Fig 1-25 The smart house with V2H

1.3.2 Advantages and disadvantages of smart house

Smart house is an efficient, comfortable, safe, convenient, and environment-friendly living environment with residence as the platform, building equipment, network communication, information appliances and equipment automation, and integrating system, structure, service and management. On the basis of maintaining the traditional living function, it gets rid of the passive mode and becomes a dynamic and intelligent modern tool. Smart house not only provides all-round information exchange function, but also optimizes people's lifestyle and living environment, helps people effectively arrange time and save all kinds of energy, and realizes the functions of home appliance control, lighting control, indoor and outdoor remote control, curtain automatic control, anti-theft alarm, computer control, timing control and telephone remote control[33].

The advantages of smart house are as follows:

1) Convenience of smart house.

When designing smart house, it provides users with life convenience with the most practical and basic home control according to users' home function needs. Including intelligent home appliance control, intelligent lighting control, electric curtain control, anti-theft alarm, access control intercom, gas leakage and other service value-added functions.

Personalized smart house control methods are also diverse. Users can take different methods to achieve the same effect, such as local control, remote control, centralized control, mobile phone remote control, induction control, network control, timing control, etc., so as to make the operation more convenient and faster.

2) Reliability and security of smart house.

smart house can take corresponding fault-tolerant measures for each subsystem in terms of power supply and system backup, so as to ensure the normal and safe use, good quality and performance of the system, so as to achieve the ability to cope with various complex environmental changes. Make the smart house run 24 hours and protect the safety of home life at all times.

3) Smart house has complete functions.

The design of smart house system scheme shall be carried out in accordance with relevant national and regional standards to ensure the expansibility and expansibility of the system. Standard TCP/IP protocol network technology shall be adopted in system transmission to ensure the compatibility and interconnection of systems between different manufacturers. The front-end equipment of the system is multifunctional, open and expandable. For example, the system host, terminal and module adopt standardized interface design to provide an integrated platform for external manufacturers of home intelligent system, and its functions can be expanded. When functions need to be added, there is no need to excavate pipe network, which is simple, reliable, convenient and economical. The system and products selected in the design can make the system interconnected with the continuously developing third-party controlled equipment in the future.

However, at the same time, there are some bottlenecks and shortcomings to be optimized in the current popularization and promotion of smart house:

1) The equipment price of smart house is high.

Although the smart house market in Japan is quite large, the initial investment cost of smart house is still preferred. Only a few separate products can not constitute the whole smart house system. The cost of initial installation is a relatively large investment, and the later maintenance cost should be considered.

2) At present, the equipment installation and operation of smart house are more complex.

Some smart house devices have cumbersome usage and complex operation, which affect the user experience.

3) There are many security risks, and there are loopholes in the information security system.

4) Lack of unified standards and confusion of industrial products.

The revolution of network communication, the popularization of PV power generation, the improvement of battery technology and the practicability of energy-saving vehicles have caused changes in the connotation of smart house, which makes Japan's smart house develop towards the integration of manufacturing energy, storing energy and saving energy. This development trend enables people to fully enjoy the living comfort brought by high technology, realize the full utilization and conservation of energy, and promote the development of green industry, which will become a new economic growth point of Japan's economy.

1.4 Research structure and logical framework

1.4.1 Research purpose and core content

The research logic of the article is shown in Fig 1-26 below. Based on the research status and application of smart house, the advantages and disadvantages of smart house are sorted and analyzed. Then this study compares and optimizes the economy of smart house composed of different energy systems from three aspects: users, equipment, and power companies.

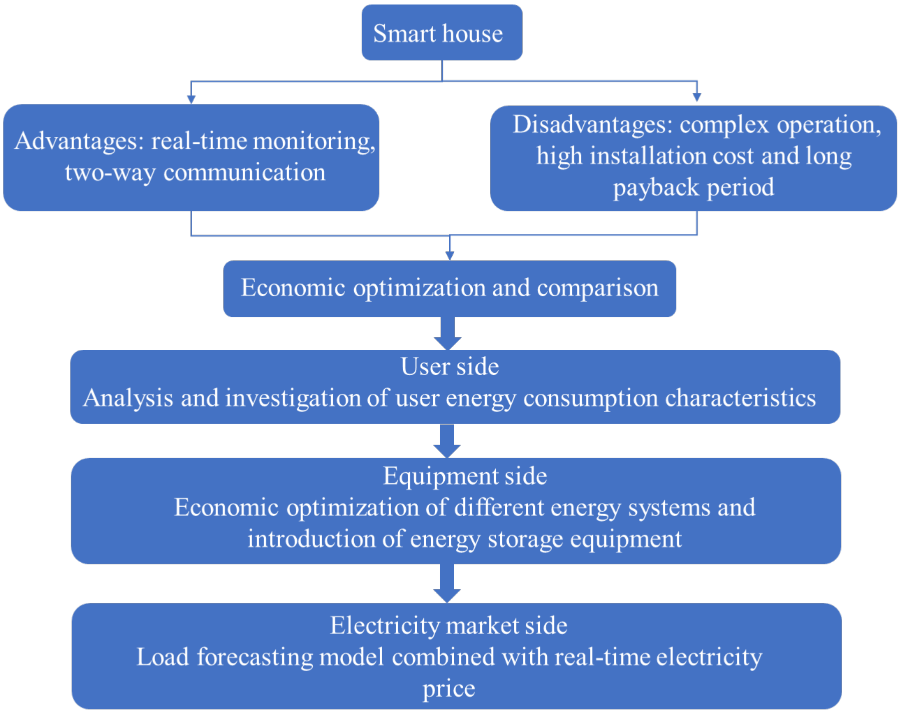

Fig 1-26 Research logic of the article

1.4.2 Chapter content overview and related instructions

The chapter names and basic structure of the article are shown in Fig 1-27. The brief chapters are shown in Fig 1-28.

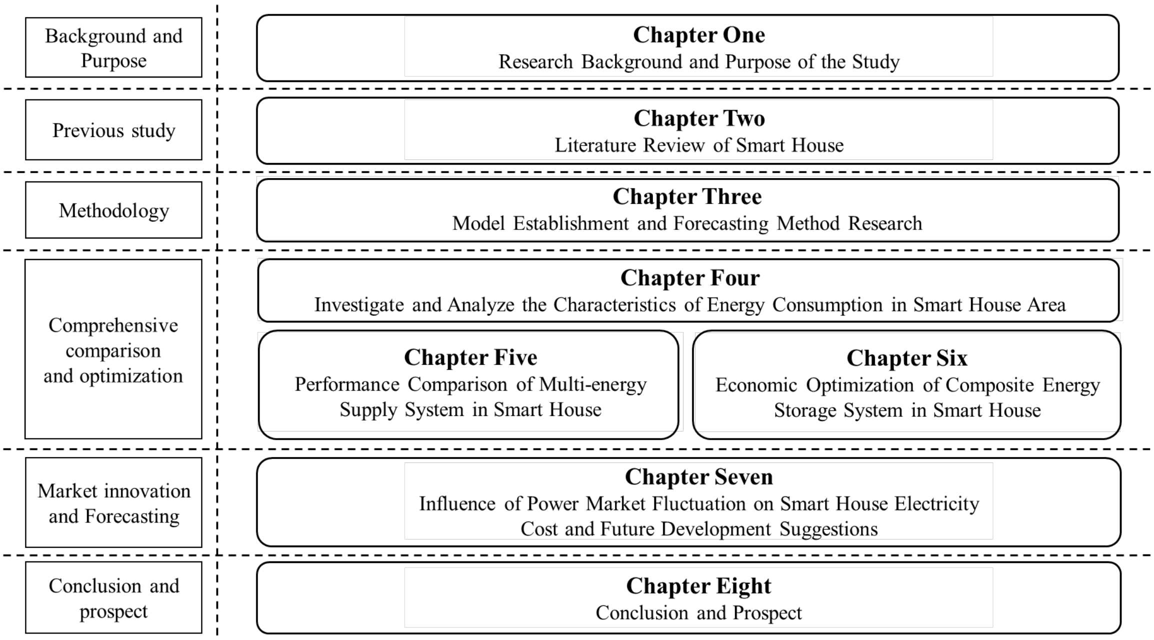

Fig 1-27 Chapter name and basic structure

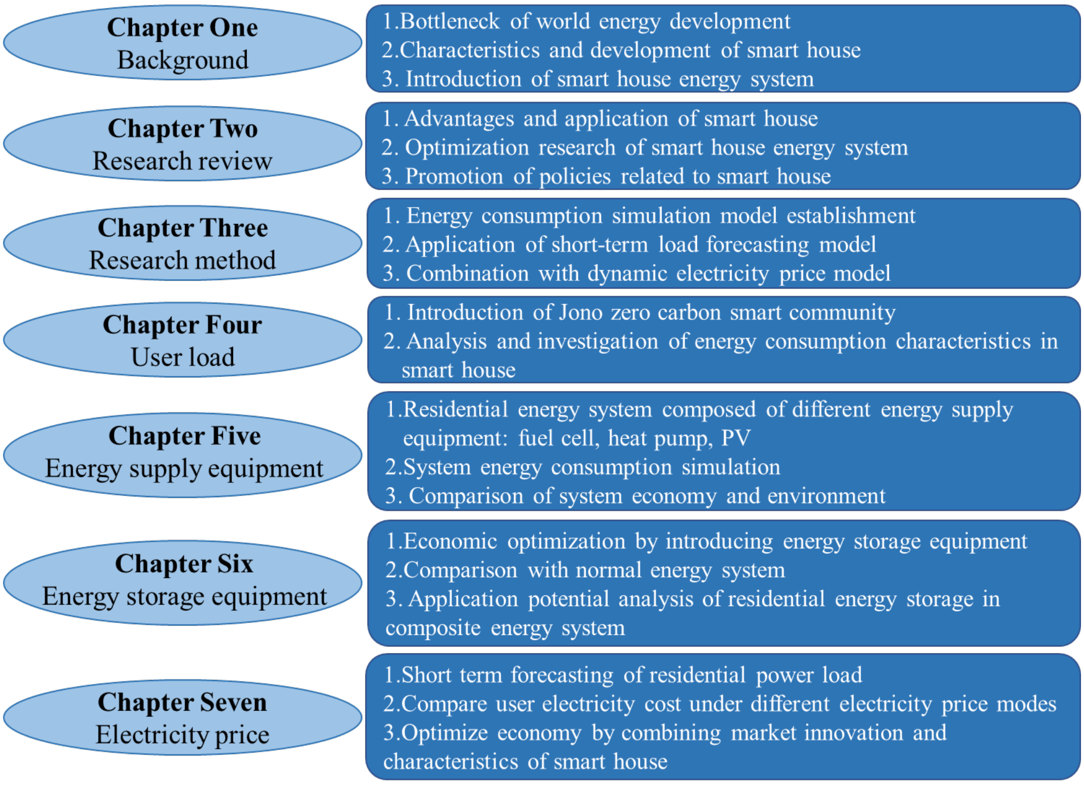

Fig 1-28 Brief chapter introduction

In Chapter 1, Research background and purpose of the study:

Smart house is one of the important methods to achieve the goal of energy conservation and emission reduction in the family sector. However, due to the high installation cost of Smart house system, the system payback period is long, which is the main problem in the popularization of smart house. This chapter first introduces the current energy background of the world and Japan, and explains the current situation of rapid growth of power consumption in the household sector. Then, it expounds the characteristics and development process of smart house. Next, it introduces the application of smart house in various countries. Then the equipment included in the smart house energy system is described. Finally, it expounds the research logic and content of this paper.

In Chapter 2, Literature review of smart house:

This part is mainly to sort out the research status of smart house. First of all, by reviewing the research on smart house technology and development in various countries, this chapter expounds the advantages of smart house in automatic control and energy management and the problem of high system price. Then it points out that the current research focus of smart house is economic optimization and the improvement of coupling degree between equipment, and describes the latest research results. Secondly, the research results of optimizing the smart house energy system through various factors such as equipment, user behavior and policy are sorted out. Finally, according to the research object of this paper, this chapter studies and combs the policies and subsidies issued by various countries in the process of promoting smart house.

In Chapter 3, Model establishment and forecasting method research:

This part is about methodological research and model building. Firstly, the research motivation and the main application simulation software are described. Then, the general load and equipment models used in the follow-up study are established. Next, different model principles and simulation system operation strategies are introduced. Then the calculation methods of system economy and environment are sorted out.

In Chapter 4, Investigate and analyze the characteristics of energy consumption in smart house area:

In this part, we conducted a questionnaire survey on residents living in smart house area. The questionnaire includes family composition, equipment installation, users' awareness of environmental protection and the use frequency of smart house energy management system. After that, this part utilizes the monitored history data to analyze the energy consumption characteristics and influencing factors of the residential customers, which feature with heat pump heat supply system in smart house.

In Chapter 5, Performance comparison of multi-energy supply system in smart house:

Due to the improvement of people's living standards, uptake of multi-functional household appliances, electricity consumption accounts for a rising ratio in the proportion of primary energy usage. Currently, electricity accounts for more than 50% of primary energy usage and city gas is about 21% of total.

The aim of this part focus on improving the efficiency of household energy usage and optimizing the economy of residential energy systems. First of all, this part classified the detail electricity consumption and generation for a Japan typical smart house with Hybrid Fuel cell and Photovoltaic System (HFPS) based on the history monitored data. Then a simulation model of the Hybrid Heat pump and Photovoltaic System (HHPS) was designed under the same user load for analyzing the energy consumption. In addition, this part also lists five kinds of electricity price schemes of electric company. The electricity costs of HFPS and HHPS were calculated based on five cases. Finally, the economy of the two systems is compared and optimized by considering the carbon tax, equipment price and energy price fluctuation. The results of this part provide policy guidance for the future Japanese government's promotion of residential fuel cell systems, while choosing the optimal path between user energy characteristics and power contract scheme.

In Chapter 6, Economic optimization of composite energy storage system in smart house:

With the popularization of distributed generation and renewable energy technology, the demand side management of residential energy system has been further developed. Aiming at the problems of low operation efficiency and insufficient system security in residential distributed system, the application of energy storage technology can realize peak shaving and valley filling, improve the system reliability and stability.

In this part, an independent smart house in “Jono smart house area” in Japan is selected as the research object. Relies on one year measured data, four cases are designed according to the introduction of different energy storage equipment. A double-level optimization model is established based on adaptive particle swarm optimization algorithm to optimize the size of energy storage equipment and system annual equipment output. The upper model optimizes the optimal size of energy storage equipment, and the lower model simulates the annual optimal equipment output according to the upper results. In addition, the system performance of the four cases is compared and analyzed from three aspects of energy, environment and economy based on the comprehensive comparison model. It is suggested to appropriately reduce the equipment price in combination with subsidy and incentive policies for further promotion. The results act as a useful reference for users to reasonably match energy supply and storage equipment to achieve cost reduction, while providing policy suggestions for the government to further carry out relevant research and industrial development in user-side energy storage.

In Chapter 7, Influence of power market fluctuation on smart house electricity cost and future development suggestions:

To address the primary energy shortage problem, Japan has implemented a series of policies and measures for residential energy conservation and emission reduction. Among them, the home energy management system (HEMS) in a smart house as a hub connecting users and power companies to realize energy visualization has been widely studied.

In this part, to predict the energy consumed on the next day based on historical data, a short-term household load forecasting model based on the particle swarm optimization regression vector machine algorithm was developed. Then a dynamic pricing model was developed to guide the users' electricity consumption behavior and adjust the grid load. According to the prediction results obtained by the load forecasting model, the annual electricity charges of users under the three pricing schemes of multistep electricity pricing (MEP), time-of-use pricing (TOU), and real-time pricing (RTP) were calculated and compared. In addition, after adjusting the users' peak load and combining it with the fluctuating future electricity prices, RTP presented evident economic advantage over MTP and TOU in terms of the annual electricity cost of the users. The study results can provide policy suggestions for the future Japanese government's promotion of RTP strategy, while acting as a reference for further developing the characteristics of HEMS and optimizing the relation between the supply and demand sides.

In Chapter 8, Conclusion and prospect:

This part summarized the research of previous chapters. And based on the conclusions, the future development of smart house and the prospect of further research are put forward.

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Chapter 2

LITERATURE REVIEW OF SMART HOUSE

CHAPTER TWO: LITERATURE REVIEW OF SMART HOUSE

2.1 Review of research on smart house application

With the continuous development of economy and technology, human's energy demand is increasing gradually and the traditional power system is facing considerable pressure to meet this demand[1]. Meanwhile, with the growing concerns of ecological environment deterioration and resource waste generated by energy consumption, it is important to improve the energy efficiency and reduce energy consumption cost[2-3]. Under the trend of global warming, various countries have restricted the use of fossil fuels such as oil, coal and natural gas, and switched to clean energy while improving the energy efficiency as a primary task[4]. The residential sector accounts for a large proportion of overall energy and electricity consumption. Due to the penetration of heat pumps and electric vehicles, the proportion of power consumption is expected to continue to grow. As a clean energy source that is easy to transmit, electric energy accounts for a large proportion of the energy consumed in daily life and production[5-6]. To control energy consumption, countries worldwide have vigorously implemented policies to encourage research and development of efficient and energy-saving technologies[7]. Among them, residential energy consumption accounts for a large proportion of the total energy consumption, and the waste generated by power consumption is more serious, which exhibits optimization significance (Fig 2-1)[8]. After the Fukushima nuclear accident in Japan, the phenomenon of insufficient power supply has significantly hindered the overall stability of Japan’s industrial production and national economic operation, and has had a huge effect on people’s normal lives. In this regard, Japan has issued a series of energy-saving and low-carbon development strategies and policies, and plans to reduce the total energy consumption by 50.3 million kL and residential energy consumption by 11.6 million kL by 2030, compared with 2013[9-10]. Recently, the visualization of energy consumption and energy management through smart house as the main energy-saving countermeasures has gradually become the focus of residential energy optimization research[11].

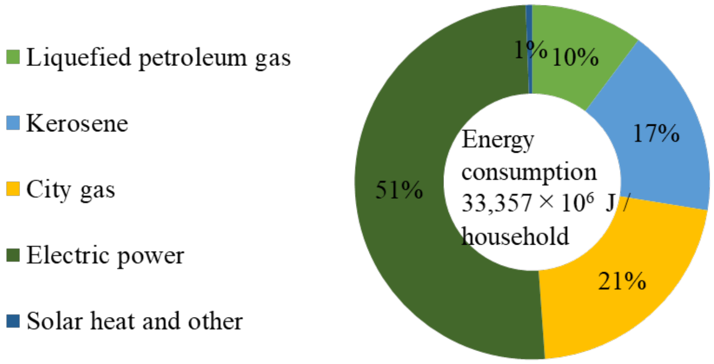

Fig 2-1 Japanese household energy source in 2016[12]

Due to the advancement of urbanization, it is expected that urban infrastructure will face great pressure[13]. Therefore, in a specific complex and harsh environment, new technology solutions will be the key to ensure the normal operation of the city[14]. In the previous sense, the universal application of Internet of things and intelligent technology will play an important role in solving some major infrastructure related problems in cities. Smart energy is a holistic approach that combines the concepts of green, sustainable and renewable energy[15-16]. The forecast shows that in the next 20 years, the world power production is expected to increase by more than 40% and its demand will increase by about 85%[17-18].The current overall market structure of Internet of things(IoT) technology is shown in Fig 2-2[19]. Most of the markets are focused on smart energy.

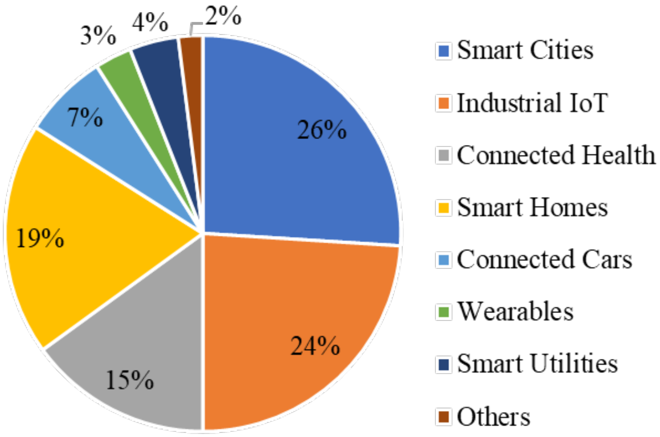

Fig 2-2 General market structure of IoT technologies[19]

As a comprehensive living environment, smart house is equipped with intelligent technology to realize functional automation, which aims to become a universal way[20]. In fact, the penetration of modern information and communication technology into daily life, especially in housing, is inevitable (Fig 2-3)[21]. The application of smart home in the concept of smart city can improve the quality of life in residential facilities and bring novel and attractive technical solutions. Through more effective time management, energy and money can be saved at the same time[22-23]. There may be different control options in the smart home concept, which can effectively integrate renewable energy technology into the home and effectively balance supply and demand[24].

Smart home is an IoT integrated residence, which provides comfort, safety, convenience and improving the quality of life for owners[25-26]. The Internet of things is the underlying platform of smart home network, interconnecting heterogeneous smart devices such as smart phones and smart meters, as well as wearable devices[27-28]. Smart home system can promote people's life and independent life. They provide valuable technologies, such as activity monitoring and health assessment, and attract the attention of users and device developers[29]. It is estimated that the global smart home market will reach US $53.45 billion by 2022, and the adoption rate of smart home will continue to grow, with a compound annual growth rate of 20.8% from 2018 to 2022[30]. By 2022, the global smart home market is expected to reach US $53.45 billion[31].

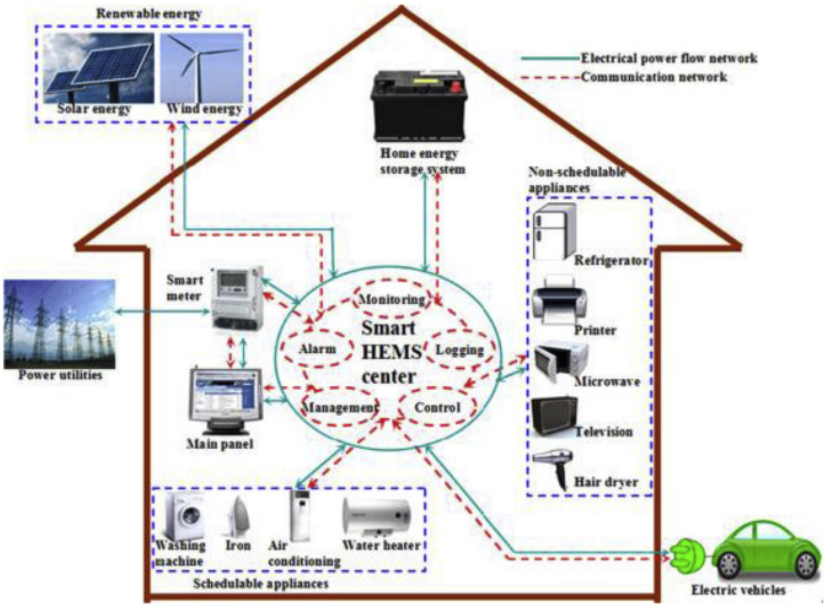

Fig 2-3 Various smart house management systems[21]

2.2 Review of smart house energy management

Smart home energy management is an extensive research field with different sub objectives and knowledge fields[32]. As shown in Fig 2-4[33]. Smart home energy management classification consists of four main layers: monitoring, analysis and prediction, scheduling and coordination. Their functions and possible knowledge areas are also listed. The research report shows that the use of smart home energy management system (SHEMS) can reduce energy consumption by nearly 15-40%.

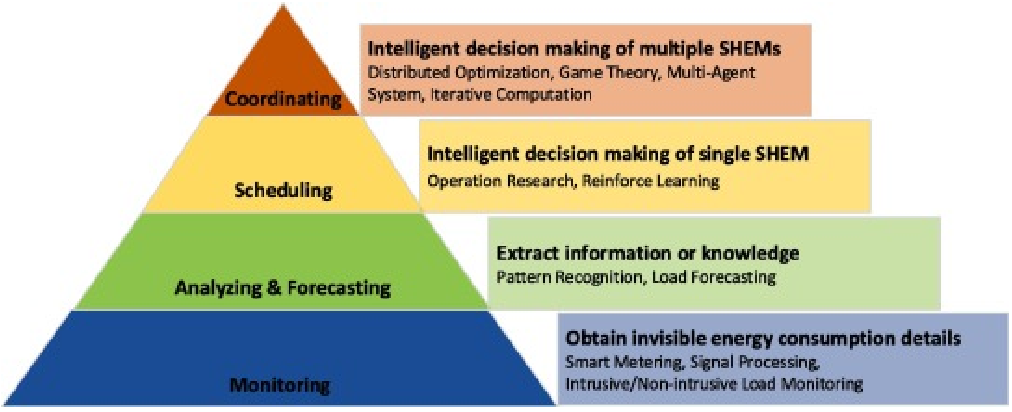

Fig 2-4 Smart home energy management classification[33]

The details of household energy consumption are the basis of household energy management[34-35]. According to the sensor installation mode, the monitoring methods can be divided into two categories: invasive load monitoring (ILM) and non-invasive load monitoring (NILM)[36]. The analysis and prediction layer reprocesses the measured or decomposed electrical energy consumption details to obtain more information or knowledge[37]. Home appliance usage pattern mining can infer users' preferences and quantify their comfort needs, which is very important for home energy scheduling with perceived comfort[38]. Forecasting is also important in active building energy system planning and operation[39-40]. On the one hand, it can reflect whether the previous understanding of building energy system is correct (such as model calibration). On the other hand, it can provide additional future information for decision support (e.g., model predictive control). Scheduling is the core task of Shem with intermittent renewable energy[41], flexible demand[42] and energy storage equipment[43]. It allows complex coupling between local energy production, consumption and storage[44]. Generally, scheduling methods can be divided into two categories: rule-based control and optimization, based control. The former is simple, fast and widely deployed in practice, because it does not need prediction information and has less computational burden[45]. The latter uses the prediction information and generates the optimal control action by solving the optimization problem. Coordination is driven by distributed intelligence in multi-agent system, in which the objectives of multiple intelligent agents are the same[46]. Neighborhood or community energy system is a typical multi-agent system[47]. The Shem of each house must address local goals and overall goals or constraints.

From the perspective of smart grid, smart home is regarded as nano-grid[48]. Nano-grids can have energy sources, such as photovoltaic modules, small wind turbines, and energy storage including plug-in electric vehicles[49]. The neighborhood interconnected nano-grid network forms a microgrid[50].

Taking electric power as the core of energy supply is an important foundation to support the continuous development of social economy[51-52]. However, with the rapid development of economy and the continuous growth of energy demand, the contradiction between the decrease of primary energy and the intensity dependence of social development on energy is becoming increasingly prominent[53]. To deal with this problem, the development and utilization of distributed energy mainly based on renewable energy has been widely recognized and developed vigorously in the world, and has become an important research object in the field of new energy research. Distributed generation technology based on renewable energy is an important supplement to traditional power generation technology.

From a global perspective, due to the acceleration of urbanization, the total amount of electric energy consumption continues to grow, among which the proportion of residential electricity consumption in the total social electricity consumption is on the rise[54-56]. Based on this situation, as a flexible energy-saving concept and method, residential distributed energy system has attracted extensive attention[57][58]. However, with many distributed generations connected to the grid and the deepening of its research, the instability and uncontrollability of system power supply has gradually become prominent. In order to reduce the negative impact of distributed generation, fully explore the economic value and environmental protection benefits brought by distributed generation to power grid and users, and improve the utilization efficiency of renewable energy, relevant researchers put forward the concept of microgrid. Many countries have formulated development plans and policies in combination with their own microgrid structure, and established corresponding laboratories and demonstration projects. A lot of research has been carried out on the operation, control, protection, energy management and impact on power system of microgrid, and some results have been obtained.

Restrepo verifies that direct-current microgrid is an effective way to interconnect distributed energy, which can provide sufficient and continuous energy for most internal load requirements[59]. Salihu introduces the design and application of a photovoltaic microgrid system in a community in Nigeria, which effectively utilizes the local abundant solar energy resources and greatly improves the economic activities and social life of the experimental community[60]. Obara investigates the planning facilities of isolated island microgrid system located on two small islands in Japan. Based on the power estimation of renewable energy output, a method for optimizing the operation of major electrical and heating equipment is developed using genetic algorithm. The simulation results show that the annual utilization rate of renewable energy is more than 40%[61].

The effective use of distributed energy and energy storage equipment in HEMS can help users reduce their dependence on the grid as well as the household energy expenditure[62-63]. Hemmati presented an energy supply mode, combined with a battery energy storage system (BESS) and HEMS, by optimizing the charging–discharging regime and BESS capacity to reduce the annual electricity bill in the home[64-65]. Lokeshgupta applied the load uncertainty model to analyze the economy of HEMS model with BESS, and the simulation results verified the effectiveness of the model [66]. Golshannavaz proposed HEMS strategy that used the residual capacity of electric vehicles and energy storage systems for reactive power compensation of home appliances, and optimized the system's economy[67]. Essa considered the state of charge of a photovoltaic (PV) battery in HEMS, and determined that the energy consumption of this system is reduced by 30% under the condition of ensuring user comfort [68]. Mehrjerdi presented HEMS incorporating a hydrogen storage system and solar generating units, and determined the optimal sizing and operation of hydrogen storage and solar systems [69]. Li proved that HEMS could achieve zero energy consumption effect by combining a roof PV, household high-efficiency heat pump, fuel-cell cogeneration system, and other energy-consuming equipment [57].

2.3 The research on energy equipment application in smart house

2.3.1 Energy supply equipment applied in smart house

Driven by the improvement in people's living standards and material needs, Japan's primary energy consumption has increased over recent year[70]. In addition, after the 2011 Great East Japan Earthquake, some power stations were shut down concerns security of energy supply, which further resulted in the reduction of the electricity generation in Japan. In order to achieve a low-carbon society as soon as possible, it is important to reduce household CO_2 emissions[71]. To solve this problem, Japan has promoted some energy-efficient residential energy systems in recent years to improve the efficiency of household energy usage and reduce the amount of CO_2 emissions from the residential sector[72]. Currently, fuel cells, heat pumps and PV are more widely used in residential energy systems.

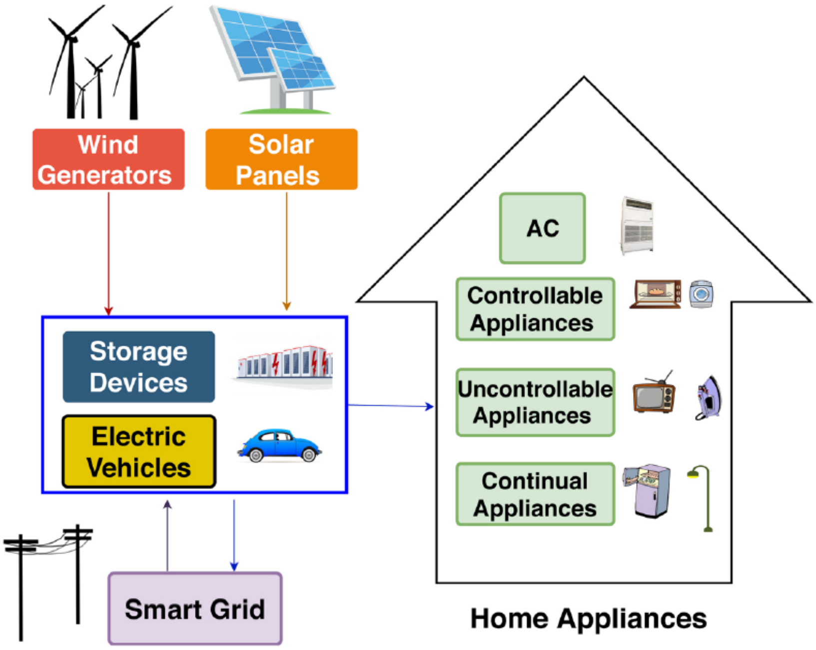

Fig 2-5 Main equipment of smart house

The adoption of PV in residential energy systems can reduced energy bills and CO_2 emissions[73-74]. Sow compared the economic analysis of residential solar photovoltaic systems in various provinces of Canada[75]. Enongene evaluated the technical, economic, and environmental potential of photovoltaic systems for generating electricity in different residential building types[76]. Fuel cell based on CHP systems are very attractive for stationary energy generation, since they allow production of electricity and heat in a decentralized, quiet, efficient and environmentally friendly way[77-78]. Nagasawa analyzed the residential fuel cells system can reduce primary energy consumption and CO_2 emissions, and offer grid reliability benefits by reducing peak electric load[79]. Pepe presented the economic analysis of Micro-CHP systems for residential applications in 2006, and find that fuel cells are still too expensive and that even the gas engines only have a small internal rate of return (<5%), and this only occurs in favorable economic circumstances[80]. As for the performance of residential fuel cell combined heat and power systems for various household types in Japan, Ozawa found that the basic PEMFC-CHP systems have an economic advantage only for four-person families with teenage children[81].

Le simulated that at an ambient temperature of between −5.6°C and 23.8°C, the coupling of heat pump and storage tank indicated the lowest annual performance[82]. Yu compared the heat pump electric load under different outdoor temperature and found that the electric load of the heat pump increases with the decrease of the outdoor temperature[83]. Blackman evaluated the payback period based on sorption heat pump component costs, and when the sorption heat pump design capacity is between 22% and 44%, the fastest payback can be achieved[84]. Marinelli stated that one of the biggest challenges for heat pump system development is the combination of heat pumps with photovoltaic and thermal systems[85]. Facci assessed the simultaneous use of heat pumps and photovoltaic panels yields a positive synergy that drastically cuts the CO_2 emission, and guarantees the economical sustainability of the investment in renewable energy sources[86]. Tang proposed a concentrating solar power system integrating photovoltaics and a solar-syngas-fueled solid oxide fuel cell and the result may provide a possibility of a new pathway to the high efficiency of full solar spectrum utilization[87].

According to the 2016 Japan household energy source situation, electricity accounts for more than 50% of primary energy use, city gas accounts for more than 20%[88]. As for the proportion of energy consumption by household applications, power, lighting are increasing due to the spread and enlargement of home appliances and changes in lifestyles[89]. In order to make the utmost of renewable energy, reduce CO_2 emissions of residential energy systems and improve energy efficiency, a variety of energy-efficient energy-supplied equipment are gradually being promoted. Japan began introducing solar power generation in the 1990s, and by the end of 2015, the cumulative installation volume had reached 32.8 million kW. Among them, 27% is for residential solar power (less than 10 kW)[90]. In May 2009, the world's first residential fuel cell sales began in Japan. The residential fuel cell system has the advantages of high energy efficiency and less transmission loss, and is equipped with auxiliary heat source to provide hot water for the household. In order to promote the residential fuel cell system, Japan has implemented a series of relevant policies since 2009[91]. Including the introduction of subsidy system, and gas companies have introduced a charging scheme for residential fuel cell system to enable users to get preferential treatment on gas costs. Within ten years since the purchase of fuel cell equipment, gas companies have provided users with free services to repair faults and other problems[92]. The price of fuel cell equipment is also gradually declining. The equipment price published in January 2009 is 3.5 million yen, but in April

2015 is 1.6 million yen, only half of the original price. Based on the support of national policies and energy saving advantages of equipment characteristics, in December 2018, the cumulative production of residential fuel cells exceeded 250,000 units[93].

As for heat pump, the residential heat pump system was first introduced in Japan in April 2001. In September 2007, the cumulative shipments of the entire market exceeded 1 million units, and in January 2014, the sales volume reached 4 million units[94]. There is a low electricity price for residential heat pump system at night, heat pump can be used to store hot water for household at night. Fikru estimated electricity bill savings for residential photovoltaic systems and found that the actual savings are 20% higher than expected[95]. The introduction of PV systems plays a positive role in the economic and environmental performance of residential energy consumption. However, due to the inherent intermittent problem of solar PV power generation, there are still obstacles in its use. The adoption of hybrid PV and other energy supply equipment can guarantee a basically stable power supply. According to the characteristics of cogeneration of residential fuel cell system, Japan Gas Company proposed a “double power generation” mode, it is a power generation method of hybrid residential fuel cell system and PV system. The residential buildings introduced HFPS generate electricity through PV system and fuel cell, which increases the electricity feed-in to grid. Meanwhile, the PV system also has subsidy policy, after the introduction, users can get double subsidies[96]. In addition, according to the characteristics of residential heat pump system consumes power at night, at the meantime, introducing PV system to provide electricity for household during the day also become a part of the user's choice.

2.3.2 Energy storage equipment applied in smart house

The characteristics of ESS with wide application range, flexible dispatch and high grid friendliness make up for the shortage of microgrid technology, and have a positive impact on its application and promotion[97]. Nevertheless, the high initial investment and long payback period restrict the system promotion by economy. Hence, the optimal design and control of ESS has become the key issue in further research[98].

Neto proposed a qualitative comparative analysis on the power management system of DC microgrid composed of AC public grid, BESS, distributed generator and user load. In addition, the system performance is optimized in combination with the autonomy of ESS, the necessity of communication line and the existence of voltage deviation[99]. Li optimized the size of the hybrid PV and battery residential system using time of use(TOU) price based on genetic algorithm, which can meet the load demand and save the annual energy cost of $2457.8[100]. Ranaweera designed a distributed control scheme for the coupling of residential battery storage unit and PV to solve the overvoltage issues caused by high PV permeability[101]. According to the existing power supply projects in remote islands, Ma introduced PV hybrid wind power and battery system. The results indicate that the combination of renewable energy and ESS can completely replace the original diesel power generation system, and it is more economical for remote islands[102].

While the promotion of residential ESS is restricted by economy, the lack of optimization strategy and evaluation method for the final choice of operation system is also one of the obstacles in the promotion process[103]. Reimuth assessed the potential impact of climate and consumption compliance on battery flow and residual load, and suggested that both be considered as influencing factors in the optimal battery size selection[104]. Akter analyzed the economic feasibility of BESS in combination with different economic indicators such as electricity charge, recovery year, net present value, energy leveling cost and CO_2 emission reduction. The results proved the profitability of BESS for residential construction investment[105]. Mulleriyawage takes family housing in Australia as an example, stating that with sufficient subsidies, the installation of residential BESS can obtain economic returns based on the current market price[106] .

At present, some studies have analyzed and summarized the application of energy storage in smoothing energy output fluctuation, assisting grid connection, participating in frequency modulation and alleviating peak shaving pressure. Most of the above literatures focus on the operation of energy storage on the source grid side and user side. Based on the existing research, the user-side energy storage is significantly different from the grid side energy storage due to the different configuration subjects, configuration environment, business model and other aspects. In the application of residential energy storage, the profit return from the promotion of energy storage is an important factor affecting the motivation of users to install energy storage. Therefore, under the price policy and market environment, the application scenario selection and benefit analysis of user side energy storage are particularly important.

2.4 Optimization research of smart house energy system

Although power companies release price information to customers through smart meters or networks, the price data are usually released in the next period a few hours in advance. Therefore, when smart house with HEMS is used for scheduling, the electricity price data within the scheduled period may be partially unknown.

Under such circumstances, only with the function of short-term forecasting, HEMS can better adjust the working state of the electric equipment according to the energy consumption data and future electricity price, to reduce the system operation cost while meeting users' demand. The commonly used short-term load forecasting methods are generally classified into traditional and artificial intelligence methods. Compared with traditional methods, the artificial intelligence short-term forecasting method clearly exhibits better prediction accuracy, and therefore, is more suitable for establishing short-term forecasting models.

Chen proposed a support vector regression model for the short-term power load forecasting of various office buildings[107]. El-Baz established an algorithm that can run independently and does not need to be connected with sensors. The day-ahead power load can only be predicted in accordance with the electric load curve [108]. Kong presented an error correction method based on dynamic pattern decomposition that could improve the prediction accuracy of different models [109].

However, the current research on load forecasting methods focuses on the prediction of the public power grid without considering the effects of microgrids and electric vehicles. To establish the prediction model, it is necessary to further verify its applicability to systems containing microgrid electric vehicles.

2.5 Research on promotion policy related to smart house

As the core of the power market mechanism, different pricing strategies combined with smart house produce different economic effects. At present, multistep electricity price (MEP) and time-of-use pricing (TOU) are two common pricing strategies adopted in the electricity market.

MEP is characterized by charging according to the monthly electricity consumption of users, where the unit price increases with electricity consumption. In contrast, TOU is characterized by the establishment of unit prices according to different power consumption periods. The unit price of electricity is usually higher in the daytime than that at night. With the continuous development of the power market and a close combination of the wholesale and retail markets, the development of the real-time pricing (RTP) mechanism has gained particular importance. The main purpose of the RTP mechanism is to reflect the market equilibrium through the price, guide consumers to use electricity reasonably, and adjust the load curve, to improve the utilization rate of the power grid equipment and generation efficiency.

Gazafroudi analyzed the participation of a smart home in various price-based demand response strategies, and revealed that the participation of the smart home in TOU not only reduces the operation cost but also leads to smart home profitability[110]. Rajalingam proposed an HEMS algorithm based on TOU, where the use of PV power was maximized to reduce the electricity cost and address the problem of peak demand[111]. Elma developed a load forecasting model in RTP-based HEMS for better matching of energy consumption with renewable energy generation, and as a result, obtained considerable improvement in the cost-savings of residential producers[112]. Doostizadeh proposed a day ahead RTP model to assist a distribution company in offering optimal DA hourly prices using smart metering[113].

The present research on minimizing the home electricity cost in smart house has mostly focused on comparing and optimizing different energy supply systems, or the operation scheduling of household appliances in the same system. The simulation and optimization methods proposed for this purpose include a genetic algorithm, a neural network, PSO, robust optimization, and linear programming. However, with the continuously reforming electricity market, the connection between the supply and demand sides is becoming strong. To maximize the advantages of real-time, two-way feedback in smart house, the RTP strategy has been developed and gradually implemented.

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Chapter 3

MODEL ESTABLISHMENT AND FORECASTING METHOD RESEARCH

CHAPTER THREE: MODEL ESTABLISHMENT AND FORECASTING METHOD RESEARCH

3.1 Motivation and main method

3.1.1 Motivation

Through the combing of the second chapter on the research of smart house, it is found that although Japan has invested a lot of research and issued relevant promotion policies for the application of smart house. However, the popularization of smart house still has some problems, such as high initial investment cost, long payback cycle and complex system operation. Based on the background of vigorously advocating energy conservation and emission reduction measures in the world, this study reduces user costs and improves the penetration rate of smart house through economic optimization of smart house energy system. At the same time, considering the advantages of smart house that can monitor residential energy consumption in real time and realize two-way communication between users and power companies, we compare the economy and environment of smart house composed of different energy systems. This study will study the economic potential, impact analysis and development prediction of smart house with composite energy system from the perspectives of users, equipment and power companies. It is hoped that it can provide new ideas for the promotion of smart house and provide theoretical reference for the research on the practical application of smart house.

3.1.2 Introduction of main method

The main method of this study can be divided into two parts: comparison and optimization of energy consumption of smart house. The economy and environment of smart house systems with different combinations of energy supply equipment are compared. The energy consumption simulation model is established based on TRNSYS.

TRNSYS which used in this paper is a transient systems simulation program with a modular structure. The modular nature of TRNSYS gives the program tremendous flexibility, and facilitates the addition to the program of mathematical models not included in the standard TRNSYS library. Main applications of TRNSYS include solar systems(solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells.

Based on MATLAB modeling, the economic optimization of intelligent residence includes two aspects: equipment optimization and electricity price selection. A two-level optimization model is established to optimize the equipment output, charging and discharging of the intelligent residential energy system with energy storage equipment. At the same time, the adaptive particle swarm optimization algorithm is applied to calculate the optimal size of energy storage equipment to reduce power cost.

At the same time, using the advantages of two-way communication and real-time monitoring of smart house, this study also establishes short-term residential load forecasting model and real-time electricity price model. It is used to highlight the advantages of smart house and reduce the power cost of users.

3.2 Energy consumption simulation model establishment and comparison method

3.2.1 Energy equipment

(1) Fuel cell (FC)

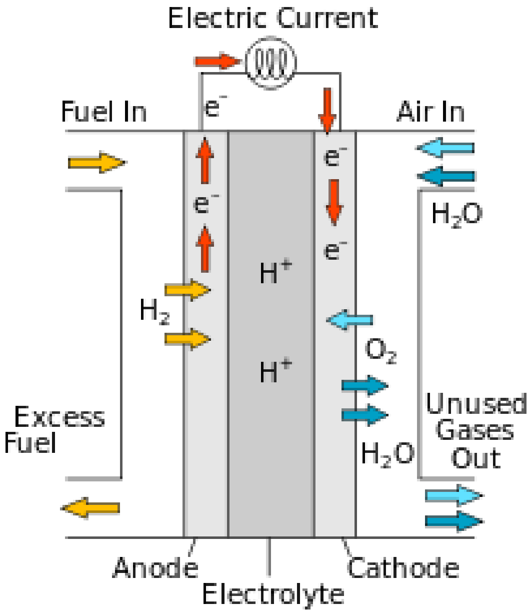


Fig 3-1 Schematic diagram of fuel cell power generation process

The principle of a fuel cell is an electrochemical device, and its composition is the same as that of a general battery. The single cell is composed of positive and negative electrodes (negative electrode is fuel electrode and positive electrode is oxidant electrode) and electrolyte. The difference is that the active material of a general battery is stored inside the battery, therefore, the battery capacity is limited. The positive and negative electrodes of the fuel cell itself do not contain active materials, but only a catalytic conversion element[1]. Therefore, fuel cells are literally energy conversion machines that convert chemical energy into electrical energy. When the battery is in operation, fuel and oxidant are supplied from outside to react. In principle, as long as the reactants are continuously input and the reaction products are continuously eliminated, the fuel cell can continuously generate electricity[2].

The fuel cell power generation model can be expressed as:

$$P_{FC} = f_{FC} \times L_h \times \delta_{FC} \tag{3-1}$$

Where, P_{FC} is the power generation power of the fuel cell; f_{FC} is the hydrogen consumption of the fuel cell; L_h is the low calorific value of hydrogen; δ_{FC} is the power generation efficiency of the fuel cell. The output thermal power model of the fuel cell can be expressed as:

$$Q_{FC} = P_{FC} \times \delta_{FC,heat} \tag{3-2}$$

Where, Q_{FC} is the output thermal power of the fuel cell; $\delta_{FC,heat}$ is the thermoelectric ratio of the fuel cell

(2) Heat pump (HP)

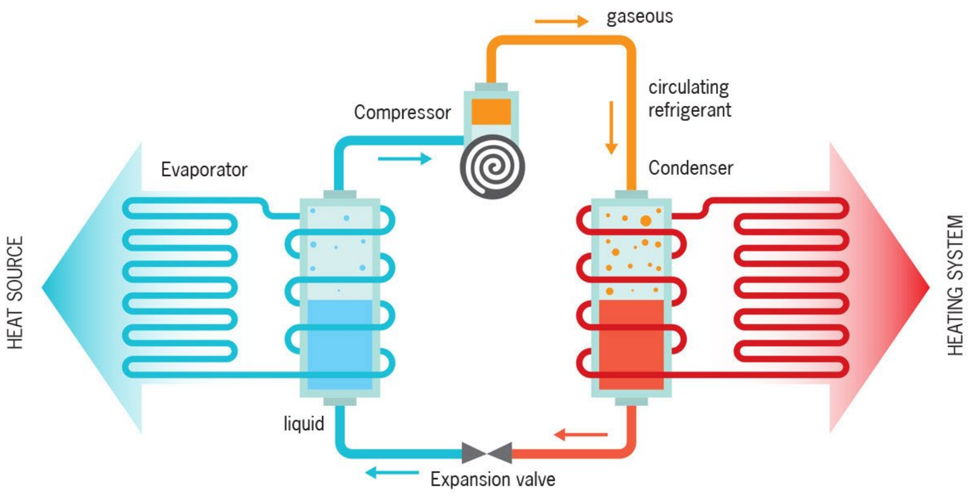


Fig 3-2 Schematic diagram of heat pump power generation process

A heat pump is a device used to warm the interior of a building or heat domestic hot water by transferring thermal energy from a cooler space to a warmer space using the refrigeration cycle, being the opposite direction in which heat transfer would take place without the application of external power[3]. Common device types include air source heat pumps, ground source heat pumps, water source heat pumps and exhaust air heat pumps. Heat pumps are also often used in district heating systems.

The efficiency of a heat pump is expressed as a coefficient of performance (COP), or seasonal coefficient of performance (SCOP). The higher the number, the more efficient a heat pump is and the less energy it consumes. When used for space heating these devices are typically much more energy efficient than simple electrical resistance heaters. Heat pumps have a smaller carbon footprint than heating systems burning fossil fuels such as natural gas, but those powered by hydrogen are also low-carbon and may become competitors[4].

The heat pump uses electricity to generate cold or heat using compression refrigeration. It has a high COP and high energy efficiency. The cooling capacity of the heat pump is expressed as follows.

(Take cooling as an example)

$$Q_{HP,cold} = P_e \times COP_{HP,cold} \tag{3-3}$$

Where, $Q_{HP,cold}$ is the cooling capacity of the heat pump, P_e is the power consumption of the heat pump; $COP_{HP,cold}$ is the energy conversion efficiency of the heat pump.

(3) Energy storage device

The principle of the energy storage device is to use the excess valley charge of the power grid at night to continue to operate cooling and heating, and store the cooling and heat through the medium, and release the cooling and heat during the peak electricity consumption during the day to provide air conditioning services, thereby alleviating air conditioning Conflicts over peak power. There are currently three popular cold storage methods, namely water cold storage, ice cold storage, and excellent salt cold storage[5]. The heat storage methods mainly include water heat storage and solid heat storage. Among them, the method of water storage can be used as heat storage in winter, and can partially replace the fire water tank of the building, so it is the most widely used.The energy supply method of the water storage tank is relatively simple, and the basic performance parameters are shown in the following table 3-1. (Taking 2500 m^3 of cold storage tank as an example, the temperature difference is 7°C.)

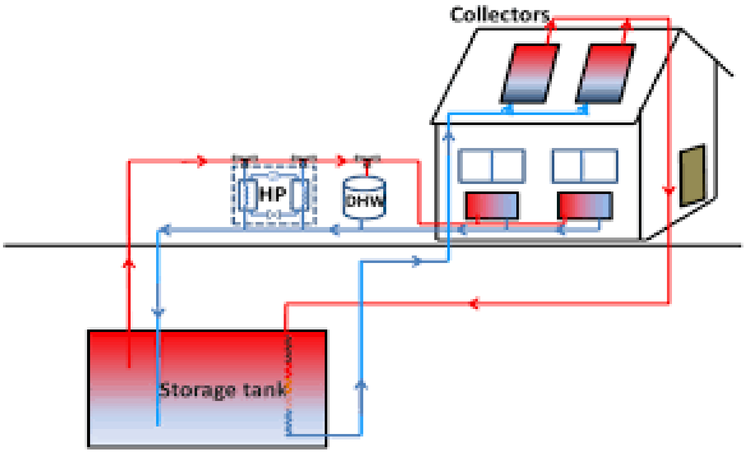


Fig 3-3 Schematic diagram of thermal storage tank working process

Table 3-1 Characteristics of water storage tank

No.	Parameter name	Data	No.	Parameter name	Data
1	Total effective water storage (m^3)	2500	5	Main tank service life	Not less than 20 years
2	Maximum cold storage flow (m^3/h)	417(6 hours full)	6	Storage tank volume utilization	Not less than 90%
3	Effective cold storage and release capacity (kWh)	20000kWh	7	Reynolds number Re	Re≦850
4	Inclined temperature layer thickness (mm)	≤1500	8	Froude number Fr	Fr≦1
9	Insulation performance	(1) The surface of the tank does not condense on the outer surface under the conditions of ambient temperature 40 °C and relative humidity 85%. (2) The 24-hour cold loss is no more than 2% of the total effective cold release.			

A battery is a source of electric power consisting of one or more electrochemical cells with external connections for powering electrical devices such as flashlights, mobile phones, and electric cars. When a battery is supplying electric power, its positive terminal is the cathode and its negative terminal is the anode. The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal. When a battery is connected to an external electric load, a redox reaction converts high-energy reactants to lower-energy products, and the free-energy difference is delivered to the external circuit as electrical energy[6].

Batteries convert chemical energy directly to electrical energy. Batteries are designed so that the energetically favorable redox reaction can occur only when electrons move through the external part of the circuit. A battery consists of some number of voltaic cells[7]. Each cell consists of two half-cells connected in series by a conductive electrolyte containing metal cations. One half-cell includes electrolyte and the negative electrode, the electrode to which anions (negatively charged ions) migrate; the other half-cell includes electrolyte and the positive electrode, to which cations (positively charged ions) migrate. Cations are reduced (electrons are added) at the cathode, while metal atoms are oxidized (electrons are removed) at the anode.

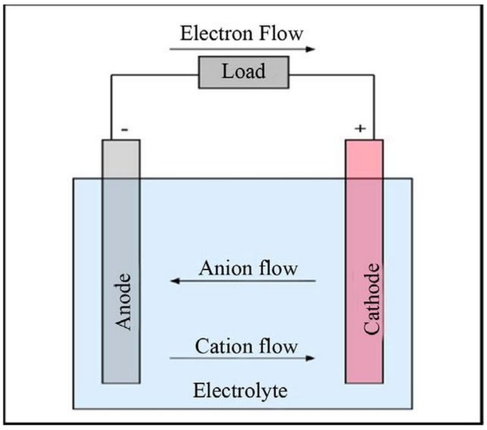


Fig 3-4 Schematic diagram of battery power generation process

(4) Photovoltaic (PV)

Photovoltaic is defined as the direct conversion of ray energy. In practical applications, it usually refers to the conversion of solar energy to electrical energy, that is, solar photovoltaic. Its implementation is mainly through the use of solar panels made of semiconductor materials such as silicon, using light to generate direct current[8]. Photovoltaic cell is an important component of photovoltaic power generation system, its probability density function is shown below, and its output power is closely related to the temperature and light intensity of the device.

$$f\left(G_t\right)=\frac{\Gamma\left(\alpha+\beta\right)}{\Gamma\left(\alpha\right)+\Gamma\left(\beta\right)}\left(\frac{G_t}{G_{max}}\right)\left(1-\frac{G_t}{G_{max}}\right)^{\beta-1} \tag{3-4}$$

Where, α and β are the shape parameters of Beta distribution, Γ is the Gamma function, and G_t is the light intensity (W/ m^2). After obtaining the average value μ and the standard deviation σ of light intensity according to statistics, the values of α and β can be obtained by the following formula:

$$\begin{cases} \alpha=\mu\left[\dfrac{\mu(1-\mu)}{\sigma^2}-1\right], \\ \beta=(1-\mu)\left[\dfrac{\mu(1-\mu)}{\sigma^2}-1\right]. \end{cases} \tag{3-5}$$

Where, the temperature of the photovoltaic cell cannot be obtained by direct measurement, so it is estimated from the ambient temperature and light intensity:

$$T_{c,t}=T_{amd,t}+30\frac{G_t}{1000} \tag{3-6}$$

Where, $T_{c,t}$ is the temperature of the photovoltaic cell, $T_{amd,t}$ is the ambient temperature.

Knowing the temperature and light intensity, the output power of the photovoltaic cell can be expressed as follows:

$$P_{pv,t} = P_{STC} \frac{G_t}{G_{STC}} \left[1 + k\left(T_{c,t} - T_{STC}\right)\right] \tag{3-7}$$

Where, $P_{pv,t}$ is the output power of the photovoltaic cell.

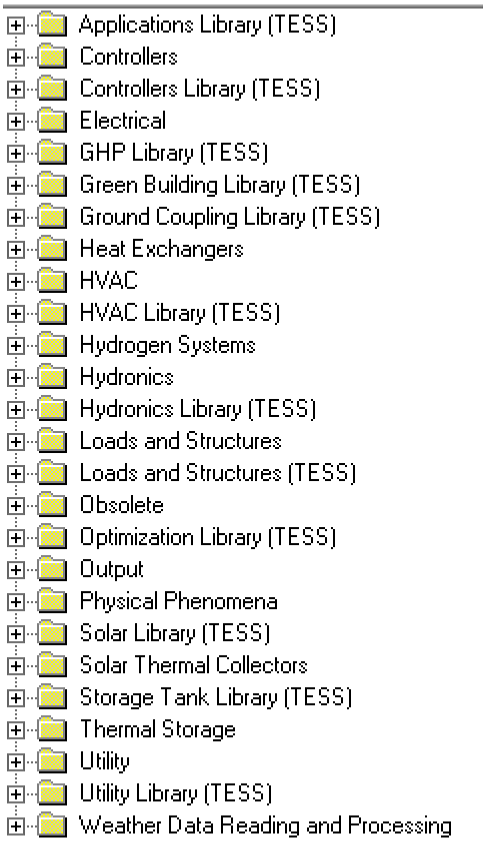
3.2.2 Energy consumption simulation model

In this research, the simulation software used in the simulation study of the heat pump combined with photovoltaic residential energy system is TRNSYS. First, the mathematical model of each component in the system is parameterized by theoretical calculation and user load demand[9]. Then, based on the mathematical model of the required components, the TRNSYS simulation software platform is used to build a simulation model of energy system research and energy consumption and economic analysis that can be used for heat pump combined with photovoltaic.

(1) Simulation software introduction

This study used TRNSYS simulation software for simulation analysis. TRNSYS is called the Transient system Simulation Program. The early development of TRNSYS software was completed at the Solar Energy Laboratory (SEL) of Wisconsin-Madison University in the United States. The subsequent improvement process was mainly carried out by some European research institutes, such as the Solar Energy Technology Research Center (TRANSSOLAR) in Germany, the Center for Building Technology and Science (CSTB) in French, and the United States Thermal Energy Research Center (TESS) completed together. Currently, the latest version of the TRNSYS software is Ver.17[10]. The simulation software consists of a number of related software packages, including simulation engine TRNOPT, executable file TRNExe, creating an editor for a stand-alone re-styled program TRNEdit, and building input data visualization interface TRNBuild.

Each module in the simulation software can correspond to the performance of a specific device or device in the system, and all the systems studied by the simulation will be connected according to these modules with specific functions to form the system model we need. Therefore, the simulation operation of the designed simulation system can be realized by calling a suitable and reasonable module and inputting the corresponding parameters required for the module. The TRNSYS simulation software consists of 13 main components, and a total of 71 standard modules can be called. And in addition to the standard modules, the US Thermal Energy Research Center (TESS) has also developed TESS Component Libraries 17.0, with 14 major components, including 86 modules, specifically for the study of HVAC systems. The specific component content is shown in Fig 3-5.



- Applications Library (TESS)
- Controllers
- Controllers Library (TESS)
- Electrical
- GHP Library (TESS)
- Green Building Library (TESS)
- Ground Coupling Library (TESS)
- Heat Exchangers
- HVAC
- HVAC Library (TESS)
- Hydrogen Systems
- Hydronics
- Hydronics Library (TESS)
- Loads and Structures
- Loads and Structures (TESS)
- Obsolete
- Optimization Library (TESS)
- Output
- Physical Phenomena
- Solar Library (TESS)
- Solar Thermal Collectors
- Storage Tank Library (TESS)
- Thermal Storage
- Utility
- Utility Library (TESS)
- Weather Data Reading and Processing

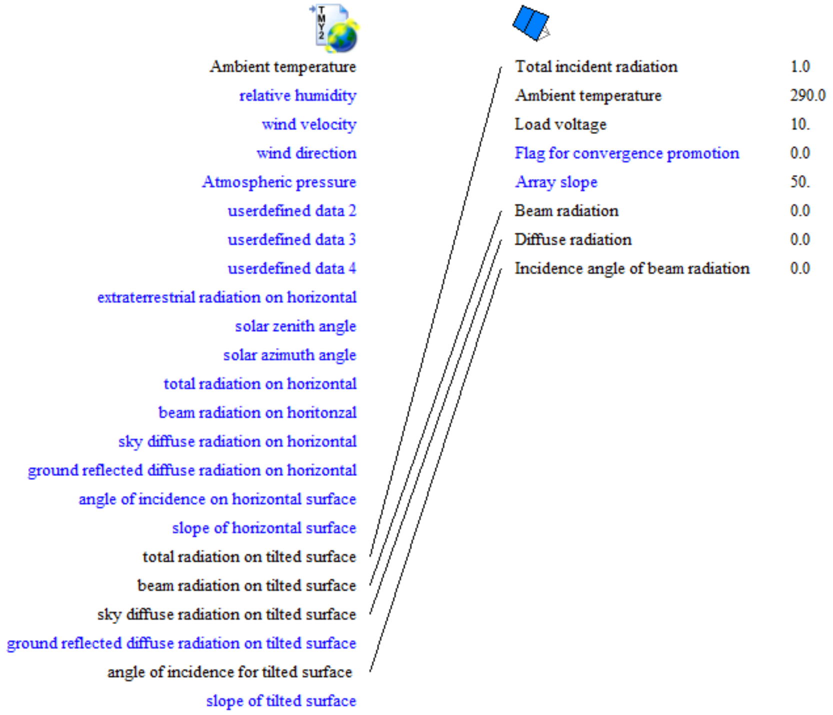
Fig 3-5 TRNSYS module interface

TRNSYS software can perform simulation calculations on solar systems, estimate the operating costs of the system for the optimization of the air conditioning system, operational simulations of certain ground source heat pump systems and floor radiant heating and cooling systems, analyze the energy consumption of buildings on a time-by-year basis, simulate calculation of fuel cell systems, cogeneration systems, and cold storage and heat storage systems. In general, TRNSYS is able to dynamically simulate the health of many systems and is used in a wide range of applications. Amir.A.Safa used TRNSYS to analyze the performance capacity of the two-stage variable air source heat pump system[11]. It is noted that the system performance coefficient (COP) of different outdoor air temperatures is maintained between 4.7 and 5.7 in the cooling mode. M.J.R.Abdunnabiad used TRNSYS to simulate a forced-circulation solar water heating system with different configurations [12]. The results show that the system differs under different climatic conditions, most likely due to the position-controlled circulating pump of the temperature sensor. Freeman.T.L used TRNSYS to perform a comprehensive analysis of different solar heat pump systems[13]. TRNSYS software also has other advantages, such as: users can use C, C++, Fortran and other programming software to write their own programs, develop new software modules that meet their needs, complement the modules in the software to achieve their own simulation system operation requirements.

The various analog modules included in the TRNSYS software need to be manually set to the module parameters when composing the simulation system. At the same time, the module's input parameters and output data need to be simulated or forcibly assigned. When a module component is called during the process of creating an analog system, the output data of a module can be imported into the DECK file that is programmed by itself or the system itself. The data in the DECK file can also be transferred to the module connected to it. The output of the system is the result of the calculation during the running process.

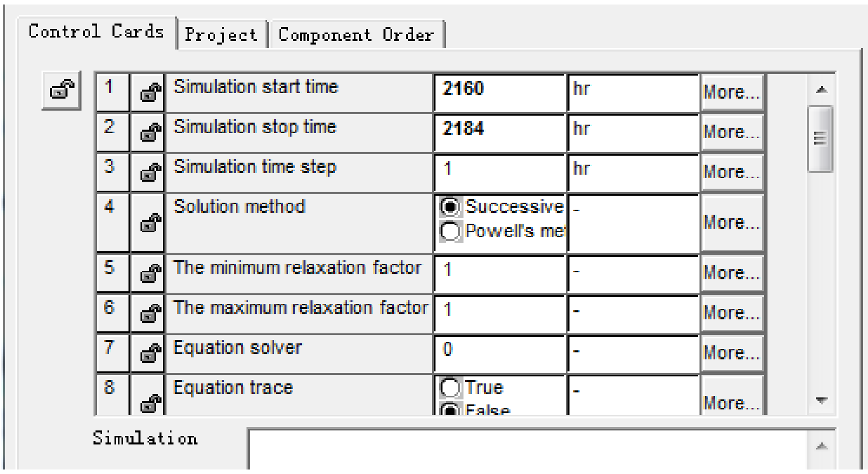
(2) Simulation model introduction

In TRNSYS software, the model building of the system is mainly the connection between modules. First, you need to find the required modules and place them in the modeling interface. Then, depending on the relationship between the module and the module, each connected module is connected using a connection button. Then, double-click the connection line connecting the two component modules, call up the menu of the connection line, connect the parameter information that needs to be transmitted between the two component modules, and the parameters are transferred from one component module to the next module according to the connection direction. Finally, adjust the parameter information of each component module to the parameter values required by the system, and set the running time and step size of the system through the system operation parameter setting menu. Run the system to get the output data of the output component. Fig 3-6 is a menu of connection lines for weather data components and photovoltaic components. Fig 3-7 shows the setup menu for the entire system.



Total incident radiation	1.0
Ambient temperature	290.0
Load voltage	10.
Flag for convergence promotion	0.0
Array slope	50.
Beam radiation	0.0
Diffuse radiation	0.0
Incidence angle of beam radiation	0.0

Fig 3-6 Connection line menu example diagram



1	Simulation start time	2160	hr	More...
2	Simulation stop time	2184	hr	More...
3	Simulation time step	1	hr	More...
4	Solution method	● Successive ○ Powell's me	-	More...
5	The minimum relaxation factor	1	-	More...
6	The maximum relaxation factor	1	-	More...
7	Equation solver	0	-	More...
8	Equation trace	○ True ● False	-	More...

Fig 3-7 System operation setup menu

3.2.3 System performance comparison method

(1) Environmental benefit comparison

In the energy generation and consumption of residential energy system, customer demand side and grid output are in a balanced relationship, and the formula is as follows:

$$E_{pur} + E_{gen} = E_{use} + E_{feed} \qquad (3\text{-}8)$$

where E_{pur} is the electricity buying from the grid, E_{gen} is the electricity generating from electricity supply equipment, E_{use} is the electricity that using by customers, and E_{feed} is the electricity from selling unused power back into the grid.

The environmental benefit analysis of the residential energy system is to calculate the CO_2 emissions generated by the energy supply equipment in one year, as described in Ep. (3-9).

$$Ce_{total} = \sum_d \sum_h (Ce_{ele} + Ce_{gas}) \qquad (3\text{-}9)$$

where Ce_{ele} refers to the amount of CO_2 emitted by energy supply equipment to provide electricity to customers, Ce_{gas} refers to the amount of CO_2 emitted when an energy supply equipment consumes gas to provide heat to customers. They are calculated by the following formulas.

As expressed in Eq. (2), the primary source of CO_2 emissions from residential energy systems is the consumption of electricity and gas to provide customers with electricity and heat. CO_2 emissions from electricity and gas are calculated with different CO_2 emission coefficients. The electric CO_2 emissions Ce_{ele} can be calculated as follows:

$$Ce_{ele} = \sum_d \sum_h [(E_{pur,d,h} - E_{feed,d,h}) \times E_{cf}] \qquad (3\text{-}10)$$

and the gas CO_2 emissions CE_{gas} can be expressed as follows:

$$Ce_{gas} = \sum_d \sum_h (G_{use,d,h} \times G_{cf}) \tag{3-11}$$

where E_{cf} is the Kyushu Electric CO_2 emission coefficient in 2017[14], G_{use} is the gas that using by customers, and G_{cf} is the town gas CO_2 emission coefficient in 2017[15]. The environmental benefit of different residential energy systems are analyzed by comparing their CO_2 emissions.

(2) Economic performance comparison

Assuming that the conventional energy system has the same needs of electricity and heat with the household which using hybrid fuel cell and photovoltaic system(HFPS) and hybrid heat pump and photovoltaic system(HHPS), the cost of electricity and gas in both systems were calculated and compared. The equation is as follows:

$$C_{total} = CE_{total} + CG_{total} \tag{3-12}$$

The calculation of the electricity cost of residential energy system is composed of purchasing electricity cost and feed-in cost, as described in Eq. (3-13).

$$CE_{total} = CE_{pur} - CE_{feed} \tag{3-13}$$

where CE_{pur} is the cost for buying electricity from grid, and CE_{feed} is the income from selling electricity back into the grid. They are calculated by the following formulas.

The cost for purchased electricity from grid is described by Eq. (3-14). It is consisted of the monthly electricity cost and the basic charge, which is determined by the customer's choice of electricity purchase plans for different electricity companies.

$$CE_{pur} = \sum_d \sum_h [E_{pur,d,h} \times PE_{pur} + PE_{basic}] \tag{3-14}$$

The income from selling surplus electricity back to the grid can be expressed in Eq. (3-15). In this equation assumes that the price of selling electricity back to the grid is constant.

$$CE_{feed} = \sum_d \sum_h (E_{feed,d,h} \times PE_{feed}) \tag{3-15}$$

The method of calculating purchasing gas cost is same as calculating electricity cost, and can be expressed as follows:

$$CG_{total} = \sum_d \sum_h [G_{pur,d,h} \times PG_{pur} + PG_{basic}] \tag{3-16}$$

(3) Payback period prediction

For the sake of comparing the economic performance of HFPS and HPPS this research predicted the period of payback year required for two systems. Ignore the equipment installation and maintenance costs of the residential energy system, the energy loss of equipment depreciation, only the cost of purchasing equipment was used as the investment cost for introducing the residential energy system. The operating profit from the introduction of the HFPS and HPPS can be expressed as follows:

$$PO = CO_{ord} - CO_{res} \tag{3-17}$$

where CO_{ord} refers to the operating cost of the household which only use ordinary water heater to provide heat, in this research it is presented as the total electricity and gas cost of the system for the year. And CO_{res} is the operating cost of HFPS and HPPS. After the introduction of the two systems which combined the investment cost and operating profit, the time required to recover the cost of investment was defined as the number of payback year. The result can be calculated by the following equations.

$$Y_p = n - FNPV_n/[(n+1) - FNPV_n] \tag{3-18}$$

where n refers to the years of equipment use, $FNPV_n$ refers to the financial net present value of the nth year, is calculated as the sum of the net cash flows of each year, can be expressed as follows:

$$FNPV = PO + PO \times (\gamma + 1) \tag{3-19}$$

where γ is the bank annualized interest rate.

(4) Sensitivity analysis

Considering that there are many factors affecting the number of payback years in the prediction of payback period of residential energy system. In this mode, the sensitivity of residential energy system is analyzed from four aspects: carbon tax price, equipment price and electricity buy-back price and gas price. The fluctuation of system payback period is analyzed through the adjustment of different influencing factors.

3.3 Load forecasting and real-time pricing model research

To maximize the advantages of real-time, two-way feedback in smart house, the real-time pricing(RTP) strategy has been developed and gradually implemented. From the perspective of electricity price strategy, this study analyzes and compares the annual electricity cost based on the dynamic electricity price of a typical Japanese residential power supply system using HEMS. Meanwhile, a short-term household load forecasting model is established to predict the user's power consumption one day in advance. In addition, an RTP model is developed to balance the power grid load, alleviate the peak concentration of electricity consumption, and reduce the electricity cost considering the feature that smart house can predict the power load in the short term.

3.3.1 Short-term load forecasting model

As one of the important contents of power system operation and dispatching, the forecasting accuracy of short-term power load directly affects the economic benefit of the power system. Extensive research has been conducted on short-term load forecasting and many effective forecasting methods have been proposed. The data source of the load forecasting model is the daily load curve of a family measured every 30 min for 365 days from April 1, 2017 to March 31, 2018. Let us consider D1, D2, …, D365 as daily loads, D1-D330 as the training sample data and D331-D360 as test data. In case of inaccurate historical load data and related factors affecting their changes, the prediction results are uncertain.

To improve the accuracy of the prediction results, fuzzy clustering and wavelet analysis are performed to preprocess the original data. Fuzzy theory is suitable for describing a wide range of uncertainties and can extract their similarity from considerable data[16]. These characteristics can improve the accuracy of short-term load forecasting. In this study, the original load data and influencing factors of day types, such as weeks, working days, and holidays, were comprehensively considered to create the original sample. The fuzzy clustering analysis method was used to cluster the samples and the dichotomy method was used to determine the samples closest to the predicted date[17]. The best similar days were obtained by an ordered arrangement. Meanwhile, the wavelet toolbox in MATLAB was used to preprocess the load data in the early stage of load prediction. Wavelet analysis can automatically adjust the sampling density according to the signal frequency, and thus, focus on any detail of the signal. The wavelet transform algorithm using the db3 wavelet transform was applied to decompose the load data. The original signal of the load data was decomposed into a low-frequency component and a high-frequency component. The low-frequency component represents the main characteristics of the signal, whereas the high-frequency component indicates noise and disturbance. By removing the high-frequency component of the signal, the basic characteristics of the signal can be retained while eliminating the disturbance factors. Short-term load forecasting based on fuzzy clustering analysis and wavelet decomposition completely utilizes the advantages of data preprocessing while eliminating the factors influencing original data in short-term load prediction to the greatest possible extent, which considerably improves the forecasting accuracy.

In this study, after preprocessing the original data, three algorithms——relevance vector machine (RVM), support vector machine (SVM) and back propagation neural network (BPNN)— were used to predict the short-term load of households, and their prediction results were compared. The purpose here was to select the most suitable algorithm for household short-term load forecasting, based on which the electricity cost of the customers could be predicted relatively accurately. When SVM and RVM are applied to load forecasting, the bandwidth σ of the Gaussian kernel function in the algorithms directly affects the accuracy of regression prediction[18]. In this study, PSO was used to optimize the SVM and RVM prediction models to obtain the optimal prediction effect[19][20]. PSO is a global optimization algorithm based on swarm optimization technology, which uses swarm optimization to search for individual optimal particles. It solves a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formula over the particle's position and velocity. Each particle's movement is influenced by its local best-known position, but is also guided toward the best-known positions in the search-space, which are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions.

A basic variant of the PSO algorithm works by having a population (called a swarm) of candidate solutions (called particles). These particles are moved around in the search-space according to a few simple formulae. The movements of the particles are guided by their own best-known position in the search-space as well as the entire swarm's best-known position. When improved positions are being discovered these will then come to guide the movements of the swarm. The process is repeated and by doing so it is hoped, but not guaranteed, that a satisfactory solution will eventually be discovered.

Because of its fast convergence speed and strong versatility, this study adopted the PSO algorithm to automatically optimize the kernel parameter σ of SVM and RVM in parameter space. Fig. 3-8 shows the flow chart of the PSO algorithm, and Fig. 3-9 presents the basic flow path of the short-term load forecasting model.

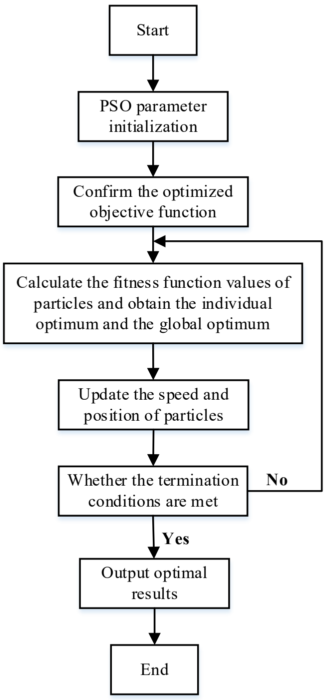


Fig 3-8 Flow chart of the PSO optimization algorithm

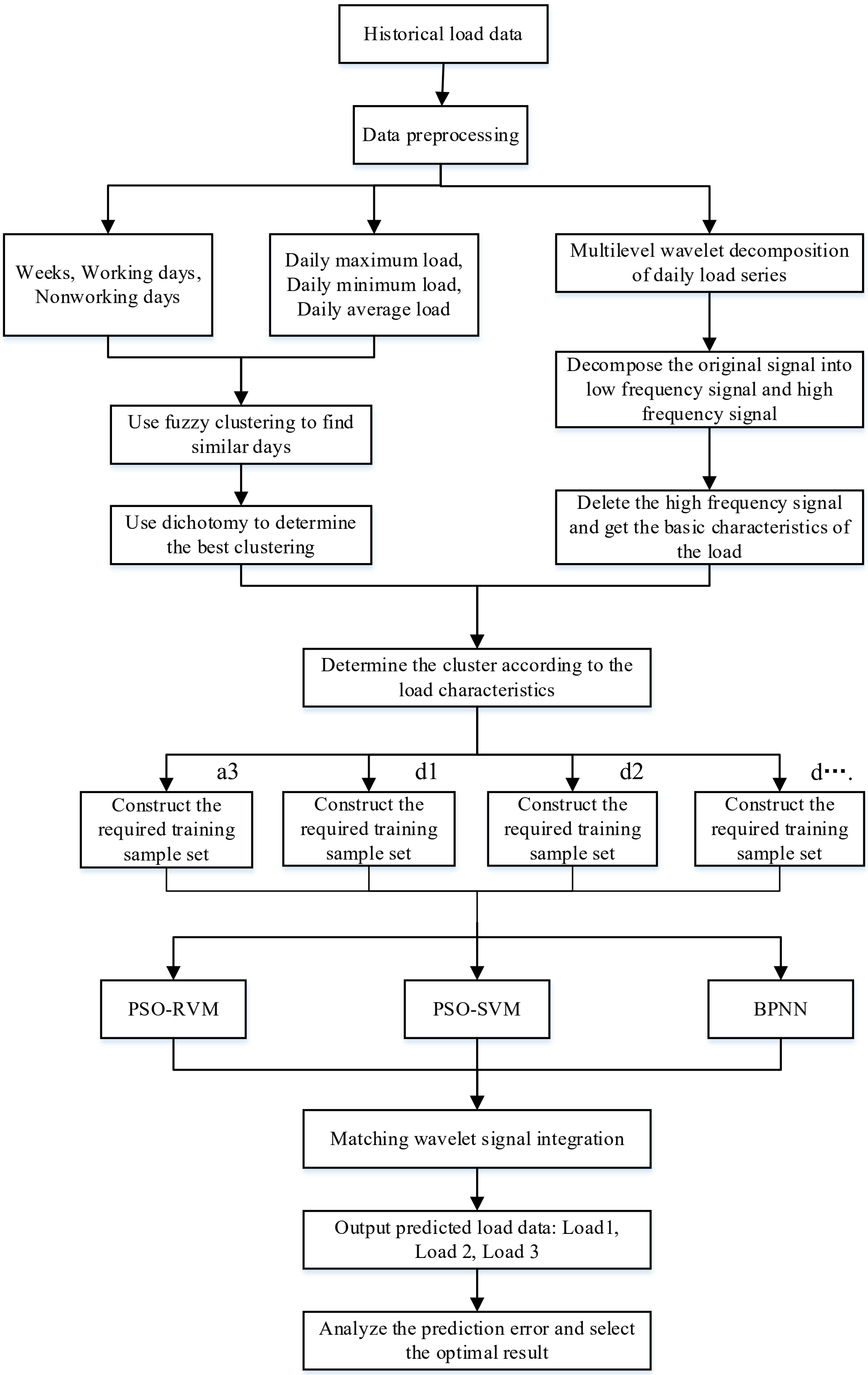


Fig 3-9 Basic flow path of short-term load forecasting model

(1) Principle of SVM load forecasting model

SVM is a machine learning method proposed by Vanpik that can effectively address sample classification and regression calculation problems. Compared with traditional forecasting methods, SVM has evident advantages in terms of accuracy of the prediction results and operation efficiency of the model algorithm; therefore, it is widely used in the field of load forecasting.

Let us consider a sample set D

$$D=\left(x_i,y_i\right),\ i=1,2,\ldots,n \tag{3-20}$$

where, x_i is the input vector, y_i is the target output, and n is the number of samples contained in the sample set. The basic concept of SVM is to introduce a nonlinear mapping $\varphi(x)$ and map the output sample set D of N and one-dimensional inputs from the original sample space to a higher-dimensional feature space. The model function can be expressed as

$$f(x)=\omega\cdot\varphi(x)+b \tag{3-21}$$

where, ω indicates the weight vector and b indicates the threshold. According to the statistical theory, SVM determines the regression function by minimizing the following target numbers:

$$\min\frac{1}{2}\|\omega\|^2+C\sum_{i=1}^{n}(\xi_i+\xi_i^*) \tag{3-22}$$

$$s.\ t.\ f(x_i)-y_i\leq\varepsilon+\xi_i \tag{3-23}$$

$$y_i-f(x_i)\leq\varepsilon+\xi_i^* \tag{3-24}$$

where, ξ_i and ξ_i^* indicate the slack variables, $\xi_i\geq0$, $\xi_i^*\geq0$; C is the penalty factor; and ε refers to the insensitive loss factor. The dual problem of SVM can be addressed by introducing a Lagrange multiplier and its regression function can be obtained by addressing the dual problem:

$$f(x)=\sum_{i=1}^{n}(a_i-a_i^*)K(x_i,\ x)+b \tag{3-25}$$

where, a_i , a_i^* is the Lagrange multiplier, $K(x_i,\ x)$ is the kernel function and the calculation can be expressed as follows:

$$K(x_i,\ x)=exp(-\frac{\|x_i-x\|^2}{2\sigma^2}) \tag{3-26}$$

where, σ refers to the kernel function parameters.

(2) Principle of RVM load forecasting model

With an in-depth research and extensive application of SVM, its inherent defects, such as excessive parameters and insufficient sparsity have been determined. To remedy these defects, Tipping proposed the RVM algorithm of which introduces Bayesian probability learning theory based on the SVM prediction formula, and then, prior probability is added to the model's weight, to improve the sparsity of RVM.

Let us consider the following training data set:

$$\{x_n, t_n\}_{n=1}^{N} \tag{3-27}$$

where, N is the number of samples, x is the correlation vector and t is the scalar output. Then the RVM regression model can be defined as:

$$t_n=\sum_{i=1}^{N} w_i\varphi_i(x) +w_0+\xi_n \tag{3-28}$$

where, w is the weight parameter vector, $w=(w_0,w_1, ..., w_N)$, ξ_n is an independent identically distributed zero-mean Gaussian noise with variance σ^2, and $\varphi_i(x)$ is a nonlinear basis function. To determine the weight of the model, the optimal value of the super-parameter should be calculated first, which can be obtained by the iterative algorithm as follows:

$$a_{i,\ ne}=\frac{\gamma_i}{u_i^2} \tag{3-29}$$

$$(\sigma^2)_{ne}=\frac{\|t-\phi\mu\|^2}{N-\sum_i \gamma_i} \tag{3-30}$$

where, u_i indicates the i-th average weight of the post-verification. If a new input value x is introduced, the probability distribution of the corresponding output obeys Gaussian distribution:

$$p\left(t_p/t,\ \hat{a},\ \hat{\sigma}^2\right)=N(t_p/y_p',\ \sigma_p^{\ 2}\ ) \tag{3-31}$$

$$y_p=u^T\varphi(x_p) \tag{3-32}$$

where, y_p can be used as the predicted value of t_p.

(3) Principle of BPNN load forecasting model

In machine learning, backpropagation (BP) is a widely used algorithm for training feedforward neural networks. Generalizations of backpropagation exist for other artificial neural networks (ANNs), and for functions generally. These classes of algorithms are all referred to generically as "backpropagation”. In fitting a neural network, backpropagation computes the gradient of the loss function with respect to the weights of the network for a single input–output example, and does so efficiently, unlike a naive direct computation of the gradient with respect to each weight individually. This efficiency makes it feasible to use gradient methods for training multilayer networks, updating weights to minimize loss; gradient descent, or variants such as stochastic gradient descent, are commonly used. The backpropagation algorithm works by computing the gradient of the loss function with respect to each weight by the chain rule, computing the gradient one layer at a time, iterating backward from the last layer to avoid redundant calculations of intermediate terms in the chain rule.

BPNN is a multi-layer feedforward neural network based on an error back propagation algorithm. It is a type of artificial neural network with strong nonlinear fitting ability and error back propagation. Fig 3-10 presents its , which comprise an input layer, a hidden layer, and an output layer, and adopts a back-propagation learning algorithm. Its learning process involves two stages: forward propagation and back propagation. In the process of forward propagation, the input information is processed layer-by-layer from the input to the hidden layer and then to the output layer. The state of the neurons in each layer only affects that in the next layer. If the desired output cannot be obtained in the output layer, the error signal will return along the output layer to the hidden layer, and the minimum error signal can be achieved by modifying the weights of the neurons in each layer.

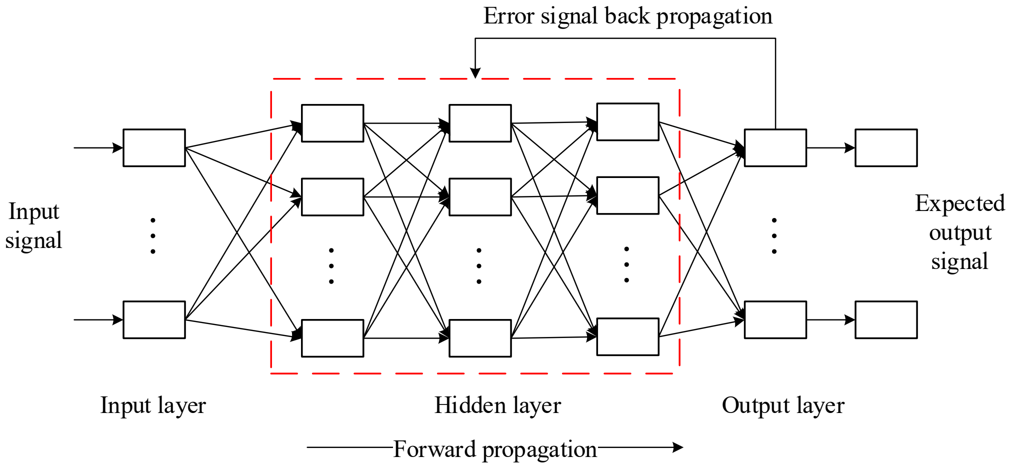


Fig 3-10 Structure of BPNN model

3.3.2 Real-time pricing model

In a smart grid, the smart house with HEMS established two-way real-time communication system between power companies and users can monitor the users' power load in real time and ensure the accuracy of power billing. It is a key to adjusting the load of the power grid to guide users' electricity consumption behavior through the RTP mechanism. The concept of real-time electricity pricing was first proposed by Schweppe in the 1980s, which is the marginal cost of providing electricity to users within a given short period (e.g.1h, 30min and 15min)[21]. In this study, to achieve the load curve peak shaving and valley filling and improve power system stability, an RTP model was developed to improve the load curve. This model assumes instantaneous power supply and demand balance, reflecting the changing relation between the supply and demand at each moment, and automatically feeds back the user load. The real-time price is determined by the total demand of the system, and thus, users can adjust their electricity consumption behavior according to the electricity price. Because the RTP is related to the user load in HEMS, i a step-linearized electricity price relation is assumed between the electricity purchase price of customers in each period and the load consumption predicted by the particle swarm optimization-regression vector machine (PSO-RVM) short-term load forecasting model[22]. The RTP electricity cost can be expressed as follows:

$$\begin{cases} p_{t1}=a_{t1}L_{t1} & 0\leq L_{t1}<\frac{1}{6} \\ p_{t2}=a_{t2}L_{t2}+b_{t2} & \frac{1}{6}\leq L_{t2}<\frac{5}{12} \\ constant & \frac{5}{12}\leq L_{t2} \end{cases} \tag{3-33}$$

where, a_{t1}, a_{t2}, b_{t2} indicate the real-time price parameters of the linearized electricity consumption of the first and second stages, and L_t is the customer electricity load. Based on the predicted electricity load demand, the model adopts a three-tiered linear pricing model to determine the real-time price of customers. According to the development trend and current situation of Japan’s electricity market, a_{t1} is set as 104.76; a_{t2}, b_{t2} as 22.4 and 13.73 respectively, and the *constant* is 23.06. The model shows that the electricity price is linearly proportional to the system demand. Moreover, this model achieves the goal of leveling the public grid load while reducing the power cost of users.

The established short-term load forecasting combined with the RTP model can amplify the advantages of real-time feedback in smart house. It uses the users’ load of the previous day as the basic data to predict the next day’s load, and feeds back the forecasted results to the power company in time. The power company generates the corresponding real-time price according to the forecasted results, and then sends it back to the user. The user adjusts the energy consumption behavior according to the recovered tariff pricing scheme to achieve two-way optimization of the power cost and load curve of the public grid.

3.4 Double-layer optimization model establishment with energy storage system

Residential energy storage system converts consumers from users of community and island level microgrid systems to participants in energy optimization management. However, due to different service objects, configuration environment, business model and other influencing factors, there will be obvious differences in energy storage system(ESS). In the application of residential energy storage, the profit return from the promotion of energy storage is an important factor affecting the motivation of users to install energy storage. Therefore, under the price policy and market environment, the application scenario selection and benefit analysis of user side energy storage are particularly important. Currently, the application and optimization of residential energy storage mostly focused on batteries, with little consideration for other forms of energy storage.

According to the load characteristics of users, this paper composite energy system with application of solar energy, electric, thermal and other types of energy, studies the application potential of residential energy storage, and designs four cases in different scenarios. Optimize the size and output of energy storage equipment in the case, and compare the system performance under different scenarios. With the aim to reasonably match the supply and storage equipment in the residential energy system, and use the user-side energy storage to achieve the purposes of peak shaving, energy conservation and emission reduction.

3.4.1 Double-layer optimization model

For the smart home with energy storage devices, this study proposes an optimization model considering the comprehensive operating cost of the system. The model comprehensively considers the cost of the system, improves the economy of the system while ensuring the safe operation of the system, and realizes the dual optimization of energy storage equipment and system energy management.

As observed in Fig 3-11, the optimization model of ESS is divided into two layers. The objective of the upper layer optimization is to minimize the configuration capacity cost of the storage device and the electricity purchase from the public grid. A mathematical model based on adaptive particle swarm optimization (APSO) algorithm was established to optimize the size and charge-discharge power of the energy storage device. Particle swarm optimization (PSO) algorithm is an optimization method that uses a group of random particles to search for the optimal solution in the solution space. Each particle has a random velocity vector, and the position of the particle is evaluated by optimizing the objective function. The objective function calculates the objective function value by taking the particle position as a parameter, and finally obtains the historical optimal solution P_i and the global optimal solution P_g of each particle.

The algorithm is shown as follows:

$$v_i^{k+1} = \omega v_i^k + c_1\mu\left(P_i^k - x_i^k\right) + c_2\eta(P_g^k - x_i^k) \tag{3-34}$$

$$x_i^{k+1} = x_i^k + \rho v_i^k \tag{3-35}$$

where, ω is the inertia weight coefficient, which is used to maintain speed during iterations, c_1 is the individual acceleration coefficient, which is used to maintain the learning of the particle itself, c_2 is the global acceleration factor used to maintain learning for all particles, μ, η is a random number with a size between 0 and 1, ρ is the constraint factor used to refresh the position of particles, usually set to 1. However, PSO algorithm may converge to the local optimal solution in the iterative process. Based on the basic PSO algorithm, a new optimal fitness update mechanism is applied in this model, which is called APSO algorithm.

The algorithm update formula is as follows:

$$P_i(t+1)=\begin{cases}P_i(t)|\cdot T, & f(X_i(t+1))\leq f(X_i(t))\cdot T\\ X_i(t+1), & f(X_i(t+1))>f(X_i(t))\cdot T\end{cases} \tag{3-36}$$

The attenuation constant T is introduced into the update formula, $T\in[0,\ 1]$. The individual optimum and the global optimum will decay at a certain rate. All particles have the same attenuation constant, but the update frequency of each particle is different. With the increase of X, P gradually decreases, and the particle frequently updates the optimal value until the number of iterations is reached, and the optimization is completed.

According to the results obtained from the upper optimization, the lower optimization is carried out, and the system energy consumption is optimized with the minimum total cost as the objective function, so as to obtain the annual optimal output of each equipment in the system.

The total cost calculation is divided into three parts: installation cost, running cost and maintenance cost:

$$min\sum C_{total}=C_{inv}+C_{run}+C_{main} \tag{3-37}$$

where, C_{inv} is the installation investment cost of the system, including PV, energy storage equipment and heat pump:

$$C_{inv}=C_{inv}^{PV}+C_{inv}^{HP}+C_{inv}^{ES} \tag{3-38}$$

where, C_{inv}^{PV} is the installation investment cost of PV, C_{inv}^{HP} is the installation investment cost of heat pump, and C_{inv}^{ES} is the installation investment cost of the energy storage equipment which introduced into the system, including the initial investment cost of battery C_{inv}^{BEES} and thermal storage tank C_{inv}^{TEES}.

The running cost C_{run} calculation of the system mainly considers two parts: importing and selling electricity from the public grid:

$$C_{run}=C_{import}^{Grid}-C_{feed-in}^{Grid} \tag{3-39}$$

$$C_{import}^{Grid}=\sum_m\sum_h E_{m,h,import}^{Grid}\times P_{ele}^{import} \tag{3-40}$$

$$C_{feed-in}^{Grid}=\sum_m\sum_h E_{m,h,feed-in}^{Grid}\times P_{ele}^{grid} \tag{3-41}$$

where, $E_{m,h,import}^{Grid}$ is the amount of electricity that users import from the power grid, P_{ele}^{import} is the unit price of electricity, $E_{m,h,feed-in}^{Grid}$ is the electricity that users feed back to the public grid, and P_{ele}^{grid} is the unit price of selling electricity.

The maintenance cost C_{main} of PV and energy storage equipment is considered in this study:

$$C_{main} = C_{main}^{PV} + C_{main}^{BESS} + C_{main}^{TEES} \tag{3-42}$$

$$C_{main}^{PV} = \sum_{m=1} K_m \left|p_m(t)\right| \Delta t \tag{3-43}$$

$$C_{main}^{BESS}(t) = \sum_{i=1} K_i \left|p_i(t)\right| \Delta t \tag{3-44}$$

$$C_{main}^{TESS}(t) = \sum_{x=1} K_x \left|p_x(t)\right| \Delta t \tag{3-45}$$

where, $p_m(t)$, $p_i(t)$ and $p_x(t)$ refer to the output power of equipment at t, K_m is PV maintenance cost coefficient, taken as 0.34 Yen/kWh, K_i is battery maintenance cost coefficient, taken as 1.43Yen/kWh and K_x is thermal storage tank maintenance cost coefficient, taken as 0.77Yen/kWh.

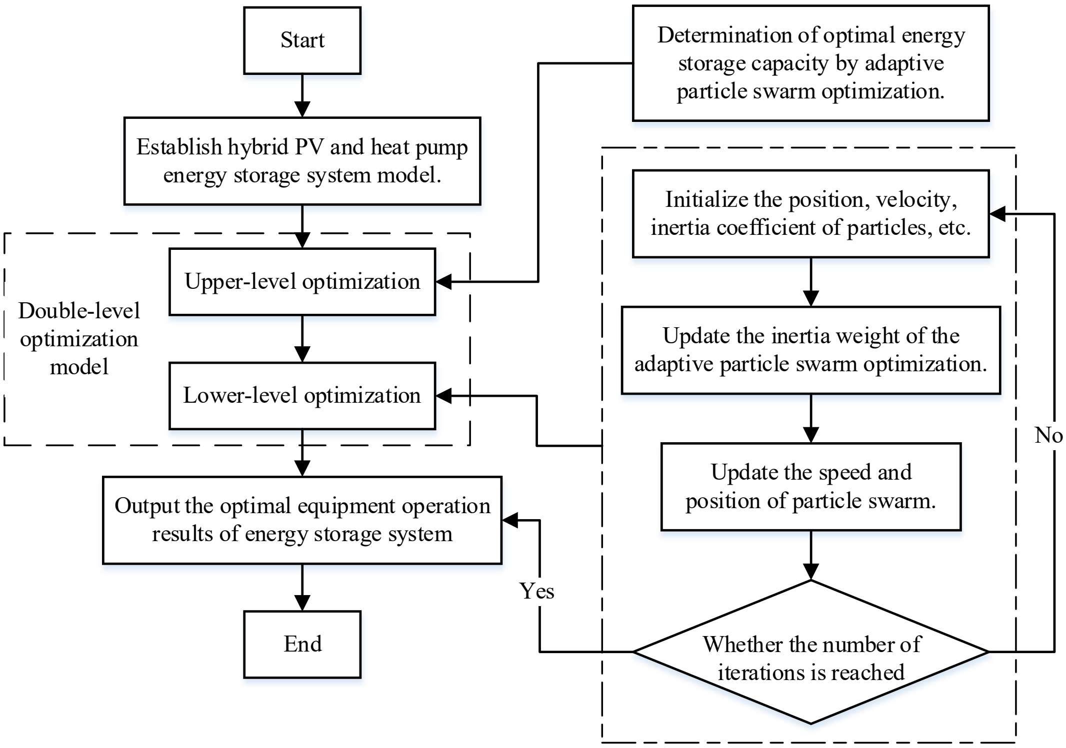


Fig 3-11 The framework of the double-layer optimization model

3.4.2 Comprehensive comparison model

In order to compare and evaluate the systems with different energy storage equipment, a comprehensive comparison model is established to compare the system performance changes from different aspects between the original case and ESS. Fig 3-12 presents the framework of the comprehensive comparison model, this model considers three indicators: energy, environment and economy. The energy performance of the system is evaluated by the primary energy saving(PES) ratio, which can directly reflect the energy-saving potential before and after the system is introduced into the energy storage equipment. In addition, because the four cases in this study do not need to consume natural gas to supply energy for the system, the calculation of primary energy saving rate can be expressed as:

$$PES = 1 - \frac{E_{ESS}}{E_{OS}} \tag{3-46}$$

where, E_{ESS} and E_{OS} are the power consumption of ESS and original system respectively.

The indicator selected for environmental performance analysis is the CO_2 emission reduction rate(CER). Reducing CO_2 emissions is currently an important way to improve environmental protection. After carbon tax policies are implemented in some countries, CO_2 emission is more directly related to economy. The CER can be calculated as:

$$CER = \frac{CE_{ESS}}{CE_{OS}} \times 100\% \tag{3-47}$$

where, CE_{ESS} and CE_{OS} are the CO_2 emission of ESS and original system.

In order to compare the economic performance of the system, two indexes of electricity cost and payback period(PP) are selected to evaluate the model. To highlight the economic differences of the study cases in the operation process, the electricity cost in the index only considers the cost that users spend to buy electricity from the public grid, to compare the economic performance from the aspect of system equipment. At the same time, in order to more clearly evaluate the relationship between the future income of the system and the current initial investment, the model introduces the number of payback period as the economic evaluation index of the system operation cycle:

$$F = CO_{OS} - CO_{ESS} \tag{3-48}$$

$$NPV = \sum_{t=0}^{T} \frac{F - C_{run}}{(1+r)^t} \tag{3-49}$$

where, F refers to the annual ESS operating profit, CO_{OS} and CO_{ESS} are annual operating cost of original system and ESS. r is benchmark return ratio of the bank, taken as 3%, and T is the actual service life of ESS. NPV is the net present value of system, when it is equal to 0, the value of t is system PP.

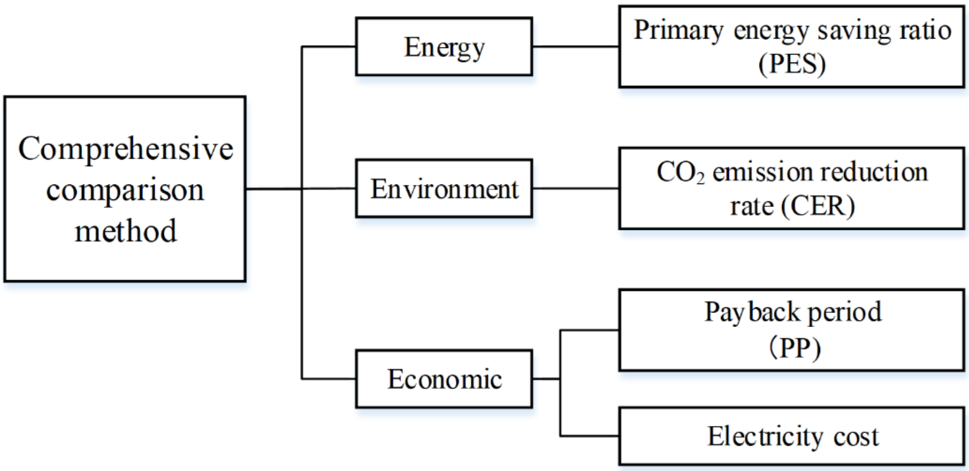


Fig 3-12 The framework of the comprehensive comparison model

3.4.3 Constraint condition

As described above, the residential energy system simulation involved in the study case is optimized by introducing the energy storage device. In the modeling process, the state of the energy storage device in each period needs to be considered, including the charging and discharging of the device and the size of the stored energy. Therefore, the model needs to satisfy the following constraints:

Firstly, the power constraints of the energy storage equipment should be met during charging and discharging:

$$-P_e < P_{ESS}(t) < P_e \tag{3-50}$$

where, $-P_e$ and P_e are the maximum power of charging and discharging of the energy storage equipment respectively. In addition, the battery should meet the state of charge constraints during operation to prevent damage to the battery caused by overcharging or excessive discharging of the device:

$$SOC_{min} \leq SOC_{(t)} \leq SOC_{max} \tag{3-51}$$

The upper limits and lower limits of SOC of the battery in this model are 0.9 and 0.1 respectively. In order to control the operation state of the energy storage battery flexibly, the ESS needs to meet the daily charge discharge balance:

$$\int \left|P_{ESS_d}(t)\right| \eta_d dt = \int \left|P_{ESS_c}(t)\right| \eta_c dt \tag{3-52}$$

where, $P_{ESS_c}(t)$ and $P_{ESS_d}(t)$ are the charging and discharging power of energy storage equipment respectively, η_c and η_d are the charging and discharging efficiency of energy storage equipment. In order to prevent excessive change of output power of energy storage equipment and reduce the service life and economy of equipment, the following constraints are imposed on the change of output power of equipment:

$$|P_{ESS}(t) - P_{ESS}(t-1)| \leq \delta P \tag{3-53}$$

where, $P_{ESS}(t)$ is the current output power of the ESS, $P_{ESS}(t-1)$ is the output power of the energy storage equipment in the previous period, and δP is the limit value of power variation per unit time.

3.5 Summary

In this part, we introduce the main research methods, application software and model establishment of the paper. This paper mainly uses TRNSYS and MATLAB to compare and optimize the energy system of smart house.

Firstly, it compares the economy and environment from the equipment level. TRNSYS is used for system modeling of different combinations of energy supply equipment to simulate system energy consumption. Then compare the power cost, CO_2 emission and payback period of the system. The purpose is to provide reasonable suggestions for users of different types and composition to select the appropriate combination of energy supply equipment.

Secondly, a double-layer optimization model is established based on MATLAB to optimize the energy system of smart house by introducing energy storage equipment. The upper optimization model is the optimization of the optimal size and output of energy storage equipment aiming at minimizing the power cost. The lower-level optimization model is the annual energy consumption optimization with the goal of minimizing the total system cost. Through the optimization results, the optimal size of energy storage equipment introduced into the composite energy system can be obtained, and the user cost can be reduced by using energy storage. At the same time, it also provides a new thinking for the coupling application of energy supply equipment and energy storage equipment.

As a link connecting users, equipment and power companies, smart house is characterized by automatic control, prediction and real-time communication. According to the above characteristics, this paper establishes the short-term coincidence prediction model and RTP price model by using MATLAB. The short-term load forecasting model is used to predict the power consumption of the next day based on the power consumption of the user the previous day. The smart house energy management system sends the prediction results to the power company. Then the electricity price of the next day is simulated according to the RTP model. Users can appropriately adjust the power consumption behavior and equipment operation time according to the electricity price, so as to reduce the power cost.

This chapter introduces the main methods applied for optimization and comparison from three aspects: users, equipment and power companies. According to the comparison between the measured data and the simulation results, the feasibility of the optimization method can be verified. The simulation software is combined with the mathematical model established in this paper, which improves the accuracy of prediction and optimization results, and has high practical value and popularization significance.

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Chapter 4

INVESTIGATE AND ANALYZE THE CHARACTERISTICS OF ENERGY CONSUMPTION IN SMART HOUSE AREA

CHAPTER FOUR: INVESTIGATE AND ANALYZE THE CHARACTERISTICS OF ENERGY CONSUMPTION IN SMART HOUSE AREA

4.1 Content

With the economic growth and increasing requirement of indoor thermal comfort, the load of building sector presents greater variability. The heat pump is one of the most promising heating technologies for energy-efficient building. In recent years, heat pump was also proven to be an economical efficient option for the residential heating supply system via power to heating transform. Residential heat pump system has gradually become a hot topic in research in various countries.

However, the realization of energy conservation and emission reduction targets depends not only on the promotion and research of smart house technology, but also on residents' awareness of energy conservation and environmental protection and energy consumption habits. In this part, we conducted a questionnaire survey on residents living in smart house area. The questionnaire includes family composition, equipment installation, users' awareness of environmental protection and the use frequency of smart house energy management system. After that, this part utilizes the monitored history data to analyze the energy consumption characteristics and influencing factors of the residential customers, which feature with heat pump heat supply system in smart house.

4.2 Introduction of Jono smart house advanced area

4.2.1 Land use plan

The project promotes the use of various low-carbon technologies, such as public transport, to control the use of private cars by introducing buses. Guide households to install eco-houses, spontaneous energy and energy-saving facilities, and optimize residential energy use by introducing residential energy management systems[1].

Fig 4-1 states the location of Jono zero carbon area in Japan and Fig 4-2 shows the land use change before and after implementation. It is planned to reduce the majority of the original residential area by 22.5%. At the same time, the area of roads and rivers has been enlarged. The area saved was converted into square and park, and it was used as a public area for outdoor activities. Such changes make the area more suitable for people to carry out more outdoor activities while meeting the living environment, strengthen the neighborhood's connections, and the increase of roads also makes the exchanges of residents in the area more convenient.

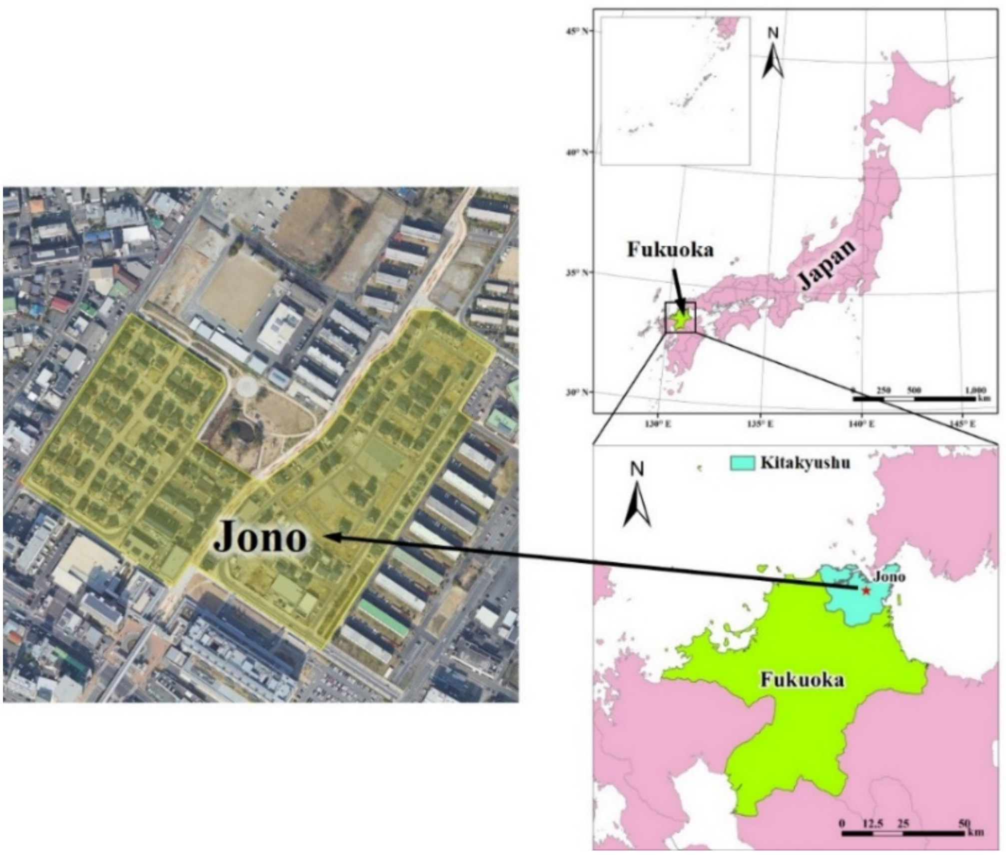

Fig 4-1 Location of Jono smart house area in Japan

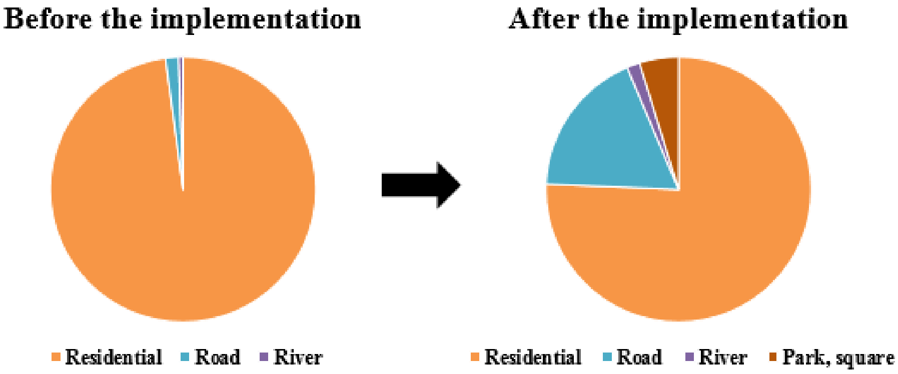

Fig 4-2 Land use area before and after implementation in Jono area

4.2.2 Composition of regional low carbon facilities and methods

In single-family homes, apartments and commercial facilities, carbon dioxide emissions from buildings can be reduced by optimizing insulation, ventilation, ventilation, and sunlight. In addition, the introduction of photovoltaic power generation systems, geothermal and other renewable energy sources while improving the efficiency of household appliances and other energy-using equipment can also be used as one of the methods to achieve low-carbon housing and improve facility performance. For housing and facilities, we aim to reduce CO_2 emissions from the renewal of buildings by maintaining the performance assuming long-term use.

In order to encourage people to use walking and bicycles to reduce the use of private cars and buses, an area of bicycle lanes is added to the area to connect the stations and the streets. It aims to improve the convenience of using public transportation by strengthening the traffic structure function. At the same time, to add a car sharing service and an introduction to electric vehicles in the area, and set up charging facilities for electric vehicles, and estimate the use of ways to reduce carbon dioxide emissions.

By providing childcare support, elderly health care and welfare services, and various life support services, the Jono area will allow people to enjoy a convenient living while also forming a residential area. Strengthening regional security management will make residents have a safe living environment.

4.2.3 Introduction to surrounding facilities

The Jono smart house area is just five minutes' walk from Jono Station and is easily accessible. The northern part of the community is the Kitakyushu General Hospital. As the core of intensive care in the Kitakyushu Medical District, the hospital opened in May 2016 in the first area of the Jono area. The hospital can reach the Jono station directly through the pedestrian walkway. There is also a contact center next to the Jono community. It connects Jono Station and Kitakyushu General Hospital through a walkway. In addition to the hospital, there are cafes and convenience stores around the community that can provide convenience to residents.

Fig 4-3 Facilities around the Jono Smart Community[2]

4.3 Questionnaire results analysis of smart house area

4.3.1 Survey introduction

In November 2017, a questionnaire survey was conducted among 60 families living in Jono smart house area. Among them, the residential forms of the survey include independent housing and congregated housing. In order to master the basic characteristics of power consumption of intelligent residence, the "occupant attribute survey" was carried out. At the same time, according to the environmental awareness of each family, the satisfaction of household power generation equipment, the utilization of intelligent residential system and the practicability of various functions of the system are investigated. Table 4-1 shows the question items involved in the questionnaire survey.

Table 4-1 Summary of questionnaire survey items

Classification	Main contents
Residential type	Residential area, power, and gas scheme
	Installation of electric supply equipment (PV and fuel cell)
	Installation of thermal equipment
	Installation of heating equipment for kitchen
Family composition	Family composition
	Basic information of family members (occupation, income, age)
	Number of vehicles
Environmental consciousness	Changes of environmental awareness before and after the installation of smart house energy system
	Changes in living habits
	Changes in electricity consumption and natural gas consumption
	Utilization of power generation equipment
System utilization	Energy management system utilization frequency
	Use frequency of real-time monitoring function

4.3.2 Questionnaire results

Based on the questionnaire of residents in Jono smart house area, we sorted the results as follows:

Among the respondents, there are 34 independent houses and 38 collective houses. The number of families with "2 persons" and "3 persons" is the largest, accounting for 34% and 32% of the total respectively. In addition, the average household size of all surveyed households was 2.8(Fig 4-4).

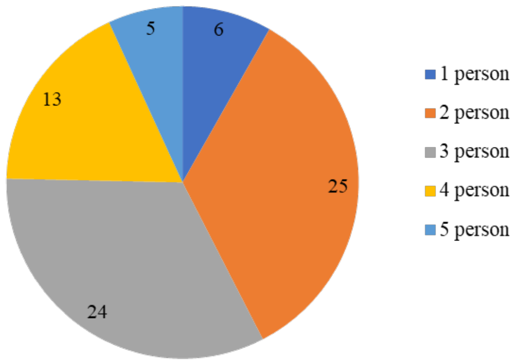

Fig 4-4 Result statistics of family size

In terms of residential area, 50~80 m^2 and 80~100 m^2 have the largest number of houses, 20 households each, accounting for 57% of the whole. Most of them are collective houses. Followed by 100~120 m^2 and 120~150 m^2 of housing(Fig 4-5).

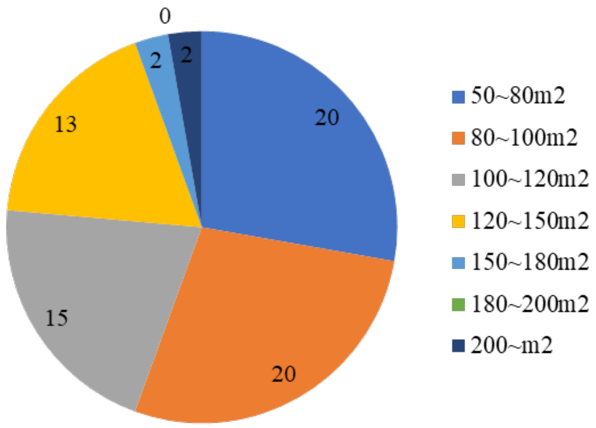

Fig 4-5 Result statistics of residential area

Among the power companies selected by families, Kyushu power is the largest, accounting for about 47% of the total. Secondly, BBIQ power accounts for about 42%. In 2016, the target of power liberalization was extended to ordinary families and small-scale shops, which were no longer bound by the existing power companies in their own residential areas(Fig 4-6).

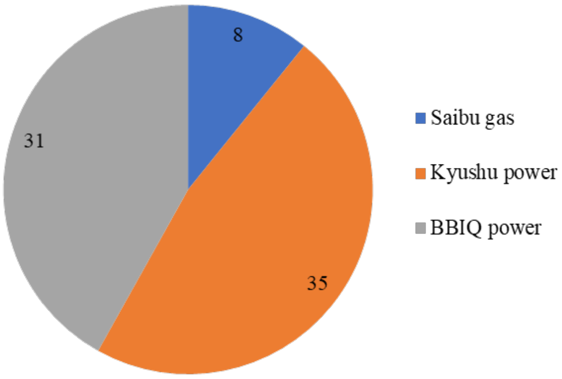

Fig 4-6 Result statistics of power company selection

As for the selection of gas companies by users, the regional monopoly of gas companies on electric companies continues to exist. Saibu gas accounts for about 87% of the total. In addition, there are families who have not signed gas contracts. In other words, 10% of all households are electrified(Fig 4-7). As for the introduction of battery in each family, only two houses have introduced battery, and most of the others have not introduced battery.

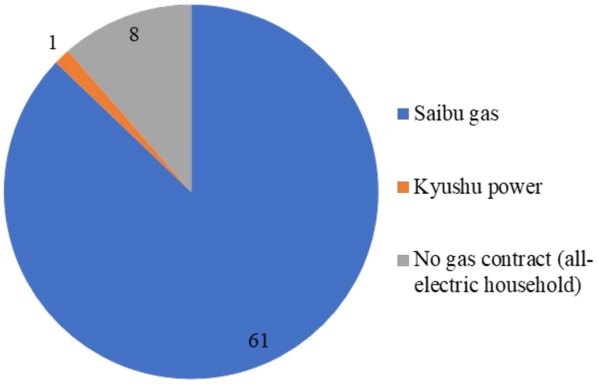

Fig 4-7 Result statistics of gas company selection

In terms of the introduction of PV power generation equipment, PV power generation equipment is not introduced into collective houses, but all families of independent houses have introduced residential PV system. The maximum introduced capacity is 4 ~ 6kW, accounting for 67% of the total(Fig 4-8).

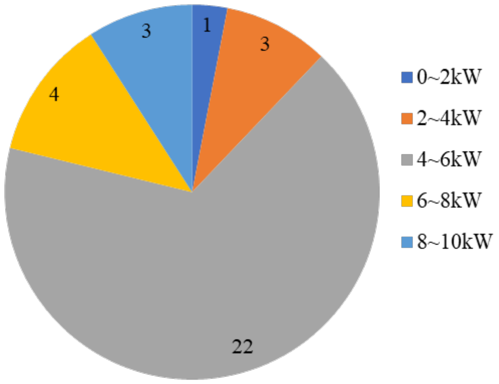

Fig 4-8 Result statistics of PV power generation equipment introduction

With regard to the introduction of ground heating, about 43% of houses have introduced geothermal. Among them, about 80% are warm water floor heating and about 20% are electric floor heating. According to the classification of housing form, it is found that the heating introduction rate of collective housing is about 18%, which is very low compared with 69% of independent housing.

In terms of the number of vehicles owned by households, the largest number of households own one vehicle, accounting for 64% of the total. Secondly, families with two sets account for 28% of the total. In addition, the average car ownership of the respondents was 1.26(Fig 4-9).

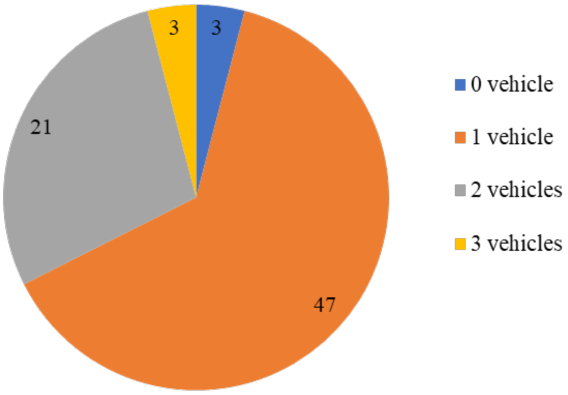

Fig 4-9 Result statistics of vehicles number

According to the fuel classification of vehicles, gasoline vehicles are still the largest, with ordinary vehicles and light vehicles accounting for about 72% of the whole, and hybrid vehicles accounting for 22%. According to the survey results and development trend, we can look forward to the popularization of hybrid vehicles in the future.

Among the hot water equipment of families, Ene-farm account for the highest proportion, accounting for about 86% of the total. If separated by residential form, all families living in collective houses use Ene-farm to supply hot water. About 73% of independent residential households have introduced Ene-farm.

As for the heating and cooking equipment of each family, IH cooking heater is the most used, accounting for 67% of the whole, far exceeding the national average of 20% in Japan. Although many families have signed gas contracts, most of the natural gas is supplied to Ene-farm.

With regard to the change of environmental awareness of residents living in smart houses, the most answers are "slightly improved", followed by "always have environmental awareness, and there is no great change on the whole". After the introduction of intelligent housing system, 64% of the families have improved their awareness of energy conservation and environmental protection(Fig 4-10).

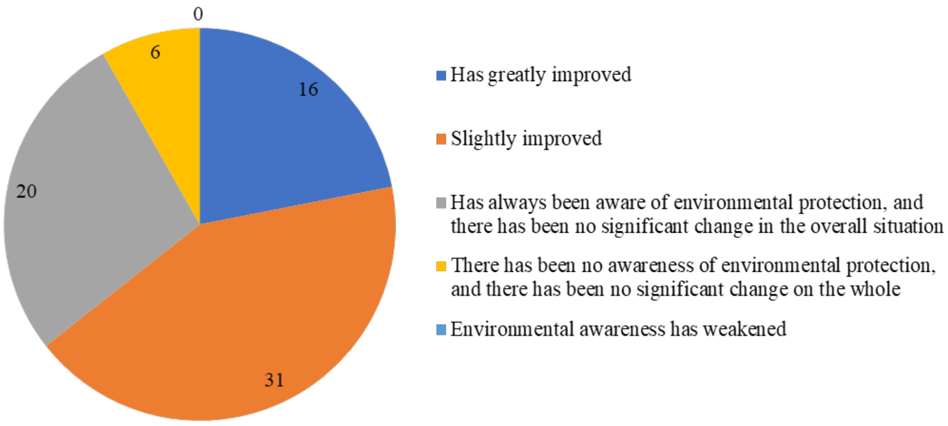

Fig 4-10 Result statistics of changes of environmental consciousness before and after the application of smart house system

For the change of electricity charge, the most answered was "slightly reduced", and then the most answered was "much reduced". Overall, about 80% of residential electricity bills have decreased to varying degrees. For the change of gas fee, the most answer is "slightly decreased", followed by "unchanged". However, 23% of the respondents answered that "gas charges have increased". The reason is that the number of homes using Ene-farm has increased.

On the value perception of low-carbon housing in Jono area, 52% of the families answered "very feeling", and 40% of the families answered "slightly feeling", and more than 90% of the families felt the value of low-carbon housing.

4.3.3 Questionnaire summary analyze

This time, a questionnaire survey was conducted among 160 families living in Jono smart house area. A total of 73 questionnaire responses were recovered. Among them, independent houses and collective houses account for half respectively. In the number of families, "2 person" and "3 person" have the largest family members, with an average family size of 2.8. The age composition of the respondents is widely distributed from children to the elderly. It can be seen that there are many elderly people and childcare families in the respondents' houses.

Collective residential households basically sign contracts with BBIQ power, but independent residential households sign contracts with different power companies. The survey results show that the competition among operators after power liberalization will lead to the possibility of cheaper electricity prices. In addition, consumers' choice of electricity price scheme suitable for their own energy consumption characteristics may reduce electricity charges.

As for the heating and cooking equipment of families, the families using IH cooking heaters account for 67% of the total, far exceeding the national average of 20% in Japan.

As for the number of cars, the average number of cars per household is 1.26. Classified by vehicle fuel, gasoline vehicles account for 72% of the total, while hybrid vehicles account for 22%, with a high penetration rate.

With regard to the changes in energy-saving awareness and environmental protection awareness after the application of smart house, about 64% of the families with improved energy-saving awareness and 49% of the families with improved environmental protection awareness. In addition, some families have always had a strong awareness of environmental protection.

The results show that the utilization frequency of smart house energy management system is relatively low. Many people in the questionnaire pointed out that they "don't know how to use" and need to be explained. In addition, some respondents suggested that it can improve users' enthusiasm, such as getting points when logging in to the website.

4.4 Introduction of smart house energy system

4.4.1 Residential fuel cell system

A residential fuel cell is a scaled down version of industrial stationary fuel cell for primary or backup power generation. And a commercially working cell is called Ene-farm in Japan and is supported by the regional government which uses natural gas to power up the fuel cell to produce electricity and heated water(Fig 4-11). The residential fuel cell system is a cogeneration system that uses natural gas to provide electricity and hot water to a residence(Fig 4-12). There are two main types, proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC).

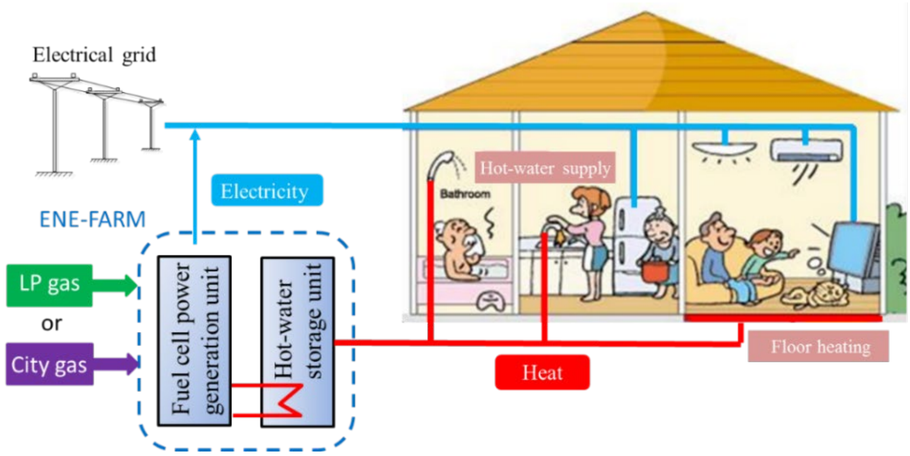

Fig 4-11 Structure of residential household with fuel cell system[3]

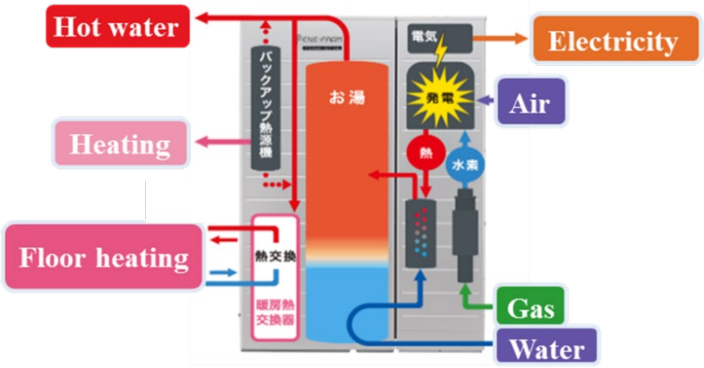

Fig 4-12 Residential fuel cell internal structure[4]

Fig 4-11 presents the detail structure of residential fuel cell system. Customers get natural gas from gas company into fuel cell and boiler. Fuel cells transform the electricity to demand side, and the heat generated is stored in thermal storage together with the heat generated by the boiler. And the stored energy in the tank will be used later in the residential house.

Because residential fuel cells have the characteristics of cogeneration, they have been slowly selected by more households in recent years. At the same time, residential fuel cells have the following advantages.

- The energy efficiency of a residential fuel cell system is high, and the heat generated during power generation can be directly utilized.
- Less loss during power transmission.
- Reduce carbon dioxide emissions and improve environmental pollution.

- The fuel cell can continue to supply power after a power outage.

Although the advantages of fuel cells are many, but because of the relatively high price of fuel cells on the market, it is still not universal.

4.4.2 Residential heat pump system

The residential heat pump system in Japan is called Eco-cute. The Eco-cute is an energy efficient electric heat pump, water heating and supply system that uses heat extracted from the air to heat water for domestic, industrial and commercial use. Instead of the more conventional ammonia or gases, Eco-cute uses supercritical carbon dioxide as a refrigerant. The technology offers a means of energy conservation and reduces the emission of greenhouse gas. A heat pump is a device that transfers heat energy from a source of heat to a heat sink. Heat pumps move thermal energy in the opposite direction of spontaneous heat transfer, by absorbing heat from a cold space and releasing it to a warmer one.

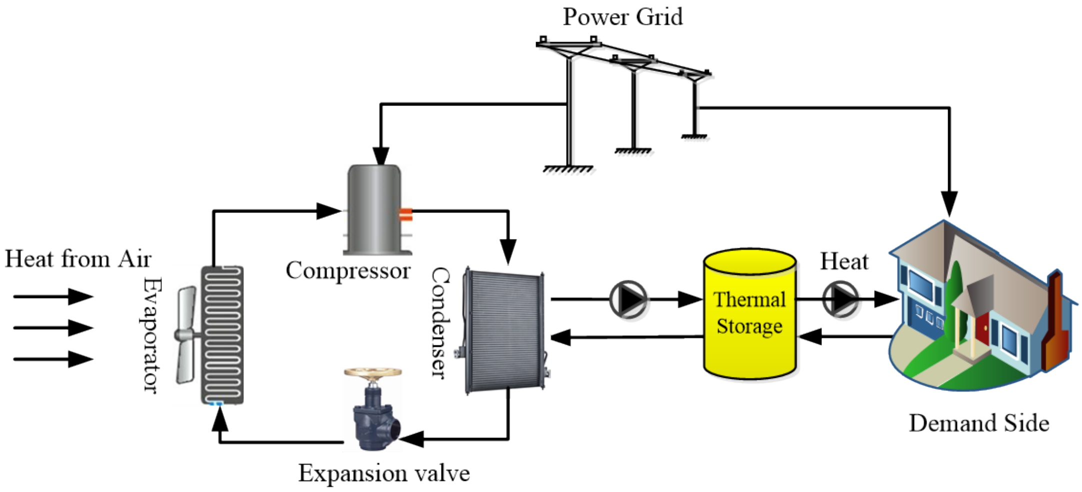

Fig 4-13 Structure of residential heat pump system

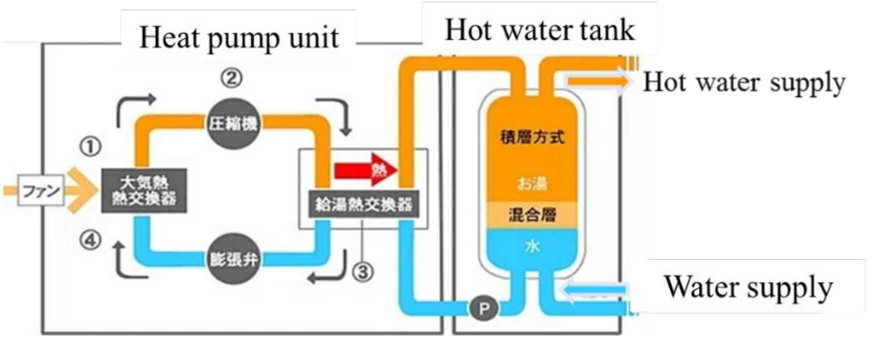

Fig 4-14 Residential heat pump internal structure[5]

Figure 4-13 presents the detail structure of residential heat pump system. Customers can use electricity from power grid, evaporator absorbs the heat form air, and transfer it to the thermal storage system. And the stored energy in the tank will be used later in the residential house.

The advantages of a residential heat pump system are:

- Long service life and low maintenance costs.
- Reduce greenhouse gas emissions and protect the environment.
- Save building space and is simple to control the equipment.

At the same time, residential heat pump systems also have such disadvantages like high initial investment and system is complicated and the installation is difficult.

4.4.3 Residential photovoltaic system

Photovoltaic (PV) is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. A PV system employs solar modules, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop mounted or wall mounted. The mount may be fixed, or use a solar tracker to follow the sun across the sky. In Japan, as of 2011, surplus power purchase system (fixed price purchase system) and various types of subsidy measures were implemented. From 2012, a system will be introduced to purchase the total amount of equipment for the public industry, and all renewable energy will also be added to the purchase target[6].

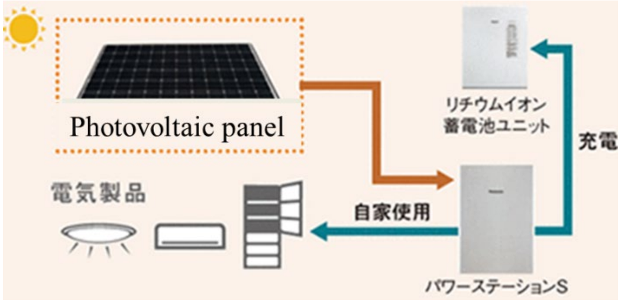

Fig 4-15 Residential photovoltaic system structure[7]

In the Jono smart house area, most households choose an energy system that combines a residential fuel cell system or a residential heat pump system with PV. Because the Japanese energy market is more expensive for the sale of surplus household electricity to the grid, PV power generation has become the main source of household investment recovery.

4.4.4 Conventional energy system

Fig 4-16 shows the structure of a conventional residential energy system. All electricity supply to a conventional residential energy system comes from the grid. The hot water supply is directly purchased from the city's natural gas input household water heater, which is heated and supplied to the user through the hot water tank.

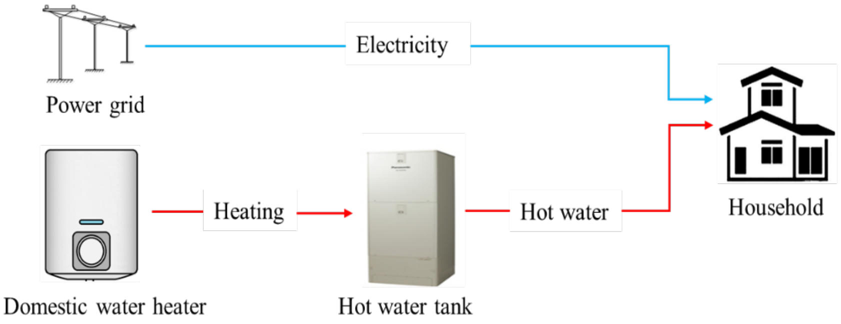

Fig 4-16 Conventional energy system structure

4.5 Analysis and comparison of smart house energy consumption characteristics

According to the data book from Kyuden Electrical Company[8], it can be seen that the Kyushu area is presenting a full electrification trend. All electrified housing number in Kyushu area has increased by 100% from 2008 to 2017.According to Ref. [9], numerous heat pump water heaters have been developed for the residential sector, alongside the promotion of all-electrification households over recent years. Energy for hot water accounts for about 30% of total residential energy consumption in Japan. As evidenced in many empirical studies, the energy consumption of each household was statistically investigated for different outdoor temperatures, family composition, house time and economic conditions. In addition, load flexibility is closely related to the load consumption patterns of different customers. This research selected 12 households located in Jono smart house area, northern part of Kyushu Island, Japan. Analyzing their residential electricity usage during the winter of 2017 week period. This section analyzed the time series power consumption by each appliance at 1-hour interval, compares the residential energy consumption after the uptake of heat pump system.

4.5.1 Introduction of object information and methodology

(1) Object information

To analyze household using heat pump residential energy systems, we collected electricity usage for 12 households in the Jono smart house area. The use of electricity from April 2017 to March 2018 was measured. In terms of data collection, we measured the electricity consumption of households such as electricity purchases, electricity sales, solar power generation, and fuel cell power generation, and the amount of gas consumed by fuel cells and backup system. At the same time, weather conditions such as outdoor temperature, wind speed, precipitation and sunshine time were collected in the Jono area. Fig 4-17 shows an example of January 1, 2018, as the data collection for a day.

At the same time, we make a survey of family members' stay-in-home time for the 12 selected customers. The survey included the composition and basic information of the family members of the respondents, and the stay-in-home time at weekday, Saturday and Sunday(Fig 4-18).

Measurement time	**Grid import**	**Feed-in**	**Solar power generation**	**Fuel cell power generation**	**Power consumption**	**Temperature (℃)**	**Wind velocity(m/s)**	**Precipitation (mm)**	**Sunshine duration**
0:00	55	0	0	239	294	5.7	1.8	0	
1:00	150	0	0	124	274	5.4	2.2	0	
2:00	310	0	0	0	310	5.2	1.6	0	
3:00	294	0	0	0	294	5.1	1.1	0	
4:00	276	0	0	0	276	7.1	2.9	0	
5:00	289	0	0	0	289	7	3.7	0	
6:00	294	0	0	0	294	6.4	3.5	0	
7:00	250	0	28	0	278	5.8	3	0	
8:00	12	172	424	0	264	5.6	3.5	0	0
9:00	3	470	752	0	285	6.1	3.8	0	0.3
10:00	1	1151	1428	0	278	6.3	3.5	0	0.2
11:00	1	573	836	0	264	7.9	2.5	0	0.2
12:00	0	1882	2153	0	271	6.5	2.7	0	0.1
13:00	0	1086	1366	0	280	6.7	3.9	0	0.2
14:00	0	1405	1673	0	268	7.6	3.4	0	0.1
15:00	3	381	639	0	261	6.9	3.2	0	0.3
16:00	203	135	337	0	405	6.9	3	0	0.4
17:00	1421	0	4	0	1425	6.6	1.4	0	0.1
18:00	1332	0	0	0	1332	6.5	1.4	0	0
19:00	2015	0	0	127	2142	5.7	1.3	0	
20:00	1008	0	0	696	1704	4.7	1.4	0	
21:00	953	0	0	699	1652	4	0.8	0	
22:00	172	0	0	568	740	2.9	2.2	0	
23:00	54	0	0	531	585	2.4	1.6	0	

Fig 4-17 Data collection of target residence in one day

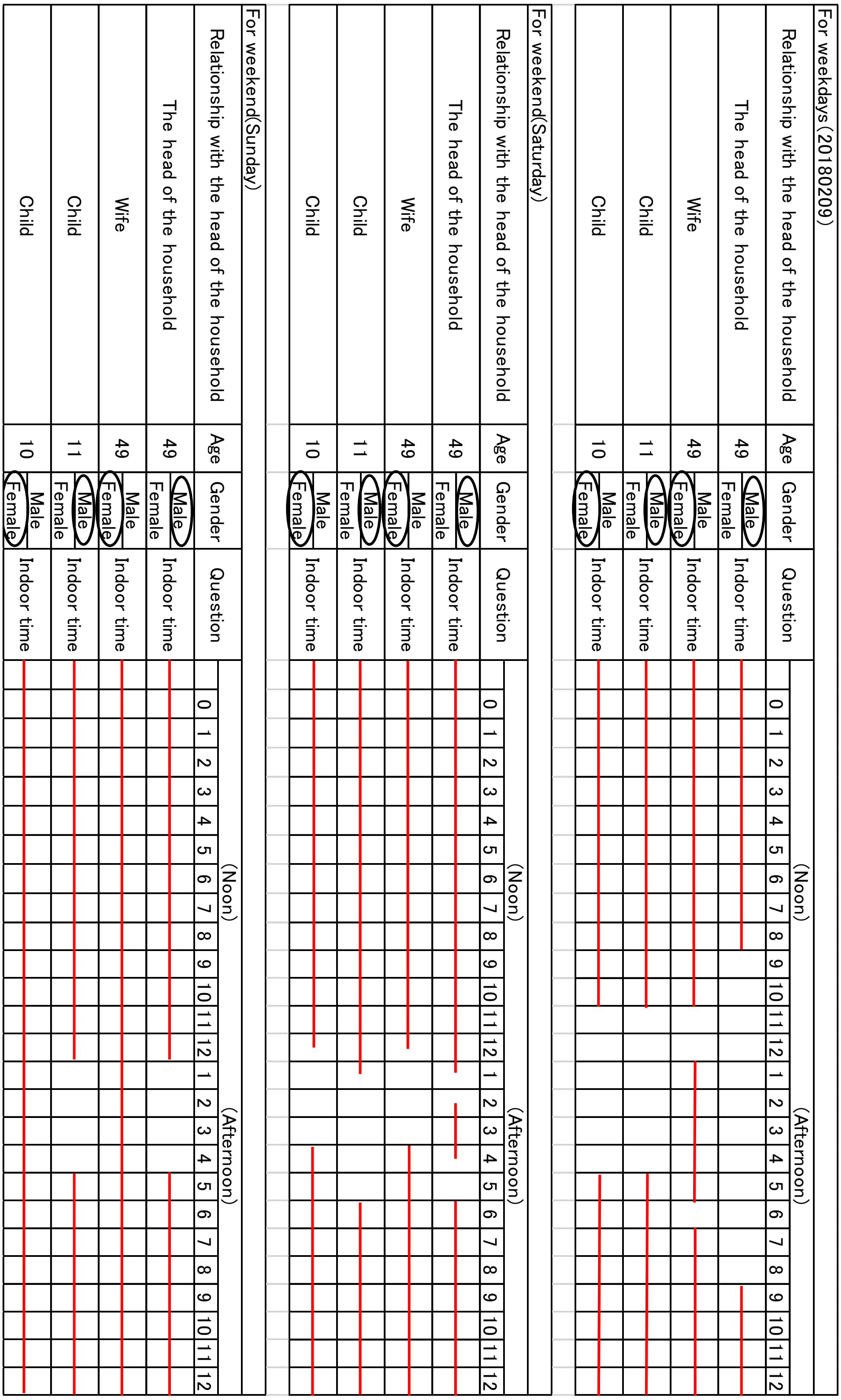

Fig 4-18 Survey example of family members' stay-in-home time

(2) Methodology of COP calculation

The performance of COP is strongly dependent on changes in outdoor temperature, the daily heat consumption of the house also change. There is an uncertainty in the cost savings, we compare the performance between heat pump systems and traditional methods of extracting heat from natural gas.

The power consumption of heat pump can be calculated as follow:

$$E_{hp} = \frac{Q_{re}}{COP_{hp}} \tag{4-1}$$

The equivalent consumption of natural gas can be calculated as follow:

$$V_{Gas} = \frac{Q_{re}}{LHV} \tag{4-2}$$

The fuel cost of natural gas can be calculated as follow:

$$C_{Gas} = V_{Gas} * Price_{Gas} \tag{4-3}$$

The power cost of heat pump can be calculated as follow:

$$C_{re} = Q_{re} * Price_{Electric} \tag{4-4}$$

The cost saving can be calculated as follow:

$$P_{user} = C_{Gas} - C_{re} \tag{4-5}$$

Where, Q_{re} refers to the heating consumption of residential house, COP_{hp} refers the COP of heat pump, LHV is the heating value of western gas, $Price_{Gas}$ is the price of natural gas, and $Price_{Electric}$ refers to the electricity price.

4.5.2 System energy characteristics and occupation impact analysis

(1) Energy saving performance

Selecting one household to analyze the power consumption of Eco-cute. As we all know the power consumption of Eco-cute have a greatly connection with outdoor temperature. As we can see in Fig 4-19, as the outdoor temperature increase the power consumption of Eco-cute is shown a decreasing trend. Taking one household as an example, when the outdoor temperature dropped from 6 degrees Celsius to minus 2 degrees Celsius, the hourly power consumption increased by 14%. In the following, we will calculate thermal load in different value of COP.

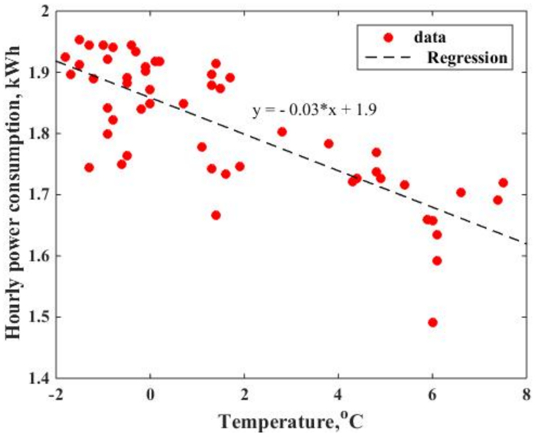

Fig 4-19 Power consumption of Eco-cute under different out temperature

Taking one of those household as an example, to analysis the measured data, and find the relationship between COP and the heat generated by heat pump. Assuming the value of COP as five different conditions between 2.5 and 3.5. Calculated according to the equation (4-1), the result indicated the thermal load under the different value of COP. Fig 4-20 shows the equivalent thermal load under different value of COP.

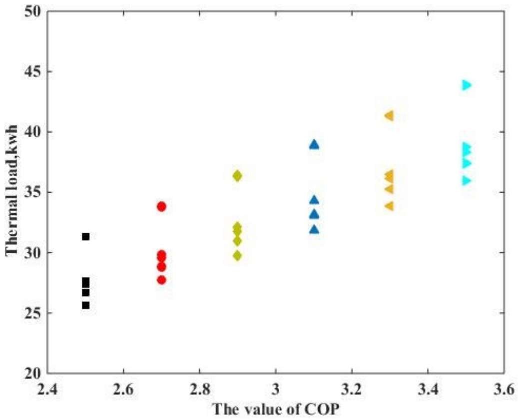

Fig 4-20 Thermal load under the different value of COP

(2) Economic performance

We make an economic performance compares between Eco-cute and natural gas boiler. The cost of the Eco-cute and natural gas boiler for the same amount thermal heat is calculated. As shown in the Fig 4-21, ranging the value of COP from 2.5 to 3.5, it shows that the cost saving is obvious at higher COP value.

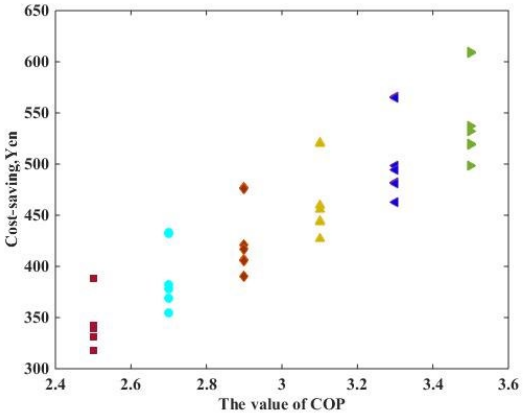

Fig 4-21 Cost saving by using Eco-cute under the different value of COP

We also calculate the cost savings performance among customers. As shown in the Fig 4-22, we fix the performance of COP at 3.5, the monthly cost savings can reach up to 5000Yen and the lowest is around 2500Yen. It indicates that Eco-cute is shown an economic advantage.

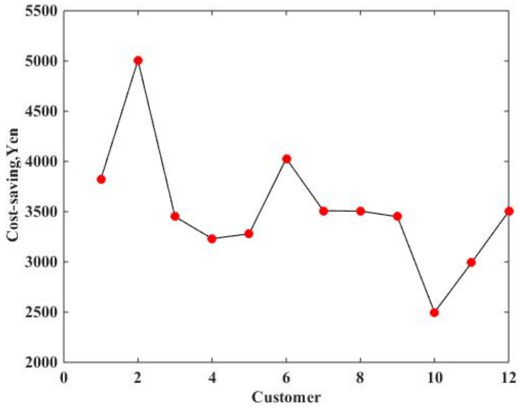

Fig 4-22 Monthly cost savings performance among customers

(3) Occupation impact

As we all know, occupation have an impact on the load consumption. We did a survey of family members' indoor hour for the 12 selected customers, the survey can be seen in the appendix. The survey result show that the number of family members of the selected households ranges from 2, 3, 4, and 5 people, we calculated the power consumption of Eco-cute for these customers, respectively. The relationship between the number of family members and power consumption of Eco-cute is shown in Fig 4-23. The result present that the power consumption is in linear relationship with the number of family members. The impact of stay-in-home time on the total power and Eco-cute consumption is shown in Fig 4-24.

Based on these two figures, it indicates that the power consumption is in linear relationship with the number of family members. Although the total power consumption and heat pump power consumption show a similar trend under different stay-in-home time, there is no obvious relationship between stay-in-home time and power consumption. This may be related to the different power consumption behavior of users and the running time of heat pump.

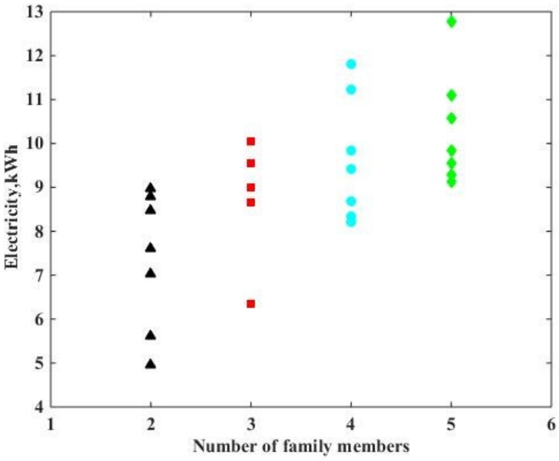

Fig 4-23 Relationship between power consumption of Eco-cute and number of family members

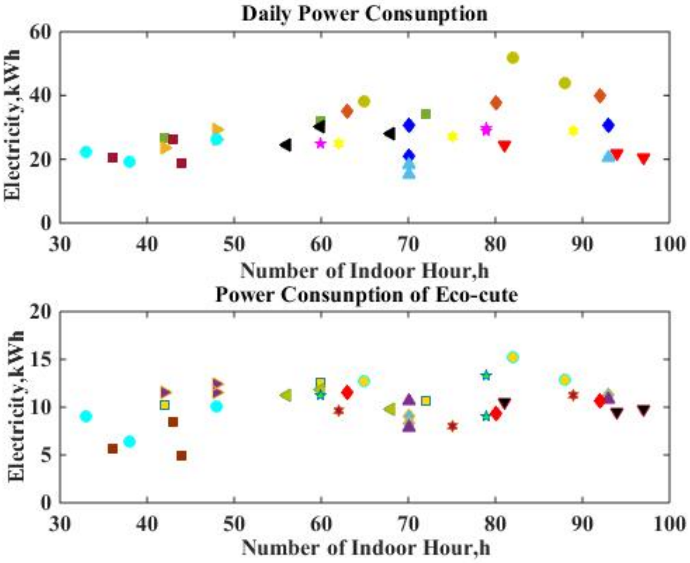

Fig 4-24 The impact of stay-in-home time on the total power and Eco-cute consumption

4.6. Summary

In this part, we introduce the basic information of Jono smart house area, sort out and analyze the results of questionnaire survey. At the same time, the energy consumption characteristics of smart house users are analyzed based on the statistics of users' residence time.

Firstly, we conducted a questionnaire survey on users living in Jono smart house area from the aspects of family composition, equipment installation, contract selection and users' awareness of energy conservation and environmental protection, and a total of 73 questionnaires were collected. According to the statistical results of the questionnaire, the average number of families living in the Jono area is 2.8 person, with a wide range of age groups. All independent houses have introduced solar power generation systems, but it is found that almost no batteries have been introduced. Moreover, the power contract companies of each family are not only local power companies, but also many families sign contracts with other power companies. The average ownership of family cars is 1.26, of which hybrid vehicles account for 22%, with a high penetration rate. More than half of households living in smart residential areas have improved their awareness of power conservation and environmental protection. However, the use frequency of intelligent residential energy management system is very low, so it is necessary to further explain the use methods and provide corresponding incentives.

After that, this part utilizes the monitored history data to analyze the energy consumption characteristics and influencing factors of the residential customers, which feature with heat pump heat supply system in Jono area. Considering that load flexibility is closely related to the load consumption patterns of different customers. We selected 12 households to analyze their residential electricity usage, the daily demand curves and load consumption pattern of heat pump system are investigated in detail.

The result presents that the characteristics of energy saving performance indicate that power consumption of Eco-cute shows a decreasing trend with increasing outdoor temperature. According to the economic performance comparison between Eco-cute and natural gas boiler, the result presents that Eco-cute shows an economic advantage, and the cost saving by using Eco-cute is obvious at higher COP value. As for the impact of occupation on the load consumption, we did a survey of family members' indoor hour for the 12 selected customers, the result show that there is no obvious relationship between stay-in-home time and power consumption. This may be related to the different power consumption behavior of users and the running time of heat pump.

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Chapter 5

PERFORMANCE COMPARISON OF MULTI-ENERGY SUPPLY SYSTEM IN SMART HOUSE

CHAPTER FIVE: PERFORMANCE COMPARISON OF MULTI-ENERGY SUPPLY SYSTEM IN SMART HOUSE

5.1 Contents

Due to the improvement of people's living standards, uptake of multi-functional household appliances, electricity consumption accounts for a rising ratio in the proportion of primary energy usage. Currently, electricity accounts for more than 50% of primary energy usage and city gas is about 21% of total. The aim of this part focus on improving the efficiency of household energy usage and optimizing the economy of residential energy systems. This part classified the detail electricity consumption and generation for a Japan typical smart house with Hybrid Fuel cell and Photovoltaic System (HFPS) based on the history monitored data. Then a simulation model of the Hybrid Heat pump and Photovoltaic System (HHPS) was designed under the same user load for analyzing the energy consumption. In addition, this part also lists five kinds of electricity price schemes of electric company. The electricity costs of HFPS and HHPS were calculated based on five cases. Finally, the economy of the two systems is compared and optimized by considering the carbon tax, equipment price and energy price fluctuation. The results of this part provide policy guidance for the future Japanese government's promotion of residential fuel cell systems, while choosing the optimal path between user energy characteristics and power contract scheme. Fig 5-1 shows the schematic diagram of the framework.

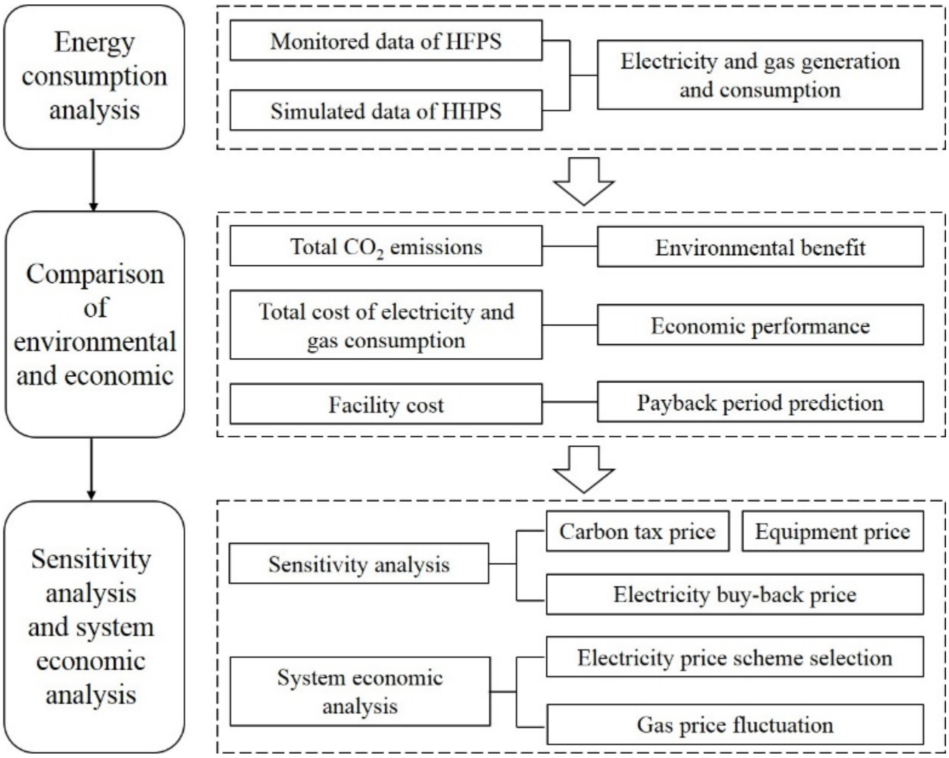


Fig 5-1 Schematic diagram of the designed framework

5.2. Measurement results and analysis

5.2.1 Introduction of object residence information

To analyze household using fuel cell, PV, and heat pump residential energy systems, we collected electricity and gas usage for 12 households in the Jono smart house area. The location of Jono region in Japan is shown in Fig 5-2. This part selected a home using a hybrid fuel cell and PV system(HFPS) as the basis for data analysis. The use of electricity and gas from April 2017 to March 2018 was measured. The total residential area of the target residence is 135m² and the number of family members is two. The energy system used in the residence is HFPS, and Fig 5-3 shows the appearance and energy system of the target residence.

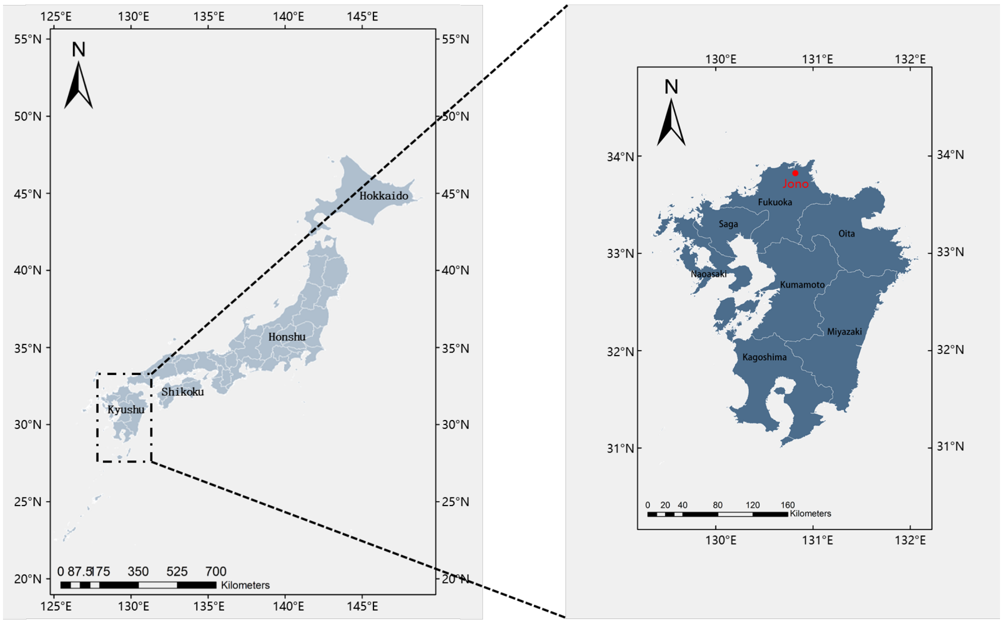


Fig 5-2 Location of Jono region in Japan

Fig 5-3 Appearance and energy system of the target residence

Fig 5-4 illustrates the schematic layout and energy flow of the three residential energy systems involved in this research. Customers get gas from Gas Company into fuel cell and boiler, the type of gas is town gas 13A in the case study. Fuel cell and PV transform the electricity to demand side, and the heat generated is stored in thermal storage together with the heat generated by the boiler. The HFPS system has a backup equipment. When the heat that fuel cell generated is not enough to supply to the consumer, the backup equipment can absorb gas to provide heat to the residence. As for the HHPS, customers can use electricity from power grid and PV, the evaporator absorbs the heat form air, and transfer it to the thermal storage. And the stored energy in the tank will be used later in the residential house. The advantage of using a residential energy system that combines with PV is that when the system generates more electricity than the user power consumption, the remaining power can be sold back to the grid, is called feed-in. The conventional energy system in the research is stated as the system which has no other energy supply equipment but only use domestic water heaters for heating.

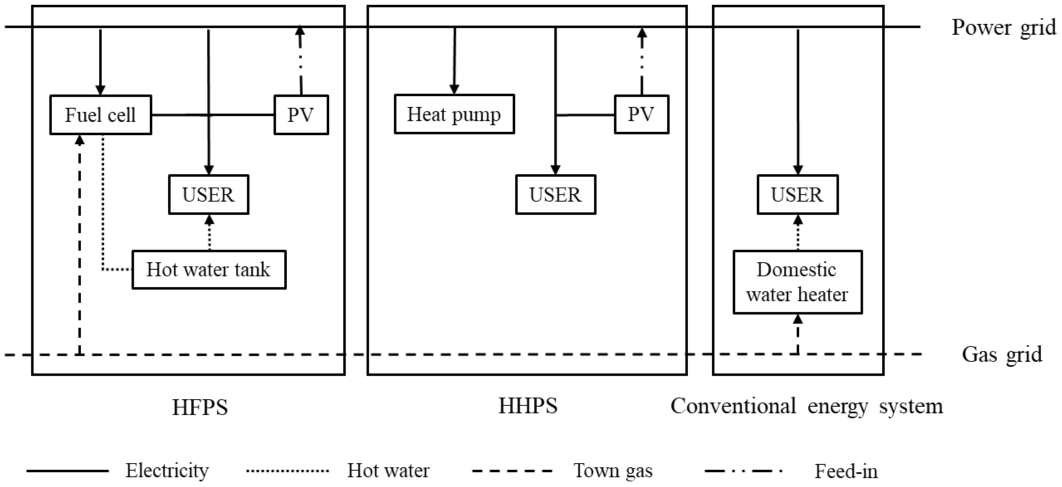


Fig 5-4 Layout of multi-energy supply system

In order to analyze the energy consumption of residential buildings, improve the environmental and economy efficiency of residential energy systems, this research through the measurement of energy use of household appliances, to understand the energy use situation of households at smart house, the peak hours and energy consumption characteristics(Table 5-1). In addition, by analyzing the energy consumption of the house to understand the running time and operation mode of the energy supply equipment, and calculating the consumption of the energy system throughout the year in combination with the price of electricity and gas. Finally, through the comparison of different residential energy systems, the characteristics of each and the future market development space are analyzed.

Table 5-1 Monthly consumption of target household

	FC power generation (kW)	PV power generation (kW)	Power consumption (kW)	Grid import (kW)	Feed-in (kW)	FC gas consumption (m^3)	Backup gas consumption (m^3)
Jan.	155.14	351.91	352.77	184.34	280.55	39.83	78.20
Feb.	161.36	501.33	326.58	135.92	445.85	42.33	59.48
Mar.	157.36	727.31	4339.4	111.50	669.59	42.76	39.27
Apr.	167.19	769.43	321.37	85.42	700.67	41.50	21.68
May.	130.21	934.28	319.17	95.60	840.92	33.14	5.02
Jun.	102.53	796.27	312.47	124.18	710.52	27.43	2.25
Jul.	79.12	732.77	474.56	238.50	575.82	21.08	1.59
Aug.	56.12	825.30	470.78	243.84	654.48	14.54	2.12
Sep.	84.68	571.79	348.85	162.46	470.09	22.02	1.12
Oct.	96.94	485.40	300.24	141.66	423.77	26.49	1.94
Nov.	128.36	498.72	333.30	143.69	437.47	32.82	31.54
Dec.	154.68	373.25	368.48	167.22	326.67	40.22	69.84

5.2.2 Power generation and consumption analysis

In order to understand the seasonal changes in household electricity consumption, we analyzed the monthly power generation and consumption of the target housing within one year.

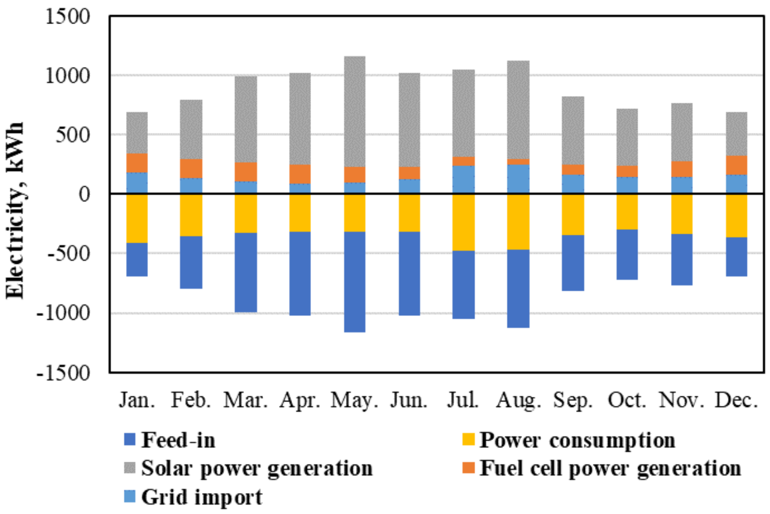


Fig 5-5 Monthly electricity generation and consumption

Fig 5-5 shows the monthly electricity generation and consumption for one year. It contains five parts, feed-in, power consumption, solar power generation, fuel cell power generation and grid import. When the user's power usage is surplus, in order to improve economy and save energy, unused power can be sold back to the power grid, this part is called as feed-in. As can be seen from the figure, the part of feed-in mainly comes from photovoltaic power generation. For the five parts of the consumption analysis, it can be seen that in July and August of the year, users buy more electricity from the grid. And the fuel cell generates more electricity in winter than in summer. In contrast to fuel cell power generation, PV systems generate more electricity in summer than in winter. This shows that the two systems of fuel cell and photovoltaic are complementary functions.

In order to analyze the user's hourly electric power production and consumption, we selected four days in different season for analysis during a year: 2017-04-15, 2017-07-15, 2017-10-15, 2018-01-15, the result is shown below(Fig 5-6).

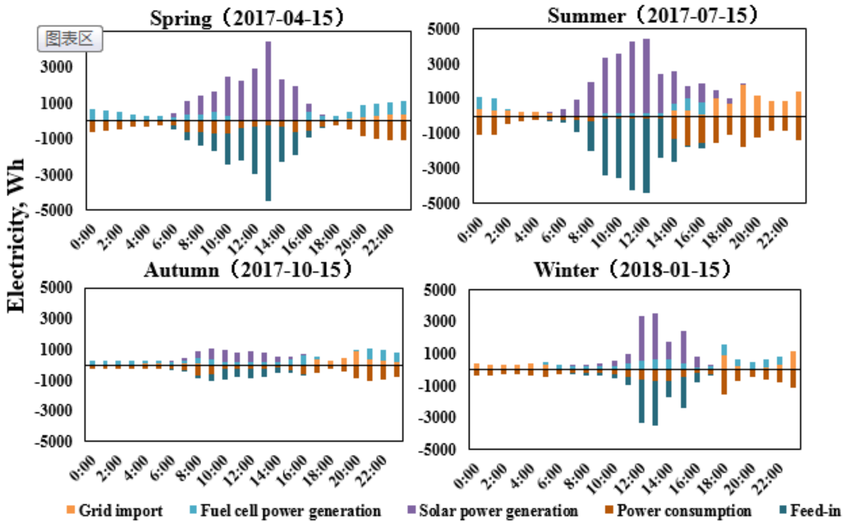


Fig 5-6 Hourly main electricity statistics

By analyzing the daily power consumption of the above four seasons, it can be seen that the main working hours of the fuel cell are in the morning and evening, while the PV power generation is mainly concentrated in the daytime. It can be more clearly seen through the hourly energy consumption that most of the user's feed-in come from PV power generation.

We also conducted monthly and hourly analysis of the user's natural gas usage. Fig 5-7 shows the natural gas usage for each month of the year in the target home. There are two main ways of supplying hot water to the energy system used in the target house. One is to provide heat to the user through the natural gas of the fuel cell, and the other is to supplement from the back up equipment. The backup system is used in conjunction with a fuel cell system. When the heat provided by the fuel cell is not enough for the user to use, the backup device starts to operate, and the burning natural gas provides heat to the user. For general households, the use of hot water is mainly concentrated in winter, with more hot water used in December and January, less in July and August. Similarly, the amount of natural gas used in the backup system is the same as fuel cell system.

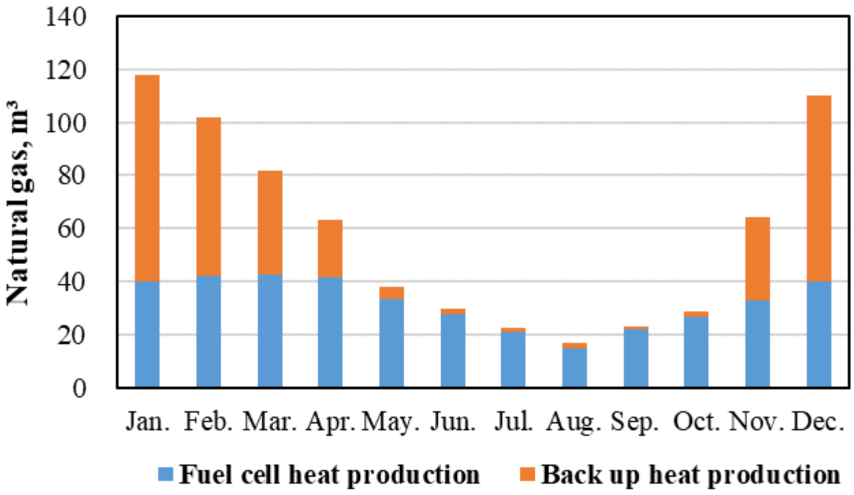


Fig 5-7 Monthly gas production

In order to understand the daily natural gas usage of the target dwellings, we selected the same four days of the analysis of the electricity consumption to sort out the natural gas consumption. Fig 5-8 shows the daily heat consumption of households in one of the four seasons. It can be seen from the figure that the households use more heat at night and the fuel cells can work at various times of the day.

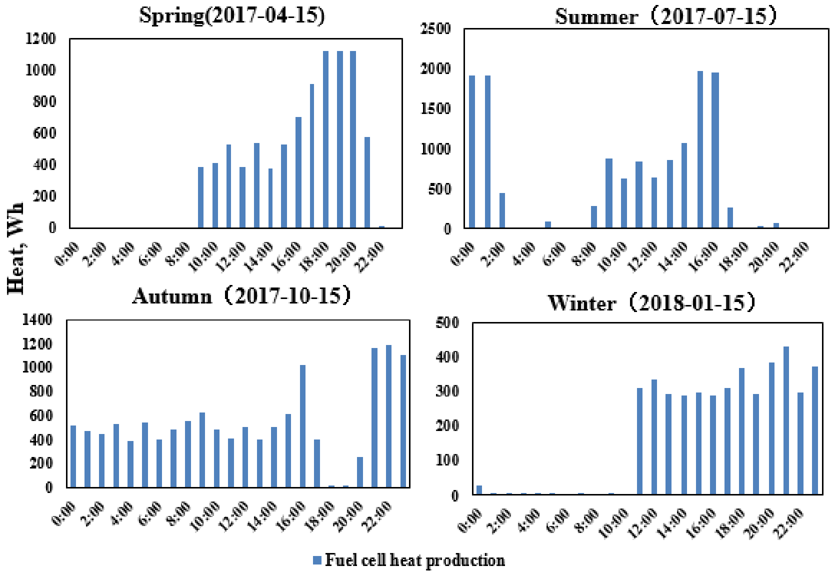


Fig 5-8 Hourly main heat statistics

5.2.3 Smart house equipment performance analysis

(1) Fuel cell

In order to understand the fuel cell's hourly power generation in a month, the monitoring data from April 1, 2017 to March 31, 2018 was collected every 60 minutes.

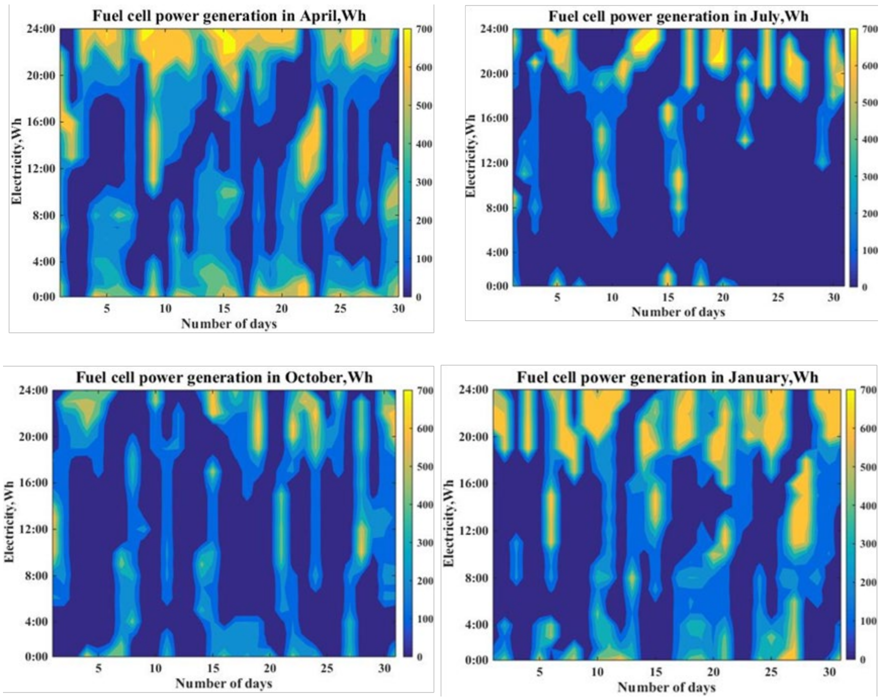


Fig 5-9 Color scales for energy production data from January, April, July and October

Fig 5-9 show the distribution and fluctuations of the color scales for energy production data from January, April, July and October, represents four different seasons. The higher the value, the closer to yellow, the lower the value, the closer to the navy. The vertical axis represents the measurement time and the horizontal axis represents the measurement date. The results show that the use of hot water from general household is mainly in evening.

(2) Photovoltaic (PV)

In order to analyze the daily power generation of photovoltaic under different conditions, we select the amount of electricity generated during the PV working hours, combined with the following variables for analysis.

- Outdoor temperature
- Sunshine duration
- Precipitation

- Wind velocity
- Solar radiation

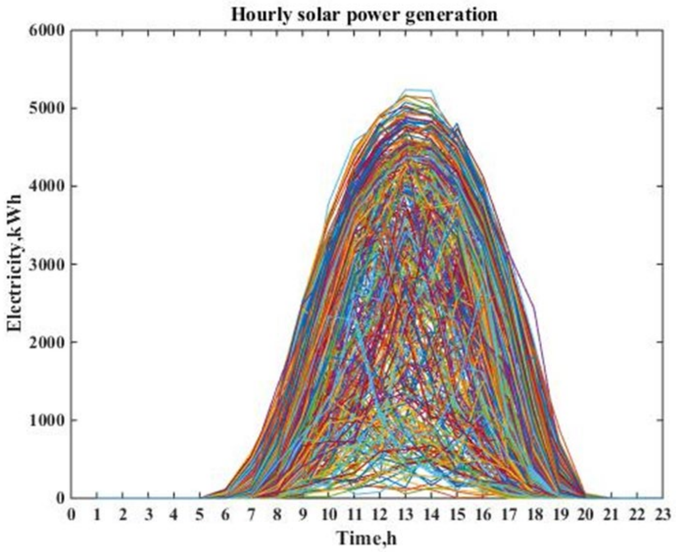


Fig 5-10 Hourly solar power generation

Fig 5-10 shows the PV hourly power generation in one year. From the figure, it can be seen that the main power generation time of PV is between 6:00 and 18:00, so we select the PV power generation during this period, combined with outdoor temperature, solar radiation, sunshine duration, precipitation and wind velocity, analysis of factors affecting PV generation by four external environmental conditions. The result indicate that the most influential factor of PV power generation is the sunshine duration and solar radiation(Fig 5-11, Fig 5-12). When the sunshine duration and solar radiation increase the power generation of PV is shown an increasing trend.

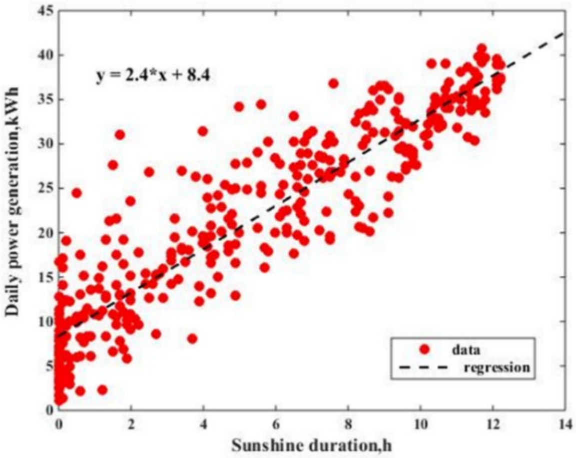


Fig 5-11 Power generation of PV under different sunshine duration

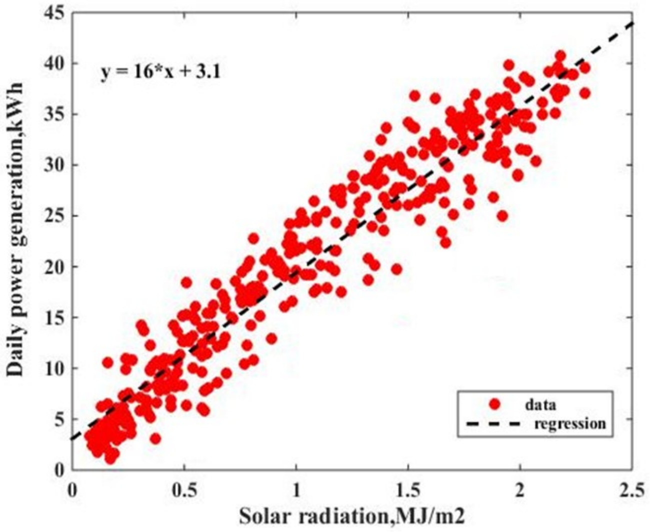


Fig 5-12 Power generation of photovoltaic under different solar radiation

In order to analyze whether the other environmental factors will affect the PV power generation, we increase the other influencing factors in turn and analyze their relationship with PV power generation. The results are shown in Table 5-2.

Increase the influencing factors in turn. The value of the R^2 increases, the greater the correlation between PV power generation and other factors. The result indicates that wind velocity and outdoor temperature have little effect on PV power generation. The most influential effect on PV power generation are solar radiation and sunshine duration.

Table 5-2 Analysis of the impact of environmental factors on photovoltaic power generation

Model Summary				
Model	R	R^2	Adjusted R^2	Std.Error of the Estimate
1	.943[a]	0.890	0.889	3.614
2	.927[b]	0.921	0.920	3.071
3	.933[c]	0.923	0.922	3.027
a. Predictors：(Constant), Solar radiation				
b. Predictors：(Constant), Solar radiation, Sunshine duration				
c. Predictors：(Constant), Solar radiation, Sunshine duration, Precipitation				

(3) Analysis of factors affecting heat consumption

In order to analyze the user’s heat consumption under different conditions, based on the measured data, we compiled the user's hourly fuel cell natural gas consumption and the natural gas consumption of the backup system, combined with the following variables for analysis.

- Outdoor temperature
- Precipitation
- Wind velocity
- Solar radiation

Table 5-3 shows the relationship between different influencing factors and the user's heat consumption. The results show that the outdoor temperature has the greatest influence on the heat consumption, and the wind velocity, precipitation and solar radiation have little effect on the heat consumption. Fig 5-13 shows the trend of outdoor temperature on the user's heat consumption, showing a negative growth.

Table 5-3 Analysis of the impact of environmental factors on user's heat consumption

Model Summary				
Model	R	R^2	Adjusted R^2	Std.Error of the Estimate
Outdoor temperature	0.799[a]	0.638	0.637	0.890
Excluded variable				
Precipitation				
Wind velocity				
Solar radiation				

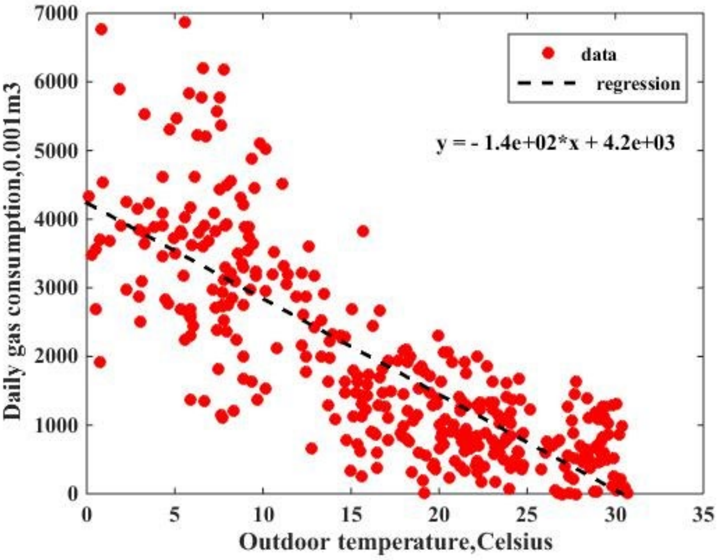


Fig 5-13 Gas consumption under different outdoor temperature

5.2.4 System performance analysis

(1) System environmental analysis

To analyze the environmental aspects of smart house energy systems, we calculate the CO_2 emissions generated by the HFPS used in the target residence in one year.

The electric CO_2 emissions C_E (kg) can be calculated as follow:

$$C_E = (E_G - E_F) * E_{CF} \tag{1}$$

The gas CO_2 emissions C_G (kg) can be calculated as follow:

$$C_G = G_U * G_{CF} \tag{2}$$

The total CO_2 emissions for a year C_T (kg) can be calculated as follow:

$$C_T = C_E + C_G$$

(3)

Where, E_G refers to the user buys electricity from the grid, E_F refers to the user sells the remaining power back to the grid, E_{CF} refers to the Kyushu Electric CO_2 emission factor, G_U refers to the user's gas usage, G_{CF} refers to the city gas CO_2 emission factor. From table 5-4, we can see that the city gas CO_2 emission factor is 2.21[1]. From Fig 5-14 we can see that the Kyushu Electric CO_2 emission factor is 0.463[2].

Table 5-4 City gas carbon dioxide emission factor[1]

Type of natural gas	13A		
Area	Unit	Fukuoka, Kitakyushu	Kumamoto, Nagasaki, Sasebo
CO_2 emission coefficient factor per `unit volume	t-CO^2/m^3N	2.29	2.35
	t-CO^2/m^3	2.21	2.27
	t-CO^2/m^3N	2.19	2.25

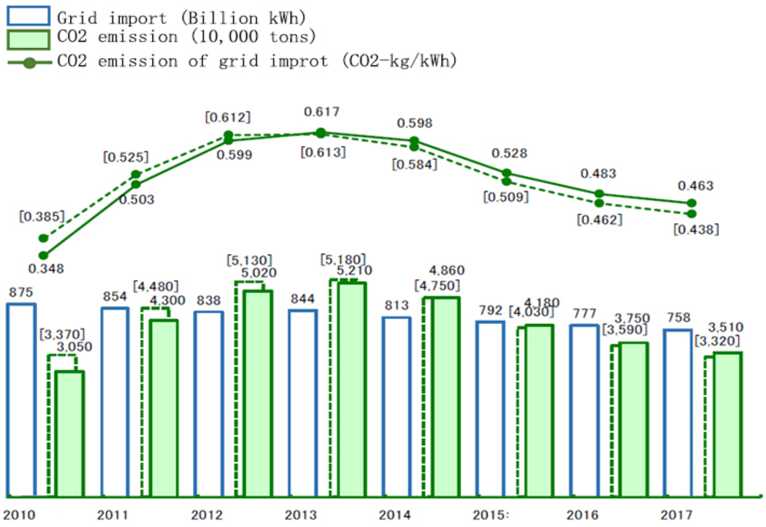


Fig 5-14 Kyushu Electric CO_2 emission factor[2]

Fig 5-15 shows the CO_2 emissions of the target residential energy system for one year. It can be seen that in January, February, November, December, the CO_2 emissions for the four months were positive, and the other months were negative. Because in these four months, the residential hot water consumption is more than other months, and the consumption of natural gas is also more than other months, and the amount of PV power generation is less than others, so the users need more grid import and get less feed-in, so the total CO_2 emissions in these four months is a positive. The reason for the negative CO_2 in some months is that the proportion of households selling electricity back to grid is relatively large. Calculated that the annual CO_2 emissions are -634.052 kg(Table 5-5).

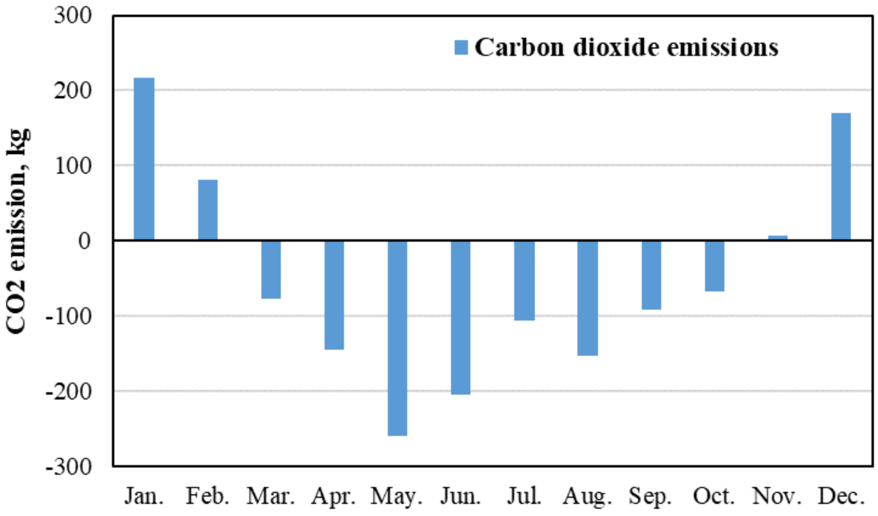


Fig 5-15 Annual CO_2 emissions

Table 5-5 Monthly carbon dioxide emissions

	CO_2 emissions (kg)
Jan.	216.29
Feb.	81.51
Mar.	-77.10
Apr.	-145.23
May.	-260.75
Jun.	-205.88
Jul.	-106.09
Aug.	-153.31
Sep.	-91.30
Oct.	-67.78
Nov.	6.21
Dec.	169.40
Sum	-634.052

(2) System economic analysis

Assuming that the households using the conventional energy system has the same electricity and heat required with the household which use the HFPS, the electricity and gas costs of the two residential energy systems are calculated and the two results are compared.

At present, Japan's electric companies and gas companies have different power plans. Each program charges different electricity prices. Users can choose the most favorable solution according to their lifestyle and family members.

The household in this part selected the power company is Kyushu Electric Power Company, the power contract is plan B, and the residential power capacity is 60A. This plan is a phased billing system, and the unit price of the electricity fee varies depending on the amount of electricity used. If the amount of electricity used exceeds a certain amount, the unit price of the electricity charge will increase thereafter, and the more electricity used, the more expensive the unit price. The unit price of electricity charge of plan B is divided into three stages, and the unit price gradually increases with the stage. The first stage is a relatively low price and the third stage is the most expensive. Fig 5-16 shows the unit price of the electricity charge for the plan. Plan B's electricity charge calculation method is based on the electricity charge plus the monthly electricity consumption[3]. Different power capacities correspond to different base costs. Table 5-6 shows the price of the base electricity charge.

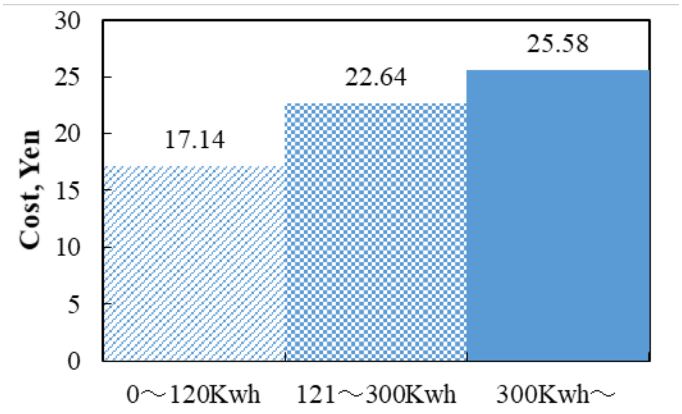


Fig 5-16 Unit price of electricity charge

Table 5-6 Basic electricity charge

	Basic charge（Yen）
10A	291.6
15A	437.4
20A	583.2
30A	874.8
40A	1166.4
50A	1458.0
60A	1749.6

The electricity charge for a conventional energy system is the base charge plus the monthly electricity consumption. The HFPS needs to reduce the cost of PV power sales on the electricity consumption costs. The target residential PV capacity is 6.3kW, and the feed-in price of PV systems with less than 10 kW is 37 Yen/kWh[4]. We calculate and compare the monthly electricity charge for conventional and target residence, and the results are shown below(Fig 5-17).

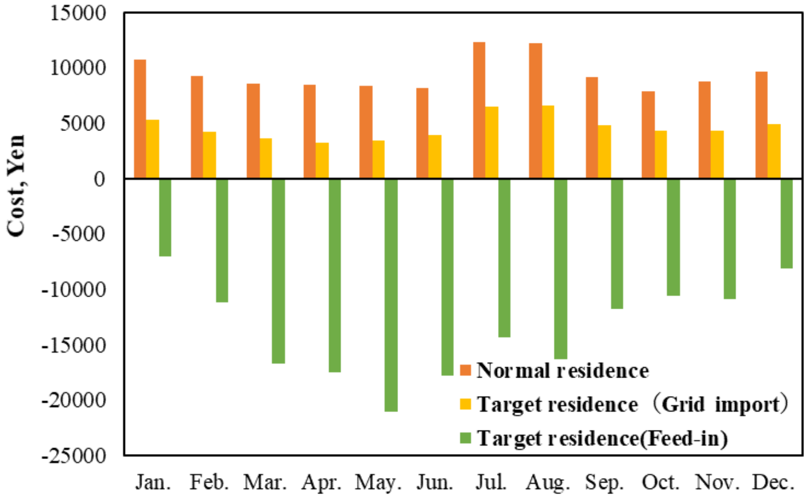


Fig 5-17 Monthly electricity charges comparison

The household in this part selected the natural gas company is Western Gas Company. The unit price of natural gas decreases as the amount of natural gas used increases, and the more natural gas used each month, the cheaper the unit price of natural gas. Fig 5-18 shows the unit price of the natural gas charge. The natural gas charge calculation method is based on the gas charge plus the monthly gas consumption[5]. Different natural gas usage per month is based on different base prices. The more the usage, the more expensive the base price is. Table 5-7 shows the price of the base natural gas charge.

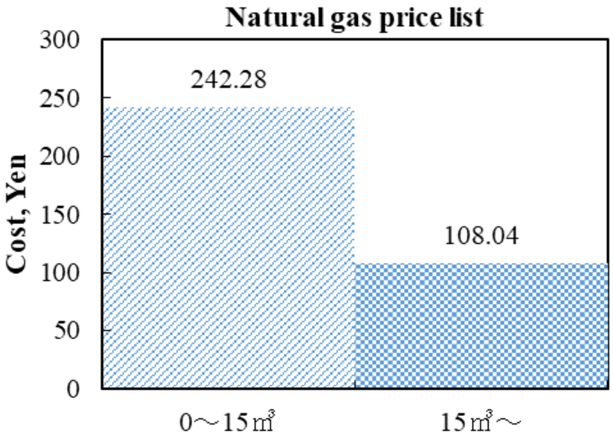


Fig 5-18 Natural gas price list

Table 5-7 Basic natural gas charge

	Basic charge（Yen）
0～15 ㎥	896.4
15 ㎥～	2916.0

Fig 5-19 shows a comparison of monthly natural gas charges for conventional and target residence, as the fuel cell consumes natural gas to provide electricity and heat to the home, so the target residence uses more natural gas than the conventional residence.

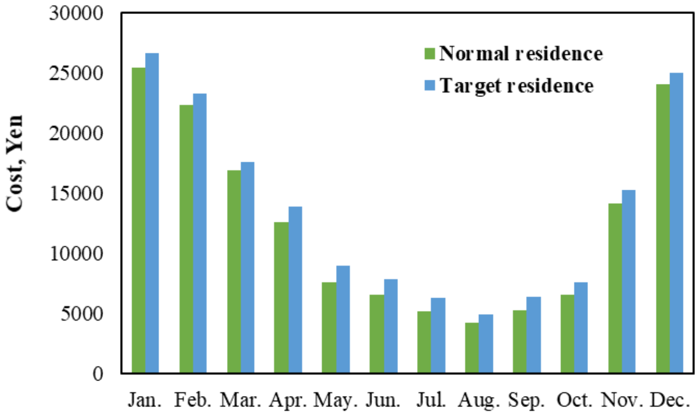


Fig 5-19 Comparison of monthly natural gas charges

(3) System payback period calculation

Compared with the conventional energy system, because the target house can sell unused PV power to the grid, so the monthly electricity and gas costs are less than the conventional energy system. We reduce the electricity and gas charges required for the conventional energy system into the electricity and gas charges required for the HFPS. The resulting cost is the operating profit after insertion and is shown in Fig 5-20. The total profit for the year is about 340,000 yen.

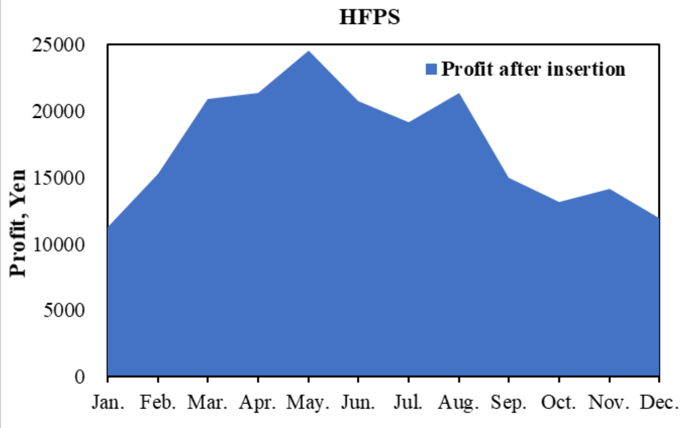


Fig 5-20 Total profit for the year

Although the insertion of fuel cell and PV can bring higher operating profit every year, the cost of initial equipment purchase is high. We investigated the market price of fuel cells and PV equipment and calculated that the household need how many years after the introduction of the equipment, the operating profit obtained can reach the investment cost of the initial purchase of equipment. We selected four prices for PV and fuel cells to calculate the year of payback. Table 5-

8 shows the equipment price.

Considering the high price of fuel cells and PV equipment, most households combine their own economic conditions, and generally choose to lend to banks when purchasing equipment. After inquiry, Fukuoka Bank‘s life loan annual interest rate is 4.5% 34). We assume that the user chooses the full loan purchase equipment and the 70% loan purchase equipment, and calculates the year of pay back of the two cases at different equipment prices.

Fig 5-21 shows the year of payback when the user fully introduces a full loan from bank into the device. When the fuel cell price is 1,300,000 and the PV unit price is 160,000/kW, the household can recover the investment cost in 8.88, and start to earn profit at 280,000 yen per year after 8.88. When the fuel cell price is 1,600,000 and the PV unit price is 220,000/kW, the household can recover the investment cost in the 13.33 years. Fig 5-22 shows the year of payback required when the user borrows 70% from a bank to purchase equipment. When the fuel cell price is 1,300,000 and the PV unit price is 160,000/kW, the household can recover the investment cost in 8.23, and start to earn profit at 280,000 yen per year after 8.23. When the fuel cell price is 1,600,000 and the PV unit price is 220,000/kW, the household can recover the investment cost in the 11.68 years. At present, the service life of fuel cells on the market is 10 to 20 years, and the service life of PV is about 17 years.

Table 5-8 The case of equipment prices changes

Case	Fuel cell equipment price(Yen)	PV equipment price(Yen/kW)
1	1,300,000	160,000
2	1,400,000	160,000
3	1,500,000	160,000
4	1,600,000	160,000
5	1,300,000	180,000
6	1,400,000	180,000
7	1,500,000	180,000
8	1,600,000	180,000
9	1,300,000	200,000
10	1,400,000	200,000
11	1,500,000	200,000
12	1,600,000	200,000
13	1,300,000	220,000
14	1,400,000	220,000
15	1,500,000	220,000
16	1,600,000	220,000

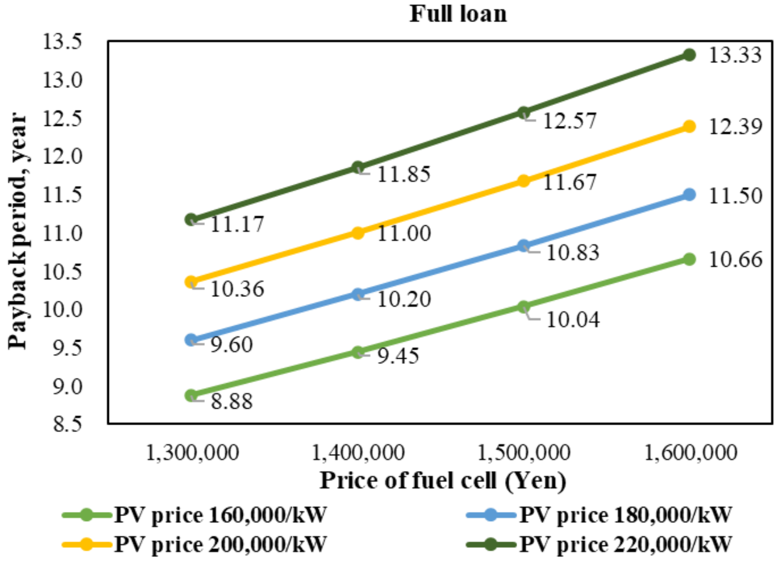


Fig 5-21 Full loan of payback period

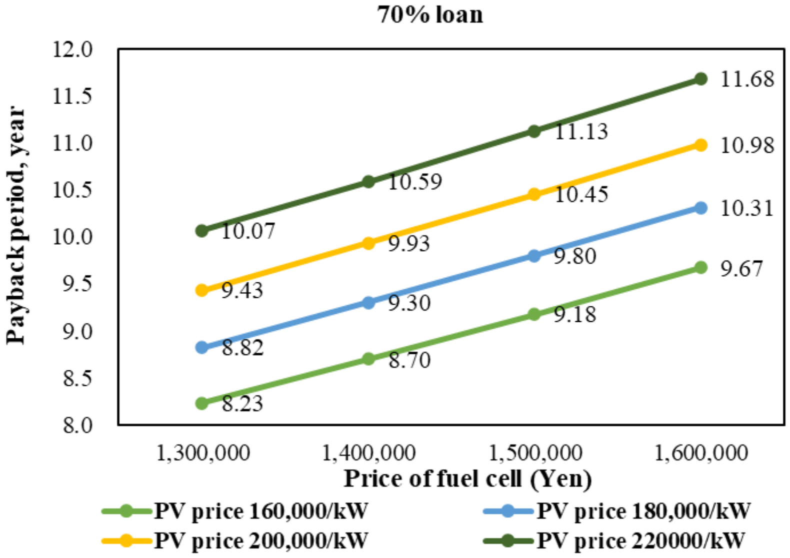


Fig 5-22 70% loan of payback period

According to the survey, the fuel cell equipment used for the target house has a capacity of 0.7 kW and a total price of 1.6 million yen. The PV capacity is 6.3kW and the total price is 1260,000 Yen. The specific price is shown in Table 5-9.

Table 5-9 Investment cost for fuel cell and PV

Equipment	Unit price(Yen)	Equipment capacity	Total price(Yen)
Fuel cell	2,280,000/kW	0.7kW	1,600,000
PV	200,000/kW	6.3kW	1,260,000

Combined with the calculation of the payback period, it can be seen that when the user purchases the equipment in full loan from the bank, the cost can be recovered at 12.39 year.

5.3. Simulation and verification of smart house energy system

5.3.1 Simulation model equipment selection

In order to compare the economics of residential fuel cell systems and residential heat pump systems in smart house, we simulated the energy consumption of the three kinds of residential energy systems, hybrid fuel cell and PV system(HFPS), hybrid heat pump and PV system(HHPS), and conventional energy system. The following is an introduction to the three system models.

(1) Hybrid fuel cell and PV system(HFPS)

Fuel cells have the advantages of cogeneration, and most of the working hours are concentrated in the evening. The PV system can convert solar radiation into electricity for the user to use, and when the user has surplus electricity, the remaining PV power can be sold to the grid. Since the main influencing factor of PV power generation is solar radiation, the main working time of the PV system is daytime. So, when a fuel cell and PV combination is used as a residential energy system, the two devices are in a complementary relationship.

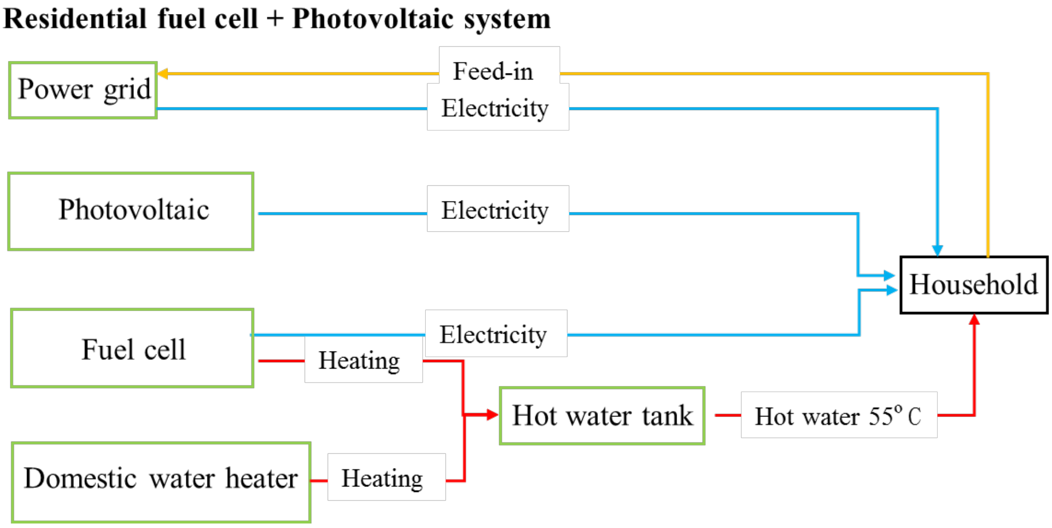


Fig 5-23 Structure of HFPS

Fig 5-23 shows the structure of a HFPS. This system has three ways to supply the electricity power the user. The first is to supply users through PV power generation. PV converts solar radiation into electricity for users. The second way is to supply power to the user through fuel cells. Fuel cells receive natural gas from natural gas companies and provide electricity to consumers after combustion. The third way is to get electricity by buying electricity from the grid. When the amount of electricity generated by PV and fuel cells is insufficient for the user to use, the user obtains electricity by purchasing directly from the grid. And when the user has remaining electricity, the remaining part can also be sold back to the grid. There are two ways for the system to provide heat to the user. The first way is to provide heat through the fuel cell. The fuel cell delivers the heat generated by the combustion of the natural gas to the hot water tank, heats the water in the water tank to the temperature required by the user, and then supplies it to the user. The second way is to provide heat to the user through the backup system. When the fuel cell provides less heat than the user, a residential water heater installed by the household can directly supply heat to the house by burning natural gas, which is called a backup system. The residential fuel cell system and the backup system work together to provide heat to the residents.

The equipment selection for the HFPS simulation, because of the system is same as the residential energy system used in the target housing, so the equipment selection is the same as the equipment used in the target house. The specific analog device selection situation is shown in table 5-10.

Table 5-10 Equipment selection information of HFPS

Serial number	Equipment name	Equipment capacity
1	PV	6.3kW
2	Fuel cell	0.7kW
3	Domestic water heater	4.6kW

(2) Hybrid heat pump and PV system(HHPS)

The heat pump system is characterized by high efficiency and energy saving. Compared to fuel cells, heat pumps use electricity to heat a home. Therefore, the heat pump system is less than the fuel cell system in terms of natural gas usage, but the power usage is more than the fuel cell system. The use of a heat pump in conjunction with a PV power generation system also complements the power consumption of the heat pump when it is supplied with heat.

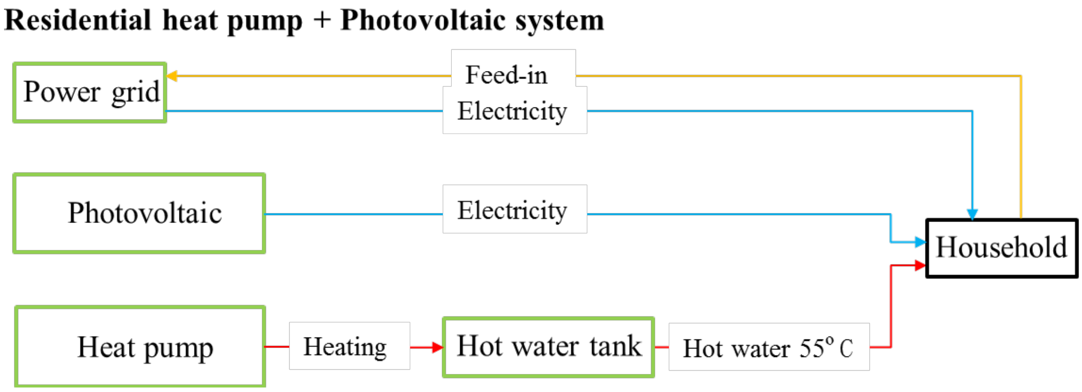


Fig 5-24 Structure of HHPS

Fig 5-24 shows the structure of a HHPS. Unlike the HFPS, there are only two ways in which a HHPS can provide electricity to households, one way to provide heat to households. Because this study compares the economics of residential fuel cell systems and residential heat pump systems, the choice of two systems for PV systems is the same. One way to provide electricity is through PV power generation, and the other is that when the amount of PV power generation is not enough for users, users can purchase electricity directly from the grid for home use. For heat supply, the heat pump provides all the heat to the home, so there is no need to install a backup system. But heat pumps also need to consume electricity while providing heat to the residents.

Table 5-11 Equipment selection information of HHPS

Serial number	Equipment name	Equipment capacity
1	PV	6.3kW
2	Heat pump	4.5kW

In terms of equipment selection for the system, the choice of PV equipment is the same as that of HFPS. Considering that the number of family members in the target house is two, a heat pump with a small hot water capacity is selected, and the hot water capacity is 370L, which can be used by 2 to 5 people. The heat pump equipment has a capacity of 4.5 kW. The specific analog device selection situation is shown in table 5-11.

(3) Conventional energy system

In order to compare the economics of residential fuel cell systems and residential heat pump systems, we will calculate the electricity and gas bills required for both the homes of fuel cells and PV and those that do not. The same applies to the residential heat pump system, where the electricity and gas costs for the home after the introduction of the heat pump and PV equipment are compared with the electricity and gas costs required for the home without the two devices. Then compare the difference between the electricity and gas charges before and after the two systems are imported, and calculate the economics of the system. The residential energy system involved in this study that does not introduce fuel cells, heat pumps, and PV is called a conventional energy system.

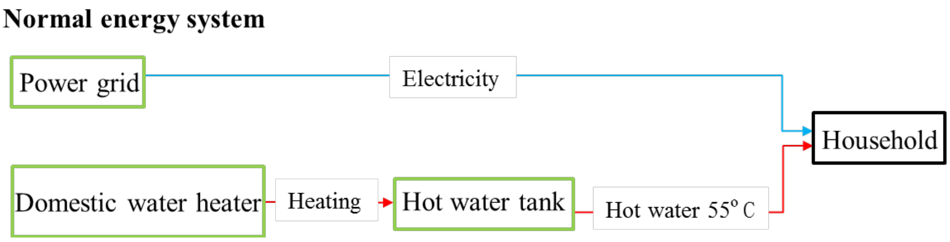


Fig 5-25 Structure of conventional energy system

Fig 5-25 shows the structure of a conventional energy system. The conventional energy system can provide electricity to the households because there are no fuel cells and PV equipment, so the way of supplying electricity is only to buy electricity from the grid. Since the amount of electricity purchased from the grid is the user's power usage, and the conventional energy system has no other power generation equipment, there is no remaining power that can be sold back to the grid. For the heat supply aspect, the conventional energy system only installs a residential water heater to provide heat to the residents. The domestic water heater burns natural gas to generate heat, and the heat is transferred to the hot water tank. The water is heated in the hot water tank to the temperature required by the user and then delivered to the house for use by the user.

Table 5-12 Equipment selection information of conventional energy system

Serial number	Equipment name	Equipment capacity
1	Domestic water heater	4.6kW

In terms of equipment selection of the system because the power supply of the conventional energy system is all from the grid to buy electricity, in the power supply, the conventional energy system does not need other equipment. In terms of thermal supply, in the conventional energy system, the thermal demand of all users is provided by a residential water heater. In order to facilitate the comparison of the three systems, we chose the same type of residential water heater as the HFPS. The specific analog device selection situation is shown in table 5-12.

5.3.2 Simulation model verification and establishment

Fig 5-26 shows a simulation model of a HFPS. The model is divided into three parts. The first part is the PV system. It consists of weather data, user load demand and PV equipment. The most commonly used meteorological data module of TRNSYS is Type109-TMY2. The main function of this component is to read meteorological parameters from data files such as TMY2, and turn these obtained meteorological parameters into unit system data that the system can recognize, and convert the converted data. Solar radiation data is entered into the system. Under the Type109-TMY2 module, the file format for reading meteorological data is the standard TMY2 file. The TRNSYS software comes with a part of the TMY2 format file, including meteorological data in Europe, America, Africa, Asia, and other places. The TMY2 file is a meteorological data file containing a typical meteorological year. It is generally taken from the last 10 years. Typical meteorological weather data include wind speed, wind direction, dry and wet bulb temperature, solar radiation intensity, etc., selected by the weather observation station for 8760 hours of meteorological data recorded and sorted. Different countries and regions have different selections of internationally used meteorological data standard years. In this study, the meteorological data used in the simulation using TRNSYS is the typical meteorological data from Kitakyushu. Enter weather data and user load demand into the photovoltaic module. The second part is the fuel cell system. The user load demand is input into the fuel cell module, and the combustion process is performed to provide power and heat to the user. The third part is the backup system. The user load demand is input into the domestic water heater and heat exchanger, and the natural gas is burned in the combustion chamber to provide heat to the household.

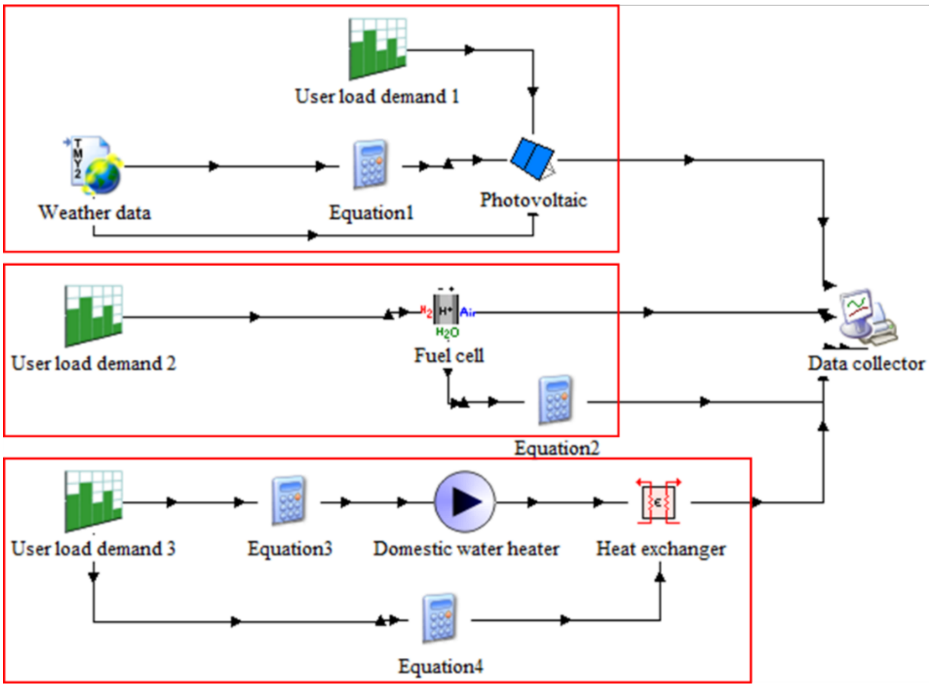
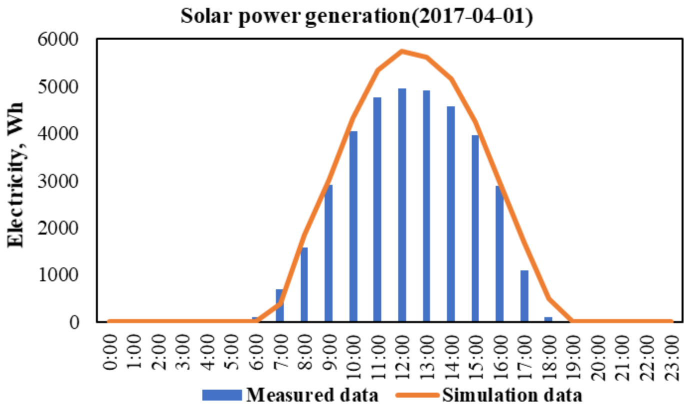


Fig 5-26 Simulation model of HFPS

In order to verify the correctness of the simulation model of the HHPS, we first obtained the energy consumption data of the house one day by running the system model. Compare the simulation results with the measured data. Fig 5-27 shows the comparison of simulated and measured data for PV power generation and fuel cell power generation.



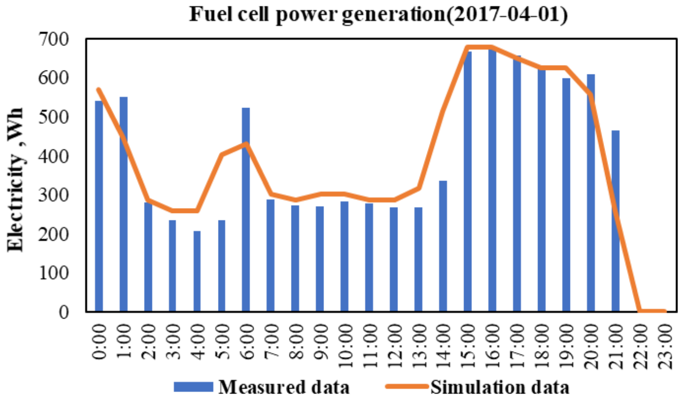


Fig 5-27 Comparison of simulated and measured data

It can be seen from the comparison between the simulated data and the measured data that the two are in good agreement. Prove that the system model is highly accurate and can be used for subsequent analysis. The fuel cell combined with the PV residential energy system simulation model outputs four data, PV power generation, fuel cell power generation, fuel cell heat production and back up heat production. The energy consumption of the system obtained by running the simulation model is shown in Fig 5-28.

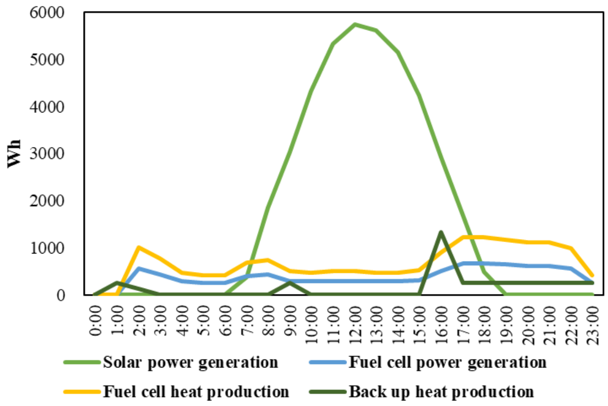


Fig 5-28 System power generation from simulation model in 2017-04-01

The components of the HHPS are PV, heat pump and weather parameters input into the PV, and user load requirements input to the PV and heat pump. Fig 5-29 shows a simulation model of a HHPS.

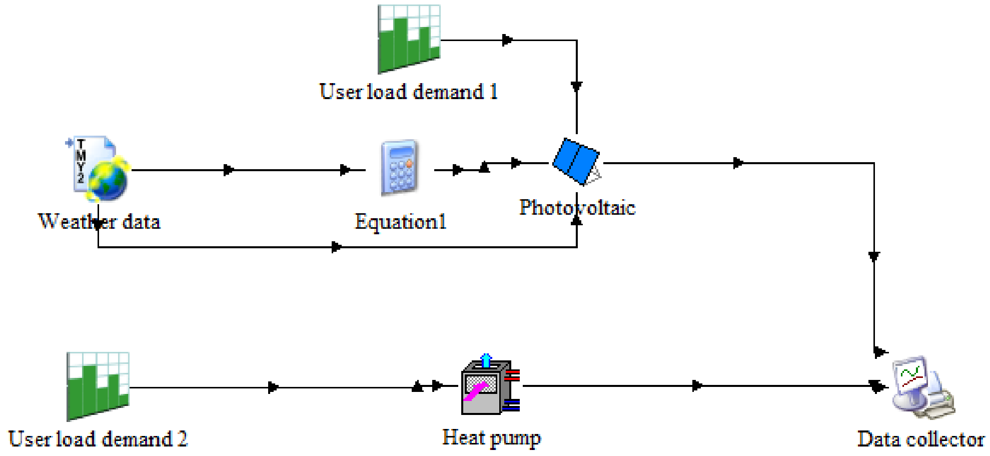


Fig 5-29 Simulation model of HHPS

As a result of the low rate of visits, a larger maximum visit to FCVs is needed on Monday to meet the demand for electricity throughout the day. On Sunday (the highest vehicle visit rate), the maximum visiting FCVs needed are 500-800. If it is necessary to establish discharge devices for the visiting vehicles, from the economic considerations, the smallest number of Sunday data should be selected to avoid the situation where the partial discharge device is stopped because of excessive discharge. Therefore, in the subsequent calculation, the maximum number of visiting vehicles is set at 500-800. The target building has two parking lots, which can accommodate 2000 and 500 vehicles respectively. Therefore, 500 is more reasonable from the actual situation.

The HHPS consists of two parts. The first part is the PV system. In order to be able to compare the economics of heat pumps and fuel cells, the simulation model for establishing two systems is that the choice for PV systems is the same. The second part is the heat pump system. This simulation model uses a water source heat pump. The main parameters of the heat pump module are the density of liquid stream is 1000kg/m^3 the specific heat of liquid stream and specific heat of DHW fluid is 4.19kj/kg. K, the blower power is 671.1kJ/hr and the total air flow rate is 0.33m^3/s. The data entered into the heat pump module are inlet liquid temperature, return air temperature, return air pressure, fresh air temperature, inlet DHW temperature and inlet DHW flow rate. The specific parameter settings are shown in table 5-13. The output data of the simulation model has PV power generation, heat pump power consumption and heat pump heat generation. In order to verify the accuracy of the system, we selected the data for one day of April 1, 2017 for output, and the results are shown in Fig 5-30.

Table 5-13 Specific parameters of heat pump

Parameter	Numerical value	Unit
Inlet liquid temperature	21	ºC
Inlet liquid flow rate	0.19	kg/s
Return air temperature	20.0	ºC
Return air %RH	50.0	%(base 100)
Return air pressure	1.0	atm
Fresh air temperature	20.0	ºC

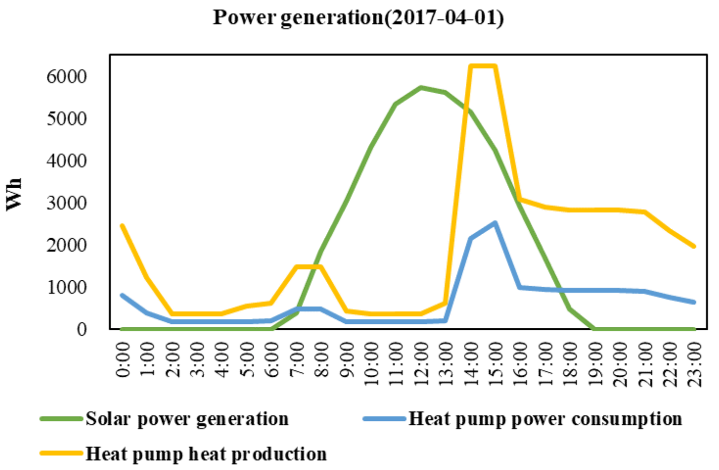


Fig 5-30 System power generation in 2017-04-01 from simulation model

In order to compare the HFPS, the HHPS and the conventional energy system without the introduction of energy efficient equipment, we also simulated the conventional energy system. Fig 5-31 shows a simulation model of a conventional energy system.

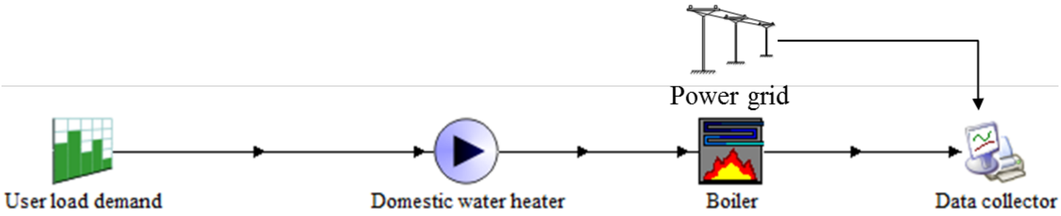


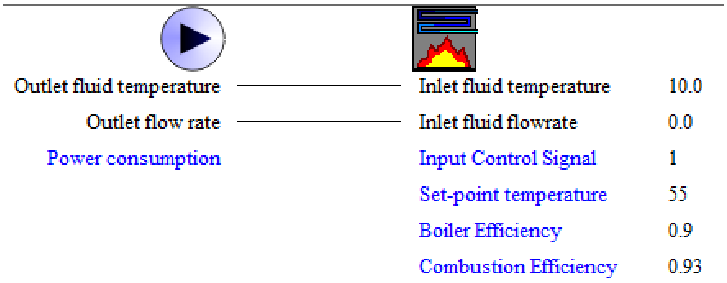
Fig 5-31 Conventional energy system simulation model

Because the conventional energy system does not use energy-efficient production equipment, it does not have the conditions to provide electricity and heat for the home. The electricity needed for the household's life is all from the grid to buy electricity. In terms of heating, a pump module was selected as a domestic water heater in the simulation. The specific parameter settings are shown in table 5-14.The maximum flow rate is 264kg/hr, the fluid specific heat is 4.19kJ/kg. K, the maximum power is 60kJ/hr and the conversion coefficient is 0.05. The data entered into the module is, inlet fluid temperature is 15℃, the inlet mass flow rate is 264kg/hr.

Table 5-14 Specific parameters of domestic water heater

Parameter	Numerical value	Unit
Maximum flow rate	264	kg/hr
Fluid specific heat	4.190	kJ/kg*k
Maximum power	60	kJ/hr
Conversion coefficient	0.05	_

The water pump injects hot water into the boiler module, performs combustion in the boiler, and delivers the heated hot water to the user. Fig 5-32 shows the connection line menu between the pump and the boiler module.



Inlet fluid temperature 10.0
Inlet fluid flowrate 0.0
Input Control Signal 1
Set-point temperature 55
Boiler Efficiency 0.9
Combustion Efficiency 0.93

Fig 5-32 Connection line menu between the pump and the boiler module

The parameter settings for the boiler components are the rated capacity is 44,284kJ/hr, it is the user's maximum heat demand for the whole year. The fluid specific heat is 4.19kJ/kg. K. The data entered into the module includes inlet fluid temperature inlet fluid flowrate, input control signal, set-point temperature, boiler efficiency, and combustion efficiency, the specific values are shown in table 5-15. Finally, the amount of natural gas required by the user is output as a system simulation result.

Table 5-15 Specific parameters of boiler

Parameter	Numerical value	Unit
Inlet fluid temperature	10.0	℃
Inlet fluid flow rate	0.0	kg/hr
Input Control Signal	1	_
Set-point temperature	55	℃
Boiler Efficiency	0.9	Fraction
Combustion Efficiency	0.93	Fraction

5.4. Simulation result comparison and discussion

5.4.1 System environment and economic performance comparison

(1) Simulation result introduction

This research involves three residential energy systems: HFPS, HHPS and conventional energy system, and the specific parameters of main equipment refers to table 5-16. The simulation result is shown in Fig 5-33.

Table 5-16 Main equipment parameters of residential energy system

<table>
<tr><td colspan="4">Main equipment parameters of residential energy system</td></tr>
<tr><td colspan="4">Fuel cell</td></tr>
<tr><td>Equipment type</td><td>Power output</td><td>Thermal output</td><td>Electricity efficiency</td></tr>
<tr><td>Polymer electrolyte</td><td>0.7kW</td><td>0.998kW</td><td>40%</td></tr>
<tr><td colspan="4">Heat pump</td></tr>
<tr><td>Equipment type</td><td colspan="2">Equipment capacity</td><td>COP</td></tr>
<tr><td>air/water</td><td colspan="2">4.5kW</td><td>3.2</td></tr>
<tr><td colspan="4">PV</td></tr>
<tr><td colspan="2">Equipment capacity</td><td colspan="2">Module conversion efficiency</td></tr>
<tr><td colspan="2">6.3kW</td><td colspan="2">19.6%</td></tr>
<tr><td colspan="4">Domestic water heater</td></tr>
<tr><td>Equipment capacity</td><td>Thermal efficiency</td><td>Hot water supply capacity(25° C)</td><td>Hot water supply capacity(40° C)</td></tr>
<tr><td>4.6kW</td><td>95%</td><td>24L/m</td><td>15L/m</td></tr>
</table>

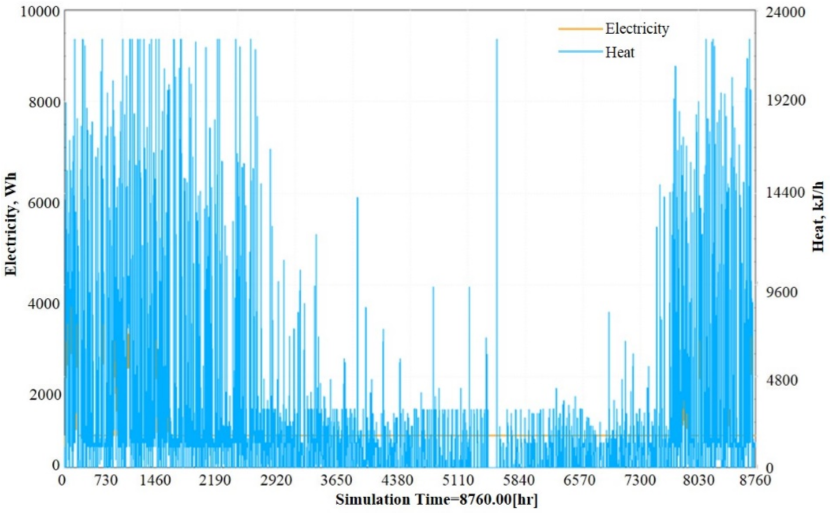


Fig 5-33 Energy consumption simulation result of HHPS

(2) Environment benefit analysis

Comparing the environmental impacts of HFPS and HHPS, this part calculated the CO_2 emissions generated by the two systems used in one year. In this part, the CO_2 emission of residential energy system is calculated from two parts: electricity consumption and gas consumption.

The CO_2 emission coefficient of Kyushu Electric Power Company in 2017 is 0.463kg-CO_2/kWh[6]. And the residential CO_2 emission coefficient of Japan Saibu Gas Company in 2017 is 2.21t-CO_2/m^3 in Kitakyushu area[7]. Firstly, the annual CO_2 emissions of the two systems are compared. Fig 5-34 displays the comparison of annual CO_2 emissions between HFPS and HHPS, it can clearly see that HFPS has a better environmental performance than HHPS. The CO_2 emissions from HFPS were negative from March to October in household. As for HHPS, only the CO_2 emissions in August and September are negative, which reached the zero-carbon standard, none of the remaining months met it.

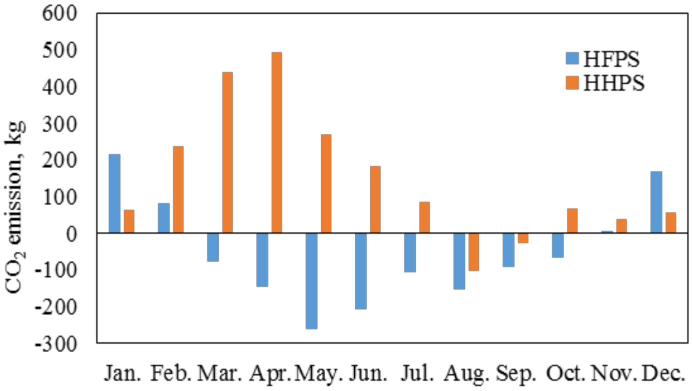


Fig 5-34 Comparison of annual CO_2 emissions between HFPS and HHPS

The calculation of CO_2 emission of HFPS is divided into three parts: grid import, feed-in and gas consumption. And the HHPS does not consume gas because heat pump can supply heat for the residence, so the CO_2 emission of HHPS is divided into two parts: grid import and feed-in. Fig 5-32 presents the CO_2 emissions generated by the energy consumption of each part of the two systems. Comparing the result of Fig 5-35, since the feed-in of system is mainly from PV power generation, the effect of PV power generation on CO_2 emissions of the two systems was not significantly different.

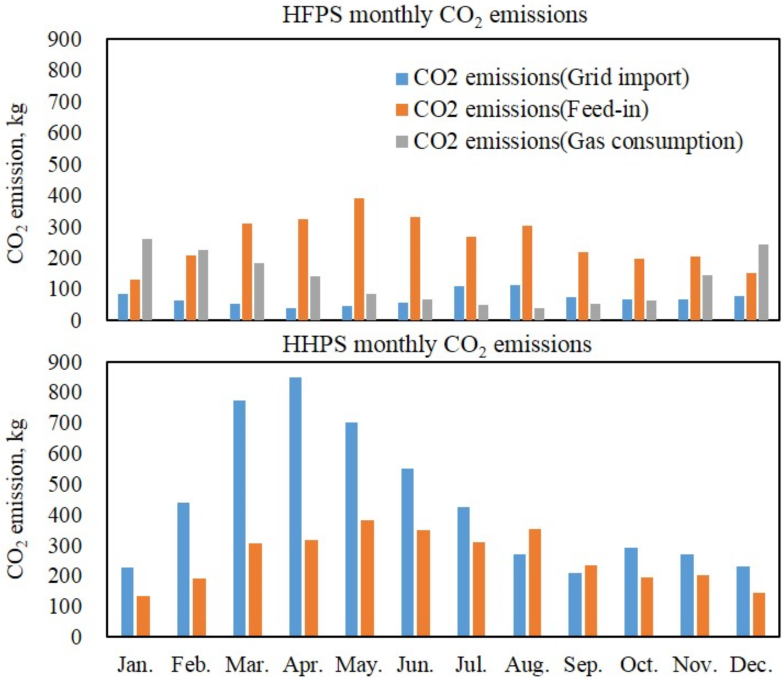


Fig 5-35 Monthly CO_2 emissions of HFPS and HHPS

Choosing one day in each season as a typical day to calculate the hourly CO_2 emissions of the two systems, the causes of the difference in CO_2 emissions of the system is analyzed. Through the analysis of Fig 5-36, it can be found that there are two main reasons. First, the fuel cell provides electricity for users, which makes HFPS sell more electricity than HHPS in the daytime. The CO_2 emission of feed-in compensates the environmental performance of the system cause the annual CO_2 emission of HFPS is less than that of HHPS. The second reason is the difference of CO_2 emission coefficients between gas and electricity. The CO_2 emission coefficient of electricity is 0.463kg-CO_2/kWh and the CO_2 emission coefficient of gas is 2.21t-CO_2/m^3. The main operation time of the heat pump is at night, which leads to the increase of the grid import of HHPS. Compared with HHPS, HFPS requires additional gas consumption, so the CO_2 emission of HFPS is more than that of HHPS in January and December. It is calculated that the annual CO_2 emissions of HHPS is 1799.69kg, and the annual CO_2 emissions of HFPS is -634.05kg.

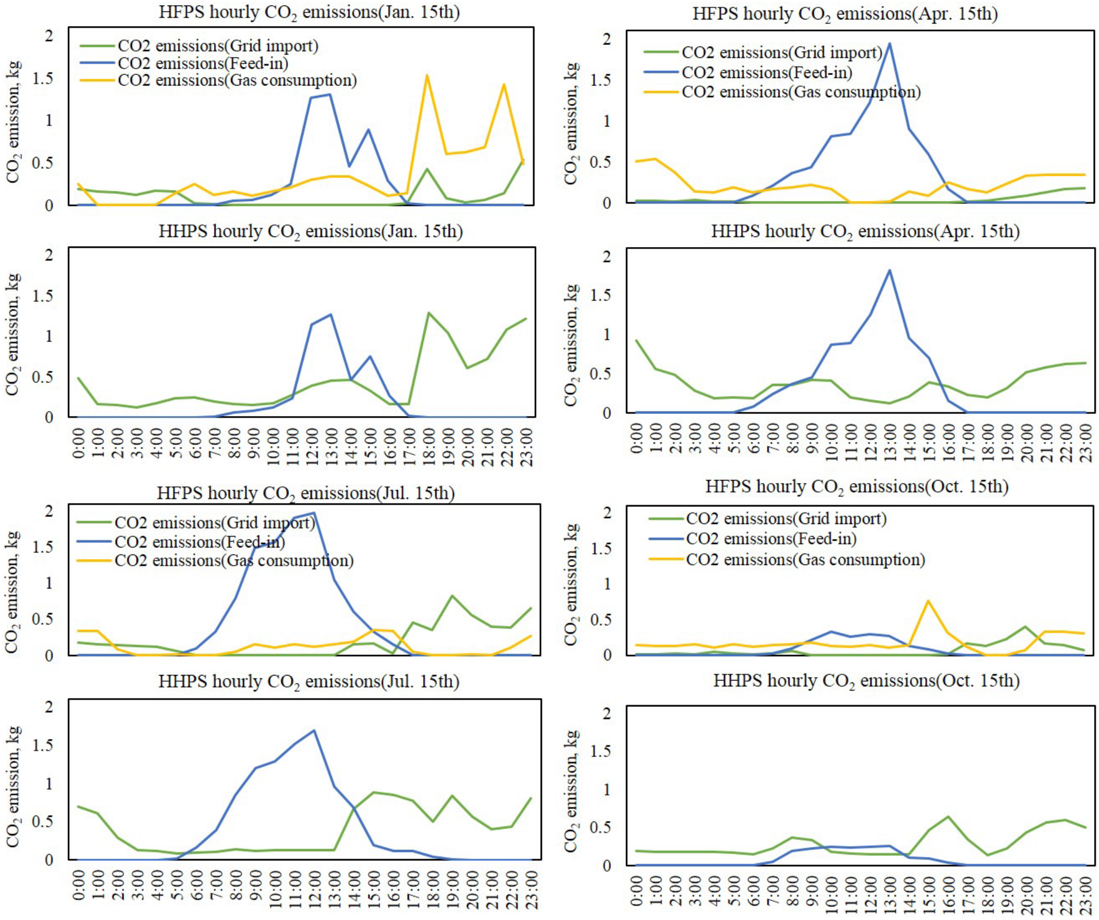


Fig 5-36 Comparison of typical daily CO_2 emissions

In this part, the calculation of CO_2 emissions caused by electricity consumption of the system is based on the CO_2 emission coefficient published by Kyushu Electric Power Company in 2017. Fig 5-37 presents the CO_2 emission coefficients of Kyushu Electric Power Company from 2010 to 2018. Since 2014, the CO_2 emission coefficients have been declining continuously and reaching the lowest value 0.347kg-CO_2/kWh in recent years in 2018.

Considering the changes of CO_2 emission coefficients in the future, the environmental performance of the two systems is calculated under the prediction of the continuous decline of CO_2 emission of electric consumption, the result is presented in Fig 5-38. The change of CO_2 emission coefficients has an impact on the CO_2 emissions of grid import and feed-in. With the reduction of CO_2 emission coefficients, the compensation of feed-in for CO_2 emission of the system is reduced, and the annual CO_2 emission of HFPS is increased. In contrast, the annual CO_2 emission of HHPS decreases with the reduction of CO_2 emission coefficients because of more electricity is purchased than sold. In general, the difference of CO_2 emission between the two systems decreases with the reduction of CO_2 emission coefficients, but HFPS still present an environment advantage over HHPS.

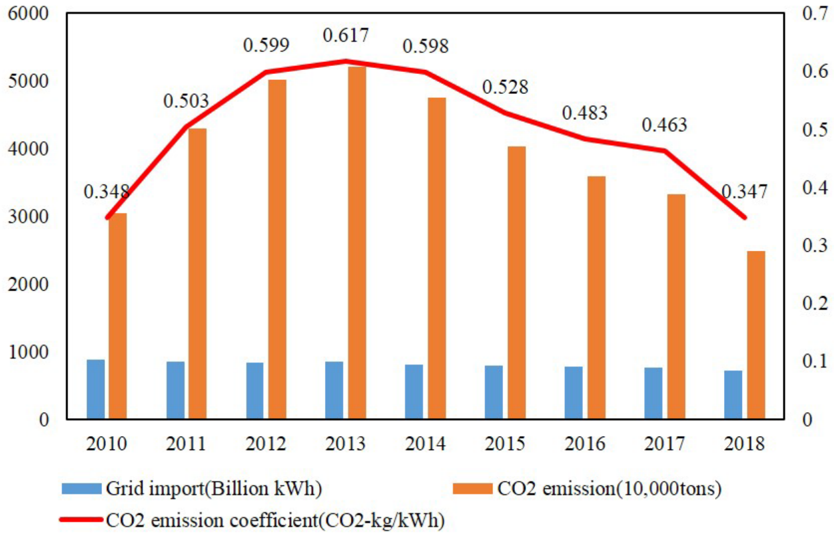


Fig 5-37 Changes of CO_2 emission coefficients from 2010 to 2018

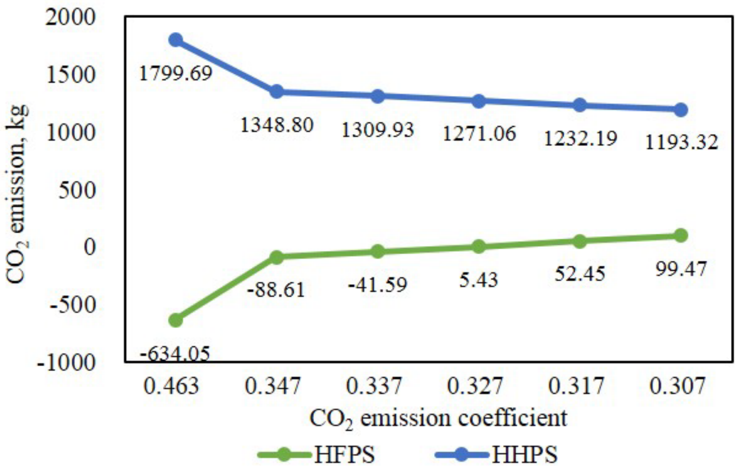


Fig 5-38 Comparison of system environment performance with the change of CO_2 emission coefficients

(3) Economic performance analysis

As the introduction of fuel cell, heat pump and PV, the cost of residential energy system is reduced. Considering that the household which used HFPS and HHPS can sell unused PV power to the grid, the monthly cost of electricity and gas were less than the conventional energy system. Based on the analysis of simulation result, the electricity and gas cost required for different residential energy system under the same user load was calculated, including HFPS, HHPS and conventional energy system. Fig 5-39 represents the annual cost comparison of three residential energy systems.

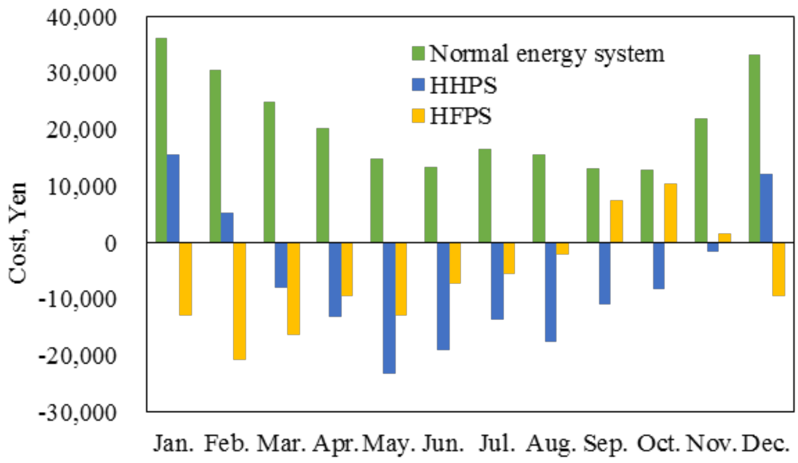


Fig 5-39 Annual cost comparison

The annual operating cost of the system is shown in table 5-17. As can be seen from the table, the total cost of HFPS and HHPS are extremely less than that of the conventional energy system. The reason is that most of the power generation of PV systems was sold back to the grid by users in some months. The calculation showed that the operating profit of HFPS is 340,892 Yen, and the operating profit of HHPS is 340,449 Yen.

Table 5-17 System annual operating cost

Energy system	Total cost(Yen)
HFPS	-76,446
HHPS	-76,004
Conventional energy system	264,445

(4) Payback period prediction

A simple prediction of the payback period of the system is a way to measure the system economic performance. The payback period in this research can be interpreted as the number of years required for users to recover costs after the introduction of residential energy system. For the sake of comparing the economic performance, the number of payback year required for HFPS and HHPS are calculated. The investment costs of the three energy systems are shown in table 5-18. According to the previous calculation, the operating profit of HFPS and HHPS is 340,892 Yen and 340,449 Yen respectively. The above two systems require the number of payback year is 10.5 years and 6.4 years respectively. It is shown that HHPS presented an economic advantage over HFPS.

Table 5-18 System investment cost

Energy system	Required equipment	Unit price (Yen)	Capacity (kW)	Total price (Yen)
HFPS	Fuel cell	2,280,000/kW	0.7	1,600,000
	PV	200,000/kW	6.3	1,260,000
HHPS	Heat pump	155,555/kW	4.5	700,000
	PV	200,000/kW	6.3	1,260,000
Conventional system	Domestic water heater	21,739/kW	4.6	100,000

5.4.2 Sensitivity analysis of price

Through the previous research on the economic and environmental analysis of HFPS and HHPS can be known, the HFPS occupies a certain advantaged in the environment benefit, but the payback period of HHPS is shorter and the economy is better than that of HFPS. In this research, a sensitivity analysis of carbon tax price, fuel cell equipment price, electricity buy-back price and gas price was performed.

(1) Carbon tax price

CO_2 accounts for 80% of the gases that are cause global warming, and with the increase in population and energy use, CO_2 emissions have gradually increased. To improve the atmosphere and reduce CO_2 emissions, Japan introduced the carbon tax in October 2012[8]. Fig. 5-40 presents the future carbon tax price changes predicted by World Energy Outlook(WEO), the carbon tax price presents an increasing trend from 2020 to 2040[9].

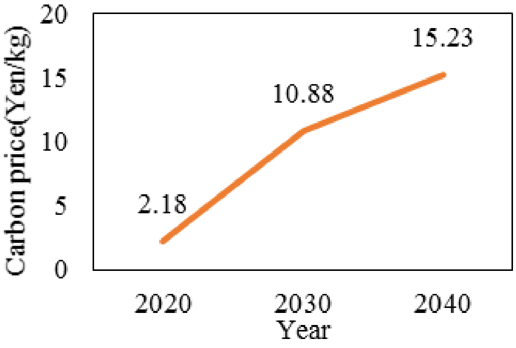
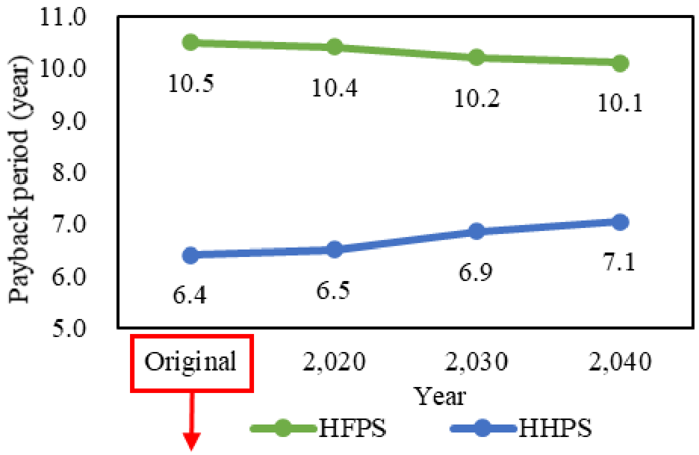


Fig 5-40 Carbon tax price change forecast

Keeping equipment prices constant and introducing the carbon tax into the system to calculate the economics, the changes in the system payback period after the introduction of the carbon tax are exhibited in Fig 5-41. The operating profit of HFPS is increase that system can reach zero carbon in most month of the year. In contraries, the payback period of HHPS growth longer after the introduction of carbon tax because of the system's CO_2 emissions are negative for only two months in a year, that leading to a reduction in operating profit. The change trend of payback period of the two system illustrates that although the introduction of carbon tax price highlights the environmental advantages of HFPS and shorten the system payback period, the impact is relatively small. In terms of the system payback period, there is still a significant gap between the two systems.



System payback period without introducing carbon tax

Fig 5-41 Changes in the system payback period after the introduction of the carbon tax

(2) Equipment price

By comparing the economic performance of HFPS and HHPS respectively, we found that one of the reasons for HFPS have a longer year of payback than HHPS is that the price of fuel cell equipment is relatively high. Current, price of solid oxide fuel cell (SOFC) and proton exchange membrane fuel cell (PEFC) in market is between 1.5 million Yen and 2 million Yen. In recent years, in order to promote fuel cell residential energy systems to more families, the price of fuel cells is also gradually decreasing year by year. As shown in Fig 5-42, the price of fuel cells is expected to fall to between 800,000 Yen and 1 million Yen by 2020, and the payback period of residential fuel cell systems will be reduced to less than 5 years by 2030[10].

Based on this situation, the payback period of HFPS concerning the capital cost drop in the fuel cell system is calculated and the results were shown in table 5-19. With the decline of fuel cell prices, the number of system payback period has shown a significant reduction. When the price of equipment dropped from the current 1.6 million Yen to 800,000 Yen, the HFPS be economic competitive compared with HHPS. Meanwhile, the result shows that the high equipment price of fuel cell is the main reason that the payback period of HFPS is longer than that of HHPS.

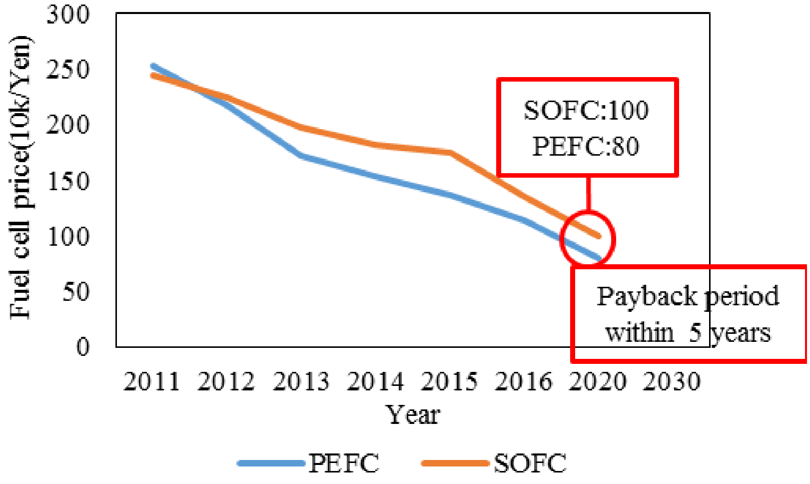


Fig 5-42 Fuel cell prices fluctuate from 2011 to 2030

Table 5-19 Equipment price and system payback period sensitivity

Energy system	Price of FC(Yen)	Payback year
HFPS	1,600,000	10.5
	1,500,000	9.9
	1,400,000	9.4
	1,300,000	9.0
	1,200,000	8.5
	1,100,000	8.1
	1,000,000	7.6
	900,000	7.2
	800,000	6.8

(3) Feed-in price

Japan first established a solar power generation and sales system in 2009. The purpose is to purchase solar power for industrial and residential use to promote the application of solar systems. Fig 5-43 presents the electricity feed-in price from 2009 to 2019[11]. Due to the high feed-in price of residential PV from 2009 to 2012, Japan has become one of the countries with the most residential PV system applications in this period. With the promotion of photovoltaic systems, the price of electricity sales has gradually decreased and output suppression has been implemented in some areas.

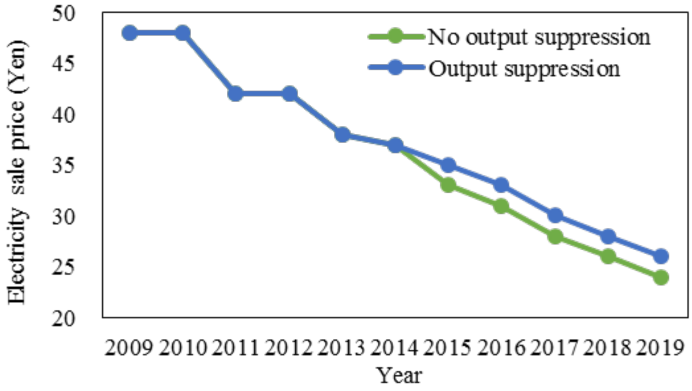


Fig 5-43 Electricity feed-in price from 2009 to 2019

Fig 5-44 shows the payback period of HFPS and HHPS calculated for the electricity feed-in price from 2009 to 2019. Obviously, with the increase of feed-in prices, the number of system payback period has gradually increased. In terms of the price of fuel cell equipment, we chose the current equipment price and the lowest price forecast for the future market. As illustrated in Fig 5-39, because the current price of fuel cell equipment is high, the payback period of HFPS is much longer than that of HHPS. However, when the fuel cell price is 800,000 Yen, HFPS and HHPS have similar payback period. As the price of feed-in price decreases, the difference between the two systems gradually decreases. Furthermore, the payback period of HHPS is growing faster than that of HFPS and it is longer than HFPS in 2019.

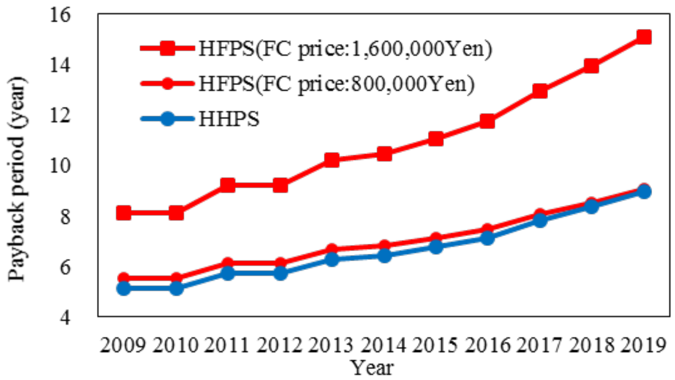


Fig 5-44 Electricity feed-in price and system payback period sensitivity

5.4.3 Price scheme selection and payback period prediction

(1) Electricity price scheme selection

In this research, customer choose to buy electricity from Kyushu Electric Power Company. The power company introduce different electricity pricing schemes and customers select suitable schemes according to their occupancy behavior. The selection of electricity cost calculations that match the residential energy system is also a way to improve the system economy. Table 5-20 lists five kinds of electricity price schemes of Kyushu Electric Power Company[12][13]. The electricity costs of HFPS and HHPS were calculated based on five cases and the results are illustrated in Fig 5-45 and Fig 5-46.

Table 5-20 Kyushu Electric Power Company electricity price cases

Case	Basic charge (Yen)	Unit price (Yen/kWh)			Characteristic
a	1749.6	~120kWh		17.14	Contract is for two years，stepped-type electricity price.
		121~300kWh		22.64	
		300kWh~		25.58	
b	1749.6	~120kWh		17.14	Contract is for one years，stepped-type electricity price.
		121~300kWh		22.64	
		300kWh~		24.5	
c	1620	Working day	Spring and autumn	23.51	Night electricity price is cheaper than daytime, spring and autumn is cheaper than summer and winter, non-working day is cheaper than working day.
			Summer and winter	26.35	
		Non-working day	Spring and autumn	17.49	
			Summer and winter	20.83	
		22:00~8:00		12.96	
d	1620	10:00~17:00	Summer	36.11	Daytime electricity price is highest, morning and evening is cheaper, night is cheapest, summer daytime electricity price is more expensive than other seasons.
			Other season	30.35	
		17:00~22:00		22.81	
		22:00~8:00		10.29	
e	1620	8:00~22:00	~80kWh	22.5	Night electricity price is cheaper than daytime, use stepped-type electricity price during daytime.
			81~200kWh	29.72	
			200kWh~	33.59	
		22:00~8:00		10.29	

For HFPS, the annual electricity cost using case e is the least consumed of the five cases. However, in terms of monthly electricity cost, July and August are the months that consumers import the most electricity in a year. The calculation result of electricity cost for these two months is that case d is more economical. Case a and case b are both stepped-type electricity price, with the difference being the contract time. In this research object, the monthly grid import is no more than 300kWh, so the electricity cost of the two cases are the same. But for customers who import more electricity each month, it is more economical to select a case with long contract. For HHPS, the selection of stepped-type electricity price scheme is not economical because the winter electricity cost is too high. In terms of annual electricity cost, case d and case e are more suitable for customers who install HHPS. The more electricity customers import, the more obvious economic advantages compared to other cases.

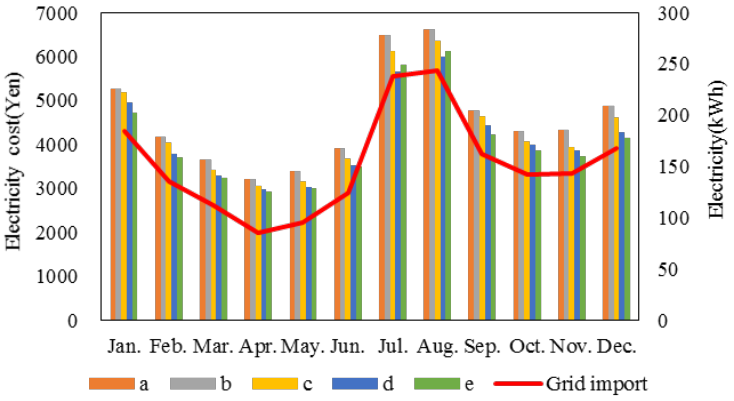


Fig 5-45 Electricity cost for HFPS based on different electricity price cases

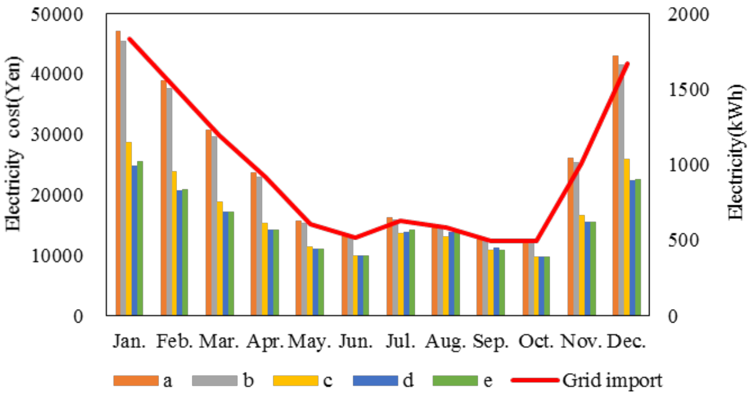


Fig 5-46 Electricity cost for HHPS based on different electricity price cases

(2) Payback period prediction with gas price fluctuation

The main difference between HFPS and HHPS in terms of energy consumption is that that while a fuel cell generates electricity, it also provides heat to the residence, and consuming both electricity and gas, where as a HHPS consumes only electricity. Therefore, fluctuations in gas prices also have an impact on the economic comparison between the two systems. Currently, the price of gas is 158 Yen / m^3, and the price is reduced every 10 Yen as a unit. The analysis of the system payback period is performed under different fuel cell equipment prices. Fig 5-47 shows the system payback period of HFPS with reduced gas prices compared to HHPS. Due to the current high price of fuel cells, it is only when the price is reduced to 800,000 yen that the reduction in as prices makes HFPS comparable with HHPS. As shown in Fig 5-47, when the price of gas is 130 Yen / m³, both two systems have the same system payback period.

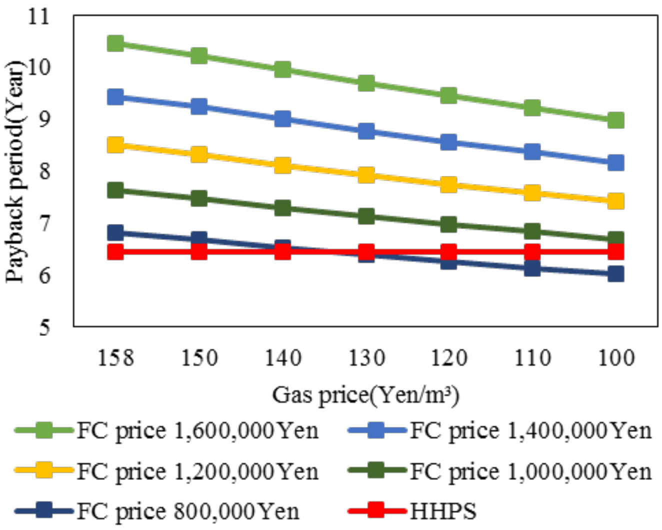


Fig 5-47 System payback period based on gas price fluctuation

5.5. Summary

For reducing CO_2 emissions and achieving a low-carbon society as an early date, Japan has promoted some energy-efficient residential energy systems in recent years. This part presented the energy consumption scenario of Japan typical households in the Jono smart house area and analyzed the energy consumption and performance of energy supply equipment based on one year's monitor data. The environment and economic performances of HFPS was evaluated. In this research, the energy consumption of residential customer with HHPS under the same customer load used by HFPS was simulated. The main conclusions of this research are summarized as follows:

(1). The annual CO_2 emissions of HFPS and HHPS are calculated and compared with the CO_2 emission coefficients. The results show that HFPS has a better environmental performance than HHPS. The main reasons for the difference of system environmental performance are the disparate operation characteristics between heat pump and fuel cell, and the different CO_2 emission factors of electricity and gas.

(2). In terms of economic analysis, HHPS presented an economic advantage over HFPS. According to the fluctuation of carbon tax price, equipment price, electricity feed-in price and gas price, this paper forecasts the changing trend of system economy. The results indicate that the main parameters affecting the system economic performance are equipment price and energy price.

(3). The carbon tax and fuel cell price fluctuation will have a positive impact on the economy of HFPS. However, the introduction of carbon tax optimizes the economy of HFPS and shortens the system payback period, but the impact is relatively small. The price fluctuation of fuel cell equipment is the main factor affecting the economy of HFPS. When the price reduced to 800,000Yen, HFPS be economic competitive compared with HHPS.

(4). Based on the energy price policy, an economic sensitivity analysis of HFPS and HHPS was performed. The decrease of electricity feed-in price leads to the longer payback period of HFPS and HHPS, and it is estimated that after 2020, HFPS will has a better economic performance than HHPS. The payback period of HFPS is shortened with the decrease of gas price. To increase the promotion of fuel cell system, the gas price needs to be reduced to at least 130Yen /m^3.

(5). Choosing the appropriate electricity price scheme is also a way to optimize the system economy. For the customer of HFPS, it is the most economical to select the scheme with different electric price in daytime and night, and with stepped-type electricity price during daytime. As for the customer of HHPS, since the operation time of the heat pump is at night, it is most economical to choose a scheme with different daytime and night electricity prices and cheaper price at night. The more electricity customer import, the more obvious the economic advantages over other schemes.

Currently although HHPS has an advantage in economy, after introducing carbon tax and accompanying the change trend of energy price policy and the fluctuation of equipment price, the payback period of HFPS is gradually shorted and is expected to be more economical considering future trend, which has more development prospects.

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Chapter 6

ECONOMIC OPTIMIZATION OF COMPOSITE ENERGY STORAGE SYSTEM IN SMART HOUSE

CHAPTER SIX: ECONOMIC OPTIMIZATION OF COMPOSITE ENERGY STORAGE SYSTEM IN SMART HOUSE

6.1 Contents

With the popularization of distributed generation and renewable energy technology, the demand side management of residential energy system has been further developed. Aiming at the problems of low operation efficiency and insufficient system security in residential distributed system, the application of energy storage technology can realize peak shaving and valley filling, improve the system reliability and stability. On this basis, the rational utilization of energy storage equipment and the coordinated operation with other energy supply equipment have become the key to improve the system economy and flexibility from the user side. In this part, an independent smart house in “Jono smart house area” in Japan is selected as the research object. Relies on one year measured data, four cases are designed according to the introduction of different energy storage equipment. A double-level optimization model is established based on adaptive particle swarm optimization algorithm to optimize the size of energy storage equipment and system annual equipment output. The upper model optimizes the optimal size of energy storage equipment, and the lower model simulates the annual optimal equipment output according to the upper results. In addition, the system performance of the four cases is compared and analyzed from three aspects of energy, environment and economy based on the comprehensive comparison model. It is suggested to appropriately reduce the equipment price in combination with subsidy and incentive policies for further promotion. The results act as a useful reference for users to reasonably match energy supply and storage equipment to achieve cost reduction, while providing policy suggestions for the government to further carry out relevant research and industrial development in user-side energy storage.

6.2 Research object and energy storage system structure

6.2.1 Research object and data introduction

After the "3.11" earthquake, the large-scale shutdown of nuclear power plants led to planned power rationing in many summer peaks in Japan. The Japanese government is putting more emphasis on the investment in power infrastructure construction and beginning to re-examine how Japan's smart grid should develop[1]. According to the different forms and functions of power grid, Japan proposes a three-tier architecture, including three levels of national, region and household. The household level includes smart house, zero energy house, battery, electric vehicle (EV) and other elements, with the aim of achieving energy efficient utilization and reducing CO_2 emissions[2]. As a two-way communication hub for energy consumption management and information transmission, home energy management system(HEMS) has been vigorously promoted and introduced into smart house. HEMS through the unified management and centralized control of distributed generation, power consumption and energy storage equipment to achieve the purpose of optimizing energy consumption in smart house.

Since 2010, the Ministry of economy, trade, and industry(METI) of Japan has carried out five-year smart grid demonstration projects in Yokohama, Toyota, Keisanai, and Kitakyushu respectively. The Jono smart house area is one of the major projects of Kitakyushu's environmental future city initiative, and is striving for a theoretical 100% reduction of carbon emissions across the entire district. To achieve these goals, the city made agreements with developers requiring energy generation measures, and the installation of home energy management systems in smart houses. Among them, part of the installation costs will be borne by the city government.

In this part, a smart house located in the Jono area was selected as the basis for data analysis. The smart house energy system of the household adopted an all-electric system combining PV and heat pump. The power use of household appliances and energy supply equipment was measured hourly from April 2017 to March 2018. Table 6-1 presents the basic information of the target residence and Fig 6-1 provides the monthly energy consumption. The energy consumption system of study residence is all-electric system, and according to the energy conservation rules, the energy consumption is divided into five parts. As the heating equipment of the energy system, the heat pump consumes electricity to meet the thermal demand of users. Affected by weather and temperature, heat pump consumes more electricity in winter and less in summer. Therefore, in the monthly energy consumption comparison of one year, the power consumption in winter is generally higher than that in summer.

Table 6-1 Basic information of the research target residence

Residential type	Total area	Range of measurement data	Residential energy system	Number of family members
Detached two-story building	120m^2	2017-04-01~ 2018-03-31	PV + heat pump	4

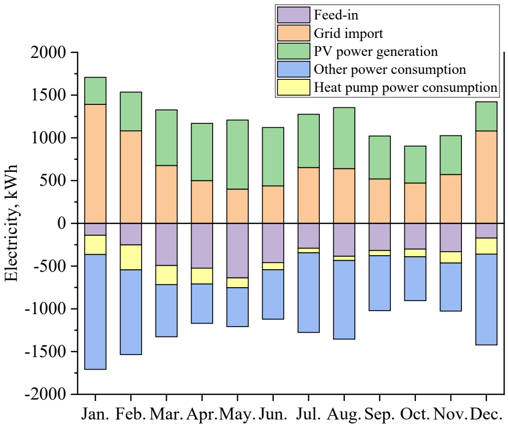

Fig 6-1 Monthly energy consumption of the target residence

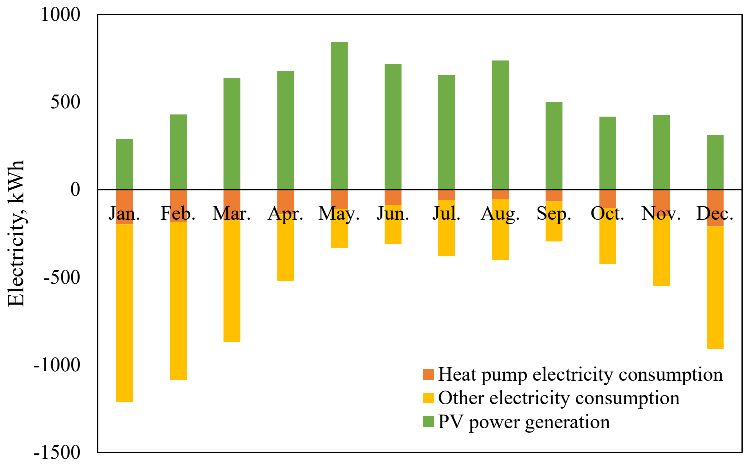

Fig 6-2 Heat pump energy consumption of the target residence

The energy supply part is composed of grid import and PV power generation. As the main power supply equipment of the system, PV power generation is as shown in the Fig 6-3. The working hour of PV is concentrated from 6:00 to 18:00, and the electricity generation in summer is significantly higher than that in winter. According to FiT(Feed-in-Tariff) policy, the part of feed-in is when the PV generation meets the electricity demand of users and there is residual power, the remaining part can be feed back to the public grid.

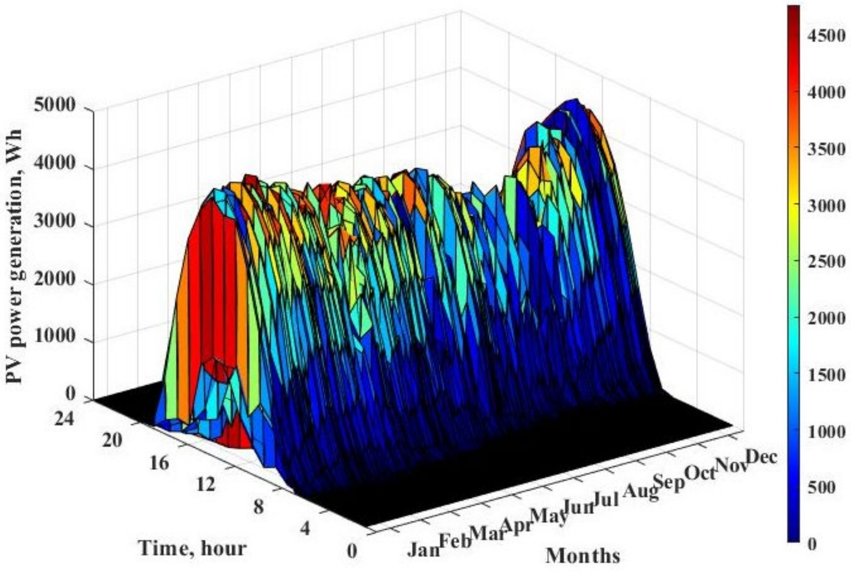

Fig 6-3 Monthly PV power generation of the target residence

6.2.2 Energy storage system structure and case introduction

As a subsidy policy for solar power generation, FiT is used to encourage the development and wide application of PV technology research and development projects. At the early stage of residential PV system promotion, due to the high equipment price, the government put forward a series of encouraging policies, including subsidies for installation costs and FiT[3]. However, with the reduction of system cost and the wide deployment of residential PV systems, the Japanese government has begun to reduce the government incentive measures such as FiT year by year[4]. Based on this situation, the economic feasibility of residential PV systems has been questioned.

Energy storage system (ESS) not only solve the above problems, but also help the system overcome the related problems caused by intermittent PV power generation[5]. Fig 6-4 depicts the smart house energy system structure after introducing energy storage equipment to the target residence. The system architecture is mainly composed of energy flow and information flow. Information flow is a real-time transmission between the user and the power company centered on HEMS. The main objective is to achieve energy visualization through automatic two-way data communication for optimal control of home appliances. The energy flow is divided into thermal and electric.

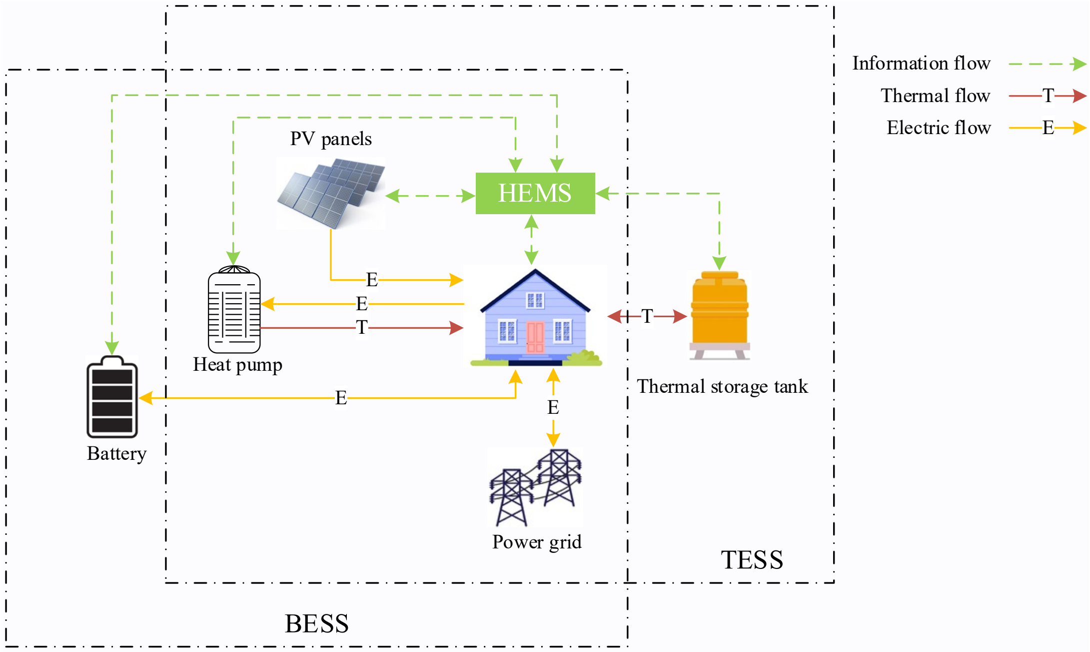

Fig 6-4 Structure of smart house with energy storage equipment

In this study, battery and thermal storage tank are selected as energy storage devices, and four cases were designed according to different scenarios as shown in table 6-2. Meanwhile, the remaining PV power generation can also be feed back to the public grid. In addition, when the system power cannot meet the user's power demand, the insufficient part can be supplemented through the purchase of public grid.

Table 6-2 Case introduction

Case	Information introduction
1	Original system (only heat pump + PV)
2	With battery energy storge system (BESS)
3	With thermal energy storge system (TESS)
4	With electrothermal hybrid energy storage system (HESS)

6.3 Energy consumption simulation results in four cases

In order to cooperate with the management strategy of smart house energy system, this study introduces energy storage equipment based on the existing energy system of the target residence. The addition of energy storage devices can better assist the PV and heat pump in the system, to the purpose of stabilizing the system performance, improving the user's economy, and balancing the power grid load.

The electricity price scheme selected by the target residence in this study is TOU, and the specific pricing information is shown in table 6-3[6]. TOU is characterized by high unit price during the daytime, low price period from 22:00 at night to 8:00 the next day, and the unit price in summer and winter is slightly higher than that in spring and autumn.

Table 6-3 Specific pricing information of TOU

Basic price (Yen/ contract)	Unit price (Yen/kWh)		
1650.0	8:00-22:00	Spring/Autumn	23.95
		Summer/Winter	26.84
	22:00-8:00		13.21

Taking the 24-hour energy consumption change as an example, Fig 6-5 depicts the brief operation process of reducing user electricity cost and peak load by introducing energy storage equipment. The mechanism can be summarized as follows: when the electricity price in the external power market is high, the internal devices of the system give priority to generating electricity to meet the power demand of users, the remaining electricity can be feed back to the power grid, and the insufficient part can be purchased by the public grid. When electricity price state in low period, users purchase electricity from the power grid to meet the power demand and charge the energy storage device, which will be released to the user in the future when the electricity price is high. Additionally, during the operation of the equipment, the energy storage device can cooperate with the system to maintain the output at the optimal operation position, thus reducing the operation cost of the system.

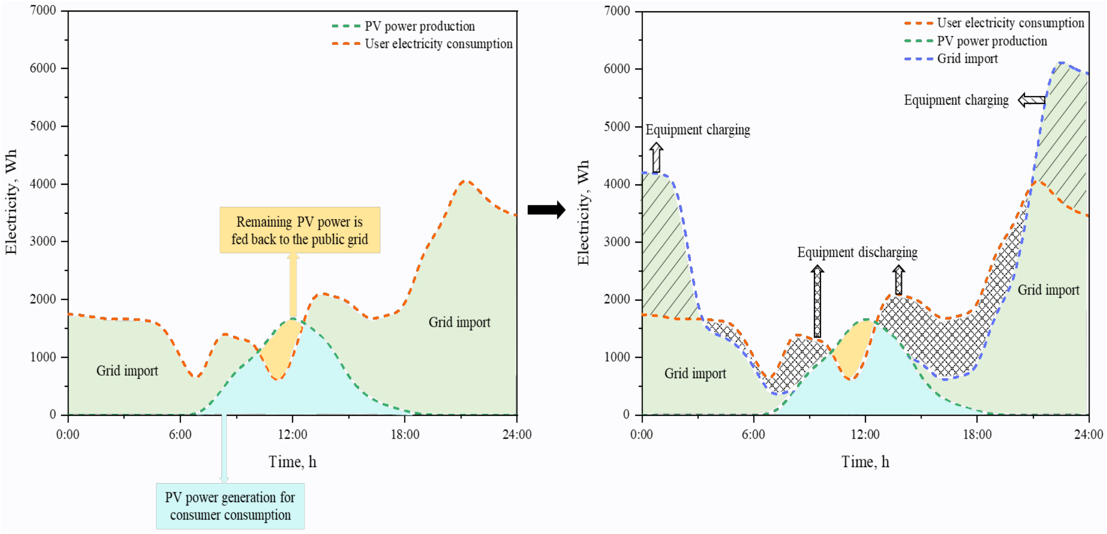

Fig 6-5 System action mechanism after the introduction of energy storage device

This study select the month of January with the largest monthly energy consumption in a year as the optimization object to optimize the size of energy storage devices, so as to screen out the optimal results that can meet the maximum power demand of users. Table 6-4 presents the optimal size of equipment capacity using the energy storage size optimization model.

Table 6-4 Optimal sizing result of energy storage device

Case	TESS size(kWh)	BESS size(kWh)
1	-	-
2	-	8.2
3	4.7	-
4	3.4	5.6

Based on the optimization results, we simulate the annual equipment output of the four cases. Four days in four seasons are selected as the typical days to analyze and compare the hourly operation of different equipment in a day. We chose April 1 to simulate the equipment output of the smart house energy system, and the simulation result is shown in below.

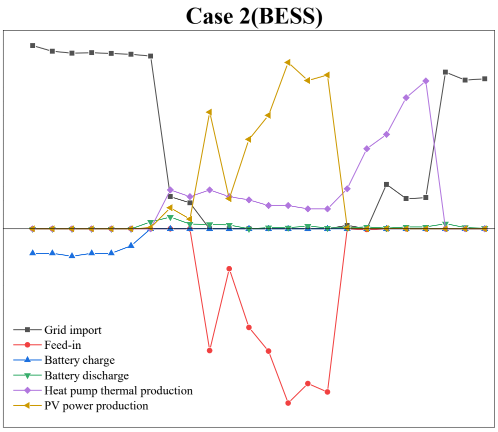

Fig 6-6 Hourly equipment output of BESS

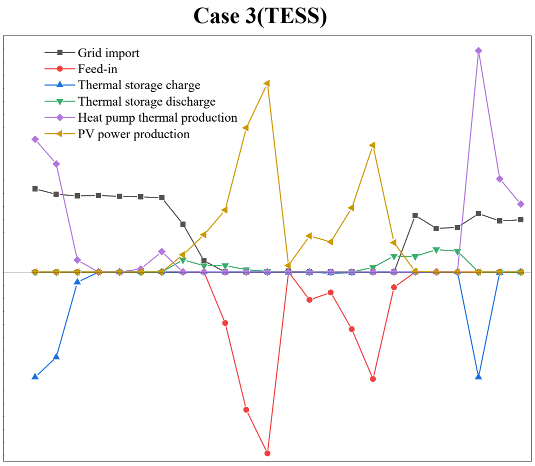

Fig 6-7 Hourly equipment output of TESS

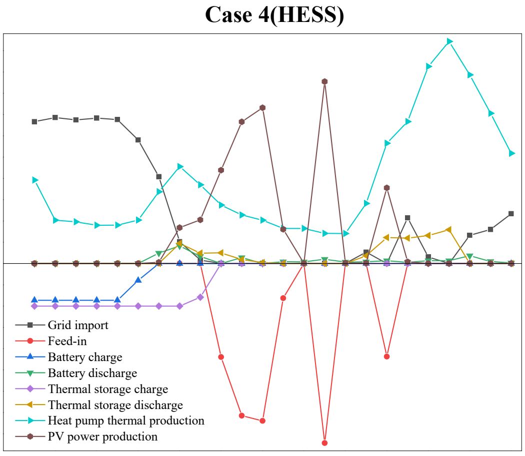

Fig 6-8 Hourly equipment output of HESS

6.3.1 Case 1: Original system (only heat pump + PV)

Case 1 is the existing original energy system of the target residence, which uses PV and heat pump to meet the electrical and thermal needs of users. Fig 6-9 depicts the hourly power load of users in four typical days. The peak of users' electric and thermal demand generally occurs at night, the power consumption in winter is significantly higher than that in other seasons, and the power consumption in summer is the least. It can be found that the change of users' load is greatly affected by seasons and users' energy consumption habits. In addition, although the heat pump consumes more energy at night, it continues to produce power throughout the day, and the equipment operates all day.

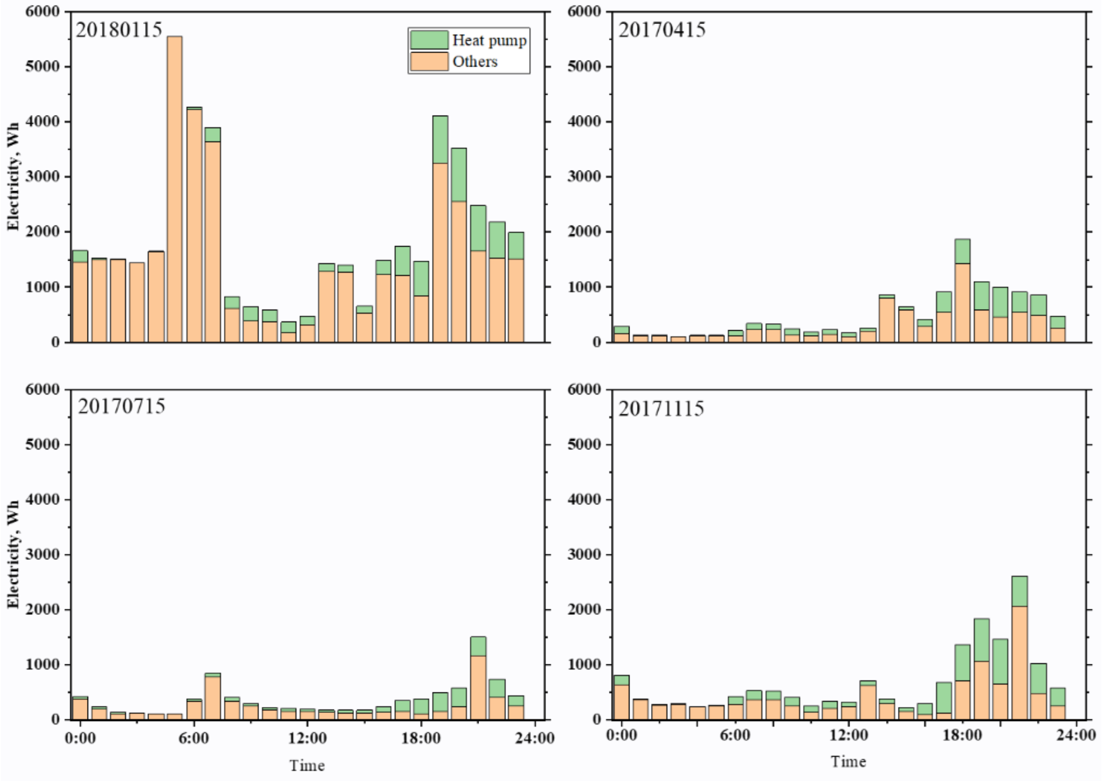

Fig 6-9 User hourly electrical load on typical day in Case 1

6.3.2 Case 2: With BESS

In this study, ESS of the imported battery is designed as Case 2. According to the upper optimization results, the optimal size of the battery is determined to be 8.2kWh. The hourly charging and discharging of the battery on typical day is shown in Fig 6-10. According to the model constraints, the battery cannot be charged and discharged at the same time. Since the electricity price scheme selected by users is TOU, the unit price is lower at night, and the user demand gradually decreases after 22:00. Therefore, the low price period at night is set as the charging time, during which the user's power demand is supplied by the public grid. The daytime is discharge time, which is used to provide power supply when the PV power generation is insufficient, so as to reduce the power purchased by the power grid during the period of high electricity price. It can be seen from the typical hourly situation that the charge and discharge of battery is mainly determined by power demand, but the seasonality is more obvious. Meanwhile, the charging and discharging amount of the battery is also affected by the PV power generation. In summer with high PV power generation, the discharge of the battery in the daytime is significantly less than that in the winter with low power generation.

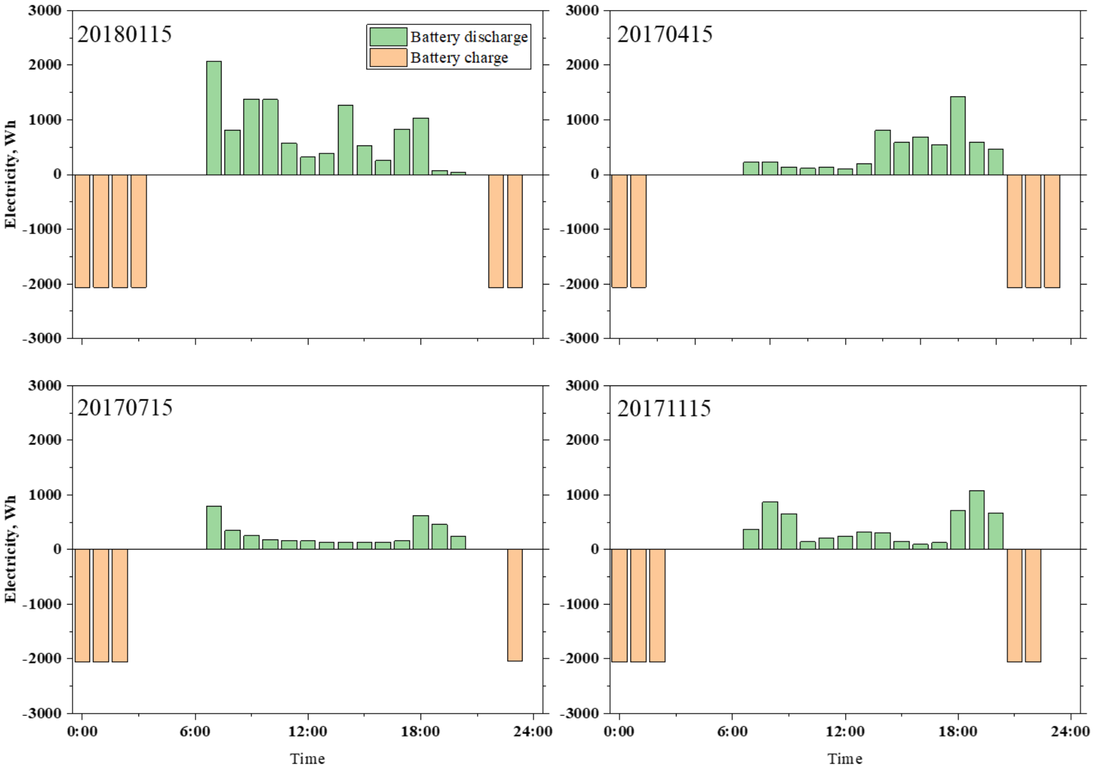

Fig 6-10 Battery charge and discharge on typical day in Case 2

6.3.3 Case 3: With TESS

In the original case of this study, the hot water load of the target house is provided by the heat pump. As shown in Fig 6-8, in order to meet the user demand, heat pump needs to operate at most times of the day, and electricity consumption occurs at both high and low electricity prices. In particular, the peak power consumption of users is from 18:00 to 22:00 in the evening, which consumes more power during the period of high electricity price.

In order to reduce the power cost of users and improve the system economic, we designed Case 3 as TESS, and the capacity of the thermal storage tank is determined to be 4.7kwh according to the optimization results. The typical daily hourly charging and discharging of thermal storage tank is displayed in Fig 6-11. Thermal storage tank operates in cooperation with heat pump. Hot water produced by heat pump is used to meet the user thermal demand at low price, and part of hot water is stored into the thermal storage tank. The thermal storage tank discharges during the high price period in the daytime to provide users with hot water, so as to reduce the electricity purchased by users due to the demand of hot water in high price.. The charging of thermal storage tank in winter is higher than that in other seasons, but the difference of charging and discharging in the other three seasons is not obvious. After the introduction of the thermal storage device, the operation time of the heat pump changes from all day to concentrated work at night, the electricity purchased increase during the low price period, and the hot water load during the peak period is mostly provided by the thermal storage tank. While reducing the cost, the purpose of peak shaving and valley filling is realized from the user-side.

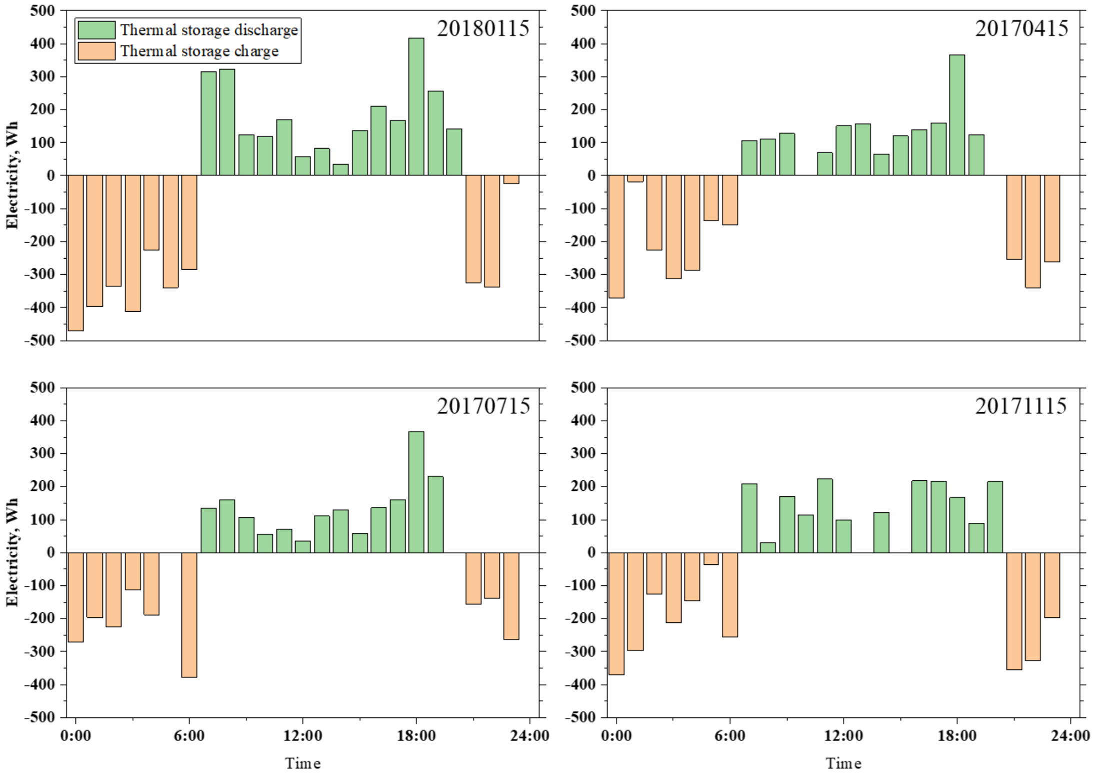

Fig 6-11 Thermal tank charge and discharge on typical day in Case 3

6.3.4 Case 4: With HESS

According to the above description, the addition of energy storage device can cooperate with other equipment in the system, so as to adjust the peak power demand of users and reduce the power purchase of power grid during high electricity price period. However, the performance and operation principle of energy storage equipment are different, and the introduction of battery and thermal storage tank into smart house energy system will produce different equipment output. Case 4 is a HESS combining battery and thermal storage tank. The hourly charging and discharging on a typical day is shown in Fig 6-12. Compared with Case 2 and 3, the charging and discharging of electrothermal hybrid energy storage system is more flexible. The difference of electricity unit price between day and night is more obvious in the HESS. But after introducing the thermal storage device, the energy discharge proportion of the battery increases compared with Case 2. Because when the energy storage equipment operates in coordination with other equipment, there is also interaction between the battery and the thermal storage tank. When the tank cannot meet the hot water demand of users during the daytime, there is also the phenomenon that battery discharges energy to heat pump for hot water supply.

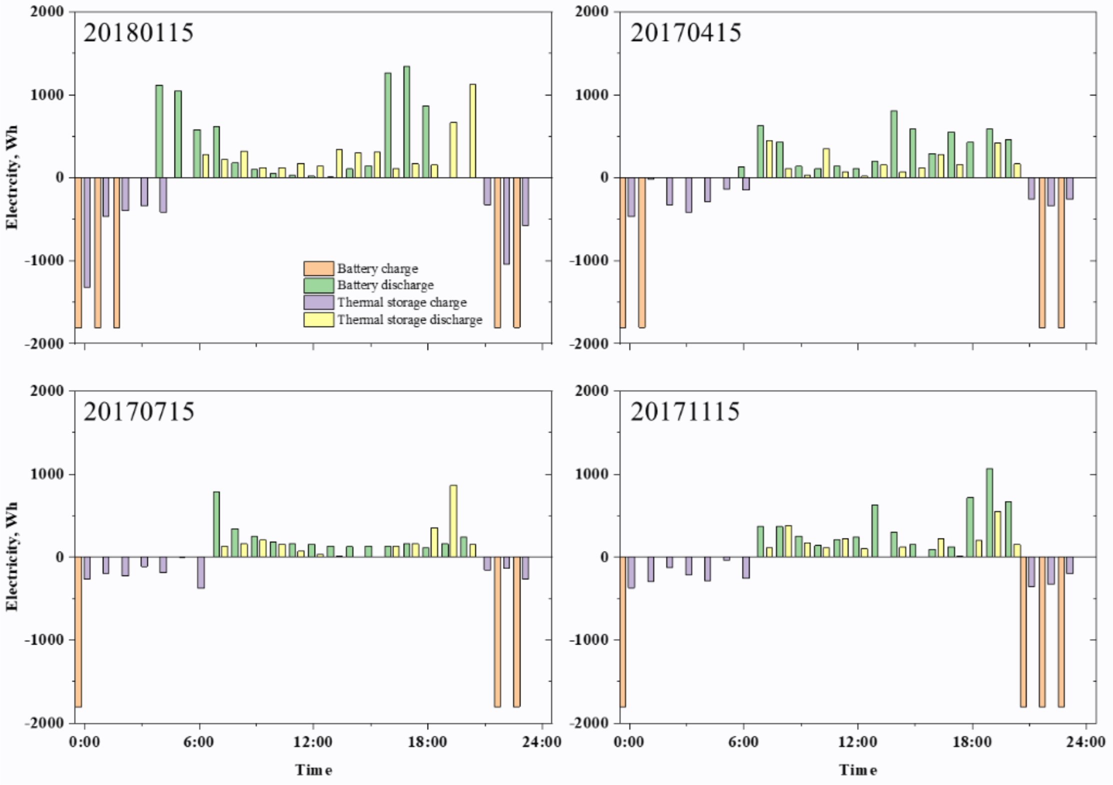

Fig 6-12 Energy storge equipment charge and discharge on typical day in Case 4

6.4 Comparative analysis of ESS performance

The comparison of typical daily results reveals only differences in hourly energy consumption and output of the case. In order to understand the impact and coordination between different energy storage equipment and the system, we simulated the annual energy consumption and output according to the optimization model. The results are compared and analyzed from three aspects of energy, environment, and economy.

Fig 6-13 states the monthly comparison of the total annual cost in four cases. The total cost is divided into investment cost, running cost and maintenance cost. Due to the high cost of equipment purchase, the proportion of investment cost in the total cost is much higher than other costs. Among them, the price of PV and battery is relatively expensive in the current market. In order to promote distributed energy and form a new social form for the purpose of stabilizing the power supply of the whole society and reducing costs as soon as possible. Meanwhile, through the popularization of renewable energy to reduce CO_2 emissions and deal with global warming, the government has implemented a series of subsidy policies for smart house with PV, battery and HEMS at the same time[7].

Combined with the subsidy policy, we calculated the investment cost of the four cases and found that the price of the subsidized battery was still high. After the introduction of energy storage equipment, the investment cost increases in varying degrees, of which Case 3 increased the least and Case 4 has the most. Moreover, after the introduction of energy storage equipment, in addition to a fixed increase in investment cost, the running cost of the system with energy storage capacity is reduced to varying degrees.

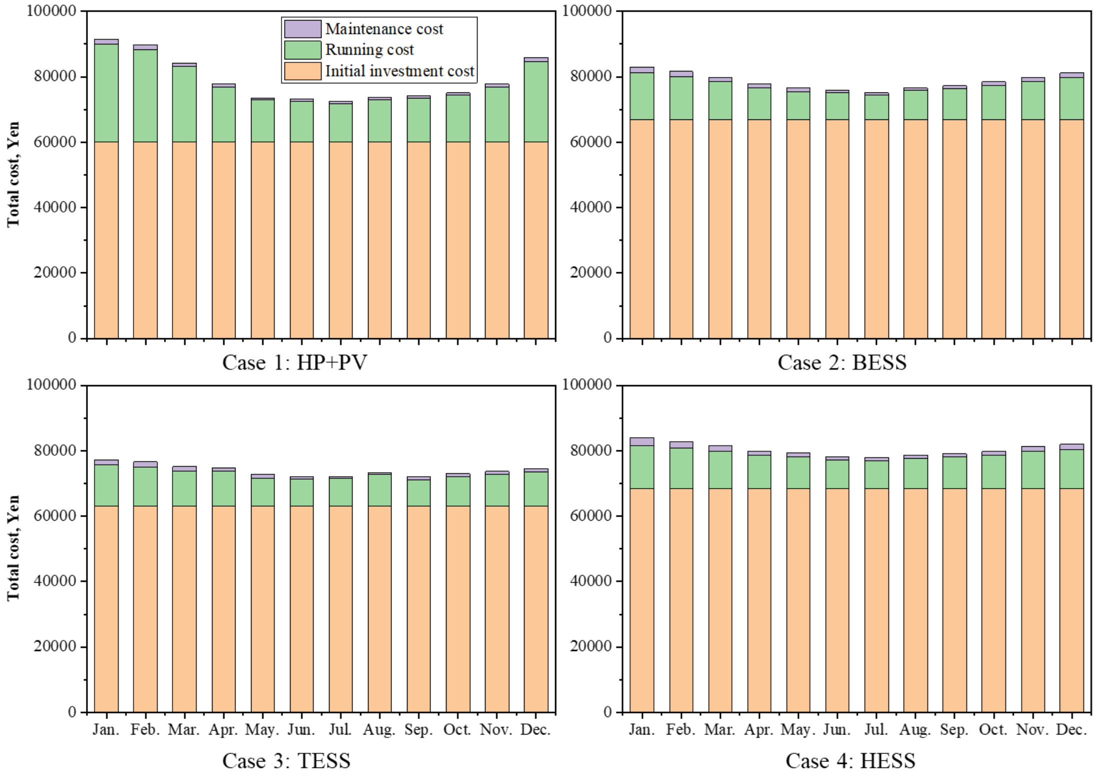

Fig 6-13 Monthly comparison of the total annual cost

Fig 6-14 represents the monthly comparison of the running cost in four cases. With the introduction of energy storage equipment, the system has an economic advantage in running cost, which is more obvious in winter. Among them, the introduction of TESS can reduce more running costs in winter. On the contrary, in June, July and August when the temperature gradually rises, the running cost of the BESS reflects better economy. The HESS has a relatively balanced ability to reduce operating costs. Although it also shows the result that winter is more than summer, it has no obvious advantages in seasonal factors compared with Case 2 and Case 3. The running cost reduction rate of case 2, case 3 and case 4 are 36.92%, 44.68% and 34.76% respectively. The PP comparison of the ESS is shown in Fig 6-15. Case 3 has the shortest recovery cycle, which is 7.84 years, and payback period of Case 4 is the longest, which is 10.29 years.

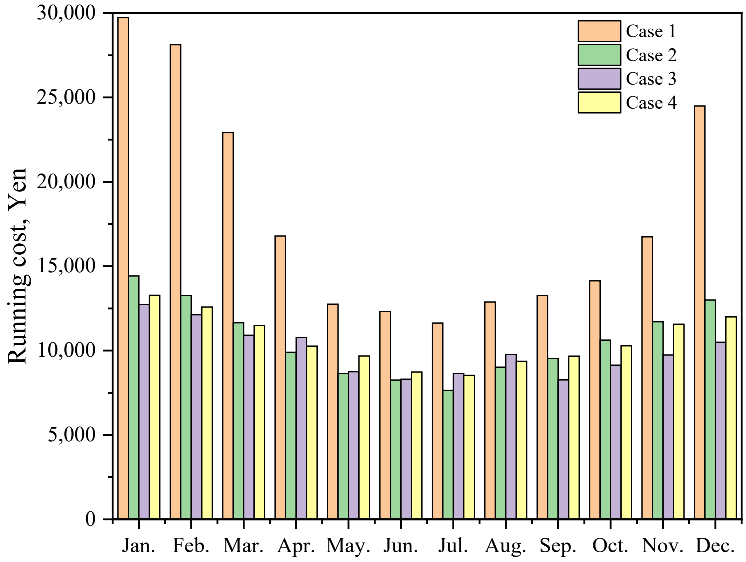

Fig 6-14 Monthly comparison of the running cost

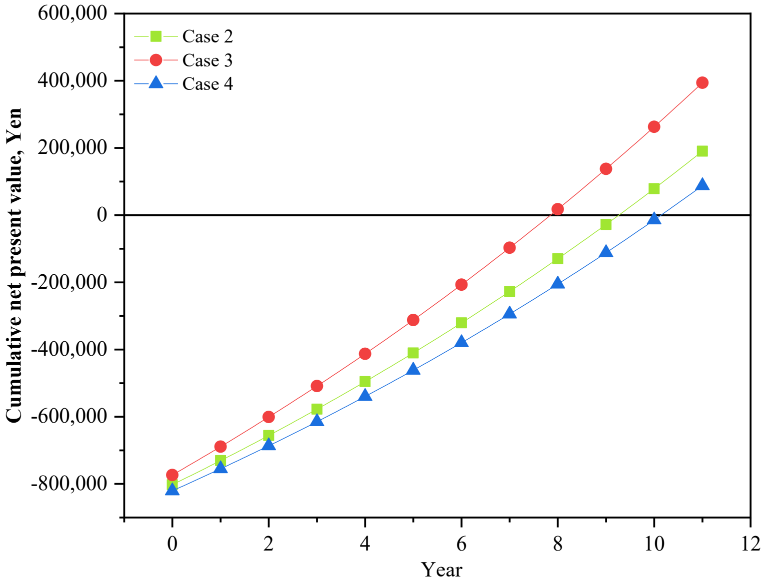

Fig 6-15 Payback year comparison of Case 2, Case 3 and Case 4

In order to compare the environment performance, we calculated the CO_2 emissions between four cases, and the results are shown in Fig 6-16. Since the ESS can store electricity during low electricity price, the CO_2 emissions of the three systems after the introduction of energy storage equipment have increased to varying degrees compared with the original system. According to the comparison results, the CO_2 emission of Case 3 is significantly higher than that of Case 2 and Case 4. While Case 4 has an environmental advantage in winter with high power consumption, on the contrary, Case 2 has a lower CO_2 emission in summer.

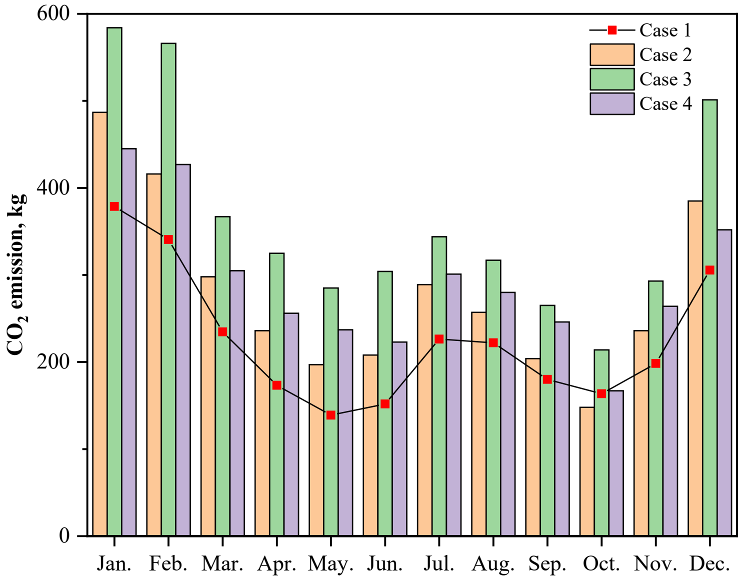

Fig 6-16 Monthly comparison of the CO_2 emissions

Table 6-5 states the comparison results of different indicators in energy, environment, and economy. As for the economic performance, Case 3 has the most advantages, requiring 7.84 years to payback the cost. In terms of environment performance, Case 2 has the lowest annual CO_2 emissions. Meanwhile, the addition of energy storage equipment can improve the absorption capacity of PV in the system. In the comparison results, Case 4 has the highest PSR, which is 54.95% in annual year.

Table 6-5 Performance comparison results of four cases

	PSR	CER (kg)	PP (Year)	Total electricity cost (Yen)
Case 1	14.31%	2714	-	981, 886
Case 2	38.14%	3361	9.32	943, 699
Case 3	33.46%	4455	7.84	905, 210
Case 4	54.95%	3503	10.29	964, 817

6.5 Sensibility analysis and case comparison

6.5.1 Electricity price

As an efficient power generation equipment using renewable energy, PV equipment is relatively expensive in the early stage of operation. In order to make up for the high price and encourage the combination of renewable energy and distributed residential energy system, the government has introduced a series of subsidy policies including FiT[8]. Under the dual promotion of policy and technology, the number of applications of residential PV systems has increased significantly, which has played a positive role in improving the environment and economy. However, in the ten years since the implementation of FiT, with the wide popularization of residential PV, the feed-in price shows a decreasing trend[4].

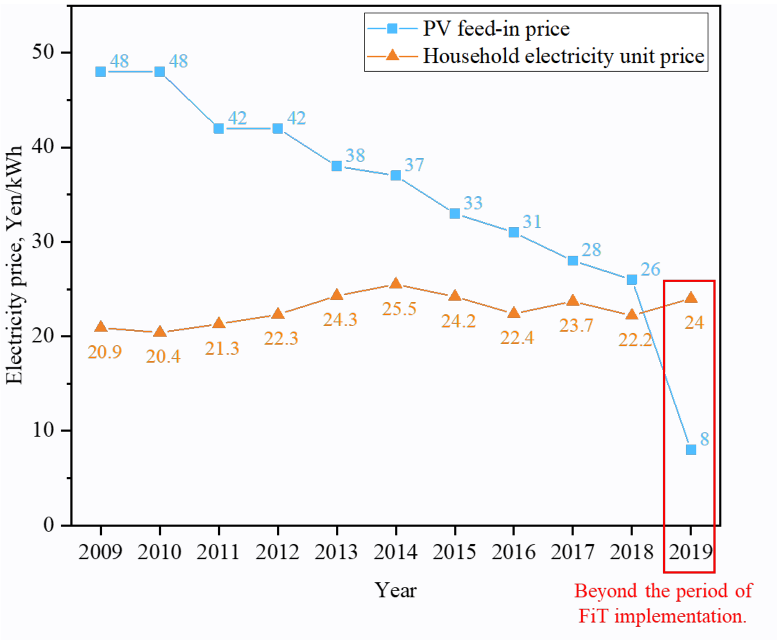

Fig 6-17 Price fluctuation of selling and purchasing electricity from public grid

Fig 6-17 depicts the price fluctuation of selling and purchasing electricity from public grid during the implementation of the policy. Since 2019, the feed-in price has dropped significantly, and this trend will continue in the coming years. PV as the main power supply equipment for residence, part of its economic advantage is reflected in the price of feed-in. We predict the PP of the ESS based on the fluctuation of the feed-in price, the comparison results are shown in Fig 6-18.

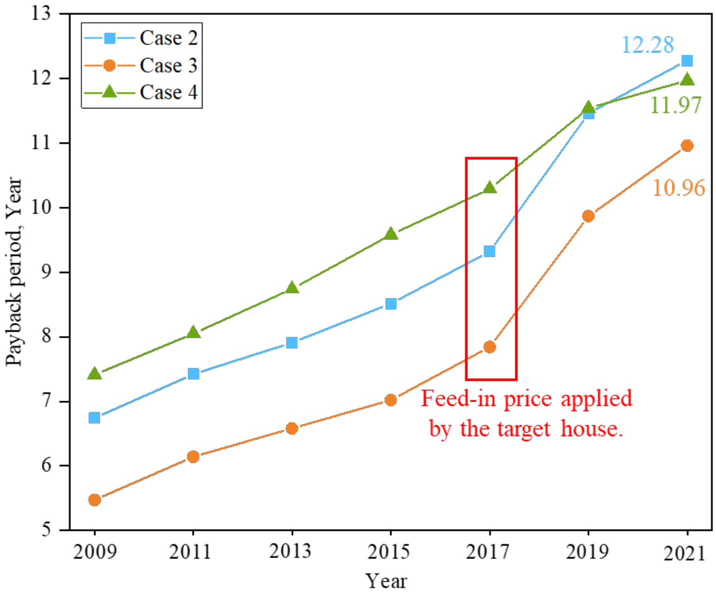

Fig 6-18 Comparison of system payback year combined with the feed-in price fluctuation

In the economic comparison above, the target residence choose the feed-in price in 2017. During the ten years of policy implementation, the recovery years of the three cases showed an increasing trend with the decline of feed-in price, and there was no significant difference in the growth rate. The HESS in Case 4 has shown a slower growth rate compared with the other two cases since the sharp decline of feed-in price in 2019. Futhermore, because of the high investment cost, the PP of Case 4 is consistently longer than that of Case 2 and Case 3 before 2019. However, after the feed-in price was significantly reduced, the PP of Case 4 is less than that of Case 2 in 2019, and it still maintained a competitive advantage in the future.

6.5.2 Carbon tax

As an important measure of global energy saving and emission reduction, carbon emission price is one of the research hotspots nowadays. Carbon emissions are currently commonly used for comparative technology or building life cycle analysis[9]. A Ozawa[10] analyzed the life cycle carbon emissions of different hydrogen carriers based on the analysis of the whole supply chain and the Japanese life cycle inventory database. The results show that the life cycle carbon emission of liquid hydrogen (LH2) and ammonia (NH3) is still 52% and 36% lower than that of conventional natural gas-combined power generation. At present, the impact analysis of carbon emission price on technology is less, and the research mainly focuses on the impact on countries or regions. B Lin[11] analyzed the impact of different ETS price levels by applying a dynamic recursive computable general equilibrium mode. They argued that ETS prices in China's ETS pilot cities are too low, and would provide little emission reduction, and suggested increasing carbon prices to $20 and focusing on the appropriate subsidies for new energy generation. J Chevallier[12] investigated the presence of outliers in the volatility of carbon prices. Three different measures of volatility for European Union allowances were computed based on daily data (EGARCH model), option prices (implied volatility), and intraday data (realized volatility).

To cope with the increasingly serious greenhouse effect caused by the massive emission of CO_2 emissions, Wilson first proposed the concept of carbon tax in 1973[13][14]. By 2019, 25 countries have implemented or planned to implement carbon tax, and more than 100 cities have promised to achieve carbon neutrality by 2050[15]. Japan has implemented carbon tax in some companies since 2012 and plans to fully introduce it by 2022 as a powerful means to achieve a decarbonized society. During the initial implementation of carbon tax, Japan raised the tax rate three times (October 2012, April 2014, and April 2016) to give the public a certain adaptation period, to avoid a sharp increase in the short-term burden on taxpayers. As of 2017, Japan's latest carbon tax pricing is 3.952 Yen/ $kgCO_2$. Combined with the current carbon tax levy price in Japan, we predict the PP of the ESS.

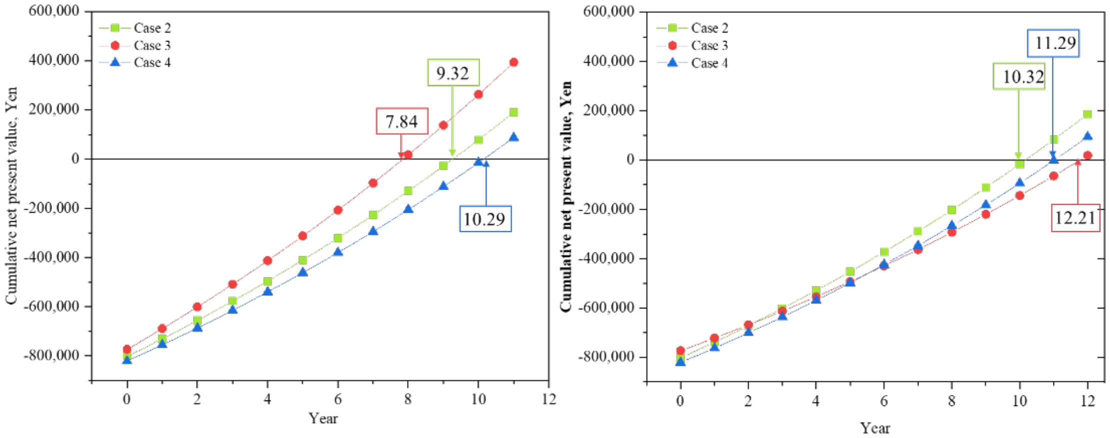

Fig 6-19 PP comparison before(left) and after combined carbon tax(right)

Fig 6-19 presents the system PP comparison before and after the introduction of carbon tax. The introduction of carbon tax has reduced the annual profit of the ESS and increased the PP to varying degrees. Case 2 shows the largest economic advantage in the combination of carbon tax, with the minimal reduction in annual profit, the system payback period is increase to 10.32 years. On the contrary, Case 3 has the longest payback years after combined carbon tax due to environmental disadvantages.

6.6 Summary

With the increasing penetration of energy storage technology into residential energy system, the cooperation between equipment and users also provides a great space for system optimization. In this part, a smart house with PV and heat pump in Jono area is selected as the research object. Based on APSO algorithm, a double-level optimization model was proposed for the capacity of energy storage equipment and the annual energy consumption of the system. The model aims to minimize the power cost and optimize the economy of the system while smoothing the peak load pressure and improving the system operation safety. At the same time, a comprehensive comparison model is established, and the four cases with different energy storage equipment are designed to compare and evaluate the model from three aspects of energy, environment, and economy. Based on the present analysis, the following conclusions can be drawn:

(1). In the scenario of applying different energy storage equipment, the equipment capacity is optimized, and the optimal size is obtained through the upper optimization model. Then, the annual equipment output of the system is simulated according to the optimal size. The hourly energy consumption simulation results state that the addition of energy storage equipment plays a positive role in reducing users' peak load and electricity purchase cost and can cooperate with PV and heat pump.

(2). The four cases show different characteristics of energy storage equipment. The charging and discharging of BESS is greatly affected by PV power generation, which reflects obvious seasonality. The charging of TESS in winter is much higher than that in other seasons, and after the introduction, the operation time of heat pump changes from all-day to concentrated work at night. Compared with a single ESS, the charging and discharging of HESS is more flexible, and the difference between daytime and nighttime electricity prices is more pronounced.

(3). The comprehensive comparison results show that TESS has advantages in economy with 7.84 years of system PP. As for environmental performance, the addition of energy storage equipment leads to the increase of system carbon emission in varying degrees, among which the increase of BESS is the smallest.

(4). In terms of energy performance, HESS has the highest PSR and can consume more PV power generation than BESS and TESS. According to the sensitivity analysis results of electricity price fluctuation and carbon tax, the PP of ESS increases in varying degrees under the background of gradually decreasing the feed-in price. However, the growth rate of HESS is the smallest, and it will reflect greater economic advantages in the future as the feed-in price continues to decline. Meanwhile, the possibility of introducing carbon tax in the future also highlights the environmental advantages of BESS and HESS.

At present, although the HESS cannot recover within 10 years, based on the price fluctuation and the gradual introduction of carbon tax, the HESS has shown development potential in both economy and environment. The higher PV absorption capacity also provides greater optimization space for the further combination of HESS and PV. However, based on the current analysis results, the high price of PV and battery is also one of the main reasons for extending the PP of the system. In order to promote the collaborative application of energy storage equipment and renewable energy on the user-side, the government has successively implemented some subsidy and incentive policies. It is hoped to further cooperate with energy storage equipment according to corresponding policies, give play to the role of user-side energy storage in the demand management and grid peak shaving, and realize the dual optimization of economy and environment.

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Chapter 7

INFLUENCE OF POWER MARKET FLUCTUATION ON SMART HOUSE ELECTRICITY COST AND FUTURE DEVELOPMENT SUGGESTIONS

CHAPTER SVEN: INFLUENCE OF POWER MARKET FLUCTUATION ON SMART HOUSE ELECTRICITY COST AND FUTURE DEVELOPMENT SUGGESTIONS

7.1 Contents

To address the primary energy shortage problem, Japan has implemented a series of policies and measures for residential energy conservation and emission reduction. Among them, the home energy management system (HEMS) in a smart house as a hub connecting users and power companies to realize energy visualization has been widely studied.

The research object of this study is a two-story detached smart house integrated with HEMS in the "Jono smart house area" in Japan. In this part, to predict the energy consumed on the next day based on historical data, a short-term household load forecasting model based on the particle swarm optimization regression vector machine algorithm was developed. Then a dynamic pricing model was developed to guide the users' electricity consumption behavior and adjust the grid load. According to the prediction results obtained by the load forecasting model, the annual electricity charges of users under the three pricing schemes of multistep electricity pricing (MEP), time-of-use pricing (TOU), and real-time pricing (RTP) were calculated and compared. In addition, after adjusting the users' peak load and combining it with the fluctuating future electricity prices, RTP presented evident economic advantage over MTP and TOU in terms of the annual electricity cost of the users. The study results can provide policy suggestions for the future Japanese government's promotion of RTP strategy, while acting as a reference for further developing the characteristics of HEMS and optimizing the relation between the supply and demand sides.

7.2 HEMS structure and research object introduction

7.2.1 HEMS structure

HEMS is an energy management system applied on the demand side. It is an extension of the demand response strategy on the demand side in the power grid[1]. As a hub connecting users and an electricity supplier, HEMS aims to optimize the power utilization of household users, relies on the scheduling of distributed energy and energy storage equipment, and uses optimization algorithms and scheduling strategies to reduce household energy consumption.

The two major features of HEMS include energy visualization and optimal control of household appliances and electrical equipment[2]. According to users' electricity demand, environmental conditions and price incentive information, HEMS applies the built-in residential electricity optimization strategy to adjust the operation of various electrical appliances, optimize the user load curve, and participate in peak load regulation.

Fig 7-1 shows a schematic of the HEMS used in a typical smart house, which is composed of energy flow and information flow. The information flow connects the electric and gas suppliers and the demand side through the HEMS, to realize a two-way communication of the energy data. Users can validate the usage and power consumption of home appliances through the HEMS. Meanwhile, the HEMS sends the collected energy consumption data to the power company, which in turn formulates the electricity price and incentive scheme according to the power load characteristics of the users and feeds the data back to the household. Finally, the users can adjust the energy consumption behavior and select an economical electricity price plan through the information displayed by the HEMS, for optimizing the power cost. The energy flow comprises electric and gas suppliers, a utility grid and the demand side. Power suppliers, public grids and other energy supply equipment imported from residential buildings provide electricity to users. A PV battery uses solar energy to provide electricity for residence during the day, and users can sell the remaining power back to the grid. The external equipment imported by users can be classified into two types: energy supply only and energy supply and storage simultaneously. Energy-only devices include heat pumps and fuel cells, which provide electricity and heat to the users during the operation time. Energy storage devices, including batteries and electric vehicles, have the function of charging and discharging. They maximize the advantages of HEMS by storing energy when the cost of power is low and releasing it to users when the cost is high.

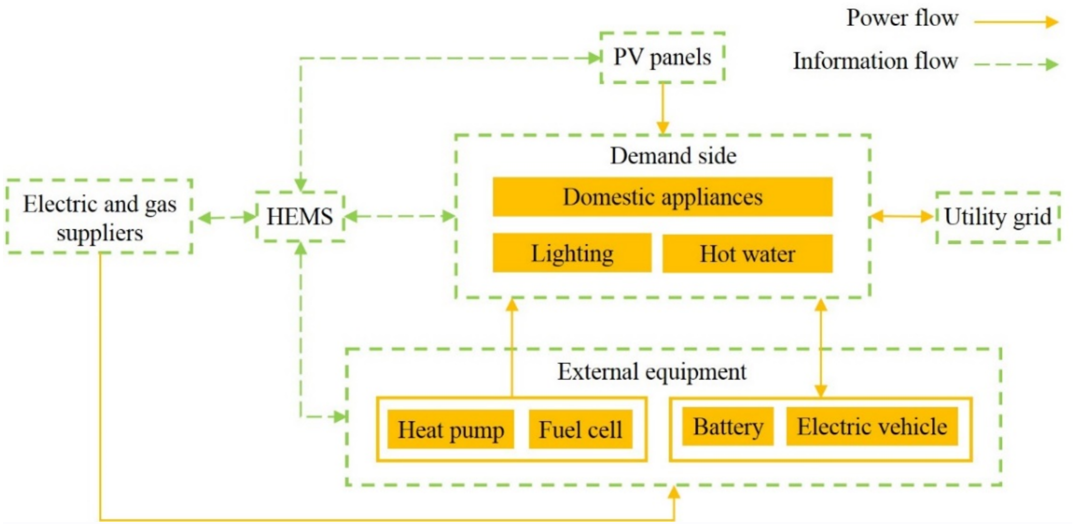
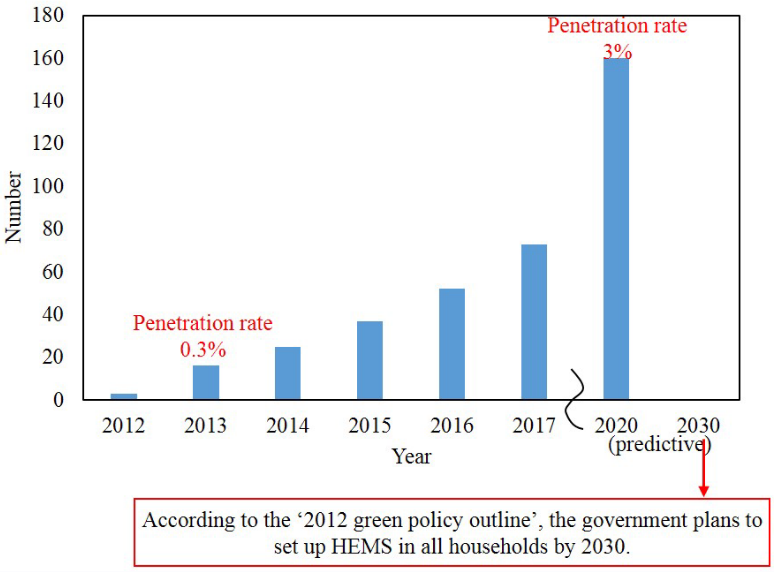


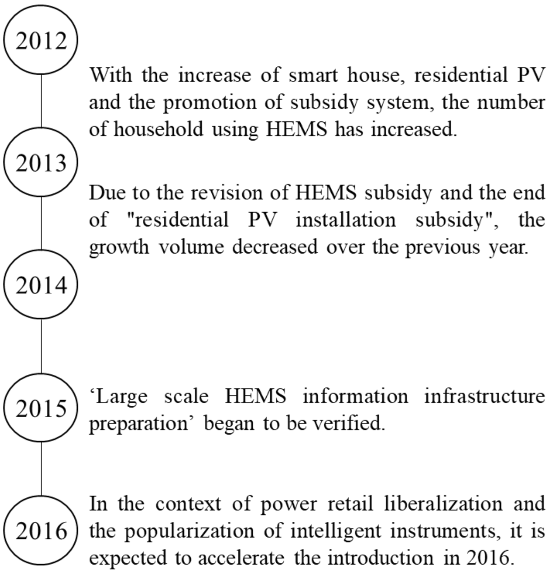
Fig 7-1 Basic framework of HEMS used in typical smart house

The home energy reports presenting the HEMS data of Japanese residences indicate cumulative two-year winter consumption reduction of 7.5%[3]. The introduction of HEMS into residence as the main approach to achieve zero-energy house (ZEH), has been widely promoted in Japan recently. Fig 7-2 shows the cumulative number of HEMS installed in Japan recently[4]. Since 2012, with an increase in the number of smart houses and residential PV systems developed and the promotion of subsidy systems, the number of households using HEMS has increased(Fig 7-3). In the context of power retail liberalization and the popularization of intelligent instruments, the introduction of HEMS is expected to accelerate in 2020 and the Japanese government plans to set up HEMS in all households by 2030.



According to the '2012 green policy outline', the government plans to set up HEMS in all households by 2030.

Fig 7-2 Cumulative number of HEMS installed in Japan



With the increase of smart house, residential PV and the promotion of subsidy system, the number of household using HEMS has increased.

Due to the revision of HEMS subsidy and the end of "residential PV installation subsidy", the growth volume decreased over the previous year.

'Large scale HEMS information infrastructure preparation' began to be verified.

In the context of power retail liberalization and the popularization of intelligent instruments, it is expected to accelerate the introduction in 2016.

Fig 7-3 Application and development of HEMS in Japan

7.2.2 Research object

In this study, a two-story detached house in the "Jono smart house area" in Kitakyushu, Japan, was selected as the research object. By introducing energy-saving equipment into the residence and using HEMS to optimize energy management, this community promotes various low-carbon technologies to achieve zero carbonization level of the home.

The building area of the target house in this study was 110 m^2 with a capacity of accommodating four family members. The main energy supply equipment of the residential energy system included a PV and a heat pump. The specific parameters obtained from the responses of the questionnaire addressed are listed in table 7-1. The energy system achieved an all-electric effect through PV power generation and heat pump heating. If the power generation of the equipment fails to meet the power demand of the users, the system can purchase power from the public grid. In contrast, if surplus PV power is available, it can be sold back to the grid, thereby reducing the electricity cost incurred by the users.

Table 7−1 Main equipment parameters of the smart house energy system

Equipment	Type	Capacity	COP	Conversion efficiency
Heat pump	Air/water	4.5kW	3.2	-
PV	-	4.18kW	-	19.6%

7.3 Load curve analysis and electricity costing calculation

7.3.1 Basic data analysis

The data of the user electric load measured every 30 min were selected as the basic research data in this study. Fig 7-4 presents the monthly energy consumption of each part of the target house. The amount of PV power generated in summer is greater than that generated in winter. Meanwhile, unused surplus PV power generated can be sold back to the grid by users, thus, the feed-in summer is higher than that in winter.

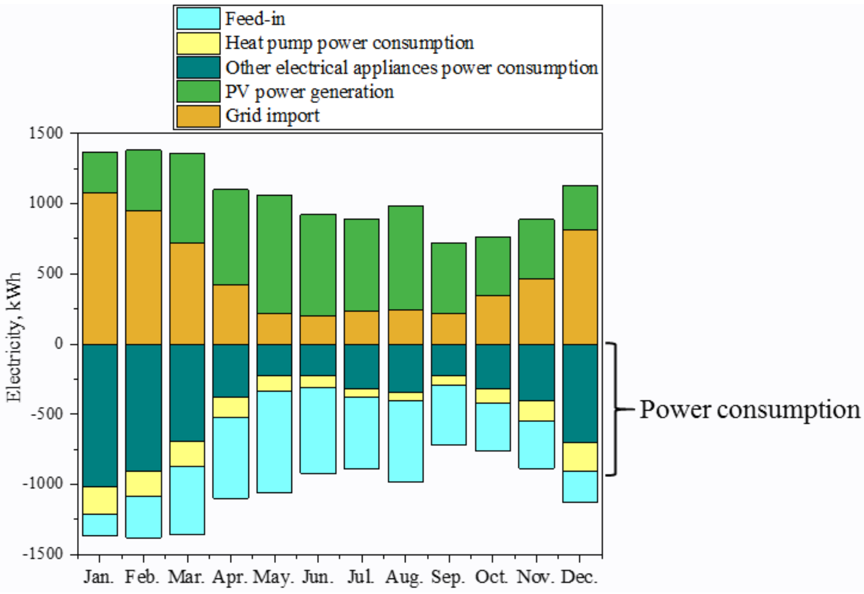


Fig 7−4 Monthly electricity consumed by the target household in one year

Fig 7-5 and Fig 7-6 indicate the hourly loads of the target residence in summer and winter, respectively. The user’s power consumption is mainly composed of the power consumed by the heat pump and other household appliances. Owing to the frequent operation and long working hours of heat pumps and air conditioners, the electricity consumption in winter is higher than that in summer. The electricity cost and load curve of the target household are analyzed and calculated below.

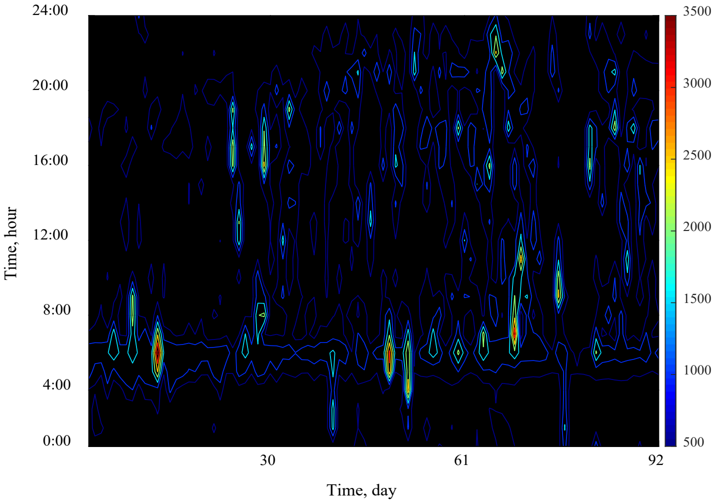


Fig 7−5 Hourly load consumed by the target household in summer

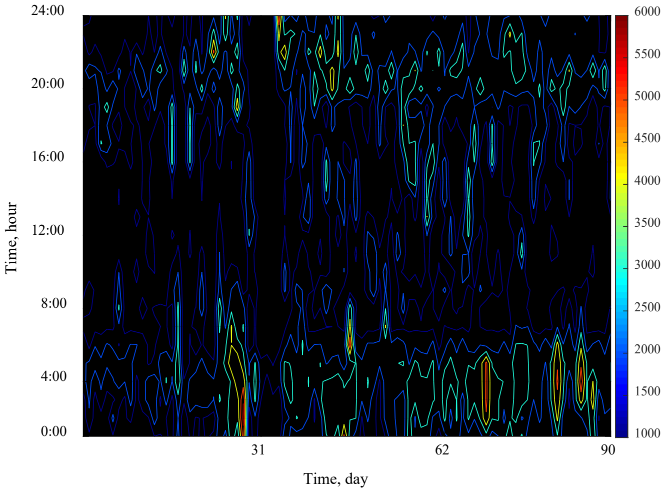


Fig 7−6 Hourly load consumed by the target household in winter

7.3.2 Electricity costing calculation

Power demand response refers to the market participation behavior of power users in response to the market price adjusted signals or according to the incentives of power companies to change their inherent usage patterns. It is a solution for demand-side management. The price mechanism forms the core of the power market mechanism. In addition, reasonable electricity price can reflect the size of social benefits, realize the optimal allocation of power resources, allow users to select a reasonable power consumption time and adapt to the intermittent characteristics of distributed power generation.

At present, the main pricing strategies used in the power market include MEP, TOU and RTP. With the characteristics of stepped-type electricity price, MEP is applicable to most types of residential energy systems and is a common choice of users.

Fig 7-7 shows the power consumed by the heat pump in a year, with its main operation time ranging from 20:00 to 8:00 the next day, and the operation peak ranges between 0:00 and 8:00. According to the operating characteristics of the heat pump, some customers also choose TOU at a lower price at night as the price scheme. Table 7-2 presents the unit price and basic charge incurred by the target household by selecting MEP and TOU[5]. The monthly electricity cost incurred by the customer is calculated by summing the basic charge and unit price.

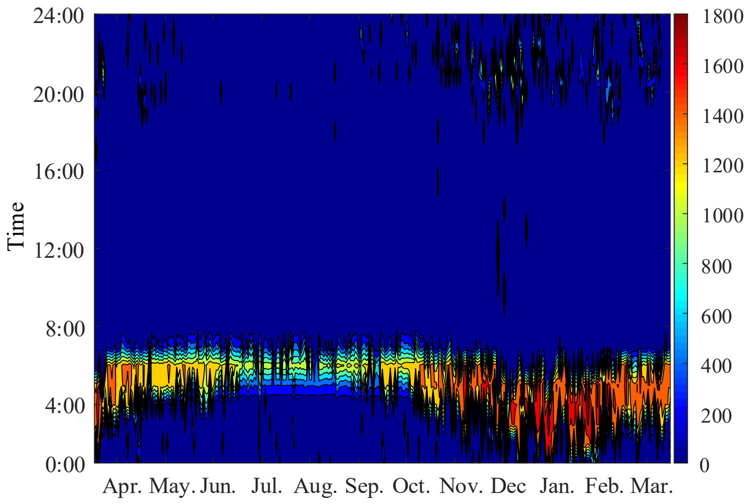


Fig 7−7 Color scale distribution of heat pump electricity consumption in one year

Table 7−2 Unit price and basic charge incurred by the target household by selecting MEP and TOU

	Basic charge (Yen/ contract)	Unit price (Yen/kWh)		
MEP	1782.0	0-120kWh		17.46
		121-300kWh		23.06
		300kWh-		26.06
TOU	1650.0	8:00-22:00	Spring/Autumn	23.95
			Summer/Winter	26.84
		22:00-8:00		13.21

The annual electricity cost of the target household selecting MEP and TOU is calculated, and the results are illustrated in Fig 7-8. Because heat pumps consume considerable power in winter and operate at night, according to the low night electricity price of TOU, its electricity cost of TOU in January, February, March, and December is lower than that of MEP. However, MEP has an economic advantage over TOU in terms of electricity cost during the summer and intermediate periods when electricity consumption is low. The calculation results indicate that the annual electricity costs of MEP and TOU are 153,917 and 157,761 Yen respectively.

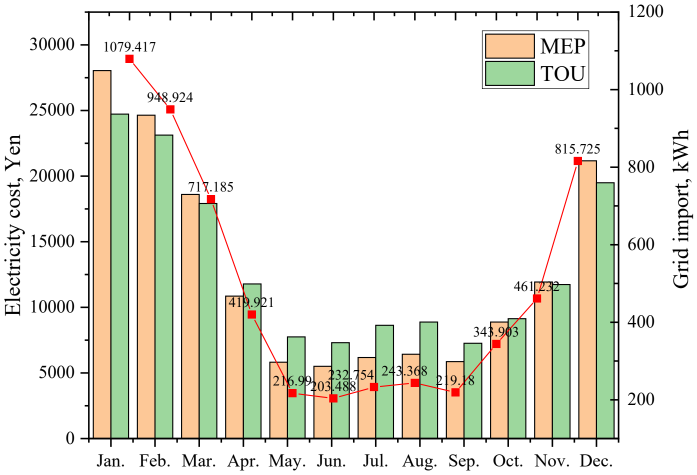


Fig 7−8 Annual electricity cost comparison between MEP and TOU

7.3.3 Electricity load curve analysis

The calculation of electricity costs of different electricity price schemes indicates that although MEP and TOU exhibit different characteristics, there is no evident difference in their annual electricity costs. Compared with other pricing schemes, RTP has an advantage in terms of power cost in combination with load forecasting. HEMS can predict the forecast data of the next day based on the measured load data of the previous day and feed the information back to the power company. The power company formulates the corresponding RTP according to the customers' energy consumption behavior.

At present, the formulation and promotion of RTP in the Japanese electricity market is not mature and the electric company has not yet launched the corresponding RTP scheme. To simulate the electricity cost after the customer selects RTP and compares it with other electricity pricing schemes, a short-term load forecasting model and an RTP model were developed in this study.

The power load of users fluctuates constantly, thus, it is necessary to analyze the load changing law to adopt an appropriate forecasting method and obtain a power load-predicted value that meets the precision requirement, to provide a basis for formulating RTP. The change in power load exhibits both regularity and randomness, and the fluctuation between them determines the predictability of the short-term power load. Therefore, it is necessary to analyze the characteristics of the power load according to the feature of power load change in short-term prediction.

The weekly periodicity of the power load change mainly refers to the regularity of the power load in a week. This is because the daily life of a household is mainly planned and arranged in a weekly cycle. Fig 7-9 presents the daily load curve of the object residence for eight consecutive weeks. The load curve indicates that the fluctuation changes occurring in the power load for one week are similar. Meanwhile, the fluctuation in the power load curve of the same week type is similar, which indicates that the change in power load exhibits a weekly periodicity.

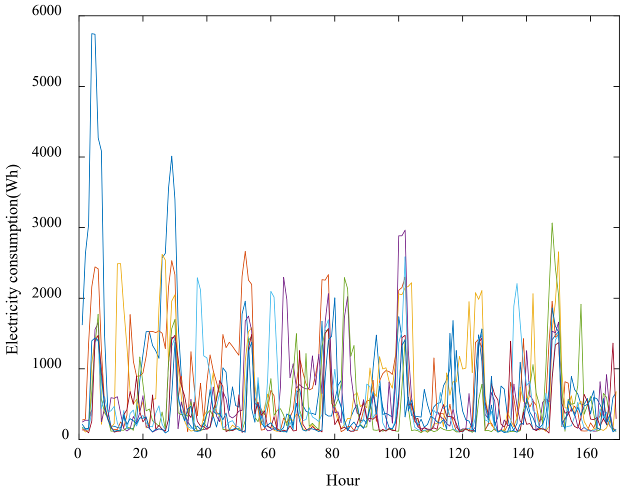


Fig 7−9 Load comparison curve of eight consecutive weeks

The daily periodicity of the power load change mainly refers to its regularity with a cycle of 24 h a day. Fig 7-10 shows the daily load curve of the target household on Monday, Friday, and Sunday in consecutive weeks. Here, although the load is constantly fluctuating, the daily load change curve has evident similarity, thus, the change in power load exhibits a certain daily periodicity.

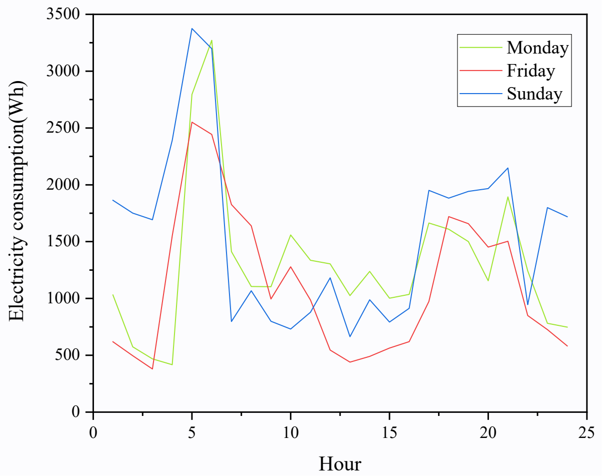


Fig 7−10 Load comparison curve of daily load

Because the power load changes exhibit the characteristic of periodicity, the change in load is similar in a certain period and the amplitude of the power load is similar at the same time every day. Fig 7-11 shows the load curve at 8:00, 12:00 and 18:00 every day for 14 consecutive days. Within a given period, the load value at the same time on different days fluctuates within a certain range, which reflects the approximate value of the load at the same time.

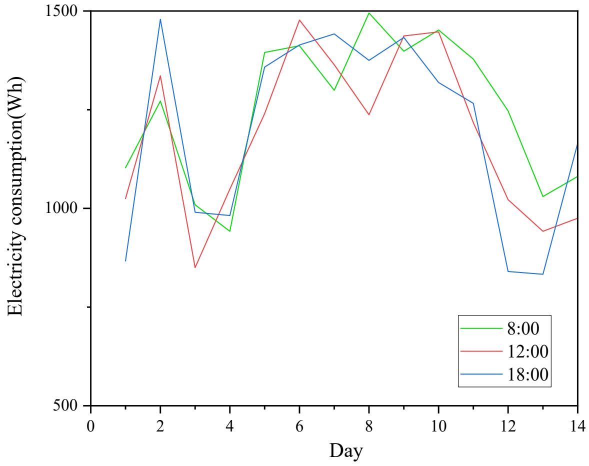


Fig 7−11 Load comparison curve at the same time for 14 consecutive days

7.4 Analysis and comparison of load forecasting results

7.4.1 Analysis of short-term load forecasting results

To verify the forecasting effect of the short-term load forecasting model and compare the three algorithms, we first selected one day as the forecasting sample and conducted forecasting at 48 time points within 30 min. The simulation was performed using MATLAB, and the predicted results and measured values were compared, as depicted in Fig 7-12, Fig 7-13, and Fig 7-14.

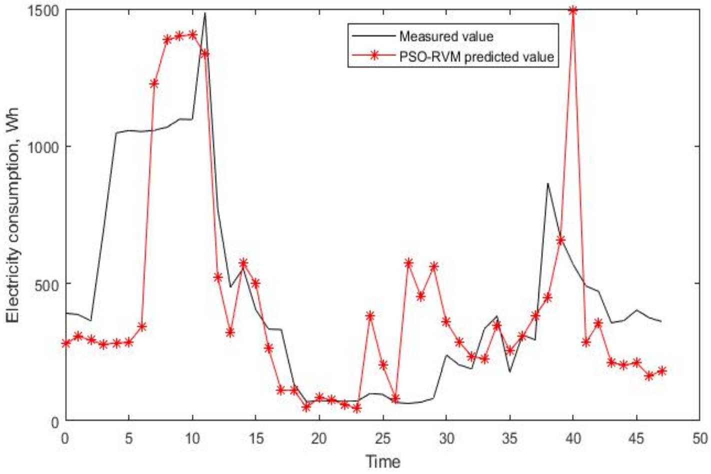


Fig 7−12 Comparison of daily load curve forecasting results in PSO-RVM

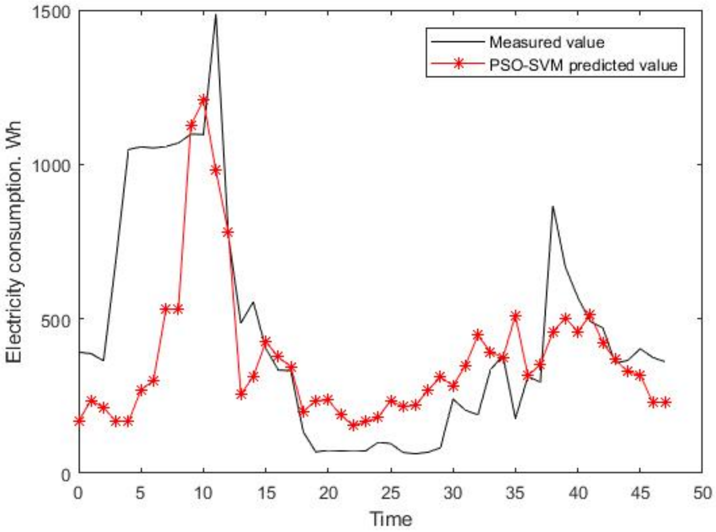


Fig 7−13 Comparison of daily load curve forecasting results in PSO-SVM

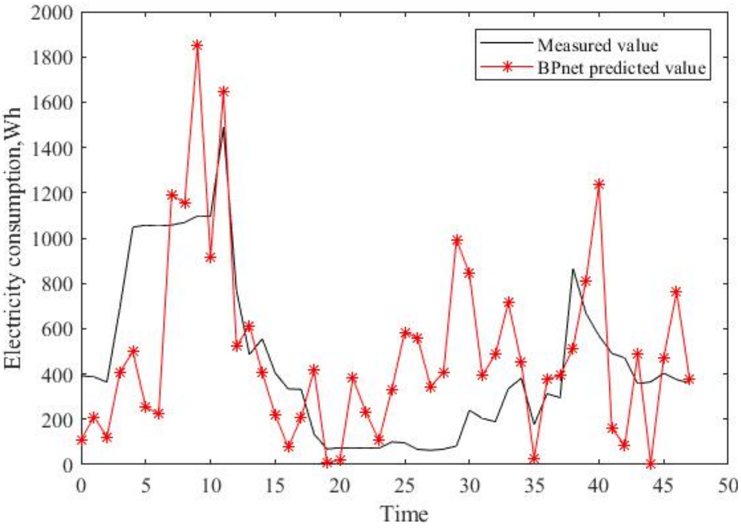


Fig 7−14 Comparison of daily load curve forecasting results in BPNN

Then we selected one week as the forecasting sample and conducted forecasting at 48 time points within 30 min. And the predicted results and measured values were compared, as depicted in Fig 7-15. According to the comparison, PSO-RVM and PSO-SVM exhibited higher prediction accuracy for low load, but the prediction of BPNN at the peak value was closer to the actual value. To quantitatively analyze and evaluate the prediction effect of the three algorithmic prediction models, the mean absolute percentage error (MAPE), root mean square error (RMSE), and maximum absolute error (MAE) were used as the accuracy evaluation indices of household short-term load prediction.

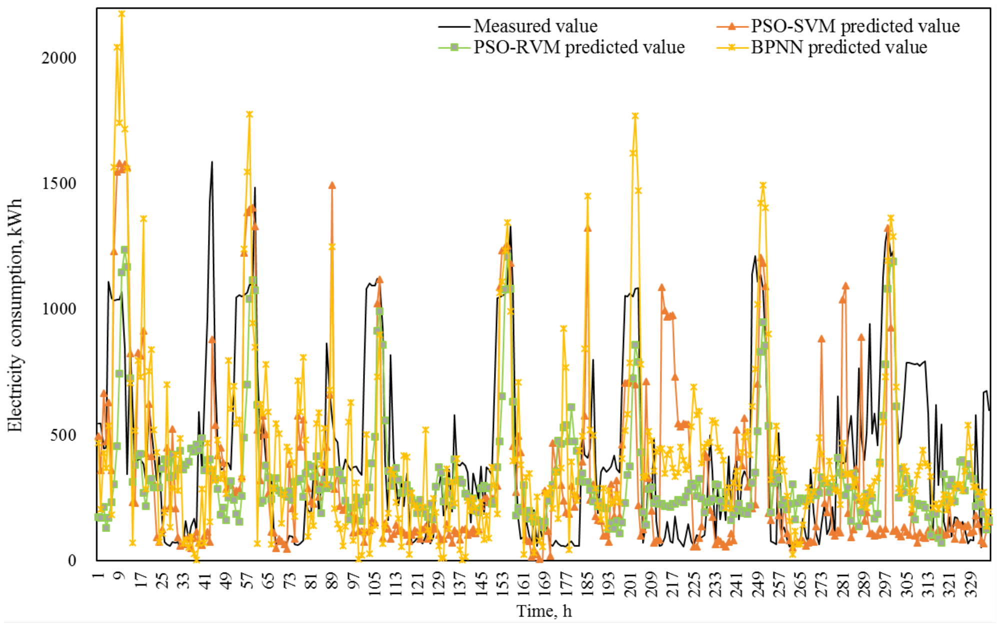


Fig 7‒15 Comparison of daily load curve forecasting results in one week

The corresponding model-prediction error is presented in table 7-3. The comprehensive prediction accuracy evaluation index indicates that PSO-RVM is more suitable for short-term load forecasting of smart house energy systems. Therefore, the prediction algorithm is nested in the short-term load prediction module of HEMS. This algorithm realizes short-term load forecasting and formulates the RTP for the customers according to the load forecasting results.

Table 7‒3 Comparison of model prediction errors

	MAPE (%)	RMSE (kW)	MAE (kW)
PSO-RVM	0.6714	0.2726	0.3128
PSO-SVM	0.735	0.2632	0.7248
BPNN	0.8437	0.3437	0.8256

7.4.2 Comparison of electricity cost among different pricing models

At present, most Japanese households select the electricity price scheme according to their respective energy consumption behavior and power demand. Among these, MTP and TOU are selected owing to their different characteristics. According to the electricity cost calculated for the target household in the early stage, the annual electricity costs of MTP and TOU are not significantly different, which does not reflect the evident economic advantages.

The developed RTP model can generate the unit price of a short interval in hours for the whole day according to the predicted load. Fig 7-16 shows the real-time electricity unit price obtained on January 1st. Fig 7-17 shows the hourly demand and electricity cost of the target household in a day based on RTP. Combined with users' electricity consumption behavior and load demand, the real-time electricity price on January 1st obtained by the model depicts a state of high electricity price at night and relatively low price in the daytime.

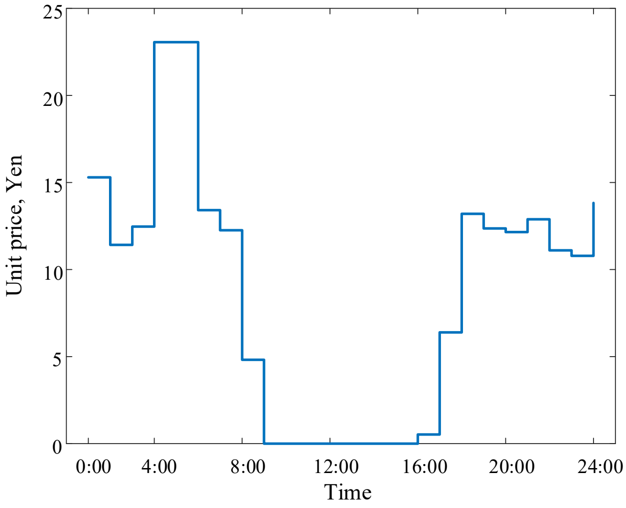


Fig 7−16 The real-time electricity unit price obtained on January 1st

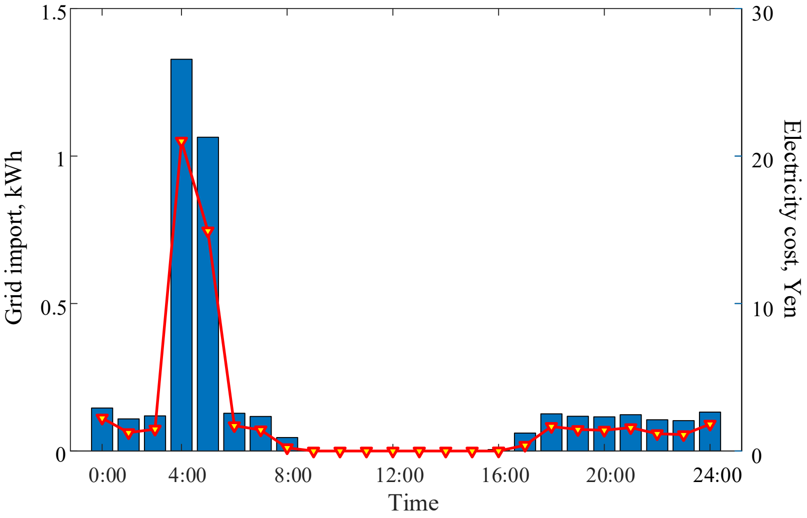


Fig 7−17 Real-time electricity cost on January 1st

To compare the effects of RTP and TOU on the power cost of users, we separately calculated the electricity costs of customers in January under the two electricity price schemes, and present the comparison results in Fig 7-18.

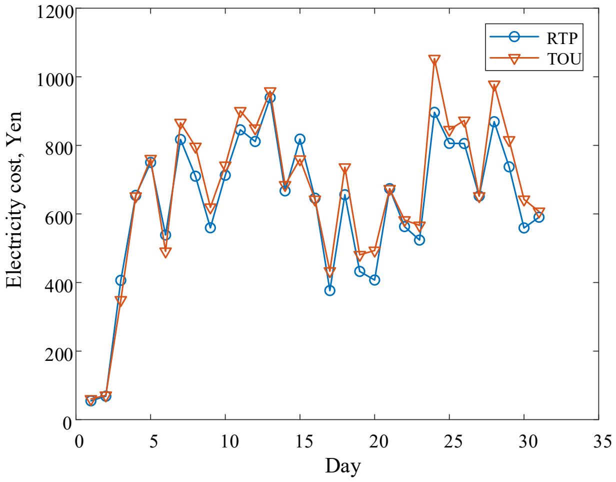


Fig 7–18 Electricity cost comparison of RTP and TOU in January

In general, RTP has an economic advantage over TOU in terms of electricity cost, but due to the long operation time of the heat pump and large power consumption at night in winter, it is still higher than TOU. The cost of electricity in January was 22,200 yen for RTP and 24,724 yen for TOU. A comparison of the annual electricity cost of the three tariff models is illustrated in Fig 7-19. In the absence of an evident gap between MTP and TOU, the application of RTP makes the system economy better than that in the other two modes. There is a huge difference in the electricity costs between MTP and RTP in winter; in contrast, the cost of TOU is evidently different from that of RTP in summer.

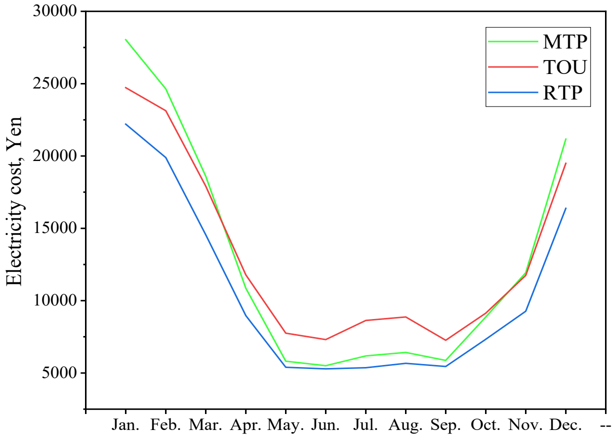


Fig 7–19 Comparison of annual total electricity cost

7.5 Sensitivity analysis and method adaptability verification

7.5.1 Sensitivity analysis of heat pump operation time

For a comparative analysis of the power cost under the three electricity pricing models, although

RTP has a better economy than MTP and TOU, the power cost in winter remains high. Fig. 19 presents the hourly power consumed by the target household in a year. The main energy consumption of the users is concentrated from 20:00 to 6:00 the next day during winter. As the main heating equipment in winter, heat pumps constitute a large proportion of the total energy consumption. According to the analysis result of heat pump power consumption presented in Fig 7-20, the operation time of the target household's heat pump ranges from 20:00 to 6:00 the next day.

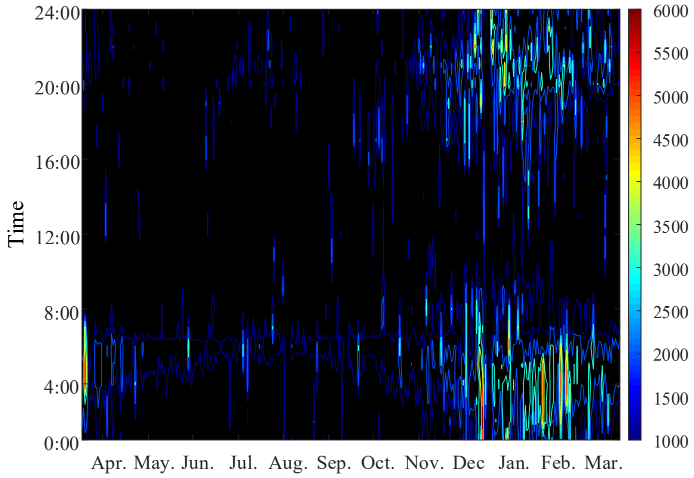


Fig 7-20 Hourly power consumed by the target household in a year

Based on the characteristic of the RTP model to balance the user load, we adjusted the operation time of the heat pump from 8:00 to 18:00 and used a water tank to store hot water to meet the user demand, to improve the phenomenon of high energy consumption at night and reduce the peak load[6][7]. January 1st, 2018 was selected as a particular day to present the hourly energy consumption of users after adjusting the operation time of the heat pump, and the result is shown in Fig 7-21.

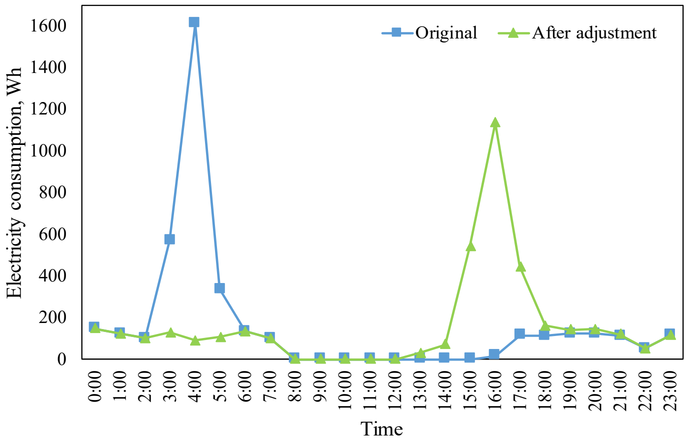


Fig 7-21 Hourly energy consumed by the user after adjustment of the operation time on the selected day

Fig 7-22 shows the annual hourly energy consumption after adjusting the operation time of the heat pump. Although, even after adjusting the operation time of the heat pump, the peak power consumed by the users continues to appear in winter due to temperature reasons, compared with the scenario before the adjustment, the hourly power consumption of users presents a contritely average state, and the peak load at night is relatively balanced with other times of the day.

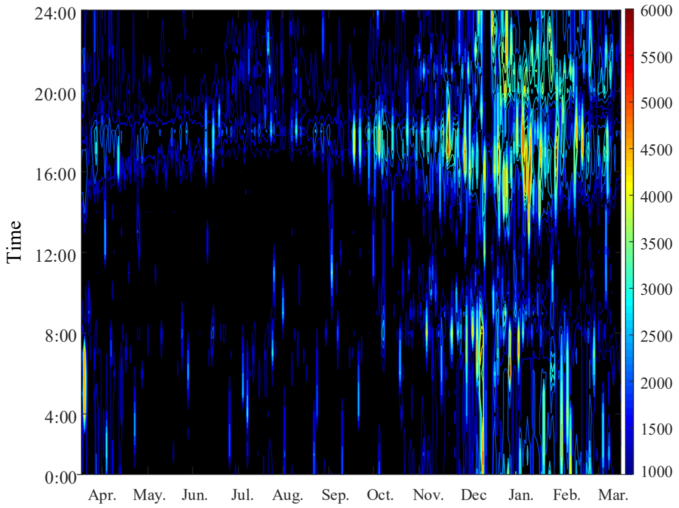


Fig 7-22 Annual hourly energy consumption after the operation time adjustment

Fig 7-23 presents the monthly electricity cost of RTP after balancing the user load. The results indicate that the use of an RTP model to balance and optimize the user load does not affect the overall trend of electricity cost, but reduces the annual total cost. The cost of electricity applied to RTP after optimizing the user load is reduced monthly compared with the original RTP. Thus, the economic advantage over MTP and TOU is more evident. The annual electricity costs before and after optimization are 125,757.3 Yen and 112,168.7 Yen respectively. The annual electricity cost calculated by the RTP model after working hours of the heat pump is 10.8% lower than that before optimization.

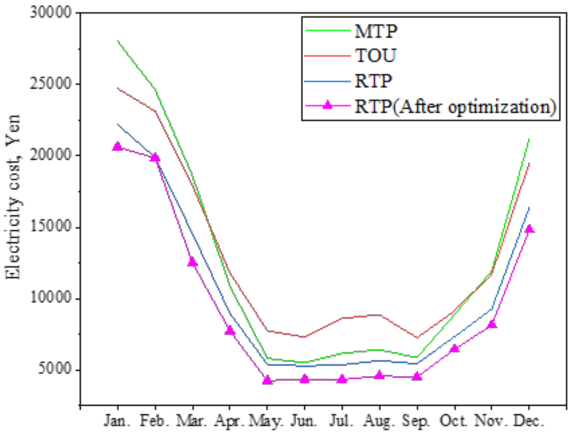


Fig 7-23 Comparison of monthly electricity cost after balancing the user load

7.5.2 Sensitivity analysis of electricity price fluctuation

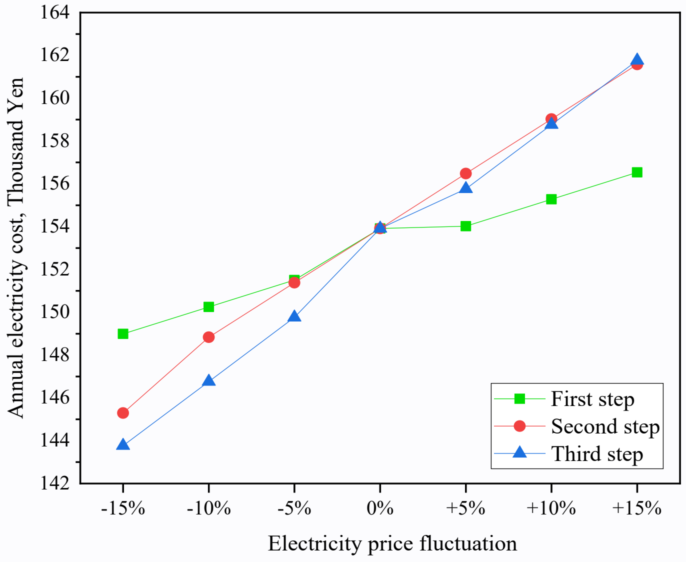
Resource shortage has always been a serious problem faced by Japan and the whole world. Power generation as the main component of energy consumption has been widely studied. To modify the power generation structure, reduce the primary energy consumption and power generation cost, some countries through electricity market liberalization to realize complementary advantages, have eliminated the trade barriers and promoted fair competition in electricity prices[8-10]. Meanwhile, the establishment of the RTP mechanism has been promoted by some countries as one an approach of power market reform. Developed countries such as the UK, France and Germany have proposed an RTP mechanism after opening the electricity market[11-15]. However, due to the lack of fierce market competition, monopoly of large power companies, and the increasing cost of power generation, the residential electricity price continues to fluctuate even the establishment of the RTP mechanism.

Considering the fluctuation in the electricity price after the implementation of the RTP scheme in other countries, a sensitivity analysis of the electricity price generated by selecting three different electricity pricing schemes is conducted within the fluctuation range of ±15%. As shown in table 7-4, to compare the effects of electricity price fluctuations in the electricity charges generated by different electricity price schemes, the fluctuation range of ±15% in the price is reflected in the electricity unit price of each stage, and the electricity charges are calculated accordingly.

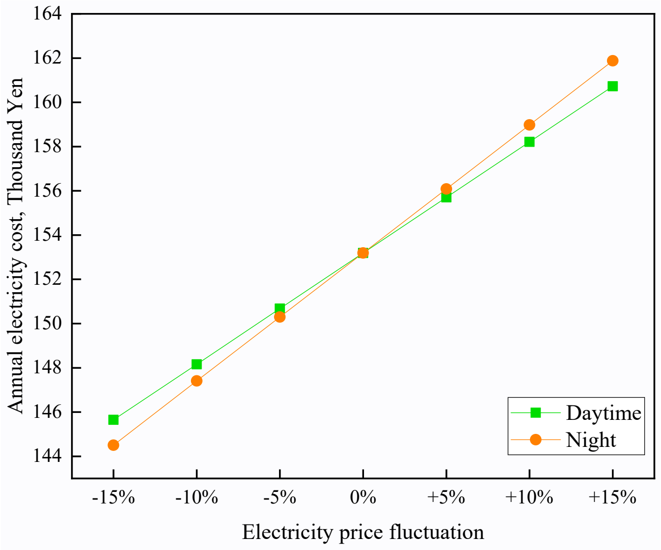
Table 7-4 Fluctuation range of unit price in different electricity price schemes

	-15% to +15% (Unit price, Yen/kWh)
MTP	First step
	Second step
	Third step
TOU	Daytime
	Night
RTP	First stage
	Second stage
	Third stage

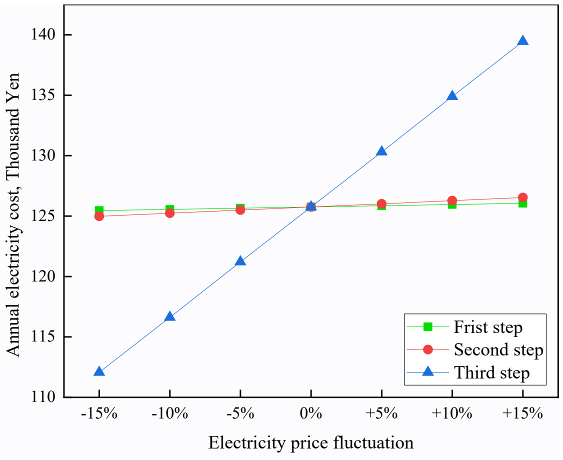
Fig 7-24 shows the annual electricity charge results obtained by adjusting the different stages of the three schemes when the unit price of electricity fluctuates within±15%.MTP is divided into three change modes according to the unit price of the three sections. The annual electricity charges under the three variation modes are obtained. When the unit price of electricity is reduced, the electricity charge obtained by adjusting the unit price in the third step results in the lowest electricity cost; in contrast, when the electricity unit price is increased, the electricity cost of adjusting the unit price in the first step is the least. Similarly, according to the peak valley price, TOU can be divided into daytime and night modes and the three-tier linear ladder model of RTP can be divided into three variation modes. To compare the electricity cost of the three schemes under the fluctuating unit price, we select the minimum electricity charge case of the three schemes, as shown in Table 7-5.



(a) Annual electricity charge of MTP



(b) Annual electricity charge of TOU



(c) Annual electricity charge of RTP

Fig 7-24 Annual electricity charge under fluctuating electricity unit price in different schemes

Table 7-5 Case of minimum electricity cost change

	-15%~0%	0%~+15%
MTP	Third step	First step
TOU	Night	Daytime
RTP	Third stage	First stage

Fig 7-25 presents the comparison result of the minimum electricity cost case among the three schemes. There is a little difference between the electricity costs generated by MTP and TOU when the electricity unit price drops. However, when the unit price increases, the electricity charge generated by TOU is less than that generated by MTP. Additionally, in the fluctuation range of the unit price, the annual total electricity price under RTP is always less than those under MTP and TOU.

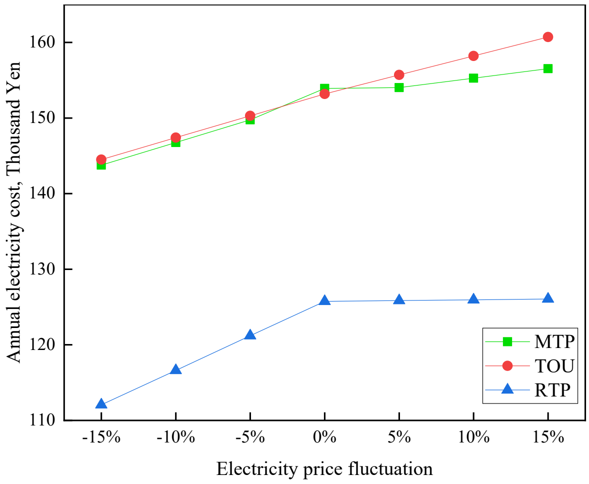


Fig 7-25 Case comparison of minimum electricity cost between the three schemes

7.5.3 Method adaptability verification

In this study, a smart house that used a hybrid PV and heat pump as the energy system was selected and HEMS was used for energy management. Based on the developed short-term load prediction model and RTP model, the annual electricity costs of the target household with MEP, TOU, and RTP under the three scenarios of basic situation, adjustment of equipment operation time, and future electricity price fluctuation were compared and analyzed. The analysis results indicated the economic advantages of the target household selecting RTP under the three scenarios.

A hybrid PV and heat pump system is a typical energy system used in Japanese households to achieve the goals of energy-saving and emission reduction. Considering the characteristics of cogeneration and the use of clean energy, a residential fuel cell system was implemented in Japan in 2008. Meanwhile, Japan gas company proposed a “double power generation” mode, which is a power generation method for hybrid residential fuel cells and PV systems. Because such a system is advantageous in terms of environment and economic performance compared with traditional residential energy systems, it is gradually becoming a potential residential energy system to be used in the future. Both the hybrid PV and heat pump system and hybrid PV and fuel cell system belong to the residential energy system promoted by Japan to achieve the goal of low carbon- and energy-savings.

To validate the adaptability of the proposed method, we selected a residential house with a hybrid PV and fuel cell system to analyze the annual electricity costs incurred under the three pricing strategies. The short-term load forecasting model and RTP model were applied to the calculated result. Fig 7-26 depicts the monthly energy consumed by residential buildings. Unlike the target house’s peak energy consumption in winter, the peak consumption of the testing house mainly occurred in July and August in summer. The main reason for the different energy consumption peaks is attributed to the difference in the operating characteristics of the heat pumps and fuel cells in the energy system. The target residence mainly relied on a heat pump to obtain hot water in winter, which consumed more electricity. However, the thermal demand of the testing house was mainly satisfied by the natural gas consumed by the fuel cell, and thus, the testing house consumed lesser electricity than the target house in winter.

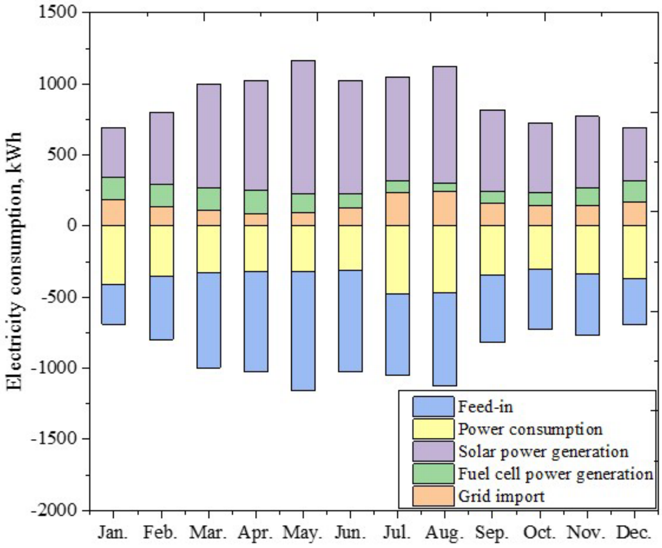


Fig 7-26 Monthly electricity consumed by the testing residence in one year

Fig 7-27 illustrates the annual electricity cost comparison incurred under the three pricing strategies applied to the target residence and testing residence. Although the electricity loads of the target and testing residences differed, their annual electricity costs exhibited a similar trend. Although the monthly cost difference of the three pricing strategies varied with the change in power consumption, in all cases, RTP exhibited economic advantages over MEP and TOU. This advantage became evident in case of high energy consumption.

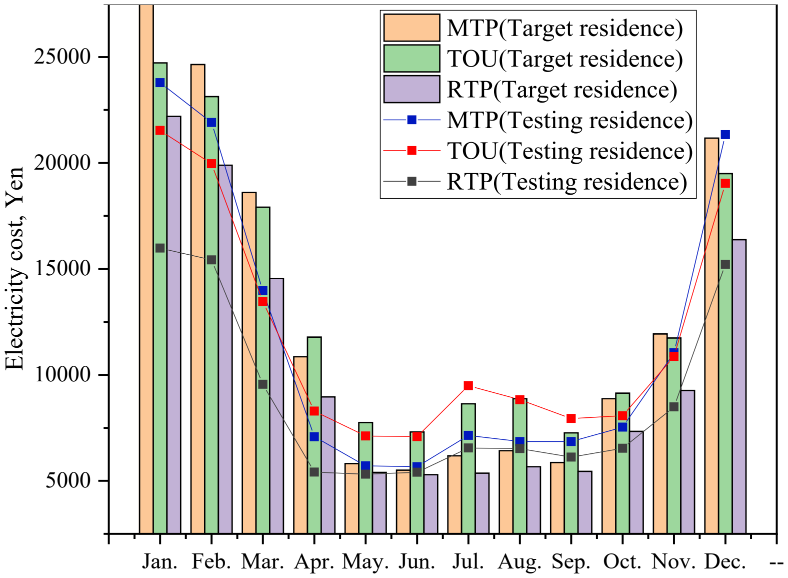


Fig 7-27 Comparison of the annual total electricity cost incurred by the target residence and testing residence under the three pricing schemes

7.6 Summary

Faced with the problem of primary energy shortage, residential energy consumption has been a main objective of Japan's energy conservation and emission reduction strategy. HEMS as a hub in smart house which connecting the supply and demand sides, realizes the function of two-way communication between users and power companies. At present, most consumers select MTP and TOU as the modes to calculate electricity charges. According to the characteristics of real-time monitoring and feedback of energy consumption data in HEMS, Japan electric power company has not yet developed an applicable RTP scheme. Here, a smart house integrated with HEMS in the Jono area in Japan was selected as the case study, and the short-term load forecasting of user energy consumption was conducted based on the historical data. An RTP model was established based on the consumer's load forecast results of the next day, with an aim to reduce the annual electricity cost incurred by the user by adjusting their energy consumption behavior and transferring the peak load. The main conclusions of this study are summarized as follows.

(1). Three algorithms, PSO-RVM, PSO-SVM and BPNN are used to predict the short-term load of the target household and their prediction accuracies are evaluated and compared. According to the evaluation result, the short-term load forecasting model based on PSO-RVM has the least error compared with the measured data, and is most suitable for short-term load forecasting of residential energy.

(2). An RTP model is established and the load of the power grid can be adjusted to guide users' electricity consumption behavior through the model. This model is compared with MTP and TOU, and the annual electricity charges of the three pricing schemes are calculated according to the prediction results of the short-term load forecasting model. The result indicates that the annual electricity cost generated by RTP is less than that generated by MTP and TOU, and RTP's economic advantage becomes evident in case of high energy consumption. Moreover, the electricity charges generated by the three schemes are also affected by seasonality. In winter, the annual electricity cost evidently differs between RTP and MTP in winter, whereas in summer, RTP and TOU significantly differ.

(3). According to the analysis of the annual hourly power consumed by the users, the main energy consumption period is at night in winter. As the main energy consumption equipment in winter, the operation time of the heat pump in the target residence is concentrated from 20:00 to 6:00 the next day. To improve the phenomenon of high energy consumption at night and reduce the peak load, the operation time of the heat pump is adjusted from 8:00 to 18:00 based on the characteristics of the RTP model to balance the user load. The cost of electricity applied to the RTP after optimizing the user load is reduced monthly compared to the original RTP. The annual electricity charge calculated by the RTP model after adjusting the working hours of the heat pump is 10.8% lower than that calculated before optimization. The results of the electricity price comparison illustrate that the combination of RTP and demand side response exhibits great potential for future use.

(4). Considering the price fluctuations that may have been generated by the adjustment of the electricity market, we forecast the unit price of electricity in Japan to be within±15%, and calculate the changes in the annual electricity prices caused by price fluctuations under three electricity pricing schemes. The result shows that with an increase in the electricity unit price, the economic advantage of TOU becomes more evident than that of MTP. In the fluctuation range of unit price, the annual total electricity cost generated by RTP is always lower than those generated by MTP and TOU.

At present, Japan's electric power company has not developed a relevant charging scheme for RTP. However, with the gradual promotion of smart house and HEMS, real-time visualization of energy will become the main trend of residential energy management. A reasonable RTP scheme can enable users to adjust their energy consumption behavior and reduce electricity charges by balancing the user load, which has a positive effect and promotion significance for the future development of the Japanese electricity market.

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Chapter 8

CONCLUSION AND PROSPECT

CHAPTER EIGHT: CONCLUSION AND PROSPECT

8.1 Conclusion

In recent years, with the improvement of people's living standards and the popularization of smart appliances, household power consumption shows an upward trend. Reasonable energy management combined with efficient and energy-saving equipment is an effective way to achieve energy conservation and emission reduction in the household sector. At present, the research and promotion of smart house in Japan are gradually increasing, and the government has also implemented relevant incentive policies. Smart house is an energy-saving residence combining renewable energy utilization and efficient energy supply equipment. At the same time, home energy management system (HEMS) in smart house has the characteristics of real-time monitoring and energy consumption intelligent management, and can realize two-way communication between users and power companies. At the same time, the combination of different equipment in the smart house energy system can also produce different energy-saving and emission reduction effects for various types of users. Based on the characteristics and advantages of smart house, this study analyzes and compares the economy and environment of different energy systems in smart house, and optimizes the economy from the three levels of users, equipment, and power market.

The main works and results can be summarized as follows:

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY, introduced the energy background of the world and Japan. Then through the analysis of the characteristics of energy background, it shown the energy consumption of the household sector is increasing year by year. After that, the development and application of smart house and the significance and purpose of application was explained. Finally, introduced the energy supply equipment and energy storage equipment in the smart house energy system o, and highlights the advantages of smart house through the utilization of renewable energy, real-time monitoring, high efficiency, and energy saving.

In Chapter 2, LITERATURE REVIEW OF SMART HOUSE, is mainly to sort out the research status of smart house. First of all, through the review of the research on the advantages and application of smart house in various countries, the current status and trends of the smart house promotion were explained. Combined with the current research and popularization of smart house, it is pointed out that there are still some problems in smart house, such as high investment cost and complex operation. Then it shown that the current research focus on smart house is economic optimization. Next, different optimization methods of smart house energy system was reviewed, such as combined with energy storage equipment, combined with renewable energy utilization, and selection of different electricity price schemes. Finally, according to the research object of this article, the incentive policies implemented by various countries in order to popularize smart house were carried out.

In Chapter 3, MODEL ESTABLISHMENT AND FORECASTING METHOD RESEARCH, is about methodological research and model building. Firstly, the software TRNSYS for energy system energy consumption simulation was expounded. Based on TRNSYS, a smart house energy system with different combinations of energy supply equipment is established, and the annual energy consumption of the system is simulated. The economy and environment of different systems are compared. Then, based on MATLAB, a double-layer optimization model is established to double optimize the energy storage equipment capacity and annual output of the smart house energy system with energy storage equipment as the goal of cost minimization. Combined with the characteristics of two-way communication in smart house, a short-term load forecasting model is established to predict the power load of users the next day according to the measured data. At the same time, combined with the development of power market, a real-time electricity price model is established to reduce power cost.

In Chapter 4, INVESTIGATE AND ANALYZE THE CHARACTERISTICS OF ENERGY CONSUMPTION IN SMART HOUSE AREA, firstly, the research object is introduced, and the completion of Jono smart house area, surrounding facilities and energy system application information are explained. Next, the questionnaire results of users living in Jono area are sorted out. The questionnaire includes family member composition, energy equipment use, energy conservation and environmental protection awareness and so on. The results of the questionnaire show that living in smart house is conducive to improve users' awareness of energy conservation and environmental protection. At the same time, the application of smart house energy system can also save users' power cost. After that, this part utilizes the monitored history data to analyze the energy consumption characteristics and influencing factors of the residential customers, which feature with heat pump heat supply system in smart house. The result show that there is no obvious relationship between stay-in-home time and power consumption. This may be related to the different power consumption behavior of users and the running time of heat pump.

In Chapter 5, PERFORMANCE COMPARISON OF MULTI-ENERGY SUPPLY SYSTEM IN SMART HOUSE, the energy consumption scenario of Japan typical households in the Jono smart house area is presented. The energy consumption and performance of energy supply equipment is analyzed based on one year's monitor data. The results show that HFPS has a better environmental performance than HHPS, but in terms of economic analysis, HHPS presented an economic advantage over HFPS. In addition, this part also lists five kinds of electricity price schemes of electric company. The electricity costs of HFPS and HHPS were calculated based on five cases. The results of this part provide policy guidance for the future Japanese government's promotion of residential fuel cell systems, while choosing the optimal path between user energy characteristics and power contract scheme.

In Chapter 6, ECONOMIC OPTIMIZATION OF COMPOSITE ENERGY STORAGE SYSTEM IN SMART HOUSE, the application and existing problems of residential distributed energy system are introduced, which leads to the concept of microgrid. Then, based on the research status of microgrid, it is proposed that the combination with energy storage equipment can realize economic optimization. After that, an independent smart house in “Jono smart house area” in Japan is selected as the research object. Relies on one year measured data, four cases are designed according to the introduction of different energy storage equipment. A double-level optimization model is established based on adaptive particle swarm optimization algorithm to optimize the size of energy storage equipment and system annual equipment output. The upper model optimizes the optimal size of energy storage equipment, and the lower model simulates the annual optimal equipment output according to the upper results. In addition, the system performance of the four cases is compared and analyzed from three aspects of energy, environment and economy based on the comprehensive comparison model. The hourly energy consumption simulation results state that the addition of energy storage equipment plays a positive role in reducing users' peak load and electricity purchase cost and can cooperate with PV and heat pump. The results act as a useful reference for users to reasonably match energy supply and storage equipment to achieve cost reduction, while providing policy suggestions for the government to further carry out relevant research and industrial development in user-side energy storage.

In Chapter 7, INFLUENCE OF POWER MARKET FLUCTUATION ON SMART HOUSE ELECTRIITY COST AND FUTURE DEVELOPMENT SUGGESTIONS, the residential electric cost with different electricity pricing model is compared. First, the research object of this study is a two-story detached smart house integrated with HEMS in the “Jono smart house area” in Japan. Next, to predict the energy consumed on the next day based on historical data, a short-term household load forecasting model based on the particle swarm optimization regression vector machine algorithm was developed. Then a dynamic pricing model was developed to guide the users' electricity consumption behavior and adjust the grid load. According to the prediction results obtained by the load forecasting model, the annual electricity charges of users under the three pricing schemes of multistep electricity pricing (MEP), time-of-use pricing (TOU), and real-time pricing (RTP) were calculated and compared. In addition, after adjusting the users’ peak load and combining it with the fluctuating future electricity prices, RTP presented evident economic advantage over MTP and TOU in terms of the annual electricity cost of the users. The study results can provide policy suggestions for the future Japanese government’s promotion of RTP strategy, while acting as a reference for further developing the characteristics of HEMS and optimizing the relation between the supply and demand sides.

In Chapter 8, CONCLUSION AND PROSPECT have been presented.

To summary, based on the characteristics and advantages of smart house, this research compares and optimizes the economy of smart house systems composed of different energy equipment. Comparative research on three different levels of users, equipment, and power market was conducted.

At the user level, smart housing can not only improve users' awareness of energy conservation and emission reduction, but also reduce electricity charges to a certain extent. However, there are still some problems in the smart house energy system, such as high equipment price, high investment cost and complex system operation. Meanwhile, as for the impact of occupation on the load consumption, the result show that there is a low correlation between power consumption and indoor hour, and the number of family members has a significant impact on the power consumption.

At the equipment level, the energy systems composed of two different equipment are compared. The results show that HFPS has a better environmental performance than HHPS, but in terms of economic analysis, HHPS presented an economic advantage over HFPS. In addition, the carbon tax and fuel cell price fluctuation will have a positive impact on the economy of HFPS. And the price fluctuation of fuel cell equipment is the main factor affecting the economy of HFPS. When the price reduced to 800,000Yen, HFPS be economic competitive compared with HHPS. Meanwhile, choosing the appropriate electricity price scheme is also a way to optimize the system economy. In the scenario of applying different energy storage equipment, the hourly energy consumption simulation results state that the addition of energy storage equipment plays a positive role in reducing users' peak load and electricity purchase cost and can cooperate with PV and heat pump.

At the power market level, although the Japan’s electric power company has not developed a relevant charging scheme for RTP, but according to the simulation result of RTP model, indicates that the annual electricity cost generated by RTP is less than that generated by MTP and TOU, and RTP’s economic advantage becomes evident in case of high energy consumption. Considering the price fluctuations that may have been generated by the adjustment of the electricity market, he result shows that with an increase in the electricity unit price, the economic advantage of TOU becomes more evident than that of MTP. In the fluctuation range of unit price, the annual total electricity cost generated by RTP is always lower than those generated by MTP and TOU.

Smart home can effectively improve the economic benefits of residential energy system, and the home energy management system can also realize the functions of real-time monitoring of energy consumption data and two-way communication, so as to strengthen the management of equipment and the regulation of power consumption behavior. At the same time, the popularization of smart home will also greatly accelerate the realization of energy conservation and emission reduction targets. It is hoped that this study can provide new ideas for the promotion of smart home and provide theoretical reference for the practical application of smart home.

8.2 Prospect

For prospect, with the expansion of the research scope of smart house, the promotion of smart house and the effect of energy conservation and emission reduction will be gradually enhanced. However, it is found that there is still room for further improvement in the application and popularization of smart house.

At present, the power market is still in the preliminary stage of the electricity price scheme implemented to cooperate with the smart house, and the characteristics of energy consumption monitoring and prediction and real-time communication of the smart house have not been brought into full play. At the same time, the high equipment price is also one of the obstacles in the promotion of smart house. At this stage, the relevant incentive policies and subsidies issued by the government are only applicable to some regions, and there are also requirements for the installation quantity of equipment. Therefore, shortening the payback period of smart house energy system is also one of the key points of optimization.

At the same time, with the fluctuation of energy prices in the future, the economy of different smart house energy systems will also be affected to varying degrees. This paper mainly focuses on the comparison and optimization of smart house systems composed of different equipment. The optimization of equipment energy efficiency and the effect of combining new energy equipment still need in-depth research.

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