博　士　論　文

INTEGRATED ASSESSMENT OF BUILDING DISTRIBUTED ENERGY SYSTEMS IN DIFFERENT CLIMATE ZONES OF JAPAN AND CHINA

日中地域別における分散型エネルギーシステムの総合評価に関する研究

2015 年 1 月

呉　瓊

QIONG WU

ACKNOWLEDGEMENTS

There are a number of people without whom this thesis might not have been written and to whom I am greatly indebted.

First of all, I would like to express my deep gratitude and appreciation to my advisor, Prof. Weijun GAO of the University of Kitakyushu, who has guided me a lot so that I can accomplish this thesis. Thanks for his patience, motivation, enthusiasm, and immense knowledge. Apart from the study, he also gives me much help and instruction for my daily life.

Furthermore, I wish to thank Prof. Yuji RYU and Prof. Yasuyuki SHIRAISHI of the University of Kitakyushu for their careful reviewing and advice on my thesis.

Also, thanks to Prof. Jianxing REN of Shanghai University of Electric Power, for his encouragement and insightful comments as well as for his advice on my research throughout my doctoral course.

I am very grateful to all members in Gao Lab, for the friendly and honest study environment that I enjoyed for many years. I wish to thank all the help and encouragement that I have received from my school mates and friends: Jianan LIU, Lianping XU, Danhua WU, Liyang FAN and Yao ZHANG, for all the fun we have had in the last three years.

I would also like to express my deepest thanks to my beloved husband who has endured the most stressful period of completing the degree right by my side, giving me support, encouragement, and comfort.

Last but not least, many thanks to my parents, for their love encouragement and supports mentally that made me possible to finish this study. Thanks for giving birth to me at the first place and supporting me spiritually throughout my life.

Integrated Assessment of Building Distributed Energy Systems in Different Climate Zones: Japan-China Comparison

ABSTRACT

Over the past few years, distributed energy resources (DER) have been receiving increasing attention as alternatives to centralized generation. It has been recognized as a good option for future energy system with respect to sustainable development and low-carbon society construction. Usually, DER means small scale electric generation units located within the electric distribution system at or near the end-users. Compared with traditional central energy supply, DER can employ a wide range of technologies including: combined heat and power (CHP), photovoltaic (PV), wind turbine and biomass system, as well as all kinds of energy recovery and storage equipments.

As is well known, the design and operation of distributed energy system is greatly dependent upon local atmospheric conditions, which on one hand, may determine building energy (thermal, especially) demands, on the other hand, affect the power generation of various technologies. For example, solar radiation intensity is a key factor which affects the electricity generation efficiency of PV unit. Thus, it is necessary to make a comparison of DER system performance in different climate zones in both Japan and China which have large diversity in climates. These diversities and complexities have led to many different climates with distinct climatic features.

In this study, various cities in different climate zones which selected from Japan and China respectively will be analyzed for the introduction of DER systems. To be detailed, Harbin, Beijing, Shanghai, Kunming and Guangzhou in China, as well as Sapporo, Hachinohe, Sendai, Tokyo, Kagoshima and Naha in Japan are selected for analysis.

In Chapter 1, PREVIOUS STUDY AND PURPOSE OF THE STUDY, current energy and environmental situations, as well as the feasibility and necessity to introduce the distributed energy system are presented. In addition, current situation of global distributed energy system (CHP and PV mainly) adoption were investigated briefly. Furthermore, the previous studies about the design and assessment of DER systems in Japan and China have been reviewed. Based on the background, the purpose of current research is proposed.

In Chapter 2, INVESTIGATION ON CURRENT ENERGY SITUATION AND DISTRIBUTED ENERGY SYSTEM ADOPTION IN JAPAN, the supply and consumption of energy and electricity in Japan are summarized. In addition, current

status of CHP system as well as PV system adoption in Japan is investigated. Moreover, the policies for CHP system and PV system adoption so far are summarized.

In Chapter 3, INVESTIGATION ON CURRENT ENERGY SITUATION AND DISTRIBUTED ENERGY SYSTEM ADOPTION IN CHINA, the supply and consumption of energy and electricity in China are summarized. In addition, current status of CHP system as well as PV system adoption in China is investigated. Moreover, the policies for CHP system and PV system adoption so far in China are summarized.

In Chapter 4, OPTIMIZATION AND EVALUATION METHODS FOR DISTRIBUTED ENERGY SYSTEM ADOPTION, firstly, based on a mathematical optimization approach where the design and structure of the energy system as well as the operation of each component are optimized, a MILP (mixed integer linear programming) problem of a distributed energy system was formulated and presented minimizing annual operating cost while guaranteeing resilience of the electricity and heating demand. The model is used to analyze the optimal design, running strategy of the DER system. Secondly, various kinds of assessment method adopted in this paper were presented in a detailed way, including multi-criteria analysis, net present value and so on.

In Chapter 5, REGIONAL ANALYSIS OF COMBINED COOLING HEATING AND POWER SYSTEMS IN JAPAN AND CHINA, regional analysis of CCHP systems in Japan and China were implemented respectively in a detailed way. Firstly, the detailed information of selected cities in Japan and China is described. Then, annual energy loads including electricity, cooling, space-heating and water-heating of various building (store, office, hospital, hotel and apartment) located in different cities within two countries are calculated. Furthermore, the economic and technical assumptions such as the price for natural gas and efficiency of CCHP system are introduced. Base on the above assumptions, the way of CCHP systems capacities selection is introduced and the hourly operation strategy is deduced. In addition, the energy, economic and environmental performances of the CCHP systems for various building types located in different climate zones (cities) are assessed and compared.

In Chapter 6, REGIONAL ANALYSIS FOR PHOTOVOLTAIC SYSTEM ADOPTION IN JAPAN AND CHINA, the hourly operation strategy as well as energy, economic and environmental performance of PV system are assessed within various building types of different cities located in Japan and China.

In Chapter 7, INTEGRATED ASSESSMENT FOR HYBRID CCHP, PV AND BATTERY DISTRIBUTED ENERGY SYSTEM ADOPTION: JAPAN-CHINA COMPARISON, by employing the aforementioned optimization method, the hourly running strategies of residential hybrid PV/CHP/battery energy supply system located in different climate zones in Japan and China are compared and analyzed. Again, the environmental and economical performance of the hybrid system are assessed in a detail way.

In Chapter 8, CONCLUSIONS AND PROSPECTS, a conclusion of whole thesis is deduced and the future study about the plan and evaluation of distributed energy systems has been discussed.

呉　瓊 博士論文の構成

Integrated Assessment of Building Distributed Energy Systems in Different Climate Zones: Japan-China Comparison

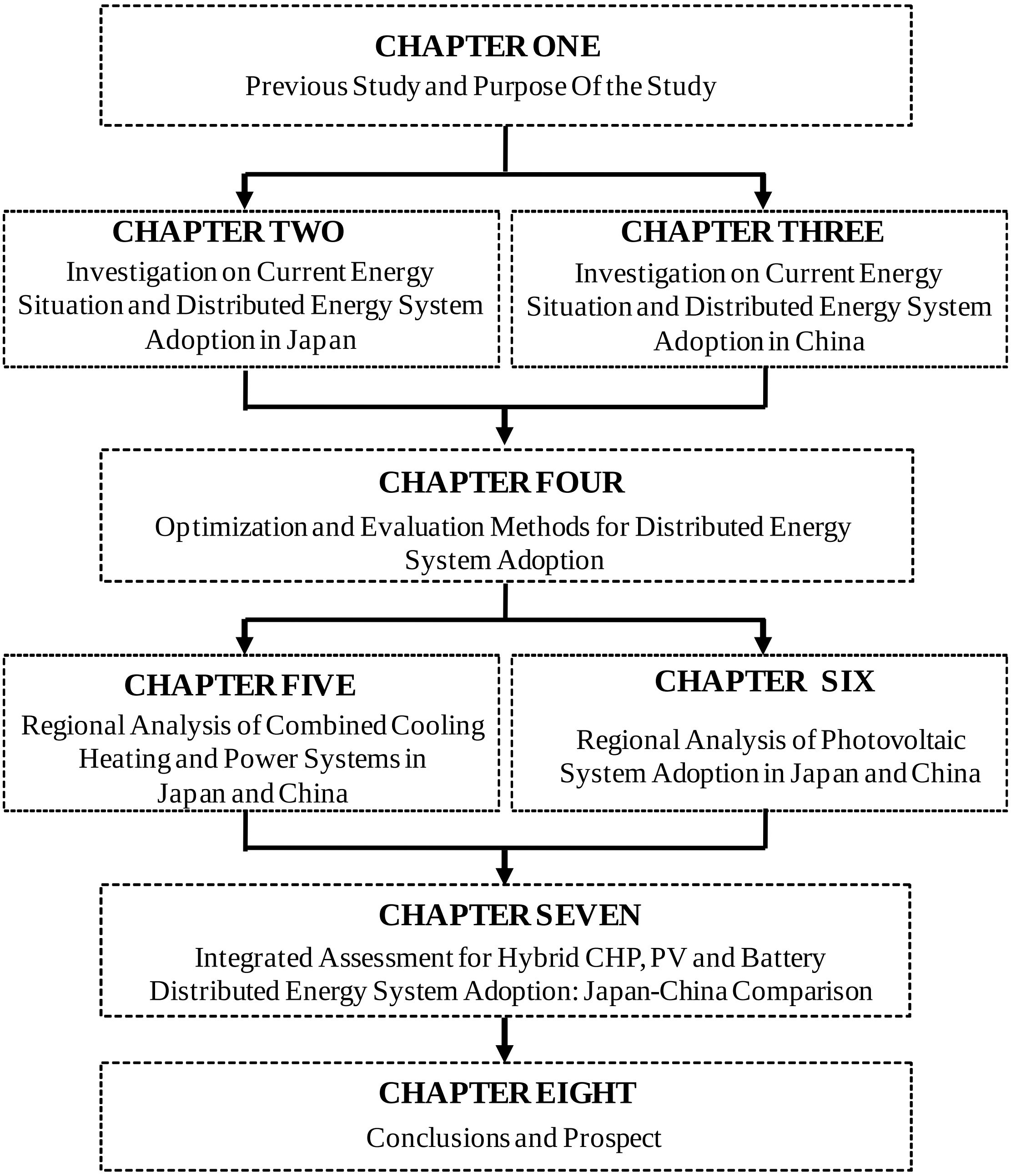


TABLE OF CONTENTS

CHAPTER ONE: PREVIOUS STUDY AND PURPOSE OF THE STUDY

1.1 Introduction

Since the 21st century, energy consumption and environmental pollution have become more and more serious due to the continuous consumption of fossil fuels which accounts for as much as 81.2% of total energy consumption according to the World Bank. As we all know, this trends in energy use are not sustainable which have resulted in not only extensive emissions of local air pollutants (SO_2, NOx, etc.), but also great press on the global environmental issues (CO_2 emissions). Furthermore, the worldwide energy consumption has been increasing rapidly almost exponentially since the industrial revolution. This increasing trend has been also accelerated by the improvement of the quality of life that directly relates to the amount of energy consumption, as well as the industrialization of the developing nations. Fig. 1-1 shows the world primary energy consumption and CO_2 emissions from 1991 to 2013. Generally, energy use shows a rising trend except for the year 2009 and 2012. Because of the worldwide economic downturn, energy consumption in 2009 decreased about 1% than that of 2008. However, the value soared by more than 5% in 2010 after the slight decrease and over passed 2008.

As to the world CO_2 emissions, it has increased to 36 billion ton in 2013, which is 1.7 times of that in 1991. It is said that China has become the largest country of CO_2 emissions and 70% of global increased CO_2 emission is from China. Again, in order to avoid the dependence on nuclear, some developed countries (e.g. Japan and Germany) begin to use coal instead. If it is not solved in a good and efficient manner, not only will human society be beyond the goal of sustainable development, but it will also make a serious impact on the living environment and quality of human society.

Among the total primary energy consumption, oil took a share of about 36%, followed by gas (27%), coal (19%), nuclear (8%), biomass (5%), hydroelectric resources (3%) and other renewables (2%) (see Fig. 1-2a) [1].

Furthermore, according to the profile shown in Fig. 1-2b, among the total final energy consumption, the building sector took up the main share with a value of about 34%, followed by transport and industry. Especially, in Asia, as the improvement of people's living quality and the acceleration of urbanization process, there is a dramatic increase in building energy consumption in this region. It was reported that the building sector accounted for approximately one third of the region's total energy consumption, and the value was projected to increase to an even higher value in the coming future. In China, building energy consumption occupies about 27% of total energy consumption which is lower than developed countries for the lower life quality, whereas as the economic structure adjustment and the improvement of people's living standards, the building energy consumption proportion must show a rising trend. The increasing in building energy consumption leads to more building-related impacts and environmental issues. For this reason, energy efficiency in buildings is today a prime objective for energy saving and environmental protection.

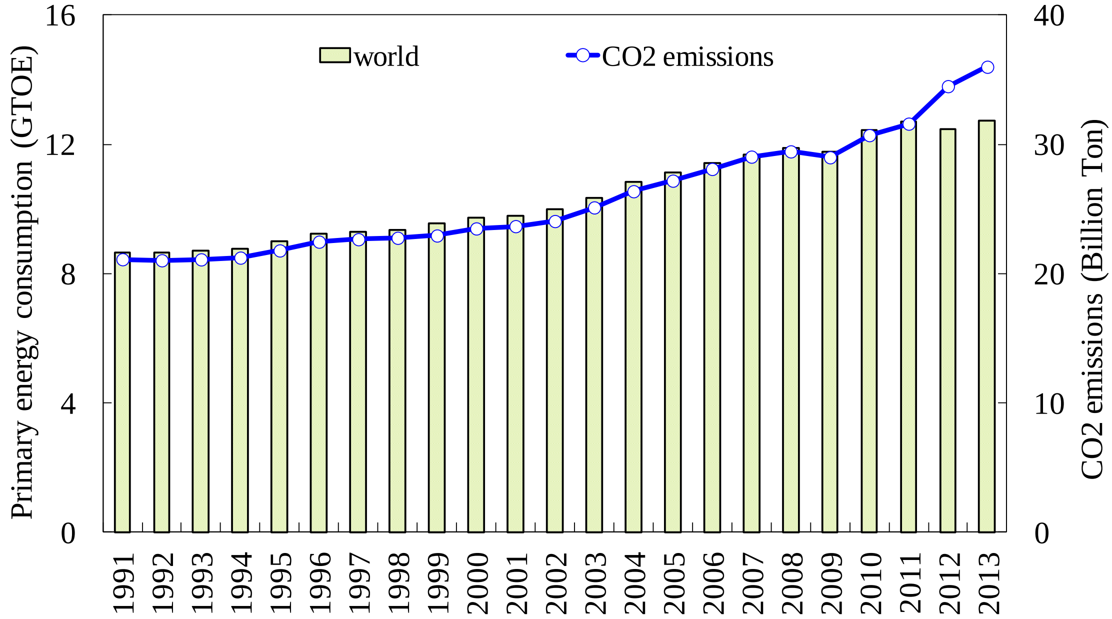
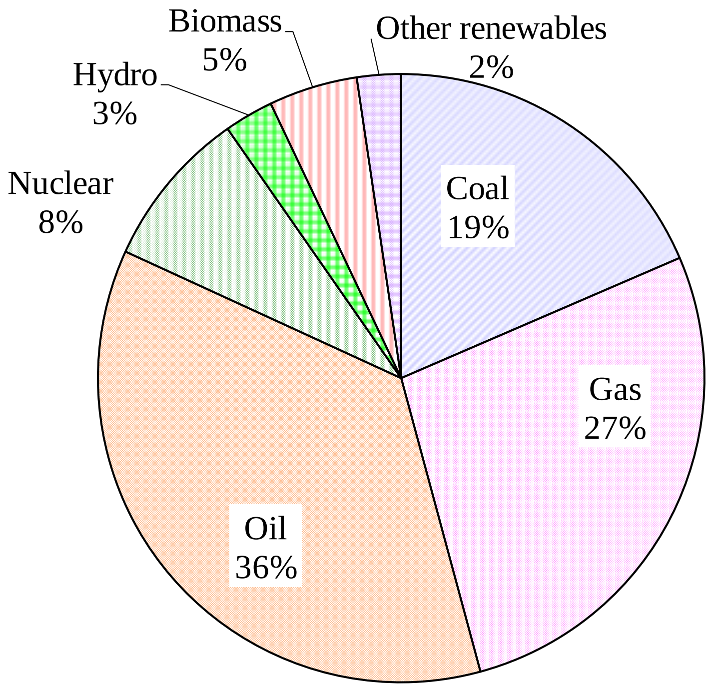
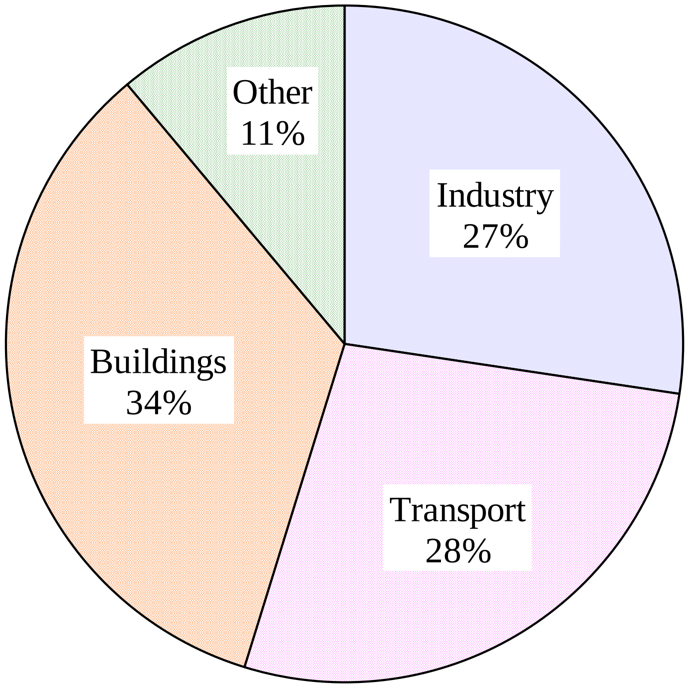


Fig. 1-1 World primary energy consumption and CO_2 emissions

(Source: World Energy Outlook 2014)



(a) Primary energy supply



(b) Final energy consumption

Fig. 1-2 Share in primary energy supply and final energy consumption in 2012

(Source: World Energy Outlook 2014)

1.2 Present situation of distributed energy worldwide

The shortage of energy and environmental problem has persuaded many countries to find alternative ways to succeed the current carbon-based energy system which must be secure, environmentally acceptable, technically easily, economically competitive, and readily available. The current fossil fuel systems must be changed gradually to clean and reliable energy systems, enabling to reach the sustainable vision of future energy systems. Among various alternatives to reduce building energy consumption, distributed energy resource (DER) has been receiving increasing attention as a good option for future building energy system with respect to sustainable development and low-carbon society development [2-3]. DER is a suite of on-site, grid-connected or stand-alone technology systems that can be integrated into residential, commercial, or institutional buildings and/or industrial facilities. These energy systems include distributed generation, renewable energy sources and hybrid generation technologies, energy storage, thermally activated technologies that use recoverable heat for cooling, heating or power, transmission and delivery mechanisms, control and communication technologies and demand-side energy management tools. Such distributed resources offer advantages over conventional grid electricity by offering end users a diversified fuel supply, higher power reliability, quality and efficiency, lower emissions and greater flexibility to respond to changing energy needs. It can be divided into two major kinds from the technical points of view. The first kind is on-site renewable energy sources, including photovoltaic, biomass energy, small-scale wind and water turbine generators, and so on.

1.2.1 Present situation of PV system

There are five kinds of solar energy including solar-heat, solar-electricity, solar-solar, solar-chemistry, as well as biological in which solar-electricity indicates photovoltaic (PV) that is a method of converting solar energy into direct current electricity using semiconducting materials that exhibit the photovoltaic effect. The direct conversion of sunlight to electricity occurs without any moving parts or environmental emissions during operation, thus, after hydro and wind power, PV has become the third most important renewable energy source in terms of globally installed capacity. Fig. 1-3 shows global cumulated PV system capacity from 2005 to 2013. Generally, the capacity shows a rising trend and grows rapidly, which has reached 100 GW by 2012, 11 times than that in 2007. By the end of 2013, the value has reached 136.7 GW yet. As to the newly installed PV capacity each year, in 2007, it is just 2.5 GW of new power capacity; whereas, by 2013, the global new PV power capacity has passed 35 GW.

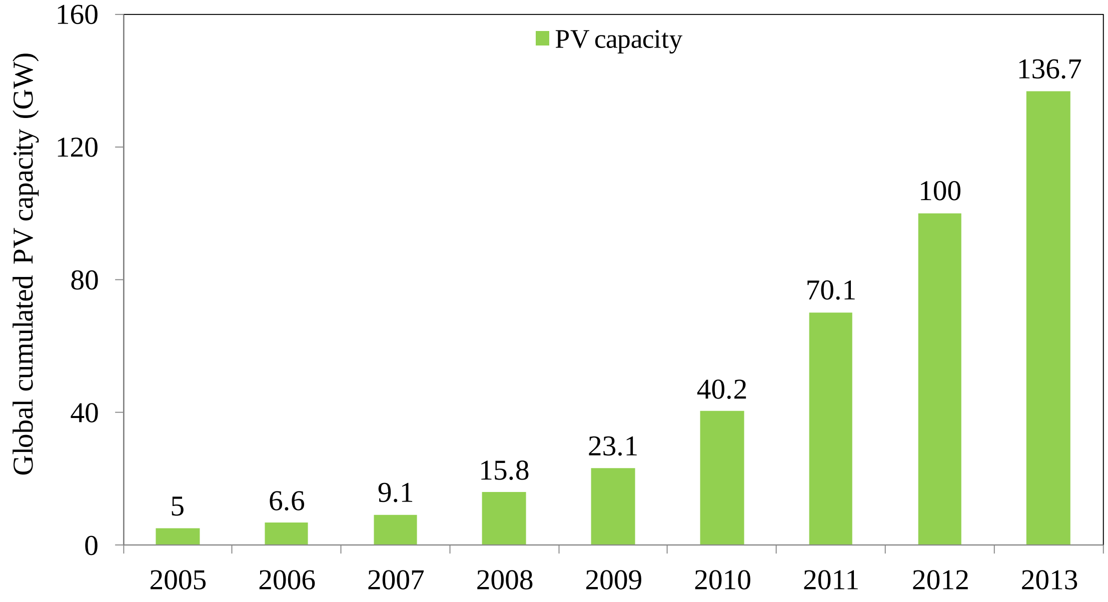


Fig. 1-3 Global cumulated PV unit capacity (GW)

(Source: World Energy Outlook 2014)

Fig. 1-4 shows the PV system capacity proportion of main countries. China, followed by Italy and the United States, is now the fastest growing market, while Germany remains the world's largest producer, contributing almost 6 percent to its national electricity demands. By the end of 2013, the accumulated PV system capacity is 35.72GW in Germany, which accounted for 32.7% of global PV capacity. The following one is Italy, the value of which is 17.66 GW, accounted for 16.6% of the world. China is the forth largest, accounting for 6.9% of the world and followed by Japan which occupied 6.7% of the world respectively. Furthermore, it worth note that generally, the PV system in Germany, America and Japan always refer to small scales within distributed energy system, which even occupied as much as 95% of total installation capacity in Japan. Whereas, the PV systems in China and Italy always have large scales. By the end of 2013, PV system with large scales accounted for about 64% of total PV capacity in China.

As to the PV cell production, Japan is the largest producer by 2007, while China has passed Japan and become the largest country in 2013 which contributes 62.6% of total production followed by other Asian countries (without Japan and China), Japan, Europe and America.

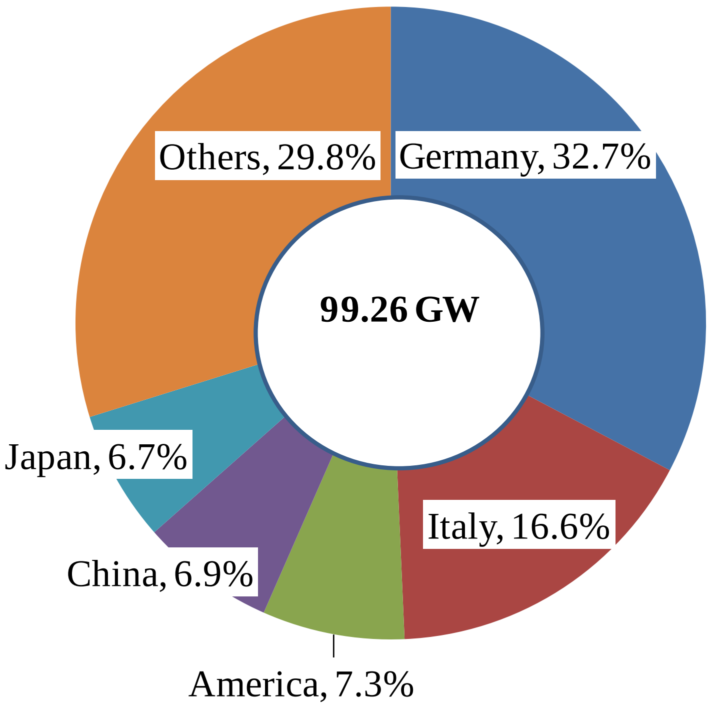


Fig. 1-4 Accumulated PV system capacity proportion by main countries in 2012

(Source: Japan energy white paper 2014)

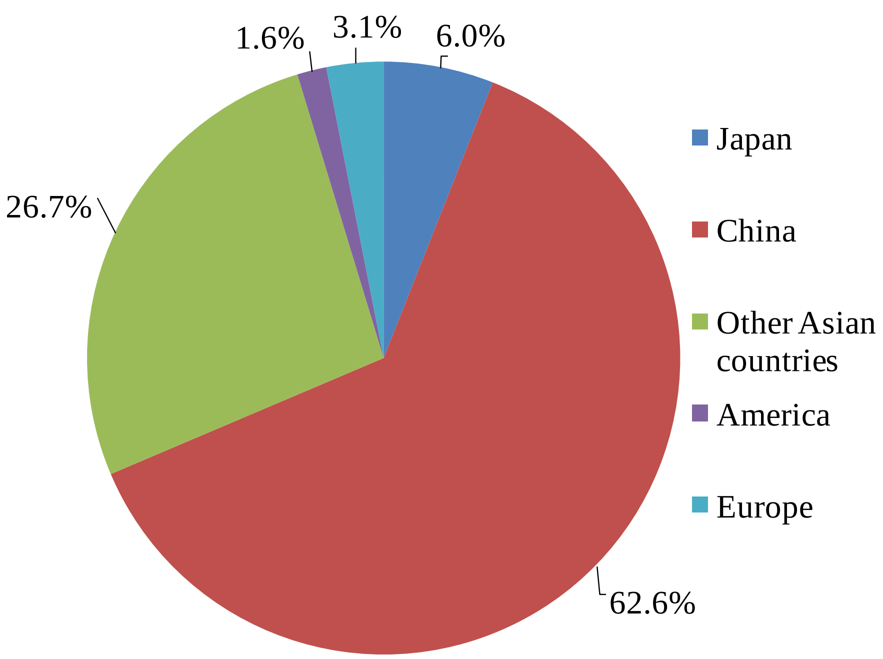


Fig. 1-5 PV cell production proportion by of main countries in 2012

(Source: Japan energy white paper 2014)

1.2.2 Present situation of CHP system

The second major kind of DER is the building cooling, heating and power (CHP) systems using prime mover technologies including reciprocating engines, gas engines, micro-turbines, steam turbines, stirling engines and fuel cells [4]. Combined heat and power (CHP), also known as cogeneration, is the simultaneous production of electricity and heat from a single fuel source. The efforts to constrain greenhouse gas emissions and concerns over security of supply of fossil fuels have led to increased attention and policy support for renewable energy over the past decade. Shares of renewable energy (RE) supply have risen over the past years and projections show the trend is likely to continue as countries transition to a low-carbon economy. Renewable energy is one of the key solutions to our energy challenges. However, transitions take time, especially when they are on the scale needed to re-invent our energy system. Even though in the coming decades the share of renewables will rise, fossil and other alternative fuels will still play a major role. For that reason, it is important to use these fuels as efficiently as possible. Co-generation offers the best of both worlds: Co-generation is a proven energy-efficient technology; Co-generation can accelerate the integration of renewable energy technologies. Thus, from the long-term viewpoint, the utilization of renewable energy should be a final solution for sustainable development and low-carbon society. However, most of the current renewable energy technologies, e.g. solar, wind energy, etc., have low energy utilization efficiency and high expense, and thus cannot compete with conventional fossil fuels with respect to the economic performance. On the other hand, from the short-term viewpoint, as an efficient approach to generate electrical and thermal energy from a single fuel source, the CHP plant is considered to be one of the feasible and effective solutions. The CHP system recovers the waste heat from the electricity generating process, otherwise that would be discarded into the environment. The heat recovered is used to satisfy the thermal demand (cooling, heating, or hot water needs) of an end-user. By recycling the waste heat, the CHP system can achieve a primary energy efficiency of 60% to 90%, a dramatic improvement over the average 35% efficiency of conventional fossil fuel based power plants. Higher efficiencies can also contribute to the reduction of air emissions including SO_2 which is the main component of local air pollutions, and CO_2 which is the main threat to the global environment.

Three categories account for the vast majority of CHP applications: Industrial; Commercial, Institutional and Residential; DHC (District Heating and Cooling). CHP has a long history within the industrial sector, which has large concurrent heat and power demands, and which also has by far the greatest installed capacity (in terms of electricity production) of the three applications. District heating also uses CHP systems extensively, providing heat for countries with long heating seasons and increasingly cooling during the summer months. However, advancements in technology development have led to the availability of smaller CHP systems, with reduced costs, reduced emissions and greater customisation. As a result, CHP systems are increasingly used for smaller applications in the commercial and institutional sectors, and are being incorporated more often into DHC systems. Table 1-1 summarises these applications.

As previous IEA reports have highlighted, co-generation is attractive to policy makers and private users and investors because it delivers a range of energy, environmental and economic benefits, including:

- dramatically increased energy efficiency;
- reduced CO_2 emissions and other pollutants;
- increased energy security through reduced dependence on imported fuel;
- cost savings for the energy consumer;
- reduced need for transmission and distribution networks; and
- beneficial use of local energy resources (particularly through the use of waste, biomass and geothermal resources in district heating and cooling systems), providing a transition to a low carbon future.

Since its first emergence, the CHP system has spread with varying success to many developed countries, and has played an important role in promoting energy efficiency in these countries. America's current installed capacity is about 82 GW of CHP at over 4,100 industrial and commercial facilities according to the EPA. President Obama seeks to increase the number of cogeneration plants in the U.S. by 50% by 2020. In Canada, cogeneration represents about 7% of the naturally produced electricity generation according to the Power of the Future with Alberta and Ontario boasting many large industrial cogeneration facilities which receive government support in the form of grants and subsidies. Beyond North America, other continents have been touched by the energy-efficient, environmentally forward CHPs. Not confined to industrial and manufacturing sectors, cogeneration facilities can be found in schools, apartment complexes, hotels, nursing homes, colleges and even breweries. In the European Union, over 11% of its electricity is produced using cogeneration with Denmark, the Netherlands and Finland leading the cogeneration charge. Cogeneration saves Europe around 200 million tonnes of CO_2 gas emissions annually. European governments turn to organizations such as the Belgium-based COGEN Europe, whose primary "goal is to work towards the wider use of cogeneration in Europe for a sustainable energy future." Europe's COGEN research indicates that at least 25% of electricity production could come from cogeneration in the next 20 years. In Japan, CCHP system has been developed rapidly during the last 20 years. The total generation capacity has increased from 200 kW in 1986 to 9,440 MW as of March 2010. The annual capacity of CHP installed is increasing by the constant 350-400 MW every year since 1986 [5]. On the other hand, as the world's largest energy consumer and CO2 emitter, China is still in its nascent stage in the introduction of the CHP system. Currently, the capacity of CHP applications in China is less than 1,000 MW. Along with the increasing primary energy consumption and CO_2 emissions, the Chinese government has recognized the merits of the high-efficient CHP system and expected it to play the main role in optimizing energy structure, increasing energy efficiency, and protecting environment. In 2010, National Energy Administration (NEA) issued "Guiding Opinions for the Development of Natural Gas fueled Distributed Generation". According to the opinions, China will construct 1,000 CHP units in 2011, and decides to expand the CHP system to all main cities with a total capacity of about 50 GW by the year 2020. Therefore, it is expected that the CHP system will experience continuing rapid expansion in China in the coming years.

On the other hand, along with rapid economic development in China, environmental problem especially air pollution becomes more and more serious. China has become the world's biggest producer of CO_2 emissions passing America in 2006. In addition, China has become the biggest energy consumer in 2009. According to the statistics, country's annual energy consumption stood at 3.25 billion tonnes of standard coal in 2010 and the figure is expected to hit 5.1 billion in 2015 if the current situation remains unchanged. Among which, building energy consumption has been increasing at more than 10% a year during the past 20 years, and occupies nearly 30% of total national energy consumption in 2010. However, Japan is believed to be one of the most energy-efficient nations in worldwide and the energy efficiency has improved by more than 30% since 1973. In addition, Japan uses only one-ninth as much energy as China to create one unit of GDP. Therefore, it may make great sense to compare the energy related issues in Japan and China.

Table 1-1 Applications of CHP systems

Feature	CHP-Industrial	CHP–Commercial/Institutional	Distributed heating and cooling
Typical customers	Chemical, pulp and paper, metallurgy, heavy processing (food, textile, timber, minerals), brewing, coke ovens, glass furnaces, oil refining	Light manufacturing, hotels, hospitals, large urban office buildings, agricultural operations	All buildings within reach of heat network, including office buildings, individual houses, campuses, airports, industry
Ease of integration with renewables and waste energy	Moderate – High (particularly industrial energy waste streams)	Low – moderate	High
Temperature level	High	Low to medium	Low to medium
Typical system size	1 – 500 Mwe	1 kWe – 10 Mwe	Any
Typical prime mover	Steam turbine, gas turbine, reciprocating engine, combined cycle (larger systems)	Reciprocating engine (spark ignition) , stirling engines, fuel cells, micro-turbines	Steam turbine, gas turbine, waste incineration, CCGT
Energy / Fuel Source	Any liquid, gaseous or solid fuels; industrial process waste gases	Liquid or gaseous fuels	Any fuel
Heat / electricity load patterns	User- and process-specific	User-specific	Daily and seasonal fluctuations mitigated by load management and heat storage

(Source: World Energy Outlook 2014)

1.3 Review of Previous Studies

Many studies have been reported on the adoption of PV and CHP system in Japan and China, respectively. In detail, as to the CHP system adoption in China, Hao et al. [6] discussed the role of building cooling, heating and power (CHP) system in energy and environmental sustainable development as well as its prospects in China, from a macro viewpoint. Wang et al. [7-10] discussed the energy and environmental performances of the CHP systems for various types of public buildings located in different climate zones in China. Ren et al. [11] examined the feasibility of introducing DER in urban areas of China and found that the CHP system was the most feasible alternative from a cost-beneficial viewpoint. Cao and Liu [12] simulated the performance of a CHP system in the air-conditioning season in China, by using thermodynamic and thermoeconomic analyses. On the other hand, as to the CHP system adoption in Japan, Ren and Gao [13] evaluated the economic and environmental performance of CHP system for residential buildings with different operating modes. Zhou et al. [14] analyzed the adoption results of various DER technologies including CHP systems for prototype buildings in Japan by using an optimization model. Ruan et al. [15] examined the optimal options of various CHP systems for the commercial buildings in Japan.

As to the hybrid system, Ranjbar et al. [16] developed an evolutionary programming based approach to do the economic analysis of combining fuel cell and wind hybrid system for supplying grid-parallel residential load. Nosrat and Pearce [17] demonstrated a new simulation algorithm and dispatch strategy for the modeling of hybrid PV-CHP systems for a typical home in Vancouver. Hamada et al. [18] described field experiments and numerical simulations on hybrid utilization of solar PV and fuel cell for a residential energy system. Hosseini et al. [19] analyzed the energy and exergy efficiency of hybrid solar-fuel cell combined heat and power systems for residential applications.

However, all of above studies focus on the examination of distributed energy system adoption in a single building, or various buildings in a country. There lacks a comparative study on the economic, energy and environmental performances from an international perspective.

1.4 Purpose of this study

As an alternative way of conventional energy supply system, distributed energy system has become a inexorable trend. However, it is of vital importance to make sure of the running strategy of DER system as well as access the DER system from different aspects (e.g. economic, environment, energy saving or integrated of them) compared with conventional system, which will give advice for the consumers and policy makers.

As is well known, the design and operation of distributed energy system is greatly dependent upon local atmospheric conditions, which on one hand, may determine building energy (thermal, especially) demands, on the other hand, affect the power generation of various technologies. For example, solar radiation intensity is a key factor which affects the electricity generation efficiency of PV unit. Thus, it is necessary to make a comparison of DER system performance in different climate zones of Japan and China. There is a large diversity in climates not only in China but also Japan. These diversities and complexities have led to many different climates with distinct climatic features. In this study, various cities in different climate zones which selected from Japan and China respectively will be analyzed within different building types. To be detailed, Harbin, Beijing, Shanghai, Kunming and Guangzhou in China, as well as Sapporo, Hachinohe, Sendai, Tokyo, Kagoshima and Naha in Japan are selected for analysis. The flow chart of the thesis is illustrated in Fig. 1-5.

- Previous study

In chapter one, current energy and environmental situations, as well as the feasibility and necessity to introduce the distributed energy system are presented. In addition, current situation of global distributed energy system (CHP and PV mainly) adoption were investigated briefly. Based on the background, the purpose of current research is proposed.

- Investigation

In chapter two and chapter three, the supply and consumption of energy and electricity in Japan and China are summarized and compared. In addition, current status of CHP system as well as PV system adoption in Japan and China are investigated respectively. Moreover, the policies for CHP system and PV system adoption so far in the selected two countries are summarized.

- Methodology

In chapter four, firstly, based on a mathematical optimization approach where the design and structure of the energy system as well as the operation of each component are optimized, a MILP (mixed integer linear programming) problem of a distributed energy system was formulated and presented minimizing annual operating cost while guaranteeing resilience of the electricity and heating demand. The model is used to analyze the optimal design, running strategy of the DER system.

Secondly, various kinds of assessment method adopted in this paper were presented detailed, which include multi-criteria analysis, net present value and so on.

- Application research

In chapter five and six, regional analysis of CCHP systems as well as PV systems in Japan and China were implemented respectively in a detailed way. Firstly, in chapter five, the detailed information of selected cities in Japan and China is described. Then, annual energy loads including electricity, cooling, space-heating and water-heating of various building (store, office, hospital, hotel and apartment) located in different cities within two countries are calculated. Furthermore, the economic and technical assumptions such as the price for natural gas and efficiency of CCHP system are introduced. Base on the above assumptions, the way of CCHP systems capacities selection is introduced and the hourly operation strategy is deduced. In addition, the energy, economic and environmental performances of the CCHP systems for various building types located in different climate zones (cities) are assessed and compared.

In chapter six, the same as CCHP system studied in Chapter five, the hourly operation strategy as well as energy, economic and environmental performance of PV system are assessed within various building types of different cities located in Japan and China.

In chapter seven, by employing the aforementioned optimization method, the hourly running strategies of residential hybrid PV/CHP/battery energy supply system located in different climate zones in Japan and China are compared and analyzed. Again, the environmental and economical performance of the hybrid system are assessed in a detail way.

- Conclusion

In chapter eight, a conclusion of whole thesis is deduced and the future study about the plan and evaluation of distributed energy systems has been discussed.

PREVIOUS STUDY	**CHAPTER ONE** Previous Study and Purpose Of the Study	
INVESTIGATION	**CHAPTER TWO** Investigation on Current Energy Situation and Distributed Energy System Adoption in Japan	**CHAPTER THREE** Investigation on Current Energy Situation and Distributed Energy System Adoption in China
EVALUATION METHOD	**CHAPTER FOUR** Optimization and Evaluation Methods for Distributed Energy System Adoption	
NUMERICAL ANALYSIS	**CHAPTER FIVE** Regional Analysis of Combined Cooling Heating and Power Systems in Japan and China	**CHAPTER SIX** Regional Analysis of Photovoltaic System Adoption in Japan and China
	CHAPTER SEVEN Integrated Assessment for Hybrid CHP, PV and Battery Distributed Energy System Adoption: Japan-China Comparison	
CONCLUSION	**CHAPTER EIGHT** Conclusions and Prospect	

Fig. 1-5 Flow chart of the thesis

Reference

[1] International Energy Agency (IEA), World Energy Outlook 2014, OECD/IEA, 2014.

[2] H. Ren, W. Gao, A MILP model for integrated plan and evaluation of distributed energy systems, Applied Energy 87(3) (2010), pp. 1001-1014.

[3] H. Ren, W. Zhou, K. Nakagami, W. Gao, Q. Wu, Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects, Applied Energy 87(12) (2010), pp. 3642-3651.

[4] D.W. Wu, R.Z. Wang, Combined cooling, heating and power: A review, Progress in Energy and Combustion Science 32(5-6) (2006), pp. 459-495.

[5] Advanced Cogeneration and Energy Utilization Centre JAPAN, < http://www.ace.or.jp/>.

[6] X. Hao, G. Zhang, Y. Chen, Role of BCHP in energy and environmental sustainable development and its prospects in China, Renewable and Sustainable Energy Reviews 11(8) (2007), pp. 1827-1842.

[7] J. Wang, C. Zhang, Y. Jing, Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China, Applied Energy 87(4) (2010), pp. 1247-1259.

[8] J. Wang, Z.J. Zhai, C. Zhang, Y. Jing, Environmental impact analysis of BCHP system in different climate zones in China, Energy 35(10) (2010), pp. 4208-4216.

[9] J. Wang, Z.J. Zhai, Y. Jing, C. Zhang, Optimization design of BCHP system to maximize to save energy and reduce environmental impact, Energy 35(8) (2010), pp. 3388-3398.

[10] J. Wang, Z.J. Zhai, Y. Jing, C. Zhang, Influence analysis of building types and climate zones on energetic, economic and environmental performances of BCHP systems, Applied Energy 88(9) (2011), pp. 3097-3112.

[11] H. Ren, W. Zhou, K. Nakagami, W. Gao, Q. Wu, Feasibility assessment of introducing distributed energy resources in urban areas of China, Applied Thermal Engineering 30(16) (2010), pp. 2584-2593.

[12] J. Cao, F. Liu, Simulation and optimization of the performance in the air-conditioning season of a BCHP system in China, Energy and Buildings 30(3) (2008), pp. 185-192.

[13] H. Ren, W. Gao, Economic and environmental evaluation of micro CHP systems with different operating modes for residential buildings in Japan, Energy and Buildings, 42(6) (2010), pp. 853-861.

[14] N. Zhou, C. Marnay, R. Firestone, W. Gao, M. Nishida, An analysis of the DER adoption climate in Japan using optimization results for prototype buildings with U.S. comparisons, Energy and Buildings 38(12) (2006), pp. 1423-1433.
[15] Y. Ruan, Q. Liu, W. Zhou, R. Firestone, W. Gao, T. Watanabe, Optimal option of distributed generation technologies for various commercial buildings, Applied Energy 86(9) (2009), pp. 1641-1653.
[16] Ranjbar M, Mohammadian M, Esmaili S. Economic analysis of hybrid system consists of fuel cell and wind based CHP system for supplying grid-parallel residential load. Energy and Buildings 2014;476-487.
[17] Nosrat A, Pearce J. Dispatch strategy and model for hybrid photovoltaic and trigeneration power systems. Applied Energy 2011;88:3270-3276.
[18] Hamada Y, Takeda K, Goto R, Kubota H. Hybrid utilization of renewable energy and fuel cells for residential energy systems. Energy and Buildings 2011;43:3680-3684.
[19] Hosseini M, Dincer I, Rosen M. Hybrid solar-fuel cell combined heat and power systems for residential applications: Energy and exergy analysis. Journal of Power Sources 2013;221:372-380.

CHAPTER TWO: INVESTIGATION ON CURRENT ENERGY SITUATION AND DISTRIBUTED ENERGY SYSTEM ADOPTION IN JAPAN

2.1 Introduction
2.2 Energy supply and consumption in Japan
  2.2.1 Total primary energy consumption
  2.2.2 Energy consumption intensity
2.3 Electricity supply and consumption in Japan
  2.3.1 Distribution of utility grid in Japan
  2.3.2 Electricity generation
  2.3.3 Electricity tariffs
2.4 Current status of CHP system adoption in Japan
  2.4.1 Periodically development of CHP system
  2.4.2 Number and capacity of CHP system in recent years
  2.4.3 Current situation of CHP adoption in residence and industry sector
  2.4.4 Application status of various CHP technology
  2.4.5 Present situation and prospect of prime mover technology
2.5 Current status of PV system adoption in Japan
  2.5.1 PV installation capacity in Japan
2.6 Policies for CHP and PV system adoption in Japan
  2.6.1 Policies for CHP adoption in Japan
  2.6.2 PV policies in Japan
2.7 Summary

2.1 Introduction

Japan's rapid industrial growth since the end of World War II doubled the nation's energy consumption every five years into the 1990s. During the 1960–72 period of accelerated growth, energy consumption grew much faster than GNP (gross national product), doubling Japan's consumption of world energy. By 1976, with only 3% of the world's population, Japan was consuming 6% of global energy supplies. The country lacks significant domestic reserves of fossil fuel, except coal, and must import substantial amounts of crude oil, natural gas, and other energy resources, including uranium. Japan relied on oil imports to meet about 42% of its energy needs in 2010. Japan was also the first coal importer in 2010, with 187 Mt (about 20% of total world coal import), and the first natural gas importer with 99 bcm [1].

Compared with other nations, electricity in Japan is relatively expensive, since the loss of nuclear power after the earthquake and tsunami disaster at Fukushima, the cost of electricity has risen significantly. While Japan had previously relied on nuclear power to meet about one fourth of its electricity needs, after the 2011 Fukushima Daiichi nuclear disaster all nuclear reactors have been progressively shut down for safety concerns. Under these backgrounds, distributed energy resources have received more and more attention in Japan.

As described in the chapter 1, distributed energy system is an efficient approach to generating electricity and thermal energy from a single fuel source. It recovers the waste heat from the electricity generating cycle, otherwise that would be discarded into the environment. Japan has been got some achievement in the application of distributed energy source. As of the end of 2002, Japan had generated 63.7MW of solar electricity for the year, making Japan the number one producer of solar power in the world. At the same time, wind power generated 46.3%MW in 2002, representing a six-fold increase compared with three years before. However, at present new energy sources account for only about 1% of the primary energy supply. This is very much low level compared with the world average value of 7%. Japan should have significant potential for development of distributed energy source for its energy shortage serious. Why can it gain the expected achievement? There are lots of reasons, including technologies and regulations barriers. Such as, selling excess distributed generation to anther electricity customer generally is not allowed.

In this chapter, the supply and consumption of energy and electricity in Japan are summarized. In addition, current status of CHP system as well as PV system adoption in Japan is investigated. Moreover, the policies for CHP system and PV system adoption so far are summarized.

2.2 Energy supply and consumption in Japan

2.2.1 Total primary energy consumption

Fig. 2-1 shows the primary energy consumption in Japan and increase ratio from 1991 to 2012. Generally, the total primary energy consumption in Japan shows a gently increase which is 0.45 GTOE in 2012. As to the increasing ratio, generally, since 2005, except the year of 2010, the primary energy consumption has been showing a negative growth trend especially in 2009 which is minus 4.7% due to the global economic downturn [1].

Fig. 2-2 shows the share of energy supply in Japan in 2012. In Japan, energy was mainly supplied by crude oil with a share of about 44.2%, followed by natural gas, coal and other renewable respectively with the ratio of 24.5%, 23.4%, and 4.0%. In addition, Japan was the world's top importer of both coal and natural gas. It is also the third-ranking oil importer consumed largely in the transportation sector. Note that, nuclear only occupied as low as 0.7% of total energy supply (11.3% in 2010), and replaced by fossil fuels and renewable energies which is due to the increased concern of nuclear safe caused by Fukushima nuclear leak [2].

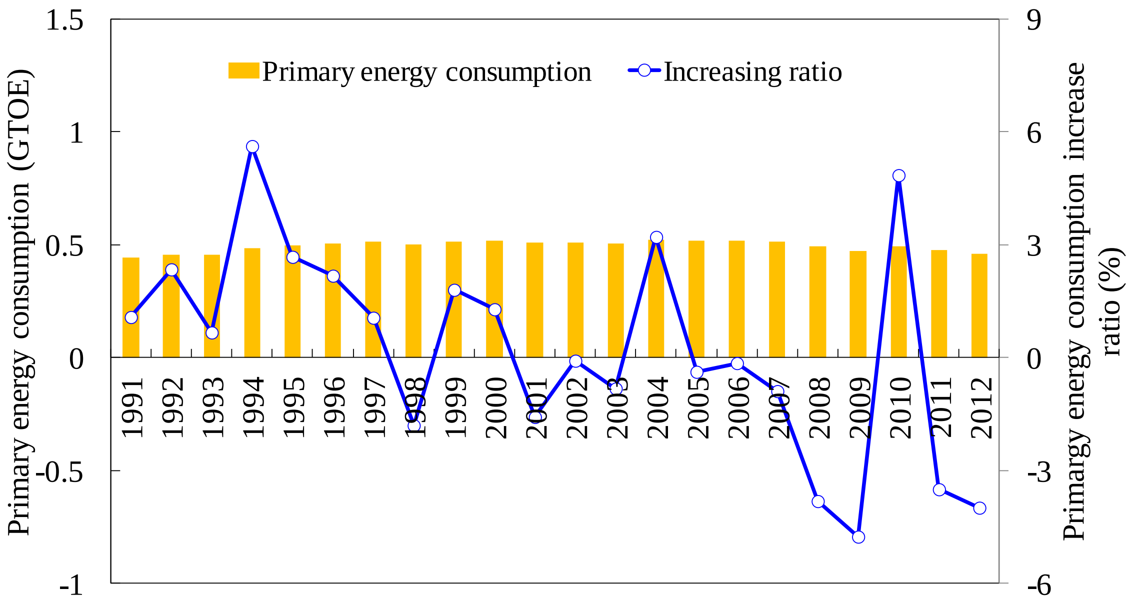


Fig. 2-1 Total primary energy consumption and increasing ratio in Japan

(Source: The World Bank)

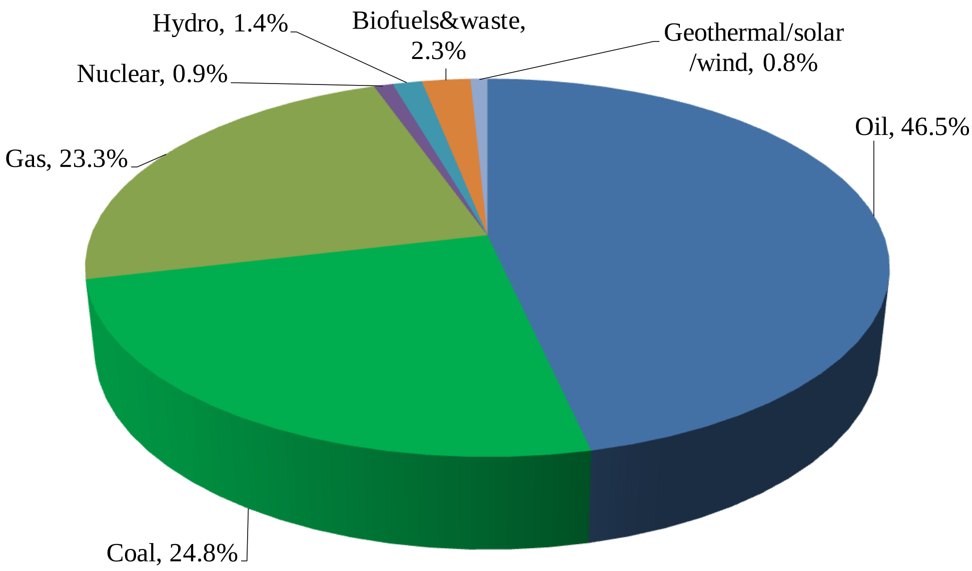


Fig. 2-2 Composition of primary energy supply in 2012

(Source: World Energy Outlook 2014)

On the other hand, from the viewpoint of final energy consumption, Fig. 2-3 shows the energy consumption of different sectors in Japan from 1994 to 2008. As shown in the figure, in Japan, the industry sector occupied the largest part of energy consumption followed by building and transportation sectors. However, in recent years, the share of industry sector showed a slight decrease and the building sector increased gradually. In 2008, industry, transportation and building sectors accounted for 42.5%, 23.6% and 33.9% respectively in national total energy consumption [3]. Therefore, it can be found that as the continuing economic development along with the improvement of living standards, the building and transportation sectors will encounter rapid increase in energy consumption.

2.2.2 Energy consumption intensity

Fig. 2-4 shows the energy supply per GDP in Japan from 1990 to 2011. Generally, energy supply shows a decreasing trend which is 0.0998 toe/1000$. In addition, it can be found out that because of the high efficiency of energy use, the value was very low in Japan compared with the value worldwide.

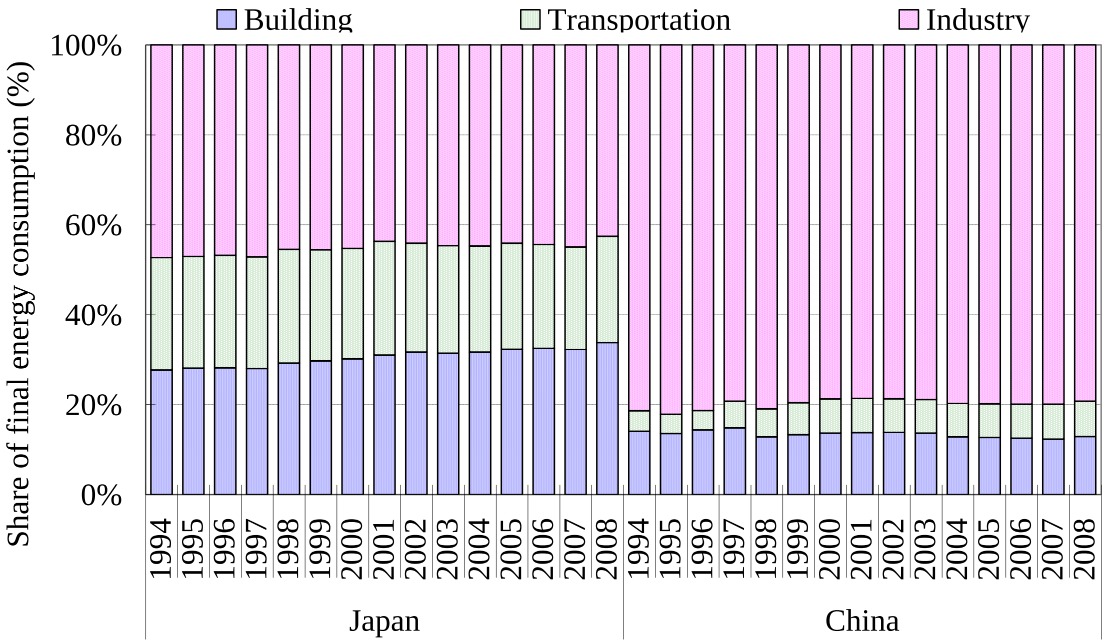


Fig. 2-3 Share of final energy consumption

(Source: World Energy Outlook 2011)

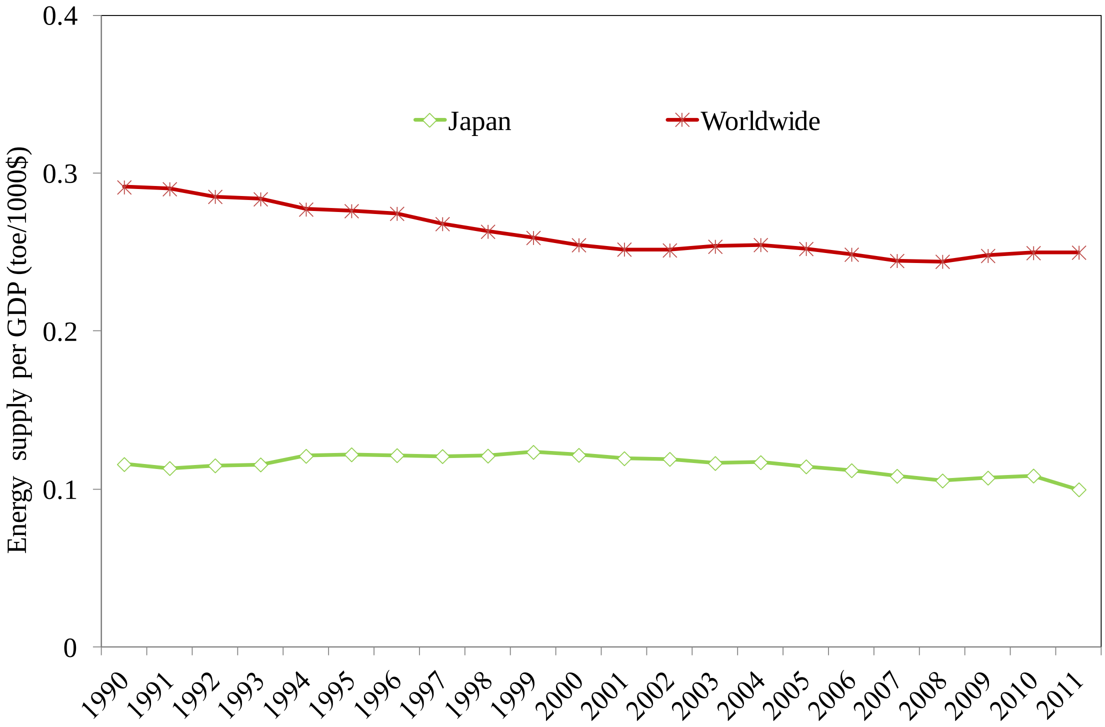


Fig. 2-4 Energy supply per GDP in Japan and Worldwide (toe/1000$)

(Source: The World Bank)

2.3 Electricity supply and consumption in Japan

2.3.1 Distribution of utility grid in Japan

Unlike most other industrial countries, Japan doesn't have a single national grid but instead has separate eastern and western grids. The two grids were originally developed by separate companies. Fig. 2-5 shows the ten utility companies in Japan. As the the figure shows, in Japan, the electricity market is divided up into 10 regulated companies: Chugoku Electric Power Company (CEPCO), Chubu Electric Power (Chuden), Hokuriku Electric Power Company (Hokuden), Hokkaido Electric Power Company (HEPCO), Kyushu Electric Power (Kyuden), Kansai Electric Power Company (KEPCO), Okinawa Electric Power Company (Okiden), Tokyo Electric Power Company (TEPCO), Tohoku Electric Power (Tohokuden), Shikoku Electric Power Company (Yonden).

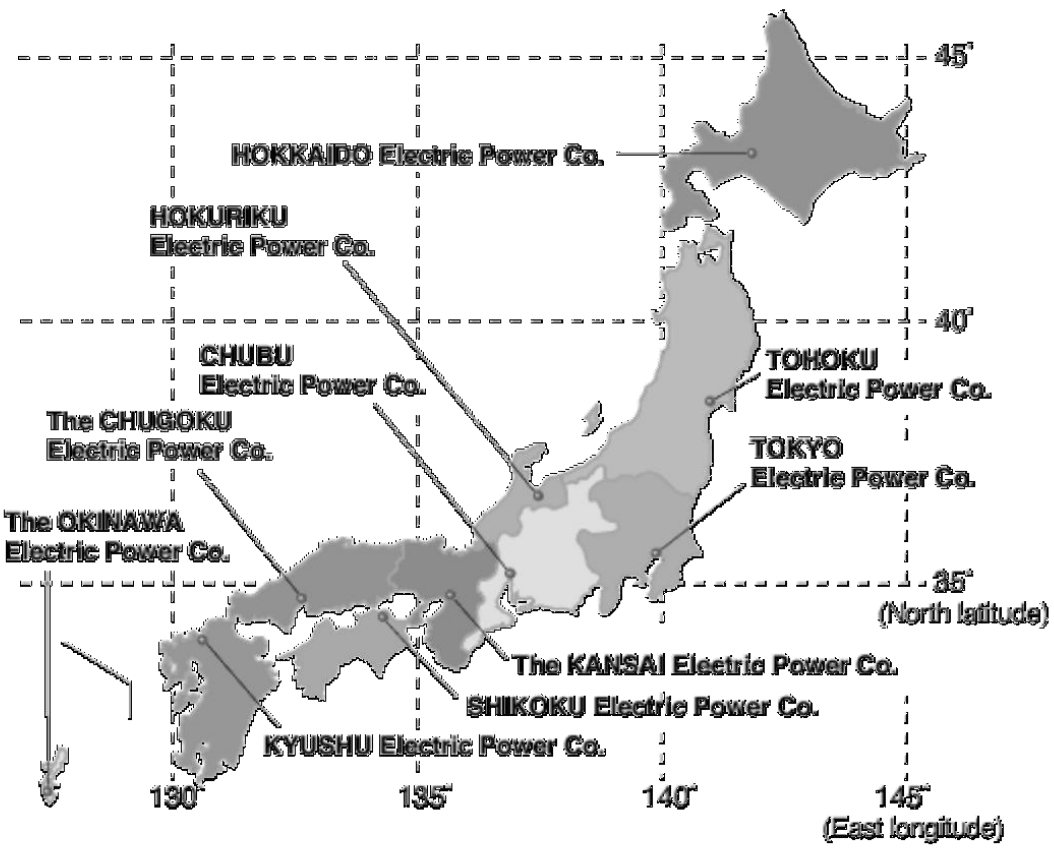


Fig. 2-5 Image of electricity supply grid in Japan

2.3.2 Electricity generation

In 2008, Japan ranked third in the world by electricity production, after the United States and China, with 1,025 TWh produced during that year. In terms of per capita electricity consumption, the average person in Japan consumed 8,459 kWh in 2004 compared to 14,240 kWh for the average American. In that respect it ranked 18th among the countries of the world. Its per capita electricity consumption increased by 21.8% between 1990 and 2004. Japan had 282 GW of total installed electricity generating capacity in 2010, the third largest in the world behind the United States and China. However, after the damage by the 2011 earthquake, capacity is estimated to be around 243 GW in mid-2011. With 53 active nuclear power generating reactor units in 2009, that year Japan ranked third in the world in that respect, after the United States (104 reactors) and France (59). Almost one quarter (24.93%) of its electricity production was from nuclear plants, compared to 76.18% for France and 19.66% for the United States. However post earthquake all plants eventually shut down in May 2012 and Nuclear Power Plant was restarted in June 2012 [3].

It is of vital importance to understand the current situation of power supply and consumption, which may reflect the nature of current electricity tariff and affect the future tariff regulation. As shown in Fig. 2-6, in Japan, the total electricity consumption was 976.3 billion kWh in 2010, and decreased to 822 billion kWh in 2012. In 2010, nuclear supplied the largest electricity consumption which occupied 30.8% of total electricity supply, and followed by gas, coal, hydro respectively. However, because of the Fukushima nuclear accident, the main energy source for power generation is gas, which has a share of about 42.5%, followed by coal, oil and hydro respectively which indicates that, fossil fuels are increasing. Note that, the renewable electricity generation increased to 1.6% which has low CO2 emissions and environmental friendly.

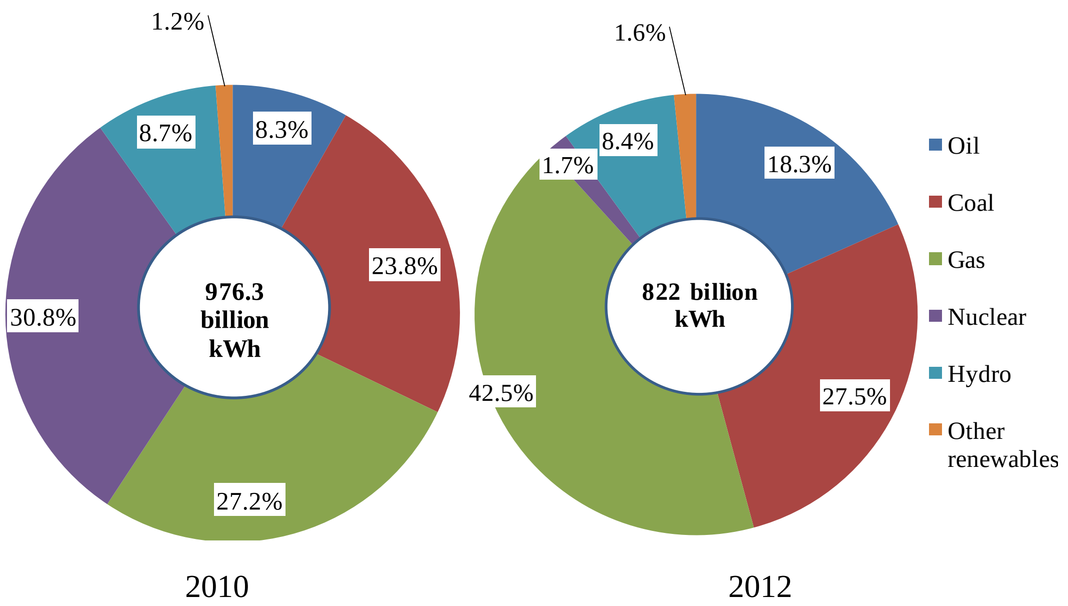


Fig. 2-6 Energy source for power generation in Japan

(Source: Japan energy white paper)

2.3.3 Electricity tariffs

Although there may be some difference among the tariffs of various companies in a single country, the fluctuation is marginal. Fig. 2-7 shows the general electricity tariff structure in Japan. Generally, residence, commerce and industry are always treated in a separate way. In addition, a normal rate and a time of use (TOU) (or time of day: TOD) rate are the main tariff types. Note that, much more alternatives are available for residential power application than commerce and industry sector. In addition, TOD tariff is adopted only in residence sector, whereas, the TOU tariff is widely employed in Japan's commercial and industrial application. Furthermore, double item tariff (composed of demand charge and energy charge) is widely penetrated in Japan.

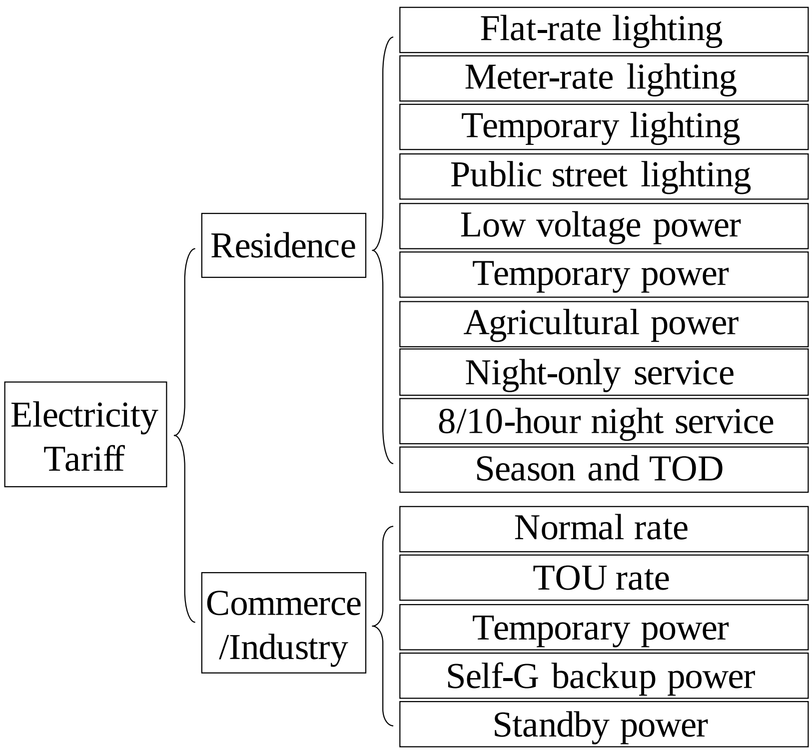


Fig. 2-7 General electricity tariff structure in Japan

As to the components of electricity tariff, as shown in Fig. 2-8, Japan has a complicated tariff components. Besides the normal energy charge, the fuel cost adjustment amount is included. In addition, in order to promote the adoption of photovoltaic system, a solar surcharge which is proportional to the power consumption is also introduced.

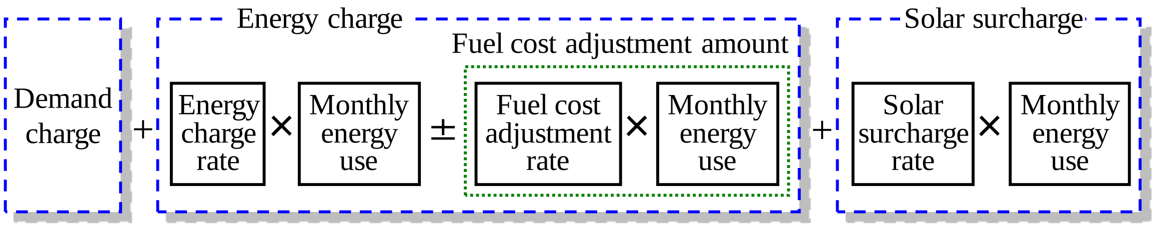


Fig. 2-8 Image of different electricity tariff types in Japan

In TOU or TOD tariffs, the electricity tariff rate may fluctuate according to the season and time period in Japan as shown in Fig. 2-9. In Japan, the on-peak period is mainly some hours at noon.

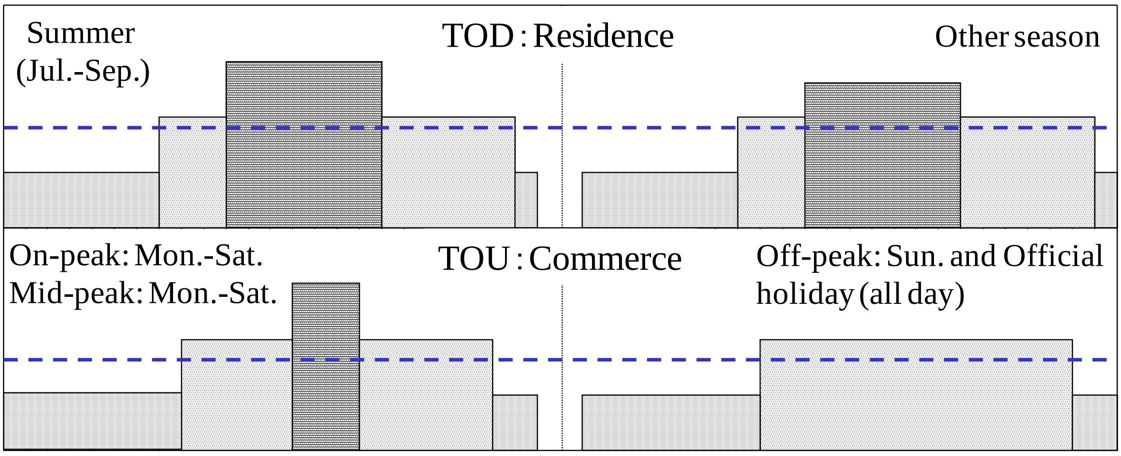


Fig. 2-9 Image of time district in Japan

2.4 Current status of CHP system adoption in Japan

Since the 70's of last century, Japan has begun to pay attention to distributed cogeneration system which is based on energy cascade utilization after two oil crises. In the last forty years, official, university and industry in Japan had high hopes for distributed cogeneration technology although experienced a development downturn.

2.4.1 Periodically development of CHP system

In the 1970s, the first gas turbine cogeneration system was put into operation, up to now, the distributed cogeneration industry has experienced the developing course of about 40 years. Note that, the development motivation changed from initial energy conservation, to emissions reduction, to security in the current. To be detailed, the whole story can be roughly divided into six stages according to the different typical characteristics in the development process [4].

(1) Stage 0: preliminary introduction period (1971 ~ 1980)

This phase is mainly concept introduction and practice stage. As early as in 1978, although it was not named "combined heat and power (cogeneration)", there was practical application examples in Japan already before official promotion of distributed cogeneration concept by American public utilities management policy law. By 1980, Japan has installed 9 sets of cogeneration equipment, including 3 civil-use, and 6 industry-use.

(2) Stage 1: first growth stage (1981 ~ 1990)

Since the 1980 s, the effect of the oil crisis has being going on, although oil price fell gradually, as well as energy, economic turnaround. Therefore, energy saving, alternative energy sources development is still widely concerned, especially distributed cogeneration system which is regarded as key energy conservation measures. At the same time of research and development of new civil and industrial cogeneration equipment, the grid connection service as well as feed in tariff (FIT) policy was also on the agenda. Under this background, the average yearly installation capacity of distributed cogeneration system has increased from 50MW to more than 400MW. Again, by 1990, the accumulated total installation capacity of distributed cogeneration system has reached to 2.03 GW, accounting for 1% of Japan's total power equipment capacity, and the total number is 1162, most of which adopt diesel engines.

(3) Stage 2: first recession (1990 ~ 1995)

After entering the 1990s, annual installation capacity of distributed cogeneration system was decreasing at an average annual rate of 20%, as the burst of Japan's bubble economy , and downturn of the economy. Whereas, relevant formulation of policy and institution was going on. In 1992, all of the 10 power companies in Japan introduced feed-in tariff policy. In the same year, 5 billion yen subsidy was granted by the ministry of economy, trade and industry (METI). In 1995, in order to promote liberalization of "power", the ministry of electric industry council created two emerging industries named specific electrical industry, wholesale supplies industry, to promote the cognition and popularity of distributed cogeneration. Under the above background, the situation has improved in the late time of the stage, at the end of 1995, the accumulated total installed capacity has reached to 3.48 GW, accounting for about 1.5% of total national power generation installation capacity.

(4) Stage 3: second time growth (1996 ~ 2004)

Since entering the stage, energy saving and environment protection of distributed cogeneration system has been widely recognized, and step into rapid growth period, the annual average installation capacity increased at growth rate of 0.4 GW. At the same time, relevant policies were introduced densely in this phase: in 1997, new energy law was issued, put forward financial support policy for the new energy system adoption owners (new energy subsidies); In 1999, alternative energy law was revised, which proposed gas-fired cogeneration system development goals for the first time, which aimed at 4.55 GW by the year 2010. In the same year, the energy conservation law was launched, promoting energy saving subsidies of high efficiency cogeneration applications. In addition, in response to the "Kyoto protocol", Japan enacted climate change countermeasure promotion law, set the goals of gas-fired cogeneration and fuel cell development; Furthermore, long-term energy supply and demand forecasting was revised, set up the goal which is, by 2010, accumulated cogeneration installation capacity is 10.02 GW.

Under the above series of policies, by the end of 2004, total installation capacity has reached to 7.79 GW, the total number is 6000, marking the peak period of Japanese cogeneration development. On the other hand, as to the technical aspect, in 1999, micro cogeneration technology stepped into the market. Again, in 2002, large scale high-efficiency cogeneration technology was put on the market. Therefore, during this period, large scale of 5MW and more of high efficient gas fired internal combustion system contributed a lot within the capacity increase; whereas, 1 ~ 25 kW micro gas internal combustion engine contributed to set number increase.

(5) Stage 4: second time recession (2005 ~ 2010)

In 2005, the "Kyoto protocol" come into force. Again, in April of the same year, Kyoto protocol achieving planning was launched, which targeted the installation capacity of gas fired distributed cogeneration up to 4.98 GW by 2010. However, since 2005, new installation capacity decreased sharply in this stage, which is on one hand for the big bulge of oil price and lower electricity price, on the other hand, for the effect caused by Lehman Shock in 2008. In 2010, the new installation capacity was as low as 110 MW, and the setting number was 215, which was the lowest level in nearly 30 years.

(6) Stage 5: third growth period (2011 - present)

In March 2011, a huge earthquake happened in Japan's northeast area, in which Fukushima nuclear power plant collapsed because of the tsunami. Thus, electricity supply in Kanto and northeast become tension unprecedented at that time.

Under this background, the stability of power supply was paid unprecedented high attention. Low carbon, energy saving, BCP (Business Continue Plan, Business continuity security program) become three main keywords in the field of energy. As an effective method to deal with the three key problems, distributed cogeneration system was widely paid attention again, new installed capacity of in 2012 has reached to 0.39 GW. And the situation is still showed a growth trend at present.

2.4.2 Number and capacity of CHP system in recent years

In Japan, the CHP system has experienced rapid development during the last decades. Fig. 2-10 shows the increased number and capacity of distributed cogeneration system in recent years. As the figures shows, before 2004, the number of CHP plants had increased rapidly, from 67 in 1986 to 1300 in 2004. However, from 2005 to 2010, the new installed number of decreased a lot. While, the new installed CHP began to rise from 2011, which reached to 935 in 2013. And as to the newly generation capacity, generally, it has increased from 200 kW in 1986 to 985.2 MW as of March 2013.

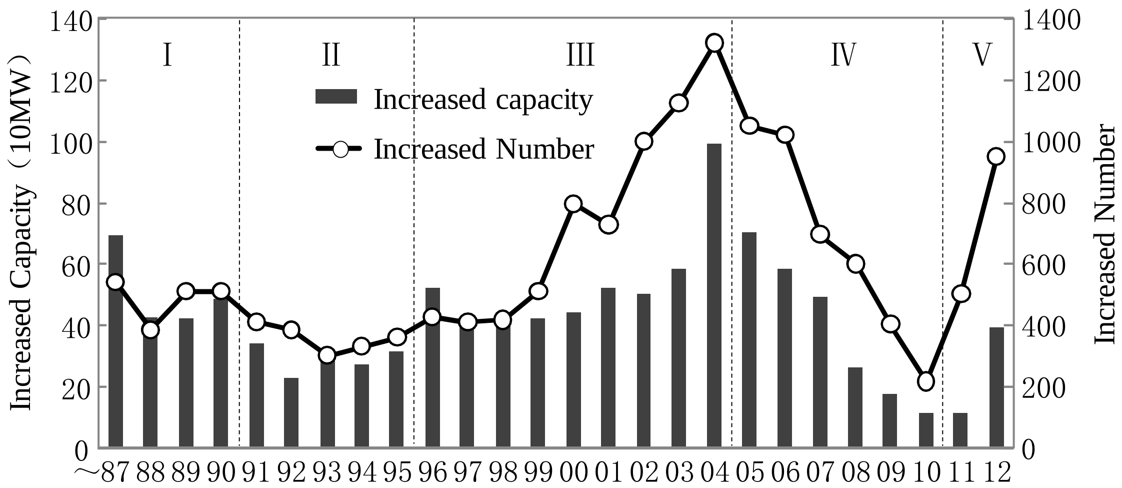


Fig. 2-10 Increased number and capacity of distributed cogeneration system in Japan

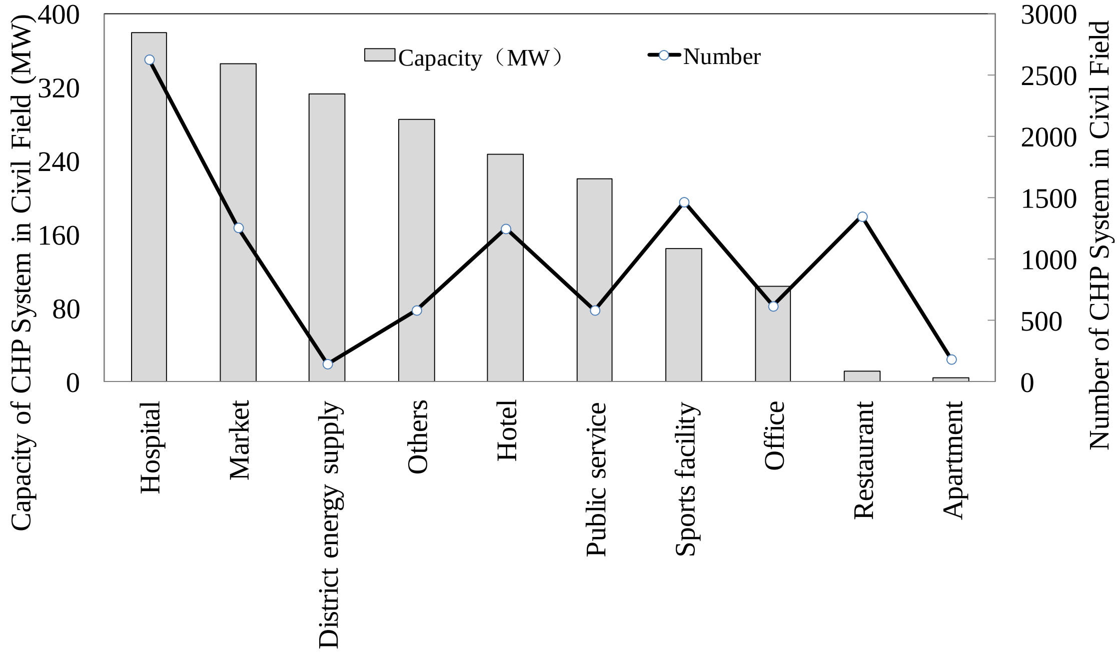
(Source: Advanced Cogeneration and Energy Utilization Centre JAPAN)

2.4.3 Current situation of CHP adoption in residence and industry sector

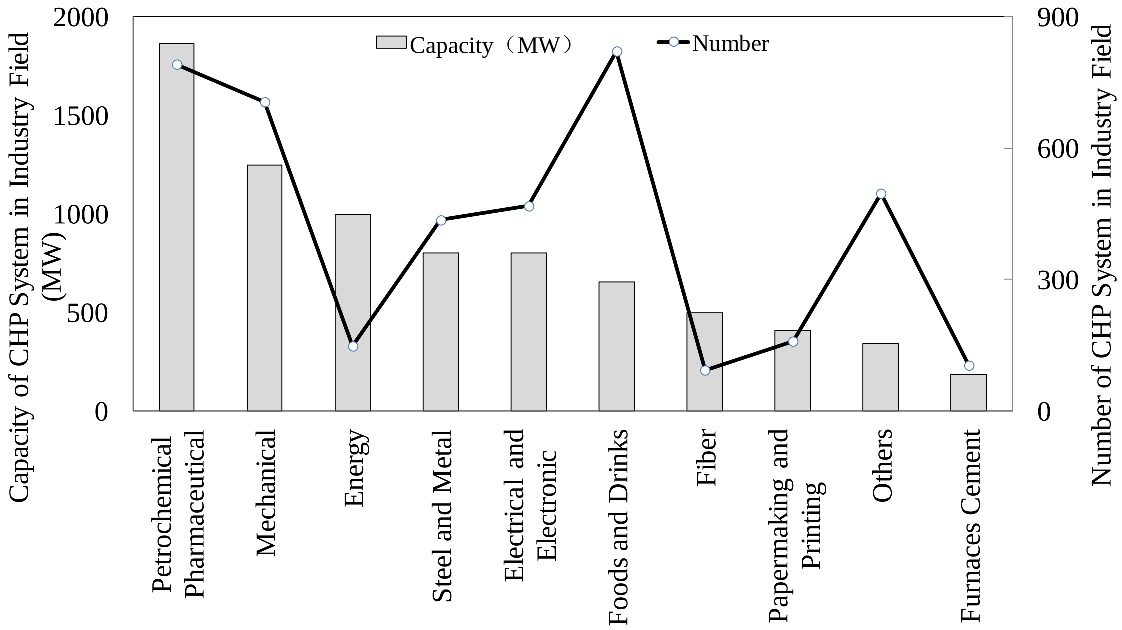
According to the statistic of co-generation and high efficient energy use center, by the end of 2012, the accumulated installed capacity of cogeneration system has reached to 9.85 GW (about 3.4% of total power generation capacity), and in which, civil-use system and industrial-use system is 2.06 GW and 7.79 GW respectively. Again, the total number is 14423, in which, civil-use system and industrial-use system is 10098 and 4325 respectively. Fig. 2-11 (a) and Fig. 2-11 (b) shows the application status for civil and industrial cogeneration system in different departments respectively. In the field of civil-use, both sets number and capacity, hospitals are the most widely used field, occupies 26% and 18% of total civil-use respectively. In addition, shopping mall, hotel, sports facilities and restaurants also occupy a lot. In terms of capacity, most of the systems are in the scale of hundreds of kW. Among them, regional power generation system always adopts the larger scale equipment, and the average capacity reach to 2.1 MW, whereas the refreshment room is small, and the average capacity is only 9 kW.

In recent years, in the civil field, under 10 kW equipment without professional operator, as well as multi sets with 25 to 30 kW parallel system increase gradually. The main application fields include hospitals that can use waste heat sufficiently, sports facilities, and restaurants, etc. At the same time, in the district heating and cooling supply system, setting the ultra large power plant system with 10 MW level, on one hand, can make full use of waste heat, on the other hand, it can supply cooling through refrigeration which use local generated power. It worth noting that, household cogeneration system which was widely focused on in Japan is not included in figure 1. Currently, there are two main kinds of micro co-generation system models in Japan. At the end of 2002, household gas fired internal combustion engine (Ecowill) with 1 kW was put on the market, and the accumulated sold number has reached to about 110000 units by the end of 2011. On the other hand, since March 2005, household fuel cell (Enefarm) with 1kW also started to sell, the sold number has reached to about 53000 units by the end of 2013. Thus, it can be concluded that although domestic fuel cell technology starts late, develops faster this year [5].

Compared with the civil field, although installation number of industrial field is less, only 43% of civil field, total installation capacity is nearly 3.8 times of that in civil field . As to the installation number, it is relatively more than other fields both in food and beverage industry. However, from the perspective of capacity, petrochemical industry and pharmaceutical industry is dominant. In addition, in terms of unit capacity, energy industry is the largest, which is up to 6.724 MW, whereas, the unit capacity in the food and beverage industry is only 794 kW, generally is more than 1000 kW.



(a) Application status of CHP system in civil field



(b) Application status of CHP system in industry field

Fig. 2-11 Application status of CHP system in civil and industry field

2.4.4 Application status of various CHP technology

The main prime movers of CHP system on the market in Japan include: Gas Engine, Gas Turbine and Diesel Engine, plus a small amount of Steam Turbine and Fuel cell. The main equipment suppliers include Mitsubishi Heavy Industries, Yammar, Hitachi, Panasonic and other international well-known companies. Fig. 2-12 and Fig. 2-13 show the adoption number and installation capacity of various CHP technology in civil and industry field respectively. No matter from adoption number or installation capacity, gas engine is the dominant type in the field of civil field (accounts for about 75% of the total number and 44% of total capacity), followed by diesel engine and gas turbine. In the industry field, diesel engine enjoys the most number, whereas, gas turbine enjoys the most capacity, which indicates that the stand-alone capacity of gas turbine is relatively larger than others(see Fig. 2-14). Generally speaking, gas engine is the most popular CHP technology at present, the installed number occupies nearly 62% of the total value in Japan. However, the applications of steam turbine and fuel cell are rear (less than 1%). This is because steam turbine is always suitable for large power station, and fuel cell technology is still immature, and the price is relatively high compared with other types.

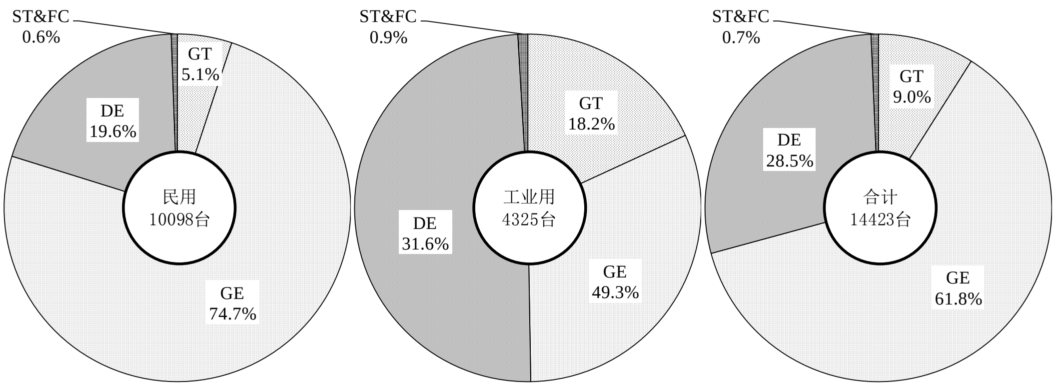


Fig. 2-12 Application status of various CHP technology（installed number）

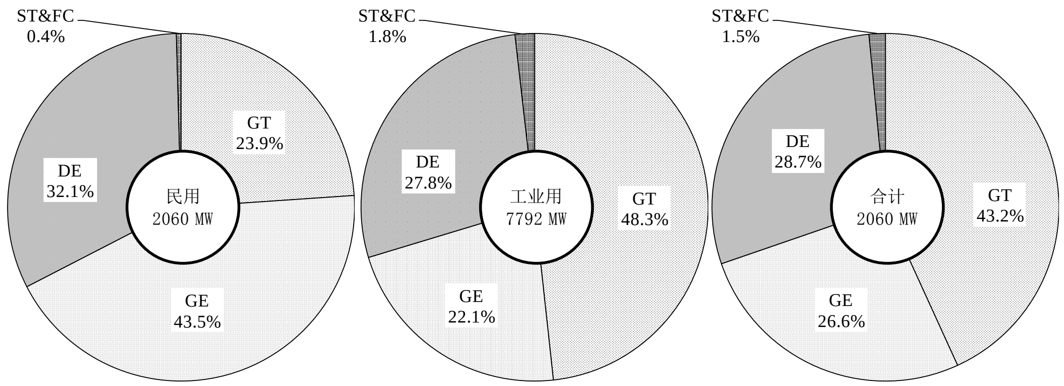


Fig. 2-13 Application status of various CHP technology（installed capacity）

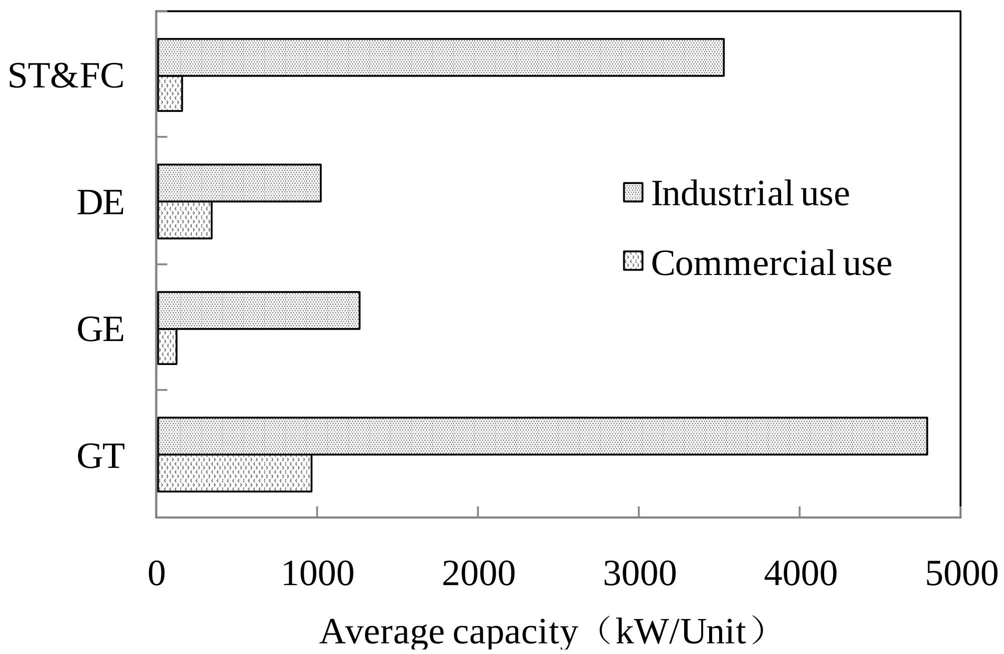


Fig. 2-14 Application status of various CHP technology (average capacity)

2.4.5 Present situation and prospect of prime mover technology

Table 2-1 analyzes four types of CHP technology from technique characteristic, fuel type, and main usage aspects. Gas engine technology has being developing rapidly in recent years, especially the application of lean-burn, miller cycle technology, the power generation efficiency of which has exceeded more than 40%, even up to 45% [6-7].

Table 2-1 Various CHP technologies

(Source: Advanced Cogeneration and Energy Utilization Centre JAPAN)

Prime Mover	Gas Engine		Gas Turbine		Diesel Engine	Fuel Cell
Fuel	Natural gas, LPG, Biomass		Natural gas, LPG, Diesel, Kerosene		Heavy oil, Diesel, Kerosene	Natural gas, LPG, Kerosene
Capacity（kW）	1～35	200～2000～10000	700～15000	16000～50000	80～15000	0.7～100
Electricity Efficiency（%）	29～33	35～43～49	24～35	33～41	33～45	37～47
Combined Efficiency（%）	85	76～80～84	75～82	82～84	64～67	87～94
Usage	Civil, Industry		Industry, Distributed Enery supply		Civil, Industry	Civil

In addition, from the aspect of energy supply security, the latest technology has break through the traditional mode of water-cooled cooling, through adopting air cooled radiator configuration, making the equipment keep going on when power cut or loss of water, enhancing disaster resilience performance. Compared with gas engine, electricity generation efficiency of gas turbine is relatively low, and the model is always larger, whereas the waste heat recovery efficiency is higher because higher exhaust temperature of exhaust steam. The capacity scales of diesel engine are mainly medium and small type, and power generation efficiency is similar to gas engine, whereas the comprehensive efficiency is relatively low.

Furthermore, fuel cell is becoming more and more popular in Japanese CCHP market. Fuel cells are an entirely different approach to the production of electricity than traditional prime mover technologies, and are currently in the early stages of development. Fuel cells can generate electricity at high electric efficiencies (up to 60 percent) using hydrogen as the fuel. They are silent in operation and have very low emissions. However, as with most new technologies, the fuel cell technology is presently very high. Still, fuel cells are available on the market and systems are installed, but in 2001 the worldwide capacity was no more than 70 MW. The commercially available units are usually a few hundred kW, but recently, the 1 kW fuel cell CCHP plant has been introduced for residential use in Japan [8].

According to the working temperature, fuel cells can be divided into four categories:

Molten carbonate fuel cell (MCFC), the working temperature of which is 500-600 ℃, and the average capacity is large; Phosphoric acid fuel cell (PAFC), its working temperature is about 200 degrees, which has been commercialized as early as in 1998, hundreds of kW models have been developed before, whereas the efficiency as relatively low; Solid polymer fuel cells (PEFC) is the key type at current, especially the residential CHP system has realized commercialization since 2009, and the power generation efficiency has reached to 37%, and the comprehensive efficiency is as high as 87% [9]. The next generation of fuel cell is solid acid fuel cell (SOFC), the working temperature is about 800-1000 degrees, expected power generation efficiency is 50%, and it has stepped into middle phase, the expected commercializing time is in 2017. In addition, Mitsubishi Heavy Industries is developing SOFC with 250 kW and gas turbine combined cycle system, the expected comprehensive efficiency can reach 55%.

Figure 2-15 is the adoption number of fuel cell system sites in each fiscal year. And Figure 2-16 is the new installed capacity of fuel cell system in each fiscal year. It shows that the adoption number is decreasing in recent years. During the early years, most of the installations are between 50 kW and 100 kW; but now the larger system is dominate, most of the systems are between 200 kW and 500 kW. Figure 2-17 shows the mean capital cost of fuel cell system. As the advancement of technology, capital cost has decreased greatly since 1991s [10].

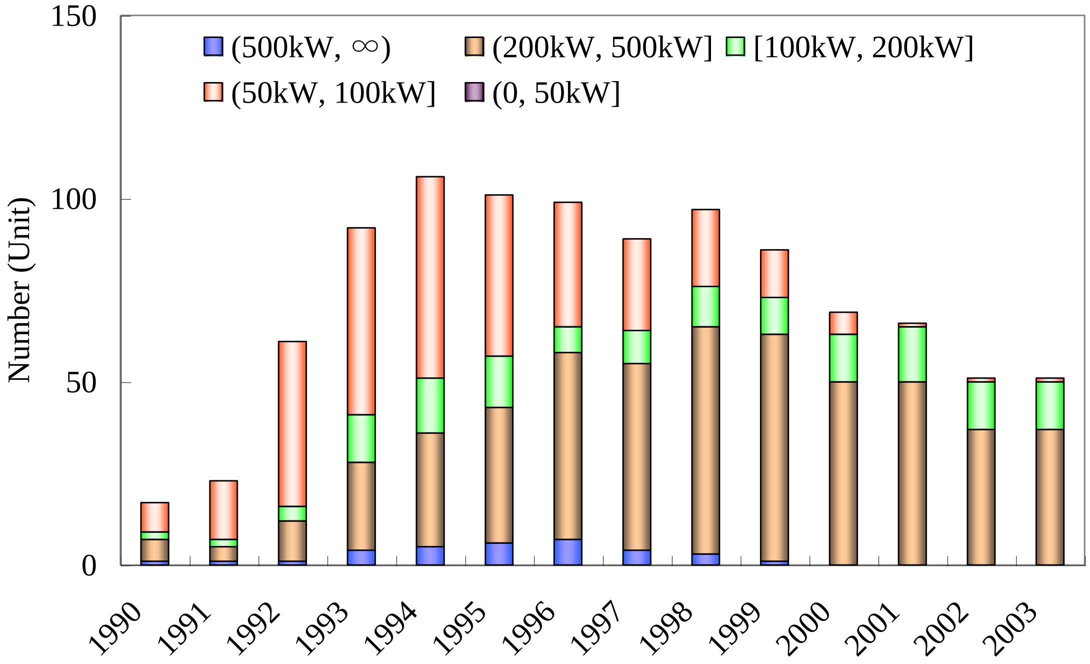


Fig. 2-15 Adoption number of fuel cell system in each fiscal year

(Source: Advanced Cogeneration and Energy Utilization Centre JAPAN)

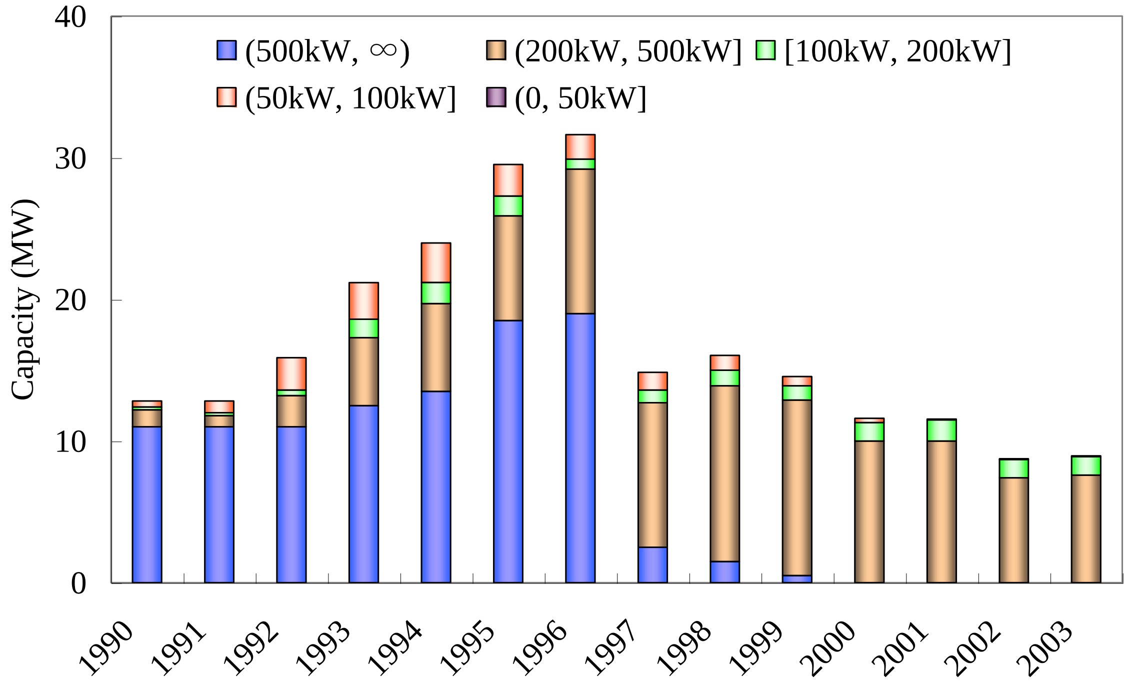


Fig. 2-16 Adoption Capacity of fuel cell system in each fiscal year

(Source: Advanced Cogeneration and Energy Utilization Centre JAPAN)

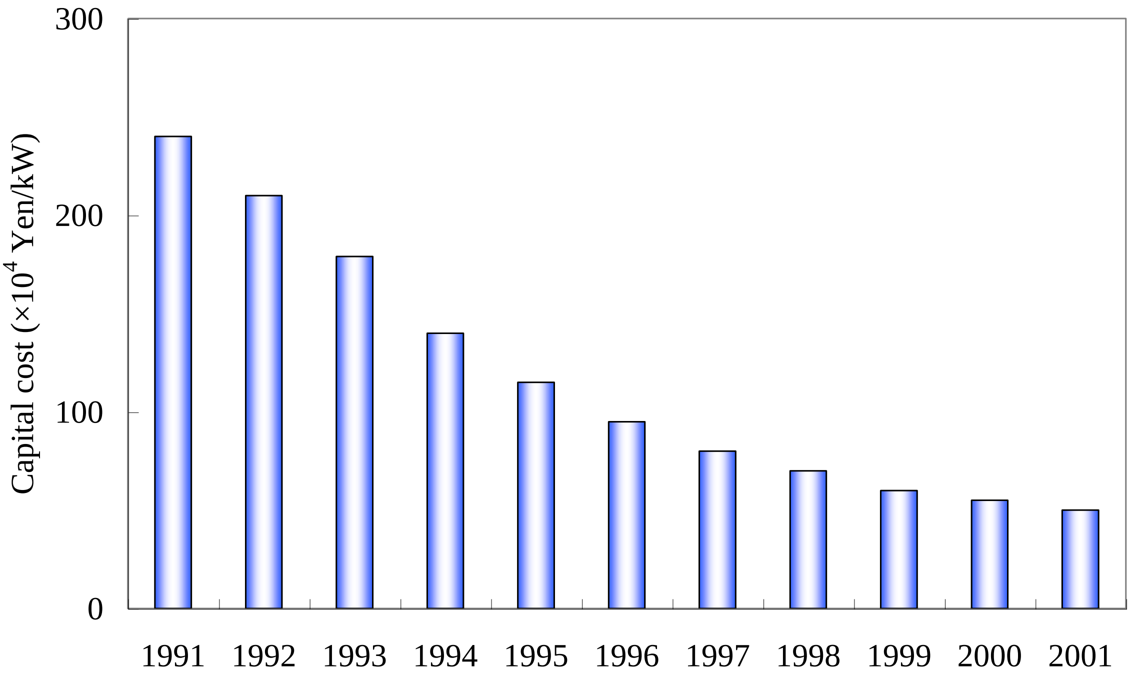


Fig. 2-17 Capital cost of fuel cell system in each fiscal year

(Source: Advanced Cogeneration and Energy Utilization Centre JAPAN)

2.5 Current status of PV system adoption in Japan

2.5.1 PV installation capacity in Japan

Japan has been one of the most successful PV industry and mature markets in the world. Figure. 2-18 shows the accumulated PV system installation capacity. As is shown in the figure, the accumulated PV system installation capacity shows a rising trend especially in recent years. Note that, by the year 2012, total installed PV capacity has reached about 7 GW, which occupies about 7% of global PV capacity. In addition, it can be found that individual homeowners are the most common PV buyers, comprising nearly 90% of the market. However, in 2012, the ratio decreased to 72% due to the rapid development of PV system in commercial and industrial market.

Between 1994 and 2005, Japan dominated the world PV market in terms of both installation and production. Before 2004, Japan was the world largest PV adopter driven by the subsidies which were abolished in 2005. Since then, some European countries (Germany and Spain) had paid much attention to the adoption of PV system by introducing the feed-in tariffs (FIT: offering long-term contracts to renewable energy producers, typically based on the cost of generation of each different technology), and overtook Japan in the world PV market. Recently, in order to develop a sustainable low-carbon society, more active policies have been proposed by the government, such as the reissue of subsidies, as well as the increase of electricity buy-back price. It is expected that total PV capacity will increase to as large as 50 GW by the year 2020.

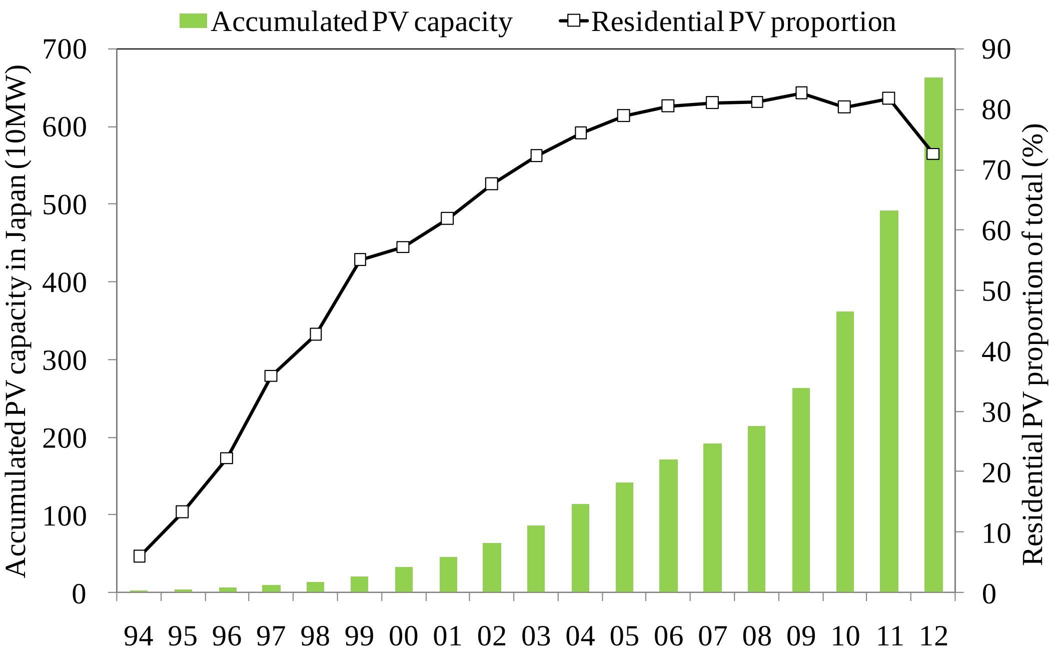


Fig. 2-18 PV installation capacity in Japan

(Source: Japan energy white paper 2014)

As introduced above, residential sector is the main market of PV system in Japan. Fig. 2-19 shows the annually and cumulative PV system installation transition. As the figure shows, the by 2013, the accumulated PV unit has reached to one million units, about 4GW. As to the yearly increased PV units, generally, it shows a rising trend except in 2013 in recent years.

At the end of 2013, rooftop solar PV installation remain the dominant type of PV installations by project number and by MW volume, with 89% of market share by capacity. The remaining 11% is spread across the ground-mount and off-grid segments in Japan.

The government in Japan has found that, the development of residential PV system is limited, it is necessary to transfer the market to non-residential (e.g. commercial, industrial, stand-alone) areas in which the PV systems always enjoy a large scale. Fig. 2-20 shows forecast of the annual installation volume of residential and non-residential PV unit. It can be found out that, before 2019, the residential sector will still enjoy the dominant market of PV unit adoption volume. However, as the decreasing of PV system adoption volume in residential sector and increasing in non-residential sector, it is forecasted that the later will overpass the former and become the main market of PV system in Japan.

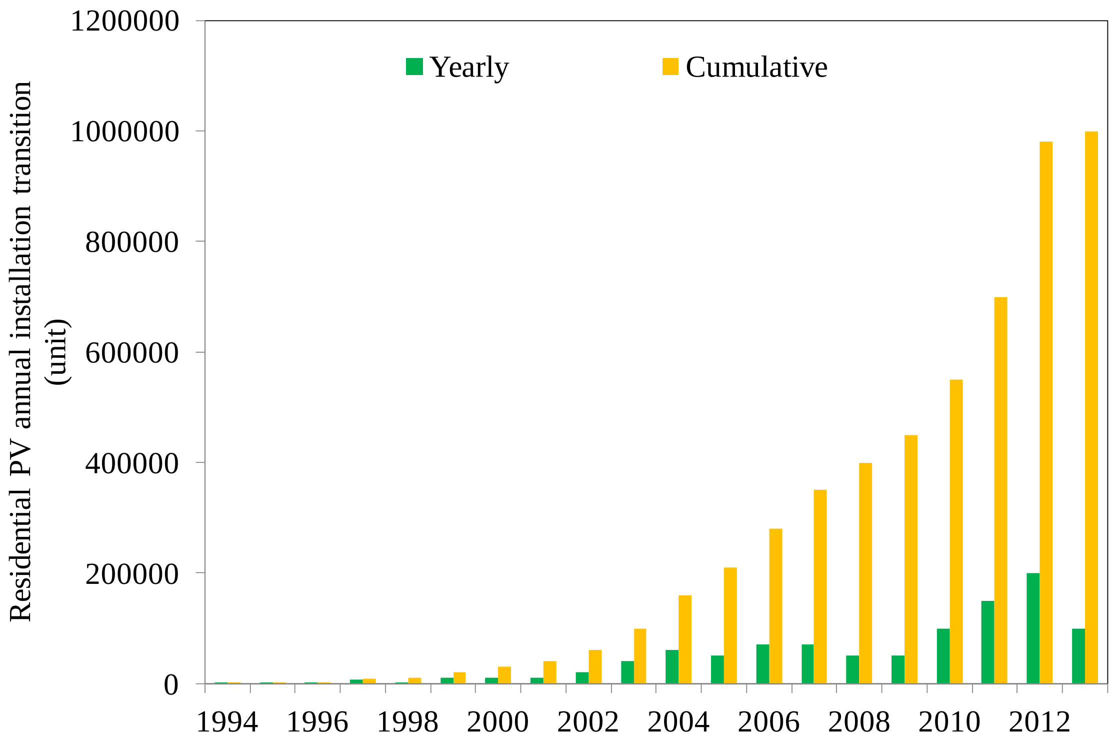


Fig. 2-19 Annually and cumulative PV system installation transition

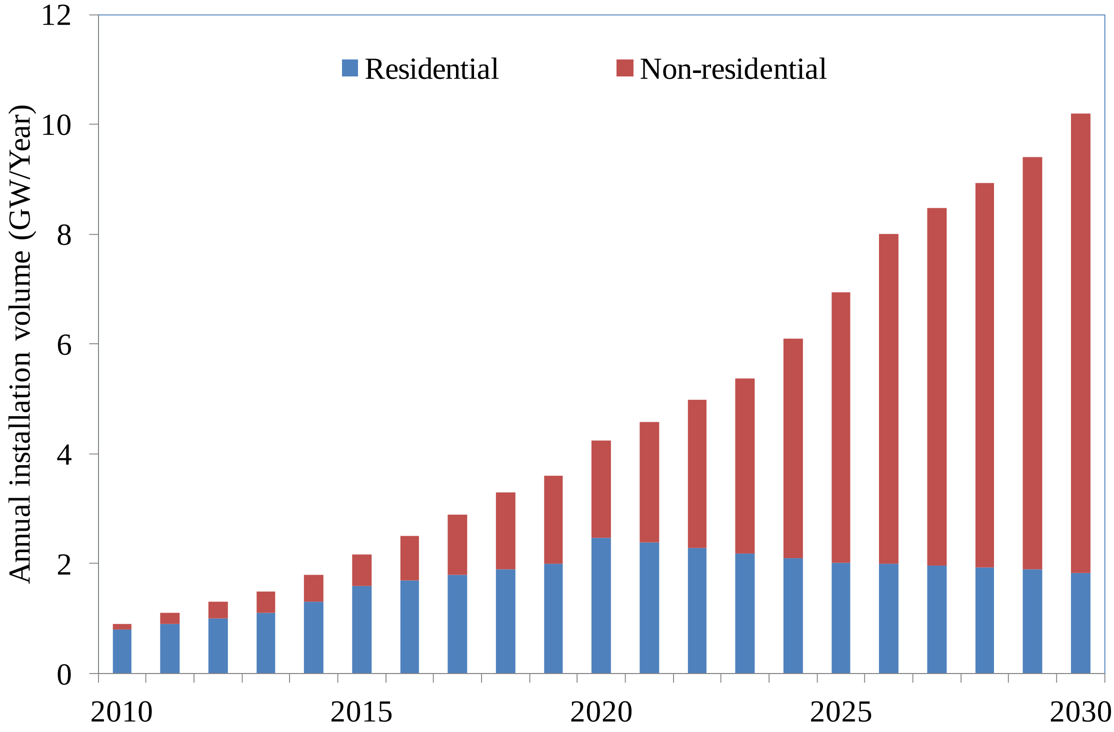


Fig. 2-20 Forecast of residential and non-residential PV unit development

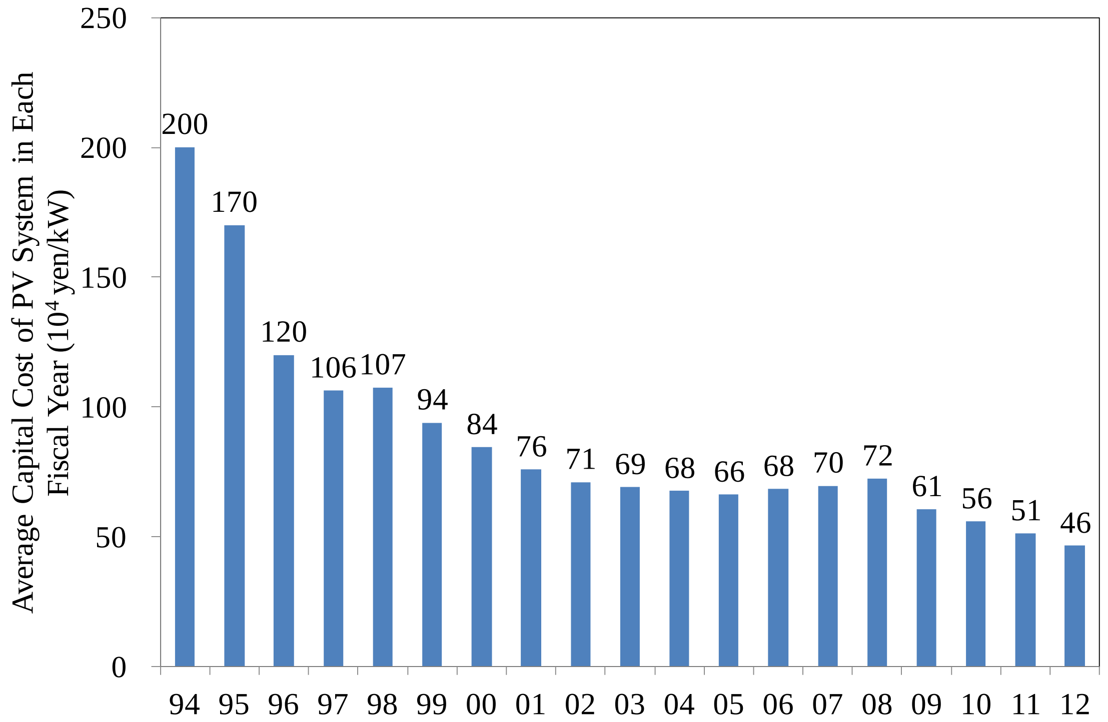


Fig. 2-21 Average capital cost of PV system in each fiscal year (10^4yen/kW)

It is widely known that, although PV system has various advantages（environmental friendly and energy saving）, the initial cost is expensive which is the main factor limit the PV unit development. Fig. 2-21 shows average capital cost of PV unit per kW which includes PV module, installation charge, accessory equipment price. It can be concluded that because of the competing market and progressing technology, generally, the capital cost of the PV system show a decreasing trend, which was reduced to as low as 460 thousand yen/kw, only 23% of the value in 1994.

Furthermore, the PV system within various capacity always has different capital cost per kW. Fig. 2-22 shows Japan non-residential PV system cost by system size. In a separate survey, METI found that the average installed cost of systems greater than 1 MW increased to ¥305 per watt in the fourth quarter of 2013 from ¥280 per watt in the same quarter in 2012. This increase is due partly to higher priced imported components because of the yen's devaluation and the rise of domestic installation costs. Another reason that non-residential system costs have not decreased quickly is that system integrators, or EPCs, do not have a strong incentive to lower their prices. This is because so many PV projects with the FY2012 FIT rate (¥42/kWh) remain uncommitted and those projects are expected to provide better profit margin than the projects with FY2013 FIT rate (¥37.8/kWh).

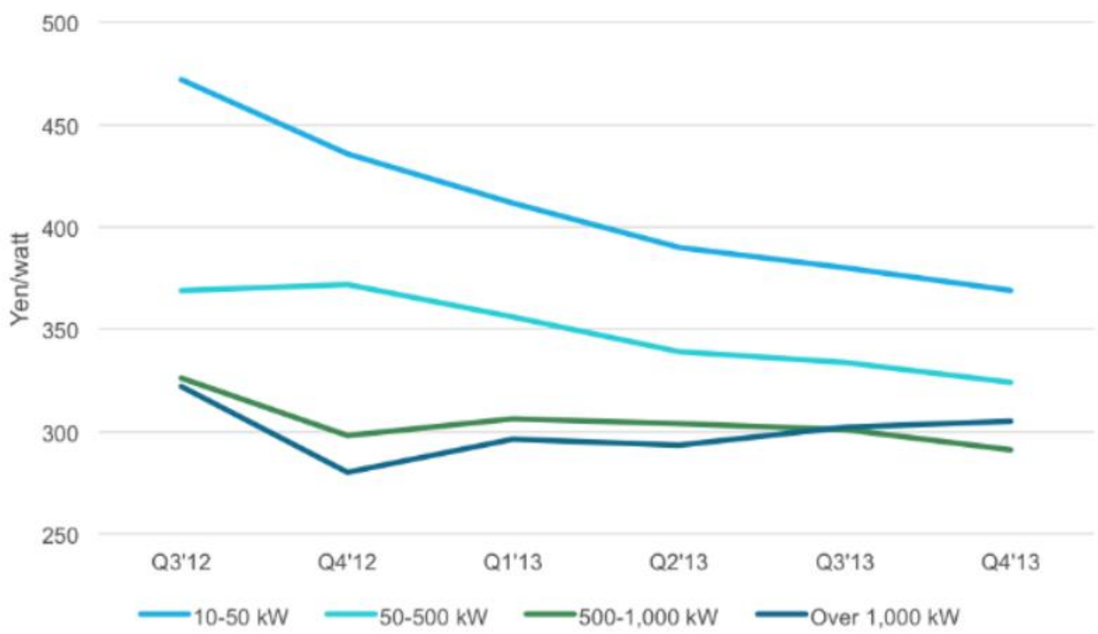


Fig. 2-22 Japan non-residential PV system cost by system size

2.6 Policies for CHP and PV system adoption in Japan

2.6.1 Policies for CHP adoption in Japan

Japan is one of the most energy efficient countries in the world. The government has proposed lots of energy targets as a strategy to reduce dependency on energy imports and to address climate change. As a consequence, combined heat and power (CHP) use has increased over the past 20 years and now provides 4% of the country's electricity production. Government support is an essential driver, with favorable subsidies and tax reductions. Investment subsidies and tax benefits are used as the main tools, rather than feed-in tariff approach. As early as in 1985, Japan has set up the cogeneration research association, and the name was changed to "Japan cogeneration center" in 1997, again in 2011, the name was changed to "the center for cogeneration and energy efficient utilization". The center is mainly engaged in activities related to investigation, research and popularization of cogeneration, which is the most authoritative civil society. Under the support of government and private consortium, Japan has launched a series of laws and regulations based to the application and popularization of distributed cogeneration system, in order to standardize the implementation and operation of the project. Also, a series of subsidies has been promoted, to promote the popularization of the project.

The main CHP support mechanisms are described below.

(1) Subsidies for High-Efficiency Natural Gas CHP

Although distributed cogeneration has experienced more than 30 years in Japan, the government still puts lots of money on it. Table 2-2 shows the various subsidy from the Japanese governments. From the national level, the ministry of economy, the environment ministry, ministry of Land Infrastructure and Transport has launched a series of subsides to promote the application of distributed cogeneration system. Environment ministry is mainly from the perspective of CO2 emissions, while Ministry of Land Infrastructure and Transport generally from the perspective of building energy efficiency, putting forward a series of subsidy policies. In addition, local governments, such as Tokyo, also launched local policies to promote the application of distributed cogeneration system. The Support Programme for New Energy Users provides subsidies for businesses that introduce qualifying new energy systems such as natural gas CHP systems and fuel cells. Distributed power supply subsidy is directly for distributed cogeneration system, the budget in 2013 is as much as 24.97 billion yen; civilian fuel cells are mainly for domestic CHP, which is as high as 25.05 billion yen. In addition, the grant rate is up to one-third of the installation cost.

Table 2-2 List of various policies

(a) Policy of Economy ministry

Name	Subsidy rate（upper limit）	Object device			Budget in 2013（100 million yen）
		Thermoelectric generator	Backup boiler	Fuel cell	
Distributed power adoption promotion subsidies（10kW-10000kW CGS）	Local government:1/2；Folk：1/3；Upper limit：500 million /year/unit	○	○	○	249. 70
Distributed power adoption promotion subsidies（>10000kW CGS）	Pipeline：1/4；Others：1/6；Upper limit：nothing	○	○	×	
Distributed power adoption promotion subsidies（self-use）	Small and medium-sized enterprises：1/2；Others：1/3；Upper limit：500 million /year/unit	○	×	○	
Energy rationalization use support business	Multi-user cooperation：1/2；Others：1/3；Upper limit：500 million /year/unit	○	○	○	110. 00
Energy rationalization use support business（Civil society）	1/3；Upper limit：180 million /year/unit	○	○	×	4. 90
Civilian fuel cell import emergency countermeasures	（Installation）1/2；Upper limit：0.45 million yen	×	×	○	250. 50
Heat utilization support of RES	1/2；Upper limit: billion yen /year/unit	○	○	×	40. 00
Heat utilization support of RES	1/3；Upper limit: billion yen /year/unit	○	○	×	40. 00

Building innovative energy-saving technology promotion business	Principle 1/3，Upper limit 2/3；Upper limit：billion yen /year/unit	○	○	－	40. 00
Smart community promotion business	2/3；	○	○	－	80. 60

(b) Policy of Environment ministry

Name	Subsidy rate（Upper limit）	Object device			Budget in 2013（100 million yen）
		Thermoelectric generator	Backup boiler	Fuel cell	
Carbon emissions reduction (hospital CHP)	1/2；	○	○	-	76.00
High efficient implementation of CO2 emissions reduction	1/3；Upper limit：50 million /unit	○	○	-	11.20
Waste energy low carbon promotion	1/3；	○	○	×	7.75
CO2 control strategy（Hot springs energy promotion）	Heat pump：1/3；CHP：1/2	○	○	×	3.70

(c) Policy of Land Infrastructure and Transport

Name	Subsidy rate（Upper limit）	Object device			Budget in 2013（100 million yen）
		Thermoelectric generator	Backup boiler	Fuel cell	
Building CO2 emission reduction	1/2；Upper limit: 5% of total cost or less than 1billion yen	○	○	-	171.00
Building energy saving transformation promoting business	1/3；Upper limit：building 50million/unit	○	○	-	

(d) Policy of Tokyo

Name	Subsidy rate（Upper limit）	Object device: Thermoelectric generator	Object device: Backup boiler	Object device: Fuel cell	Budget in 2013（100 million yen）
Residential fuel cell, battery	1/4；Upper limit：225 thousand	×	×	○	100.00
Official building CHP	1/2； Upper limit：300million	○	○	×	
Self-use power generation equipment	1/2； Upper limit：15million	○	×	-	-

(2) Accelerated tax depreciation of CCHP investment

Table 2-3 shows the tax depreciation of distributed CHP system. The Taxation System for the Promotion of Investment in Energy Supply-Demand offers a 7% tax exemption for small and medium-sized projects or an accelerated tax depreciation of 30% of the standard acquisition value of CCHP equipment. All of the distributed CHP system tax depreciation policy is promoted by economic ministry, which is implemented from two aspects: investment tax and fixed capital tax. However, both of them are not suitable for fuel cell system (table).

Table 2-3 Tax depreciation of distributed CHP system

Policy	Object device: Thermoelectric generator	Object device: Backup boiler	Object device: Fuel cell	Content
Green investment	○	○	×	Return 30%, more for 7% return for small and medium-sized enterprises
Special measurement for fixed capital	○	○	×	5/6 of standard tax in the first 3 years

(3) Administrative procedures for grid connection

The government has introduced special procedures for grid connection of CCHP systems including guidelines for distributed power grid connection and guidelines for grid connection technique requirement. Again, in 1995, electricity low was modified realizing FIT of distributed energy source. Furthermore, ten power company in Japan also launched FIT themselves. Generally, FIT is less than electricity price which promotes the principle of surplus electricity sold out. After the earthquake in east Japan, because of the deficiency of electricity supply, FIT is most high in Tokyo power company. Table 2-4 shows the FIT of distributed CHP system. For example, as shown in table, in summer, daily FIT is 12.64 yen/kWh, FIT in nighttime and holiday is 8.42 yen/kWh, which is about 2-3 times of other companies. In addition, FIT is relatively low in Hokkaido, which has little difference in other companies.

Table 2-4 FIT of distributed CHP system

(Source: Advanced Cogeneration and Energy Utilization Centre JAPAN)

Power company	Daytime in Summer （yen/kWh)	Daytime in other seasons （yen/kWh)	Nighttime & holiday （yen/kWh)
Hokkaido	3.5	3.5	3.5
Tohoku	7.55	7.55	7.55
Tokyo	12.64	11.45	8.42
Middle area	8.7	6.5	3.1
Hokuriku	4.33	4.33	4.33
Kansai	5.09	5.09	5.09
Chugoku	6.93	6.93	6.93
Shikoku	6.8	6	3.4
Kyushu	7.5	6.6	3.6
Okinawa	8.85	8.85	8.85
Average	7.189	6.68	5.477

(4) Low-interest loans for district energy

This loan scheme provided by the Development Bank of Japan consists of low-interest loans for DHC projects. The objective is to reduce costs and accelerate investment in DHC. The scheme targets electricity utilities in particular.

(5) Preferential gas price

Table 2-5, table 2-6 and table 2-7 shows the gas price list for general gas use, residential CHP system as well as commercial CHP system.

Table 2-5 General gas price list

List	Monthly use（m3）	Basic charge （yen/month/unit）	Unit price（yen/m3）
A	0-20	745.2	165.78
B	20-80	1026	151.74
C	80-200	1198.8	149.58
D	200-500	2062.8	145.26
E	500-800	6382.8	136.62
F	800-	12430.8	129.06

Table 2-6 Gas price list for residential CHP system

Type	Adopted Month	List	Monthly use （m3）	Basic charge （yen/month/unit）	Unit price （yen/m3）
Eco-will	12~4	A	0-20	745.2	165.78
		B	20-80	1242	140.94
		C	80-	2192.4	129.06
	5~11	A-F	Same as general	Same as general	Same as general
Ene-farm	12~4	A	0-20	745.2	165.78
		B	20-80	1458	130.14
		C	80-	1890	124.74
	5~11	A	0-20	745.2	165.78
		B	20-	1458	130.14

Table 2-7 Gas price list for commercial CHP system

Type	CGS capacity	Basic charge （yen/month/unit）	Basic charge for using （yen/month/m3）	Maximum need basic charge （yen/month/m3）	Unit price （yen/m3）
1	25kW	14256	432.73	5.95	80.81
2	15~25	14256	432.73	5.95	82.38
3	3~15	14256	432.73	5.95	85.9

2.6.2 PV policies in Japan

Before, less focus has been placed on PV. more government support in the areas of legislation, policy, and financial support, with the aim of expanding the industry and opening up a domestic market for PV.

Since the introduction of the RPS system in 2003, electric power supply by renewable energy has doubled. Moreover, since the surplus electricity purchase system was introduced in 2009, the introduction of residential photovoltaic power generation has largely increased.

Under the feed-in tariff scheme, if a renewable energy producer requests an electric utility to sign a contract to purchase electricity at a fixed price and for a long-term period guaranteed by the government, the electric utility is obligated to accept this request. The FIT is changing every year because of the competing market and progressing technology. Table 2-8 shows different FIT for PV system with various capacity in recent three years

Table 2-8 Different FIT for PV system with various capacity in recent three years

(Source: Ministry of Economy, Trade and Industry)

Year	< 10kW (surplus electricity)		> 10kW (total electricity)
	Single system	Double generation	
2012	42 yen; 10 year	34 yen; 10 year	43.2 yen; 20 year
2013	38 yen; 10 year	31 yen; 10 year	38.88 yen; 20 year
2014	37 yen; 10 year	30 yen; 10 year	34.56 yen; 20 year

Table 2-9 shows the various policies for PV system in Japan.

In 2005, the federal government of Japan concluded that the domestic PV market became self-sufficient and discontinued the residential incentive program. In the meantime Germany and a few other countries expanded their share of the market by infusing national FIT policies. In 2006, Japan faced its first market contraction. The domestic market suffered not only from the lack of incentives, but also lack of modules since domestic module makers shifted their focus to Europe for greater demand and better profits. To stop the domestic market from further decline, the federal government brought back the residential PV incentive program in January 2009 with an incentive rate of ¥70 per watt. The domestic PV market was revitalized and Japan celebrated its one million solar-roof installations in April 2012. Japan shifted its focus from the traditional residential segment to the non-residential segment with the launch of the national FIT program in July 2012. The national government believed that deploying the larger, non-residential segment was a quick way to expand the national PV market and to catch up with Germany and Italy.

Table 2-9 Policies for PV system in Japan

Department	Releasing Time	Policies	Contents
New Energy and Industrial Technology Development Organization（NEDO）	1980	Promoting financing of solar system	In the form of interest subsidies to promote financing
Utility grids	1992	Start of FIT	Surplus PV power can be purchased by the utility grids according to the electric price
New Energy Foundation（NEF）	1994	Supplying subsidies to PV adoption consumers	Supply subsidies to PV adoption consumers
The Ministry of Economy, Trade and Industry (METI)	2002	Renewables Portfolio Standard (RPS)	Furthering the use of RES by annually imposing an obligation on electricity retailers to use a certain amount of electricity from new energy
New Energy Foundation（NEF）	2005	Abolish of country yard PV subsidy	Abolish of country yard PV subsidy
New Energy Foundation（NEF）	2009	Restarting of FIT	Restarting of FIT
The Ministry of Economy, Trade and Industry (METI)	2009	Surplus electricity fixed price system	FIT，48 yen/kWh
The Ministry of Economy, Trade and Industry (METI)	2012	Purchasing all electricity generated from RES	Not just the surplus one, all electricity generated from RES can be purchased by the utility grid

2.7 Summary

In this chapter, the supply and consumption of energy and electricity in Japan are summarized. In addition, current status of CHP system as well as PV system adoption in Japan is investigated. Moreover, the policies for CHP system and PV system adoption so far are summarized.

According to the investigation, Japan has achieved great success in the introduction of distributed energy resources including both CHP and PV systems. To promote the development of distributed energy system in Japan, various policies including subsidies, tax depreciation ,FIT and other incentive policies have been introduced.

Reference

[1] International Energy Agency (IEA), World Energy Outlook 2014, OECD/IEA, 2014.

[2] METI, Japan. 2004. Trend of energy consumption in residential and commercial sector, The Ministry of Economy, Trade and Industry (METI), http://www.enecho.meti.go.jp/english/energy/index.html

[3] World alliance for decentralized energy, World Survey of Decentralized Energy 2005, March 2005

[4] Advanced Cogeneration and Energy Utilization Centre JAPAN, < http://www.ace.or.jp/>.

[5] Soderman, J., Pettersson, F.: Structural and operational optimization of distributed energy systems. Applied Thermal Engineering 26 (2006) 1400-1408

[6] Huang Jiayi, Jiang Chuanwen, Xu Rong, A review on distributed energy resources and MicroGrid. Renewable & Sustainable Energy Reviews (2007)

[7] Kari Alanne, Arto Saari, Distributed energy generation and sustainable development. Renewable & Sustainable Energy Reviews 10(6) (2006) 539-558

[8] New energy and industrial technology development organization (NEDO). http://www.nedo.go.jp/english/index.html

[9] Agency for natural resources and energy, Ministry of economy, Trade and industry, Energy in Japan, May 2005

[10] D.W. Wu, R.Z. Wang. Combined cooling, heating and power: A review. Progress in Energy and Combustion Science, 2006, 32(5-6): 459-495.

CHAPTER THREE: INVESTIGATION ON CURRENT ENERGY SITUATION AND DISTRIBUTED ENERGY SYSTEM ADOPTION IN CHINA

3.1 Introduction

China became the world's largest energy consumer (18% of the total) since its consumption surged by 8% during 2009 (up from 4% in 2008). In 2012, China accounted for one-fifths of the world’s total primary energy demand. Coal remained the fuel of choice for the country, accounting for nearly 68.5 percent of total energy use. China also accounted for about half of the global consumption of coal. In Beijing, 16.7 percent of the PM 2.5 particles results in coal fire. Recently, with the heating being turned on in northern China, concerns have been raised over the pollution caused by the inefficient coal-based system. To tackle it, China has decided to cut consumption of the fossil fuel to below 65 percent of primary energy use by 2017. The plan also aims to raise the share of non-fossil fuel energy to 13 percent.

Moreover, in order to cope with the continuing global warming, before the 15th Conference of the Parties (COP 15), the Chinese government proposed its voluntary reduction target in the carbon intensity per unit of GDP, by 40-45% by 2020 from 2005 levels. It is anticipated that in the coming 12th five-year-plan, not only the energy intensity target but also the carbon intensity target will be included. Therefore, it can be found that although having no obligation and numerical target to reduce CO2 emissions according to the Kyoto Protocol, in order to acquire an advantage position in the post-Kyoto period, as well as promote the international understanding and illustrate its international responsibility as a large country, sustainable low-carbon development has been recognized as one of the most important considerations while establishing national development plan in China. Especially, as the main producer of CO2 emissions, energy sector is expected to play the main role by introducing both renewable and energy conservation technologies. However, in the past few years, energy conservation activities have been always focusing on measures for single equipment or customer, and an integrated viewpoint is escaped while planning regional energy systems taking into consideration local features and system cooperation In order to overcome this problem, based on the consideration of local generation for local consumption, a concept of distributed energy system (so-called microgrid) has been proposed, due to its high overall efficiency (combined heat and power), excellent environmental performance (renewable technologies), and other benefits.

In this chapter, the supply and consumption of energy and electricity in China are summarized. In addition, current status of CHP system as well as PV system adoption in China is investigated. Moreover, the policies for CHP system and PV system adoption so far in China are summarized.

3.2 Energy supply and consumption in China

3.2.1 Total primary energy consumption

Fig. 3-1 shows the total primary energy consumption and increase ratio in China. As the figure shows, China has a larger amount of energy consumption than Japan (chapter 2). In recent years, with rapid economic growth and improvement of the living standard, annual energy consumption in China has increased rapidly. By the year of 2012, Chinese energy consumption reached 2.73 GTOE (tones of oil equivalent) which was as much as 5.9 times than that of Japan, and become the world largest energy consumer. In China, the value did not change a lot before 2001, but it increased obviously from 2002 and kept a steady growth. On the other hand, as to the increase ratio, the peak value occurs in 2004 with 16.9%. Although the energy consumption increases in recent years, the ratio show a decreasing trend.

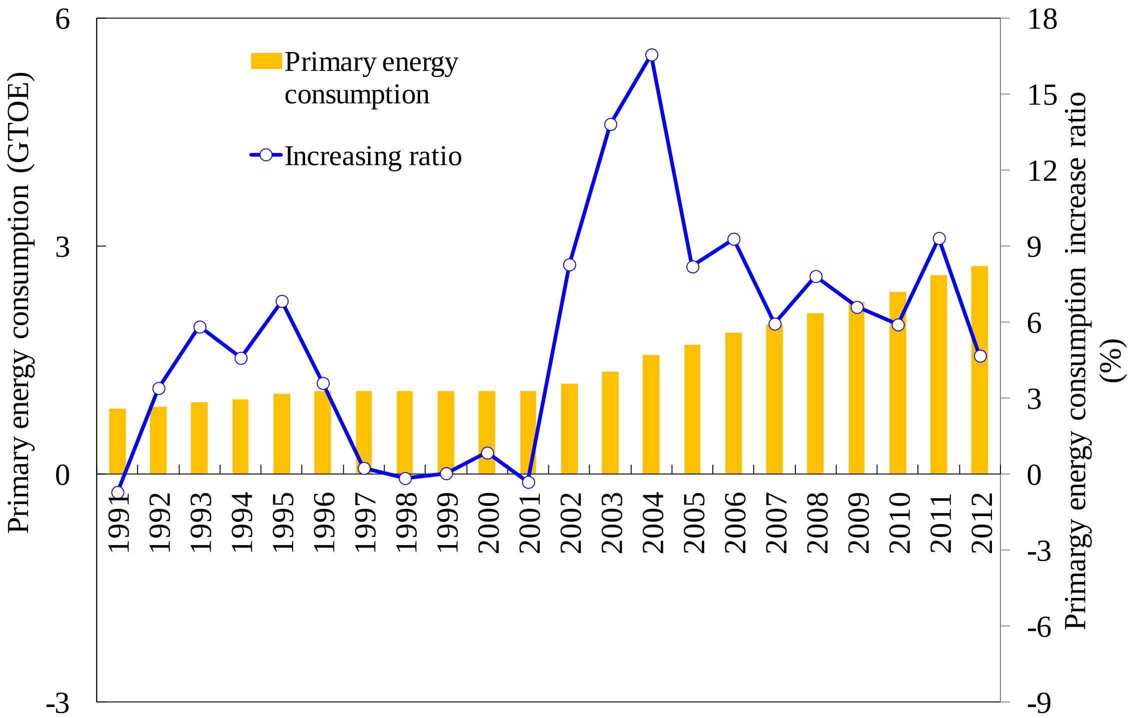


Fig. 3-1 Total primary energy consumption and increase ration in China

(Source: World bank)

Fig. 3-2 shows the share of energy supply in China in 2012. From the figure, it can be concluded that coal was the main energy supply source with 67.9% of total energy supply, followed by crude oil, biomass and waste, natural gas, hydroelectric resources, and nuclear, and accounted for 16%, 7.5%, 4.2%, 2.6% and 0.9%, respectively.

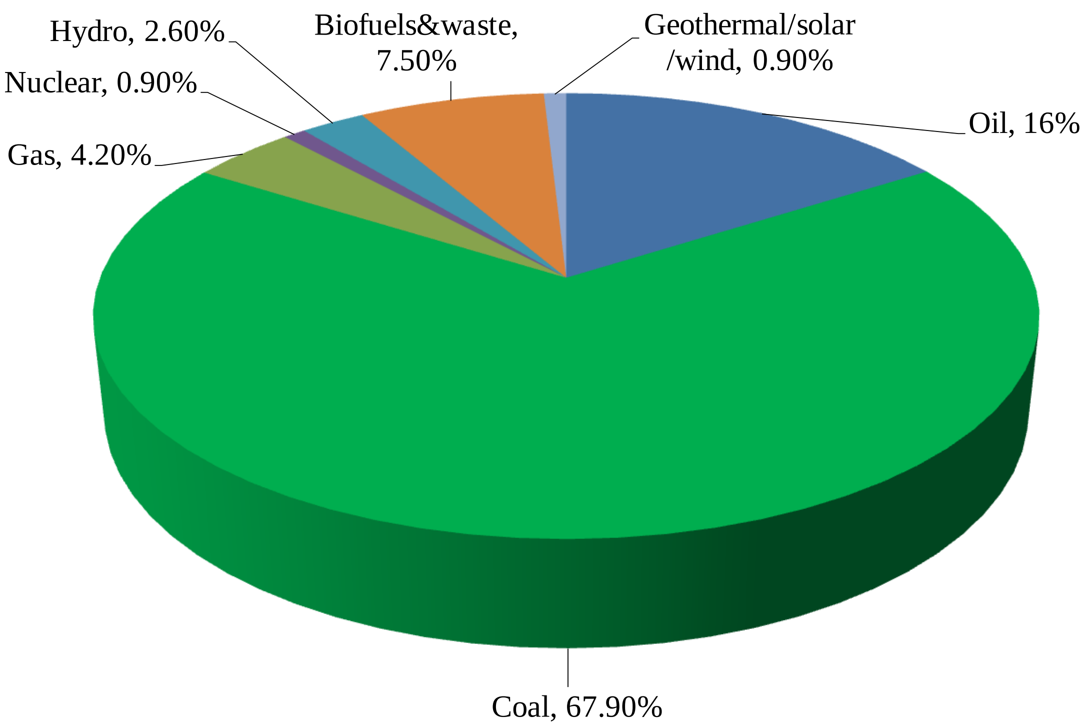


Fig. 3-2 The share of primary energy supply in China in 2012

On the other hand, from the viewpoint of final energy consumption, Fig. 3-3 shows the energy consumption of different sectors in China from 1994 to 2008. As shown in the figure, in China, the industry sector was the main energy consumer with took up about 80% of the total energy consumption. The building sector had a share of about 13% in 2008. In addition, the transportation sector illustrated an increasing trend in energy consumption from 5% in 1994 to 9% in 2008, among total primary energy consumption.

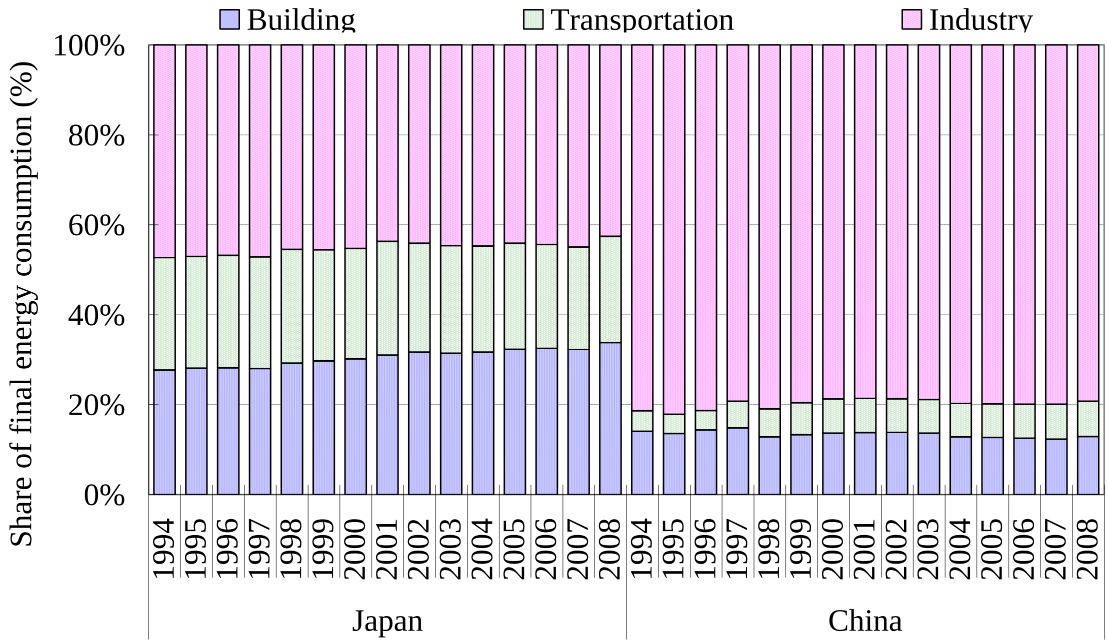


Fig. 3-3 Share of final energy consumption

(Source: World Energy Outlook 2011)

3.2.2 Energy consumption intensity

Fig. 3-4 shows the energy consumption per unit of GDP in China from 1990 to 2011. As to China, with the development of technology and energy saving consciousness, the energy consumption intensity showed a gradual decrease in recent years. However, it should be noticed that the value was still relatively higher compared worldwide value. Therefore, energy conservation is still the first priority in China along with the continuing economic growth [1].

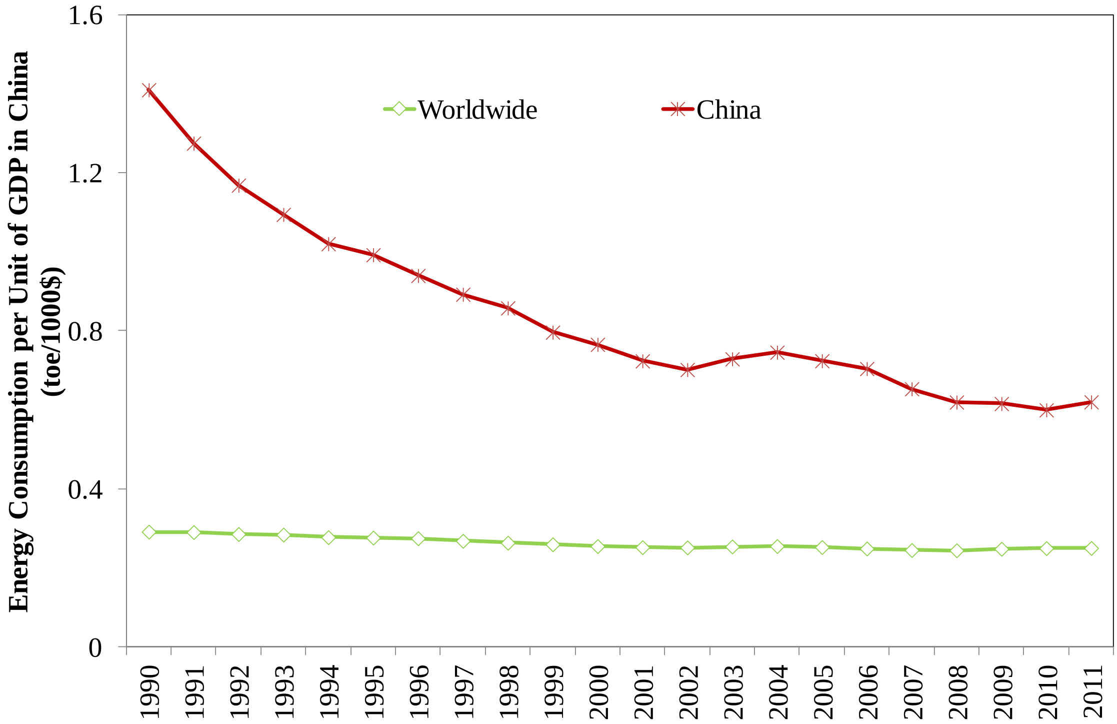


Fig. 3-4 Energy consumption per unit of GDP in China (toe/1000$)

(Source: The World Bank)

3.3 Electricity supply and consumption in China

3.3.1 Electricity supply utility grid

In China, the electric utility service is more complicated than that in Japan. As shown in Fig. 3-5, generally, national electricity consumption is served by two companies, namely, Southern China Grid and State Grid which is further divided into five sub-grids which include: Northeast China grid, Northern China grid, East China grid, Central China grid, Northwest China grid. In addition, each sub-grid is composed of some province level companies.

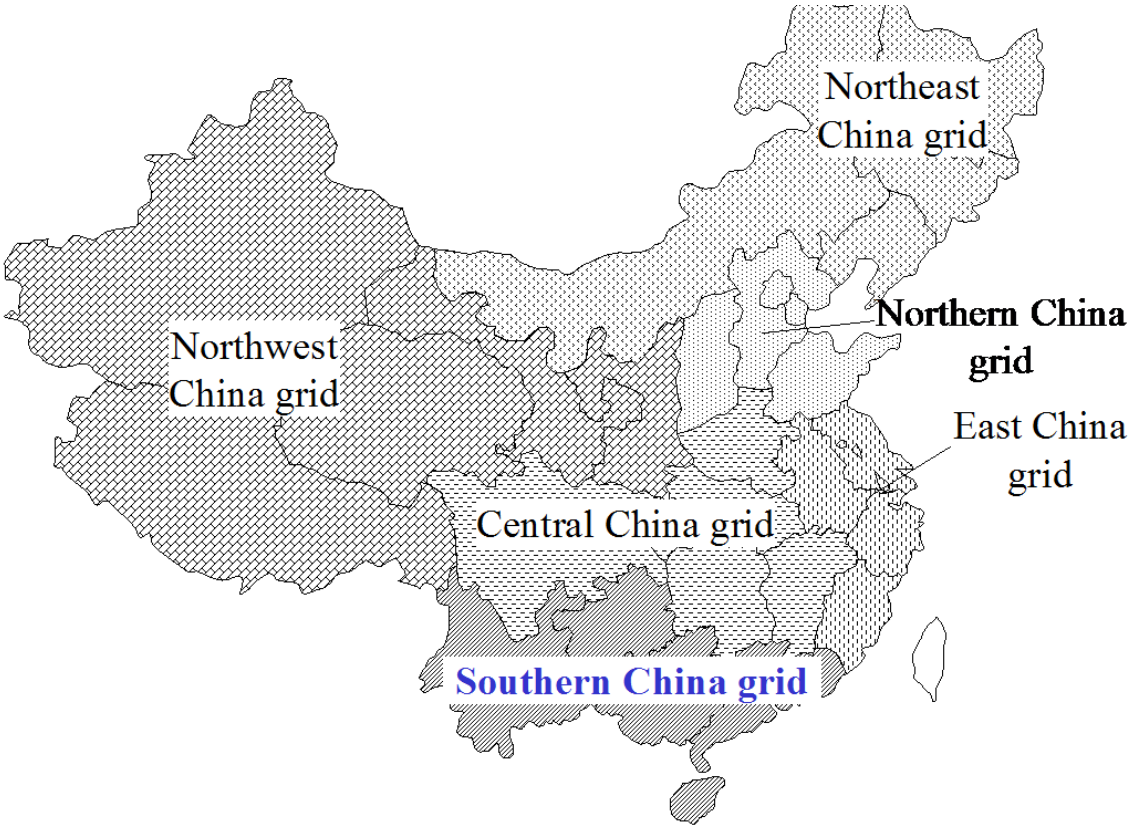


Fig. 3-5 Image of electricity supply grid in Japan and China

3.3.2 Energy source for power generation in China

Fig. 3-6 shows the energy source for electricity generation in China. As shown in the figure, the total power generation is 931 GW. Coal plays the absolute main role in power generation, with a share of about 71.6%. Hydro is another main source for power generation in China which a ratio of about 21.6%. Furthermore, it is interesting to notice that due to recent rapid development of wind farm, the capacity of wind turbine is increased over that of the nuclear station [2].

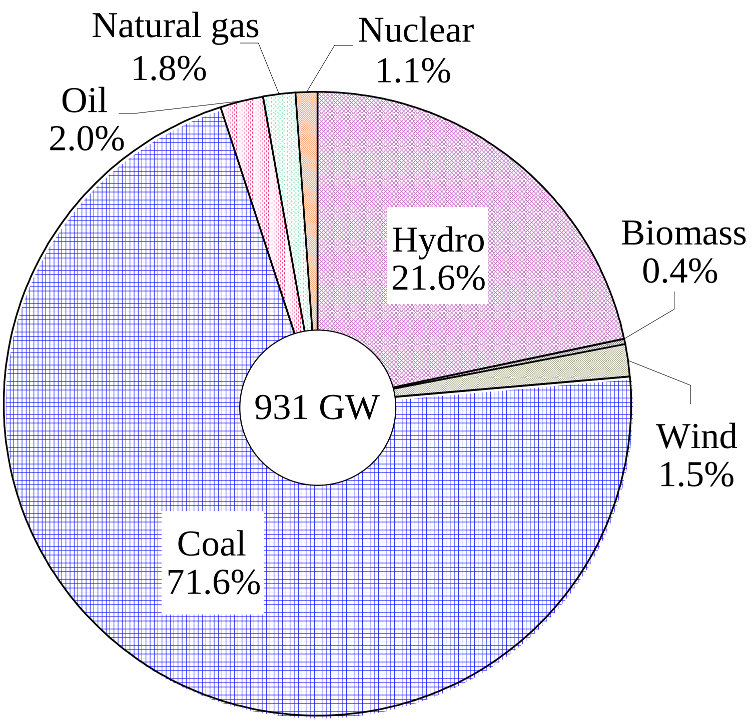


Fig. 3-6 Energy source for power generation in China

(Source: World Energy Outlook 2011)

3.3.3 Electricity tariffs

Fig. 3-7 shows the general electricity tariff structure in China. Generally, similar with the situation in Japan, residence, commerce and industry are always treated in a separate way. Note that, special industry with relatively high energy consumption is endowed a specific tariff which is not indicated in Japan. Although double item tariff (composed of demand charge and energy charge) is widely penetrated in Japan, it is still an alternative one in China.

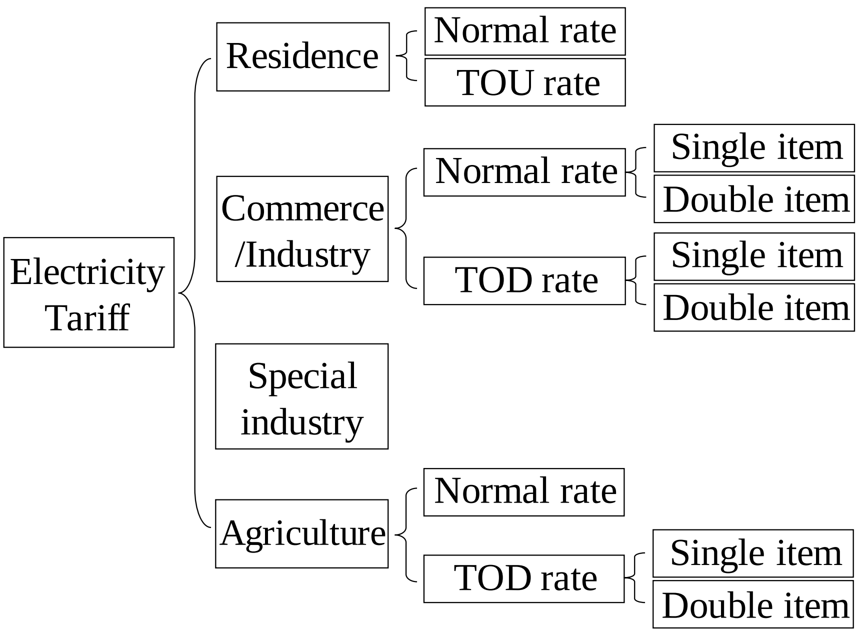


Fig. 3-7 General electricity tariff structure in China

As to the components of electricity tariff, as shown in Fig. 3-8, China has the simplest one which is only composed of energy charge and demand charge (sometimes is neglected).

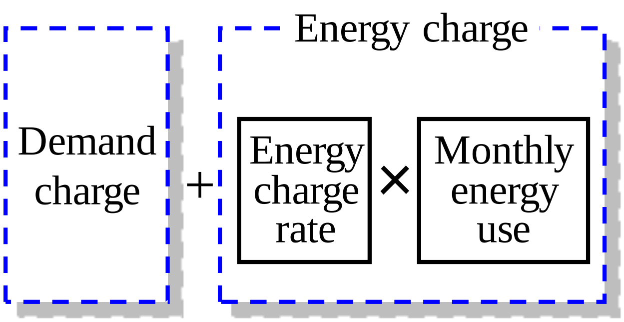


Fig. 3-8 Image of different electricity tariff types in Japan and China

Fig. 3-8 shows the image of time district in China. In TOU or TOD tariffs, the electricity tariff rate may fluctuate according to the season and time period, in China, some morning and evening hours are also considered as the on-peak hours.

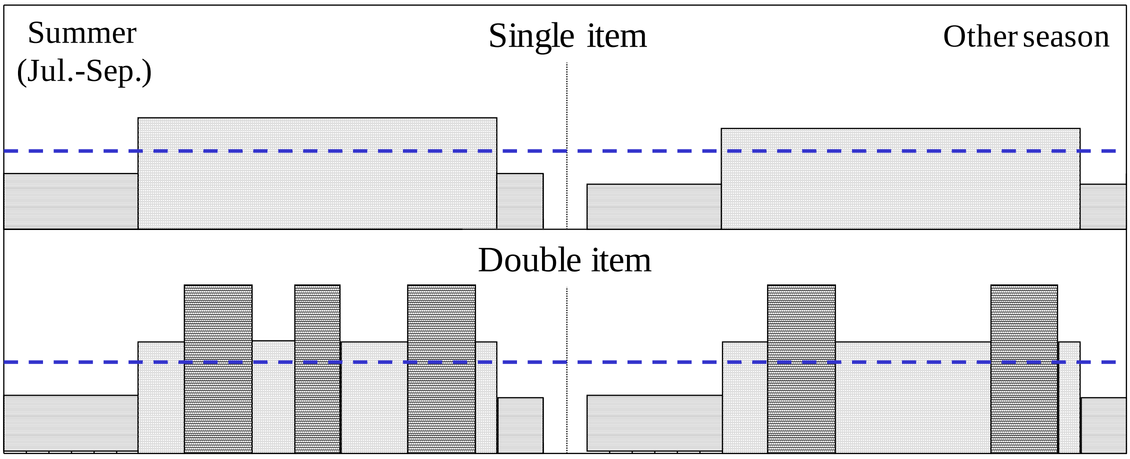


Fig. 3-9 Image of time district in China

3.4 Current status of CHP and PV system adoption in China

Coal consumption plays a central role in China's economy. Seventy percent of China's energy consumption comes from coal, much higher than the global average. Coal burning creates a negative impact on China's environment and generates massive amounts of carbon dioxide. The World Bank estimates that by 2020, the external costs from coal usage will reach 13% of China's GDP. In the 2008 edition of the International Energy Outlook, the Energy Information Administration predicts that in 2030, China will generate more than half of the world's total carbon dioxide emissions from coal use. At the same time, as the world's largest developing country, China's energy demand has been increasing steadily. The Energy Information Administration also predicts that China's net electricity consumption will continue to grow at an average annual growth rate of 4.8%. By 2030, China will consume 20% of world total electricity output. On the supply side, it is estimated that in 2010, after accounting for coal, hydro, and nuclear, there would be a 6.4% shortage in electricity supply. The shortage will grow to 10.7% in 2020. The gap between electricity supply and demand will have to be filled by renewable energy. PV powered systems will play a critical role.

China, as the world's fastest growing developing country, has fuelled a massive demand for energy. Chinese leaders, from the central government to regional levels, are addressing China's rising energy needs and encouraging the development of renewable energy sources.

3.4.1 Current status of CHP system adoption in China

In China, gas distributed generation was introduced at the end of last century. However, it has groped in the dark for a long time, and failed to form guiding policies and regulations. In October 2011, National Development and Reform Commission, Ministry of Finance, the Ministry of Housing, Energy Board jointly issued the "Guidance on developing natural gas distributed energy", which firstly advocates the gas distributed generation development from the national level [3-4].

China is the second-largest energy consumer and carbon emitter in the world.1 As a result of economic development, China's energy consumption has been growing rapidly in recent years and energy and environmental issues have become a key challenge to China's sustainable development. As a result, the Chinese government has begun to pay unprecedented attention to energy efficiency and emissions reductions, proposing an ambitious target to reduce energy intensity by 20%. As important energy efficiency technologies, combined heat and power (CHP) and district heating and cooling (DHC) have received a good deal of attention by the Chinese government. Over the past several decades, China has issued a series of policies to promote CHP/DHC; as a result, China has become the second-largest country in terms of installed CHP capacity. In 2006, CHP capacity in China increased to over 80 GW, providing 18% of nationwide thermal generation capacity [5].

China views CHP as an energy-efficient and environmentally friendly energy supply option. As such, CHP use in China has grown. Due in part to government promotion, China's CHP market developed significantly in the past decades, as shown in Fig. 3-10 and 3-11. At present, China is second in the world in installed CHP capacity, which increased from10GWin 1990 to30 GW in 2000, with an annual growth rate of 11.6%.3 By 2005, CHP reached almost 70 GW of capacity, with an increasing annual growth rate of 18.5% from 2001-05. During this time, the share of CHP capacity in thermal generation increased from 11.3%in 1990 to 17.8%in 2005 [5].

In 2006, there were more than 2 600 CHP units in China, representing over 80 GW, providing about 18% of the thermal generation capacity. The heating supply from CHP was nearly 2300 PJ, representing an 18% increase compared to 2005. The National Development and Reform Commission estimates that, compared to separate production of heat and power, CHP has resulted in energy conservation of 67Mtce.

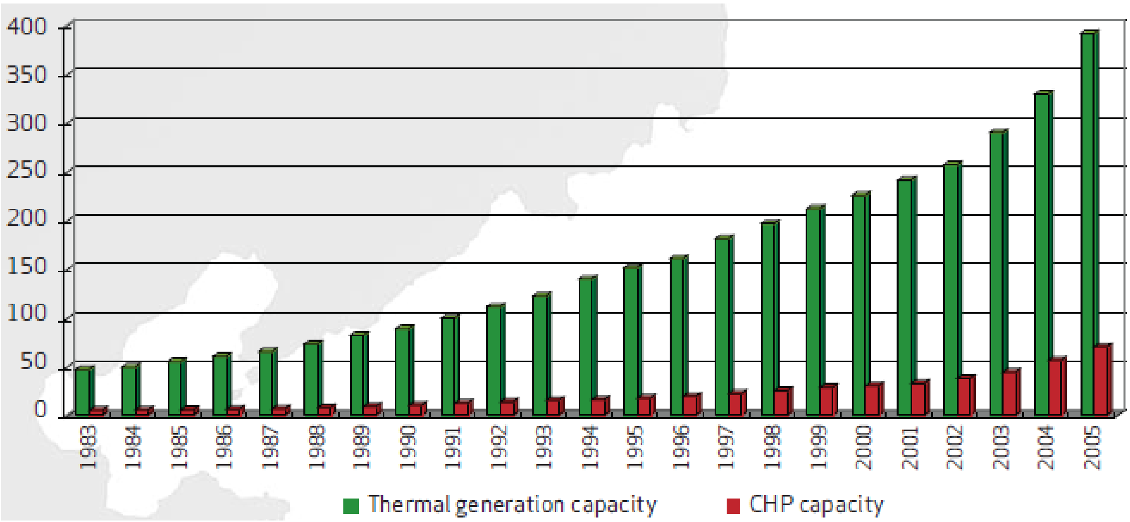


Fig. 3-10 China's thermal generation and CHP capacity

(Source: The International CHP/DHC Collaborative)

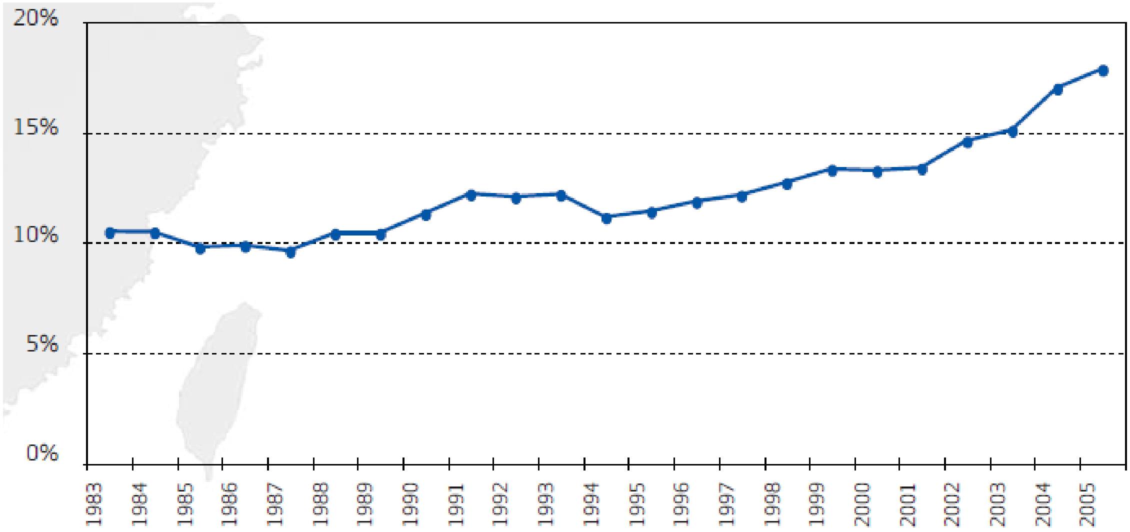


Fig. 3-11 The share of CHP capacity in thermal power generation in China
(Source: The International CHP/DHC Collaborative)

Table 3-1 shows the national CHP heating supply, including the 15 traditional heating provinces during 2003-05. These 15 provinces are the main market for heat, accounting for 60-70% of demand. In the traditional heating areas, CHP provides heat for both the industry and residential sectors, and there are steam pipelines and hot water pipelines in important heating areas. CHP heat demand is also rapidly increasing in the southern provinces to meet increasing heat demand of growing industrial and residential sectors. To meet this growing demand, China has started to install large (200-300 MW) CHP units in recent years. These units have important energy saving features compared with existing smaller-scale units.

Table 3-1 CHP heating supply (PJ)

(Source: The International CHP/DHC Collaborative)

	2003	2004	2005
National	**1 484.2**	**1 657.4**	**1 925.5**
BeiJing	54.0	50.4	60.9
TianJin	46.9	49.2	57.2
HeBei	117.8	122.7	138.1
ShanXi (capital Taiyuan)	41.0	44.3	53.1
NeiMenggu	55.5	54.4	52.9
LiaoNing	197.5	195.9	209.2
JiLin	88.1	98.0	101.3
HeiLongjiang	81.8	91.8	99.8
ShanDong	243.0	191.1	266.8
HeNan	36.9	29.5	40.4
ShanXi (capital Xi'an)	11.6	12.9	13.8
GanSu	32.7	34.9	37.0
QingHai			
NingXia			2.0
XinJiang	27.0	26.6	32.9
Total traditional heating area[6]	**1 033.8**	**1 001.7**	**1 165.4**
Percentage	**69.7%**	**60.4%**	**60.5%**

3.4.1.1 Current status of CHP in Shanghai

There is a lake of detail data of current CHP system adoption status in other countries except Shanghai, the economic center in China. Throughout the history of gas distributed generation development in China, Shanghai always plays the leading role. In 1998, Huangpu Central Hospital built the first cooling, heating, and power system, which opens the gate of the gas distributed generation development in China [6-7]. Currently, the gas distributed energy development in Shanghai are facing grim situations: on the one hand, the devices depend on import and price raises sharply, which leading to the initial investment and operating costs showed double high, seriously affecting the economic system; on the other hand, the relevant institutions system, mechanisms system and policy system are imperfect, so that the gas distributed energy system is difficult to fully play its energy saving advantages. However, referencing to the development status and prospects of foreign city, we can foresee that the gas distributed generation in Shanghai will have huge potential in the future, and it will support a low-carbon transition of Shanghai electric power industry.

As of 2014, the total number of gas distributed energy projects is 31 in Shanghai, with total installed capacity of 54322 kW, nearly 0.27% of total installed capacity in Shanghai, and average installed capacity is about 1752 kW (Fig. 3-12).

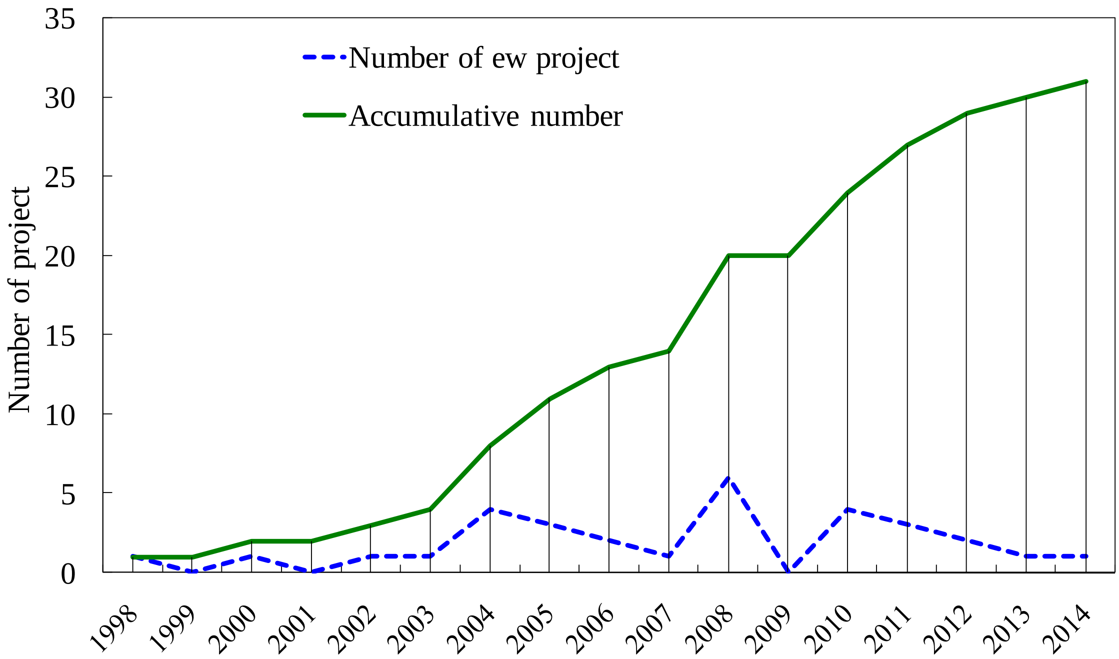


Fig. 3-12 Number of distributed generation projects in Shanghai

The projects include hospital, hotel, office building, factory, transportation hub, large blocks, etc.; that prime movers include micro and small gas turbine, internal combustion engine and Stirling engine, etc.; and that system design consists of combined heating and power and combined cooling, heating and power. Furthermore, the increment of the installed capacity in recent years mainly comes from regional distributed energy projects, such as the Hongqiao business district and international tourist resort. This also shows that applications of gas distributed generation in Shanghai has transformed from dominant building type to area type

At present, there are 13 projects under normal operation, the total capacity is 21641 kW, accounting for about 40% of total installed capacity of all projects; there are 4 projects for teaching experiment, the total installed capacity is 275 kW; 5 projects have been stopped, the total installed capacity is 2258 kW, accounting for about 4% of total installed capacity; the main reasons for shutting down include the inaccuracy load forecast, out of business, municipal movements and biogas drying up.

In addition, the operation status of the project under operation is also diverse. Operation hours of some projects are high and their running efficiency is relatively good. However, operation hours of some projects are very short, so economic efficiency of these projects is low. Fig. 3-13 is the operation time variation of some projects under normal operation.

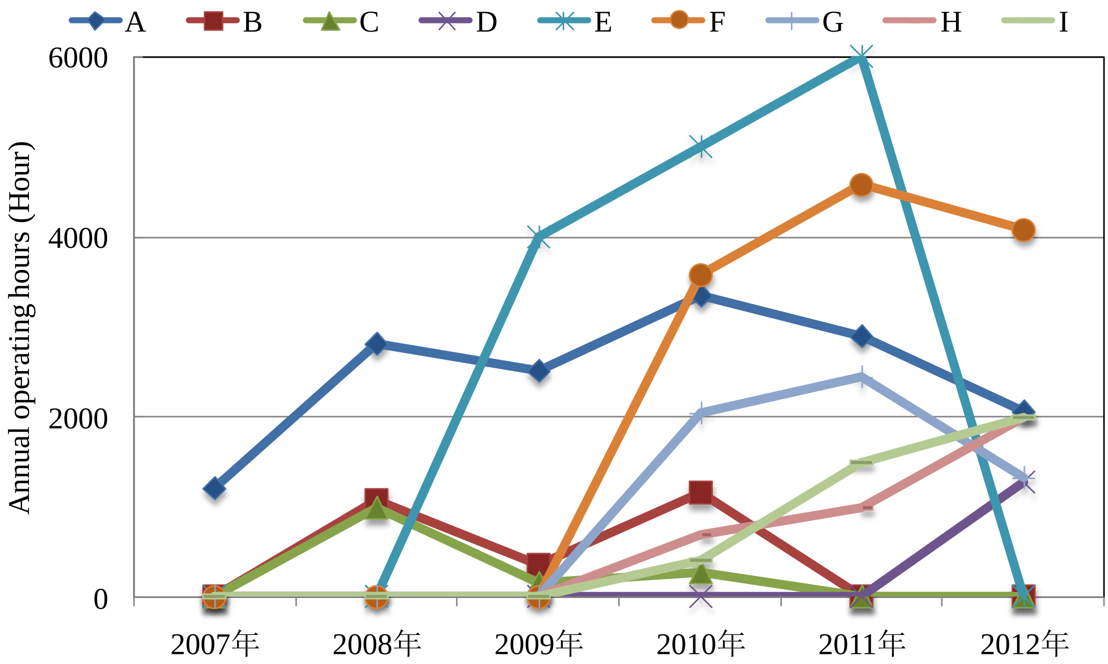


Fig. 3-13 Annual operating hours of various distributed generation in Shanghai

3.4.2 Current status of PV system adoption in China

The amount of solar energy is rich in China, and land surface receives as much as 5000 billion GJ solar radiant energy every year. The daily total amount of solar energy received is 335-837 kJ/cm2. It is said that China has become the world's largest consumer of solar energy. It is the largest producer of solar water heaters, accounting for 60% of the world’ s solar hot water heating capacity, and the total installed heaters is estimated at 30 million households. Solar PV production in China is also in rapid development.

China’s domestic market started to increase obviously under the promotion of China’s PV power generation demonstration projects, in 2009 although this lagged behind the international phase. Fig. 3-14 shows the accumulated PV system capacity and new installed PV capacity from 2000 to 2013. As the figure shows, before 2008, total PV installation capacity in China are marginal. By the end of 2008, total PV capacity in China was only about 140 MW, which is far below that of Japan. However, since 2009, the capacity in China has been increasing rapidly which increased by 2500MW for 2011 and 5000MW for 2012, both of the growth rate is over 100%. Note that in 2012, the accumulated PV installation capacity occupied as much as 8% of global PV capacity and has surpassed Japan. In addition, solar power in China is a growing industry with over 400 photovoltaic (PV) companies. In 2013, China has become the world's leading installer of solar PV, adding a record 10 GW of capacity to a cumulated total of 18.3

GW. This is more than twice as much as in 2012 when China installed about 5.0 GW of solar panel capacity. In addition, among all the applications, about 43% is for remote areas power supply, 40% is for communication and industrial applications. The rapid development of PV unit, on one hand, leads to the dependence of Chinese PV cell industry, which is the world third largest producer on the foreign market; on the other hand, results in large environmental load due to PV cell production, rather than reducing emissions though the application of PV system.

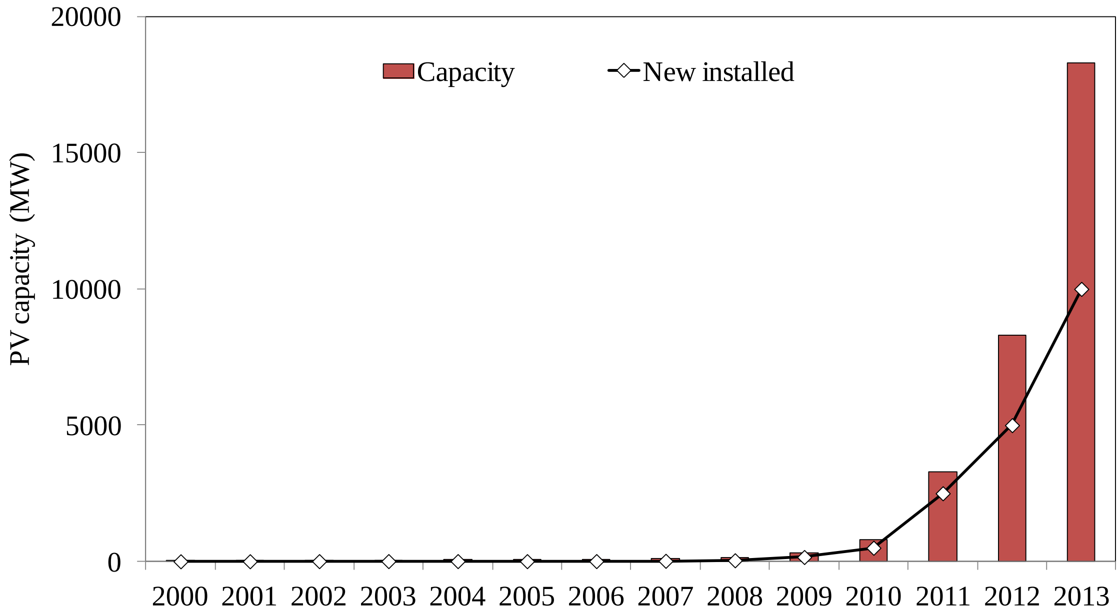


Fig. 3-14 PV installation capacity in China

In contrast to the installation market, China’s manufacturing industry performs miracles. Since 2004, the growth rate of China’s solar cell production exceeded 100% in five consecutive years. In 2007, China’s production of PV cell modules ranked first in the world [8]. In 2009, it accounted for more than 50% of global total production [9]. In 2010, four of the world’s largest five PV manufacturers were Chinese enterprises: Suntech, JA Solar, Yingli Green Energy and Trina Solar, with shares of 6.6%, 6.1%, 4.7% and 4.7% of global cell production respectively [10].

Recognizing the global opportunities in PV products and systems, China has been building a massive PV industry representing all facets of the supply chain, from polysilicon feedstock, ingots and wafers to cells and modules. In 2007, China took the world's number one spot in solar cell manufacturing with a total production of over 1GW. In 2008, China manufactured 2GW of solar cells, representing 30% of the global total production, to secure a leading position. Virtually all of this PV production has been exported. In 2008, China installed 40 MW of PV domestically—only 0.7% of the global total. According to China's 11th Five-Year Plan, China will reach only 17% of the world average level of PV-generated power by 2010, and only 6% of the world average by 2020. This report recommends an accelerated adoption of PV power in China to reach global average level of PV power generation by 2014. PV cost trend Through continuous technological innovation, the cost of PV has decreased a lot.

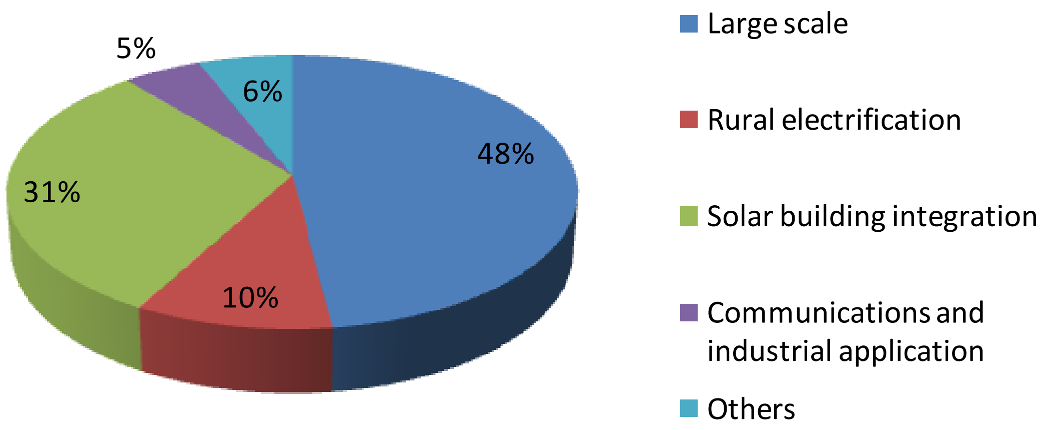


Fig. 3-15 PV installation proportion of different types in China

Before the year of 2008, PV market in China mainly refers to independent power generation which includes solar power supply goods, solar communication tools as well as rural electrification. However, by the end of 2010, large grid-connected ground PV power systems and PV integrated building have occupied the main market. Residential PV system has a request for the roof area, thus it is more suitable for villas, back lands, as well as single-family houses in the countryside in China. However, as to the urban area, residential PV system is hard to pop, on one hand for the limited roof area of the apartment, on the other hand, for the household allocation problem. Fig. 3-15 shows various kinds of PV system installation capacity proportion in China. As the figure shows, large-scale dominates the main PV market which occupies as much as 48% of total adoption, and followed by solar building integration and rural electrification.

The key measure to promote PV adoption is decrease the investment cost. According to CMEN (China Magisterial Energy Navigator), electricity generation cost of PV system has decreased a lot and been close to traditional electricity price, which is due on one hand to PV battery anti-dumping of European countries, on the other hand, to decreased PV manufacturing cost. Under this background, the goal of PV installation capacity of the Twelfth Five-year Plan has increased from 21GW to 40 GW. Again, as the decrease of PV manufacturing cost, the unit cost of PV system will keep decreasing and even lower than commercial and industrial electricity price. Note that, BIPV is the dominate style in developed countries, whereas only adopted in demonstration building in China.

3.5 Policies for CHP and PV system adoption in China

3.5.1 Policies for CHP system adoption

Historically, Chinese governments have found that CHP technology is an important energy conservation and environmental protection strategy. Therefore, since the 1980s, a number of CHP policies have been issued, as shown in table 3-2.

Among the policies mentioned above, some of the most important policies are described below in more detail.

(1) Some Regulations for CHP Development (1998) and Regulations for CHP Development (2000)

In February of 1998, SPDC (State Peace And Development Council), SETC (State Economic and Trade Commission), MOC, and MOEP (the Ministry of Environmental Protection) issued Some Regulations for CHP Development (1998). A key feature of these regulations was that, for the first time, the ratio between heat and electricity was considered an important indicator to define and approve CHP.

In August of 2000, Some Regulations for CHP Development (1998) was revised, and SPDC, SETC, MOC, and SEPA (State Environmental Protection Administration) issued revised Regulations for CHP Development, which proposed specific regulations on CHP technical indicators, management measures of CHP system, as well as the relationship between CHP and the utility grid. This is the most important regulation governing CHP development in China, and includes the following highlights:

- Requirements for local governments to make CHP development plans;
- Detailed CHP projects approval conditions;
- CHP technical indicator requirements, including overall efficiency levels, heat and power ratios. For example, for turbine CHP units, it pointed out that the overall annual energy efficiency must exceed 45%; for CHP units larger than 50MW, the annual heat and power ratio must be more than 100%; for CHP units of 50-200MW, the annual heat and power ratio must be more than 50%; and for condensing CHP units greater than 200MW for district heating, the heat and power ratio in heating period should be more than 100%.
- Power management departments should provide inspection comments for CHP system connected to the utility grid.
- The CHP projects should be sized based on available heating load, in order to maximize efficiency.
- Guidance encouraging the maximum use of waste heat, coal tailing, and other waste fuels for CHP.

Table 3-2 Policies for CHP system adoption in China

Year	Policy	Content
1989	Provisions of Encouraging Developmentof minitype Cogeneration and Close Confinement of Condenser Small Electric Construction	Set preferential interest rate to small thermoelectric loan which within state credit plan
1994	Environment Conservation Plan of Electric Utility Industry of 2000	Plan to develop cogeneration plant in urban in 2000, and in town in 2010.
2001	Technical Specification of Cogeneration Program Feasibility	Stipulate cogeneration project feasibility study content depth, calculation method, investment estimate preparation method, financial evaluation method
2004	Medium and Long-term Plan of National Energy Conservation	Set regional cogeneration as one of ten key energy conservation projects.
2007	Provisional Regulations of Cogeneration and Gangue Comprehensive Utilization Power Generation Project Management	Set the rule of cogeneration and gangue comprehensive utilization power generation project.
	Plan of National Top Ten Energy Conservation Project	Set the implementation plan of cogeneration and other ten key energy conservation project.
2010	Guidence Advice of Power Generation Natural Gas Distributed Energy	Plan to build 1000 natural gas distributed energy projects by the end of 2010 and install capacity of 50million kw by 2020.
	Technical Specifications of Distributed Power Inserting into Power Grid	Set the technical specifications of distributed power energy which insterted in 35 kV and below voltage level grid.
2011	Technical Specifications of Gas Cogenerated Heating Electricity and Refrigeration Program	Set the technical specification of gas cogenerated heating electricity and refrigeration program
2013	Decision on cancellation and handing over a number of administrative approval projects	Press thermal power project approval down to the provincial department
2014	Energy conservation and emissions reduction improving action plan of coal electricity (2014-2020)	Development of cogeneration unit is put forward

• Suggestions to use CHP to improve energy efficiency.

• In the heating range of planned CHP project, other newly-added small coal boilers projects will be restricted if the planned CHP capacity may cover the heating demand.

• A goal to implement heat metering on the basis of heat consumption by 2010.

(2) Chinas Medium-Term and Long-Term Energy Development Plan (2004) and Implementation Scheme of the National 10 Key Energy conservation Projects (2007)

In November of 2004, the State Council issued the NDRC's China Mid-Term and Long-Term Energy Conservation Plan, which considered CHP as an important energy conservation field, listed as one of the 10 key national energy conservation programmes that are critical to realize the energy conservation target. In 2007, NDRC promulgated the Implementation Scheme of the National 10 Key Energy Conservation Projects, which provided important details on CHP target applications and supporting policies, including:

• Stated Goal: In 2005-10, 45 GW of new CHP units will be constructed in the Northern heating area, and 8 GW of new CHP units in the Southern area for industrial heat applications;

• Key Applications: Promoting CHP development in the residential and industrial sectors, and encouraging distributed CHP system using waste fuels.

(3) Temporary Regulation for Cogeneration and Power Generation of Integrated Utilisation of Coal Tailings (2007)

On January 15, 2007, NDRC and MOC issued the Temporary Regulation for Cogeneration and Power Generation of Integrated Utilization of Coal Tailings. Compared with Revised Regulations for CHP Development (2000), more administrative regulations on CHP were proposed.

• The local government was required to stipulate a plan for CHP and coal tailing utilization.

• Regions with severe winters and concentrated heat loads should actively develop CHP to replace small heat-only boilers. In regions with hot summers and cold winters, CHP should be developed where there are concentrated heat loads, and CCHP is also encouraged under the proper conditions.

• In areas with existing CHP plants, the regulation discourages the development of additional end-use sited CHP plants.

• Except for large-scale enterprises such as petroleum, chemical, steel, and paper industries, the regulation does not encourage the use of CHP to serve single enterprises.

• Encouraging the use of a variety of approaches to solve heating problems in medium and small cities, such as the use of biomass, solar, geothermal and other renewable energy, as well as the use of natural gas, coal gas, and other resources to implement

CHP.

• The grid electricity price should be determined by provincial pricing administrative agencies and authorized city and county governmental agencies, which will make decisions based on relevant national regulations, heat cost and profit ratios.

• CHP should be given an advantage for connecting to the grid.

(4) Guidance Opinion on Pilot Programmes of Urban Heating Reform (2003)

In July of 2003, MOC, NDRC and other agencies jointly promulgated the Guidance Opinion on Pilot Programmes of Urban Heating Reform. It aimed to stop welfare heating and promote commercial district heating. This regulation proposed specific requirements for district heat metering. In addition, the pilot projects for heating reform were started in the provinces of Northeast China, North China, Northwest China, Shandong and Henan.

(5) Urban Heating Price Management Temporary Measures (2007)

In 2007, NDRC and MOC issued the Urban Heating Price Management Temporary Measures, which encouraged CHP/DHC, and dictated the reform of heating prices. In these measures, regulators will gradually use two price components: the basic heat price and the metering heat price. This regulation also encouraged the development of CHP and district heating and allowed non-public capital (including foreign capital) to invest, construct, and manage heating supply facilities to promote the gradual commercialization of district heating industries. The heat tariff, in principle, is determined by the government (tariff administrative agencies at the regional and local levels), but in some regions (where conditions are suitable), the heat tariff may be determined by the market – i.e., by heat suppliers and their customers.

(6) China Energy Saving Law (1997 Edition and 2007 Revised Edition)

In the China Energy Conservation Law (1997), CHP was listed as an energy conservation technology that should be nationally encouraged. In October 2007, NPC approved the China Energy Saving Law (Revised Edition). Its articles relevant to CHP/DHC include the following:

• Article 31:The country encourages the industrial enterprises to use high-efficiency energy conservation equipment, such as motors, boilers, kilns, blowers, and pumps; and encourages energy-efficient technologies, including CHP/DHC, residual heat and pressure utilization, clean coal-fired technologies, and so on.

• Article 32: The power grid enterprises should arrange clean and efficient CHP, utilize residual heat and pressure units, and take other measures according to the requirements of the Energy Conservation Power Control Management formulated by the appropriate State Council department, the online power price executing the country concerned requirements.

• Article 78:The power grid enterprises bear liability if they do not comply with the requirement in Article 32.

In 2004, five departments including Shanghai municipal development and reform commission (NDRC) jointly issued the “Opinions about encouraging the development of gas-fired air conditioning and the distributed energy system in Shanghai”, which was the first policy about the development of distributed energy system in China; in 2008, Shanghai introduced the second round incentive policy. In 2013, Shanghai government issued the latest “Special measures to support the development of gas distributed energy system and gas-fired air conditioning in Shanghai”, establishing a series of relevant incentive policies. In addition, “Twelfth five-year plan of energy development in Shanghai” explicitly puts forward to develop regional cogeneration and distributed energy system, and decides to increase the capacity of cogeneration to 2 million kW and install 50 to 60 gas distributed energy systems by 2015.

On the technical level, the Shanghai construction and traffic committee issued the “Engineering technology regulations of the distributed energy system” in 2005, which is the first technical specification of gas distributed generation in China. On the application level, although special support policies have been issued for more than 10 years, the development of the gas distributed generation is still not satisfied.

In summary, Shanghai is always leading the development of gas distributed generation in China from either policy or technical viewpoint. However, present situation suggests that the existing policies and mechanisms are not strong enough to promote rapid development of gas distributed generation in Shanghai. The main reasons can be summarized as the following two points [11-12]:

(1) Existing theory for gas distributed generation is not sufficient to support the benefit distribution in the market oriented economy framework

Theory analysis framework of the gas distributed generation is not perfect in China. Most of existing construction mechanism and grid-connecting policy references that for traditional centralized power plants, and fails to give full consideration the strong coupling characteristic of the supply side and demand side. This situation makes the gas distributed generation become a “heterogeneous” in the current market oriented economy framework.

(2) Existing policies and economic environment are not good enough to support the development of gas distributed generation

Although Shanghai has introduced a series of subsidies to promote the development of gas distributed generation, these policies fail to enhance its competitiveness fundamentally so as to adapt to developing needs of the market economy. Therefore, the gas distributed generation is still in the state of government support and lack of the independent survived ability in Shanghai. Existing policies and mechanisms are insufficient to support the sustainable development of the gas distributed generation.

At present, Shanghai has put forward the strategic goal to construct a low-carbon and energy-saving global city. As one of the key directions of Shanghai's clean energy development, promotion and application of gas distributed generation is the important guarantee to achieve this goal. Therefore, it is necessary to examine the developing theory and policy of gas distributed generation, to exploit new ideas and new patterns of gas distributed generation development.

The Shanghai government always pays enough attention to the development of gas distributed energy system, and has introduced three rounds of incentive policies.

(1) The subsidy of equipment investment

According to the third round of policy, the subsidy for equipment investment is given by 1000 RMB/kW for gas distributed generation which are built in hospitals, hotels, factories, shopping malls, business building, comprehensive business center and other buildings, industrial parks, large transport hub, tourism resort district, business district and etc. Furthermore, if the annual overall efficiency is larger than 70% and annual utilization hours is more than 2000 hours, addition 2000 RMB/kW will be available, while the highest subsidy of each project is 50 million RMB.

(2) Discounted natural gas price

In 2005, the Municipal Development and Reform Commission and the Municipal Price Bureau established preferential gas price for gas air conditioning and gas distributed energy system. The gas price for distributed energy supply system is 2.04 RMB/m^3 in 0-80000 m^3/month and 1.94 RMB/m^3 above 80000 m^3 /month in November 2005.

At present, the gas price for distributed energy system implemented by Shanghai is the lowest price in all types of users, which is approximately 64% to 68% of benchmark contract sales price of the same grade industrial users and battalion regiment users.

(3) Grid-connecting policy

For the distributed energy system which conforms to “engineering technology regulations of the distributed energy system” and is designed following the heat tracking principle, the grid enterprise must accept its grid-connected according to relevant regulations and sign grid-connected agreement with the investor, and actively provide related services.

3.5.2 Policies for PV system adoption

In the last decade, China’s photovoltaic (PV) industry has developed rapidly, with the joint promotion of the world market and domestic policies, and China has now become the largest PV manufacturer in the world. Meanwhile, the international market has responded to China’s rapid development, in light of the Chinese government’s industrial policies, and “anti-dumping and anti-bribery investigation”, focusing on China’s solar industry policies, has been proposed [11]. Unlike the international practice, which attaches importance to subsidies for the market demand-side, China’s policies focus on government regulation, concentrating mainly on the product popularization and application stages, with insufficient investment in research and development in the early stage. On the other hand, however, China’s PV policies are gradually changing from production supply prioritization to demand-side policy domination. while simultaneously increasing investment in research and development, China’s PV policies should continue to reinforce the market demand-side policies and gradually exit the production supply-side policies.

In 2009, the government issued the policy Accelerating the Implementation of solar PV Building, which use the renewable development funding to support demonstration project on buildings. See Table 3-3 for the subsidy standards for renewable energy building application urban demonstration projects and solar PV building application demonstration projects integrating various policy instruments and supportive measures.

Table 3-3 Subsidy standard for Chinese photoelectric building application demonstration projects

<table>
<tr><th>Solar roofs program</th><th>Buidling material type and component type PV buidling integration project</th><th>Installation type PV buidling integration project</th><th>Subsidy applicant</th></tr>
<tr><td>2009</td><td>20 Yuan/Wp</td><td>15 Yuan/Wp</td><td rowspan="2">Solar PV project employers or solar PV product manufacturers</td></tr>
<tr><td>2010</td><td>12 Yuan/Wp</td><td>13 Yuan/Wp</td></tr>
</table>

In 2009, the Ministry of Finance, Ministry of Science and Technology, National Energy Administration and other departments initiated "Large-scale PV Power Station Concession Bidding" and the "Golden-Sun Pilot Project". The former installed approximately 4.3 GW large-scale solar power stations between 2009 and 2012, mainly in northwestern China, which has sufficient solar resources for this. The latter supported over 700 different PV power generation projects focused on a user side distributed PV system and independent PV system for regions without a power supply. Golden-Sun's gross planned installed capacity in mainland China was over 5.8 GW, which played an important role in initiating a domestic PV market, promoting PV technology and eliminating grid-connected policy obstacles. See Table 3-4 for the subsidy standard for the Golden-Sun project.

Table 3-4 The subsidy standard for the Golden-Sun project.

Golden-Sun project	User side PV power generation project	Remote areas without electricity independent PV power generation project	Subsidy applicant
2009	Subsidy as per 50% of total investment	Subsidy as per 70% of total investment	Solar PV project employers
2010	Subsidy proportion as per 50% of supply price	Subsidy proportion as per 70% of the supply price	Employers and equipment suppliers
	Fixed construction cost (4-6 Yuan/watt)	Fixed construction cost (6-10 Yuan/watt)	

Table 3-5 summarized the various policies for PV system introduction in China.

Table 3-5 Various policies for PV system introduction in China

Department	Releasing Time	Policies	Contents
Ministry of Finance, ministry of housing and urban-rural	2009	Accelerating the implementation of BIPV application	Solar roof plan
Ministry of Finance, Ministry of science and technology, National Energy Administration	2009	Implementation of golden sun demonstration projects	The central government set special funds to support PV technology demonstration project in all fields and key technology industrialization
National Development and Reform Commission (NDRC)	2011	Perfecting PV FIT policy	Perfecting PV FIT policy
National Energy Administration	2012	Solar power development "twelfth five-year" plan	Goal: by 2015, solar power reaches to 21 GW, in which, PV power and thermal power is20 GW and 1 GW respectively
National Energy Administration	2012	Notification about declaration of scaled distributed PV system demonstration area	Unified subsidy for both self-use electricity and surplus electricity from PV system demonstration project
State Grid	2012	Opinions of distributed PV power grid-connected service	Subsidizing PV system that is below than 6 MW: FIT, free access to the grid
National Energy Administration	2013	Supplement on policy about scaled distributed PV system demonstration construction plan	kWh subsidy: unified subsidy for both self-use and surplus electricity from PV system demonstration project, there is additional subsidy for surplus electricity which is equal to Local desulfurization benchmarking electricity price

3.6 Summary

In this chapter, the supply and consumption of energy and electricity in China are summarized. In addition, current status of CHP system as well as PV system adoption in China is investigated. Moreover, the policies for CHP system and PV system adoption so far are summarized.

Currently, the gas distributed energy development in China are facing grim situations: on the one hand, the devices depend on import and price raises sharply, which leading to the initial investment and operating costs showed double high, seriously affecting the economic system; on the other hand, the relevant institutions system, mechanisms system and policy system are imperfect, so that the gas distributed energy system is difficult to fully play its energy saving advantages. However, referencing to the development status and prospects of foreign city, we can foresee that the gas distributed generation in Shanghai will have huge potential in the future, and it will support a low-carbon transition of Shanghai electric power industry.

To achieve the proposed long-term development goal, at the technical level, we should re-examine the gas distributed energy systems, develop some new ideas, and new model of gas distributed energy application. At the policy level, according to specific application background, the existing institutions system, mechanisms system and policy system should be innovated and developed, so as to promote the marketization process of gas distributed energy system.

References

[1] The World Bank, <http://data.worldbank.org/>.

[2] International Energy Agency (IEA), World Energy Outlook 2011, OECD/IEA, 2011.

[3] Hirohisa Aki, Akinobu Murata, A Study on the Introduction of Natural Gas Combined Heat and Power Systems in Commercial Buildings in Urban Areas of China, The 21st energy system, economy and environment conference, 2005.

[4] Takanobu Kosugi, Koji Tokimatsu and Weisheng Zhou, Cost-benefit evaluation of a new energy technology transfer to China — Introducing a natural gas cogeneration system —, Policy Science 9(2), 2002, pp39-44.

[5] The International CHP/DHC Collaborative, CHP and DHC in China: An Assessment of Market and Policy Potential, International Energy Agency.

[6] Ji Xuan, Weijun Gao, Xingdong Wei, Haifeng Li and Hiroki Tsutsumi, Sensitivity analysis of influencing parameters of energy saving effect by introducing a co-generation system in a skyscraper complex in Shanghai, Journal of Environmental Engineering (Transactions of AIJ) 74, 2009.

[7] H. Kang and Z. Wang, Distributed energy system and reasonable application of natural gas, Heating Ventilating & Air Conditioning 3, 2008.

[8] CASM, China's 12th Five-Year Plan for the Solar Photovoltaic Industry. <http://www.americansolarmanufacturing.org/news-releases/chinas-five-year-plan-for-solar-translation.pdf>.

[9] EPIA. Global Market Outlook for Photovoltaic until 2014. <http://www.solarplaza.com/report/global-market-outlook-for-photovoltaics-until-2014>.

[10] U.S. Department of Energy. Renewable energy databook. <http://www.nrel.gov/tech_deployment/state_local_activities/state_data_book.html>.

[11] S. Zhang, Y. he, Analysis on the development and policy of solar PV power in China, Renewable and Sustainable Energy Reviews 21 (2013), pp. 393-401.

[12] Y. Ruan, Q. Liu, W. Zhou, R. Firestone, W. Gao, T. Watanabe, Optimal option of distributed generation technologies for various commercial buildings, Applied Energy 86(9) (2009), pp. 1641-1653.

CHAPTER FOUR: OPTIMIZATION AND EVALUATION METHODS FOR DISTRIBUTED ENERGY SYSTEM ADOPTION

4.1 Introduction

Distributed energy system offers end-users increased flexibility in provision of energy as they can generate on-site or purchase from the utilities. However, it will also result in more complex systems to design, operate and management as it introduces physical connections between traditionally separate supply sectors. Therefore, the increasing appeal of distributed generation means that there is a need for new tools to analyze and evaluate distributed generation, both from a system perspective and from the perspective of potential developers.

As an integrated system, the planning and appraisal of sustainable energy systems involve rather complex tasks. This is due to the fact that the decision making process is the closing link in the process of analyzing and handling different types of information: environmental, technical, economic and social, etc. Such information can play a strategic role in steering the decision maker towards one choice instead of another. Some of these variables (technical and economic) can be handled fairly easily by numerical models whilst others, particularly ones relating to environmental impacts, may only be adjudicated qualitatively (subjective or not). In many cases therefore, traditional evaluation methods such as cost-benefit analysis and the main economic and financial indicators (NPV, ROI, IRR etc.) are unable to deal with all the components involved in an environmentally valid energy project. Multi-criteria methods provide a flexible tool that is able to handle and bring together a wide range of variables appraised in different ways and thus offer valid assistance to the decision maker in mapping out the problem.

Currently, there are many kinds of multi-criteria methods, such as: Analytic Hierarchy Process (AHP), Multi-Attribute Global Inference of Quality (MAGIQ), Data Envelopment Analysis, Evidential Reasoning Approach, Dominance-based Rough Set Approach (DRSA), and so on. It is generally assumed that there are no better or worse techniques, but techniques better fitted than others to particular decision problems.

Uncertainty is another problem faced by the decision makers during the planning of energy projects. In order to overcome this problem, fuzzy methods have been developed. By using the fuzzy sets, those cases where it is difficult to rely on proper estimations of the probability distributions or parameters can be dealt with.

In this chapter, the optimization method and various evaluation methods for the building distributed energy system will be introduced in detail.

4.2 Overview of the optimization method

In this study, a general method has been developed to find an optimal integrated system among different distributed energy combinations, minimizing the total annual running cost while guaranteeing reliable system operation. PV, CHP and energy storage are considered in this model. In order to minimize the annual operation cost of energy consumption, it is important to develop a reasonable running strategy. The integrated DER optimization is formulated here as a MILP (Mixed-integer linear programming) model which is consisted of input data, objective function, constraints as well as outputs. The inputs contain energy system structure (see Fig. 4-1), energy load, technique features of different distributed energy supply system (CHP, battery and PV cell), energy policy, as well as electricity tariff rate and natural gas price. Through the simulation analysis, the following will be deduced: (1) Annual running cost of the system satisfying the objection function and constraints; (2) Optimal running strategies of the CCHP unit, PV cell as well as battery; (3) Sensitive analysis of FIT rate. MILP, is a very general framework for capturing problems with both discrete decisions and continuous variables. This includes: assignment problems; control of hybrid systems; piecewise-affine (PWA) systems (including approximations of nonlinear systems); problems with non-convex constraints (e.g., collision avoidance).

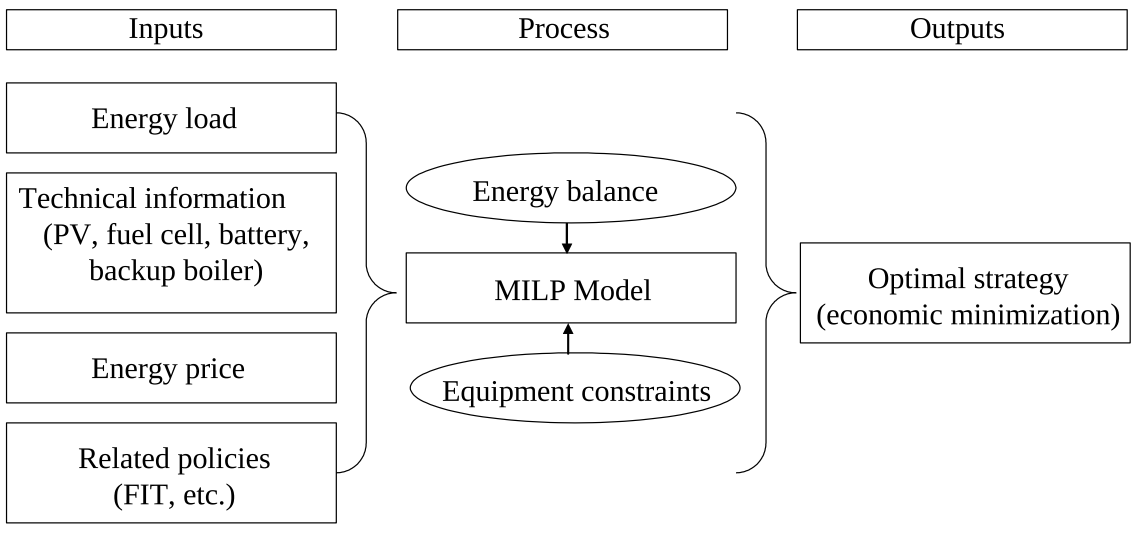


Fig. 4-1 Flow chart of the optimization model

4.3 Mathematical model

4.3.1 Objective function

For the economic efficiency of the energy system is the key indicator when energy end-users implementing energy management decision. Thus, in this mathematical model, the annual running cost is considered as the minimization objective function and it can be evaluated as the sum of grid electricity purchasing cost, CHP operation cost, afterburner cost, subtracting the annual revenue from selling surplus electricity. Note that, to be simplicity, ignoring the maintenance costs of the energy supply equipments and assuming the electricity generation rates as well as the heat recovery rates are constant.

$$\min\{C_{total} = C_{pur}^{grid} + C_{run}^{fc} + C_{gas}^{su} - C_{sal}^{grid}\} \tag{1}$$

where, C_{total} represents total annual energy cost, C_{pur}^{grid} is electrical energy purchased from grid, C_{run}^{fc} is fuel cost of CHP, C_{gas}^{su} means fuel cost of afterburner. Furthermore, C_{sal}^{grid} is the surplus electrical energy income which derived from electricity sold back to the utility grid.

Annual electrical purchase cost from utility grid is described in Eq. (2). It is calculated with cumulative amount of electricity purchase including purchased for load demand as well as for battery charging, multiplied by the utility electricity rate.

$$C_{pur}^{grid} = \sum_m \sum_h d_m \cdot (E_{m,h,self}^{grid} + E_{m,h,STB}^{grid}) \cdot P_{m,h,elec} \tag{2}$$

where, m, h is time intervals. d_m is number of days in each month, $E_{m,h,self}^{grid}$ is purchased electricity from grid for self-use, $E_{m,h,STB}^{grid}$ is purchased electricity from grid for battery charging, $P_{m,h,elec}$ is grid electricity rate.

The running cost of CHP includes fuel cost and maintenance cost. For the latter has been ignored in this paper, the running cost is just determined by fuel cost, and as shown in Eq. (3), it is calculated with cumulative fuel consumption for each period and multiplied by the tariff rate. In which, the hourly fuel consumption is equal to the hourly electrical power production from CHP divided by CHP electrical efficiency.

$$C_{run}^{fc} = \sum_m \sum_h d_m \cdot P_{gas} \cdot (E_{m,h}^{fc} / \eta_e^{fc}) \tag{3}$$

where, $E_{m,h}^{fc}$ is the hourly electrical power production from fuel cell. P_{gas} is natural gas price. η_e^{fc} is fuel cell electrical efficiency.

Similarly, as illustrated in Eq. (4), the running cost of the backup boiler is calculated with cumulative fuel consumption of each period and multiplied by the gas rate. In which, hourly fuel consumption of the backup boiler is equal to thermal energy supplied by the backup boiler divided by thermal efficiency.

$$C_{gas}^{su} = \sum_{m}\sum_{h} d_m \cdot P_{gas} \cdot (H_{m,h}^{su} / \eta_{th}^{su}) \tag{4}$$

where, $H_{m,h}^{su}$ is thermal energy supplied from afterburner, η_{th}^{su} is afterburner thermal efficiency.

An income will be received when electricity buy-back is available by the utility grid, as shown in Eq. (5), it is calculated by cumulative surplus electricity from PV sell to grid multiplied by the FIT rate.

$$C_{sal}^{grid} = \sum_{m}\sum_{h} d_m \cdot P_{sal}^{PV} \cdot E_{m,h,sal}^{PV} \tag{5}$$

where, P_{sal}^{PV} is tariff for selling electricity, $E_{m,h,sal}^{PV}$ is surplus electricity from PV sell to grid.

4.3.2 Main constraints

The main constraints in this optimization model contain energy balance and the performance characteristics of each system component.

4.3.2.1 Energy flow constraint

The energy flow constraint contained two parts: electric and heat demand. The electric consumed by local loads must be equal to electricity provided by PV cell, CHP, utility grid and battery dynamically. It can be expressed as

$$E_{m,h}^{load} = E_{m,h,self}^{grid} + E_{m,h,out}^{STB} + E_{m,h,self}^{PV} + E_{m,h}^{fc} \qquad \forall m,h \tag{6}$$

where, $E_{m,h,out}^{STB}$ is electrical power from battery, $E_{m,h,self}^{PV}$ is electrical power from PV for self-use.

Similarly, as illustrated in Eq. (7), heat load of each hour must be equal to the sum of heat supplied by the backup boiler and the recycled heat from the CHP.

$$H_{m,h}^{load} = H_{m,h}^{su} + H_{m,h}^{fc} \qquad \forall m,h \tag{7}$$

where, $H_{m,h}^{fc}$ is thermal recovered energy from fuel cell.

4.3.2.2 Performance characteristics of each system component

(1) CHP unit

The electric and heat generated from the CHP unit must below than the rated capacity which can be described as in Eq. (8) and Eq. (9) respectively. The rated heat can be calculated with the rated power of FC multiplied by the heat-to-power ratio.

$$E_{m,h}^{fc} \le E_{\max}^{fc} \qquad \forall m,h \tag{8}$$
$$H_{m,h}^{fc} \le E_{m,h}^{fc} \cdot HER \qquad \forall m,h \tag{9}$$

where, $E_{\max}^{fc}$ is maximum limit of electrical power from fuel cell. HER means thermal to electrical ratio (%).

(2) PV module

The total power output of the PV generator including power for self-use as well as sell to the utility grid are equal to the rated power which is determined by the solar radiation intensity, area of solar panels as well as system efficiency. It can be described according to the following equations [2]:

$$E_{m,h,self}^{PV} + E_{m,h,sal}^{PV} = R \cdot A \cdot \varphi \qquad \forall m,h \tag{10}$$

where, R is hourly solar radiation value, A is area of the PV panel. φ is photoelectric conversion efficiency.

(3) Storage battery

The storage battery is used to store surplus electrical energy during valley load period and supply power to load in case of peak demand. At any hour, the state of battery is equivalent to the previous state of charge and to the energy production and consumption situation of the system during the time from h to h+1 [2]. Type (11) illustrates the available battery capacity at hour h+1 during the charging/discharging process. It points out that the storage capacity at hour h+1 is equal to the initial capacity at hour h, plus the charging amount supplied by the utility grid and CHP system, deducting the discharging part used for the residential electric demand. Similarly, type (12) illustrates the situation when h is 24. Type (13) stipulates the initial capacity of the battery is 0 (0 clock of the first day in a year).

$$E_{m,h+1}^{STB} = \varepsilon \cdot E_{m,h}^{STB} + E_{m,h,STB}^{grid} + E_{m,h,STB}^{FC} - E_{m,h,out}^{STB} \qquad \forall m,h \ne 24 \tag{11}$$
$$E_{m+1,1}^{STB} = \varepsilon \cdot E_{m,24}^{STB} + E_{m,24,STB}^{grid} + E_{m,24,STB}^{PV} - E_{m,24,out}^{STB} \qquad \forall m \ne 12,h \tag{12}$$
$$E_{1,1}^{STB} = 0 \tag{13}$$

where, $E_{m,h+1}^{STB}$, $E_{m,h}^{STB}$ means available storage capacity of the battery at hour h and h+1. ε is battery efficiency during charging /discharging process.

Furthermore, there is another important condition limiting the operation of battery as well. In the discharge process, there is a threshold for the residue energy of battery, namely, not all energy can be released [1]. The storage capacity is subject to the following constraints:

$$\lambda \cdot E_{\max}^{STB} \le E_{m,h}^{STB} \le E_{\max}^{STB} \qquad \forall m,h \tag{14}$$

where, λ is minimum residue energy coefficient of battery. $E_{\max}^{STB}$ is maximum allowable storage capacity of the battery.

Again, for the battery cannot charge and discharge simultaneously, the following constraints must be added. The battery can be charged either from the utility grid or from the FC unit.

$$E_{m,h,STB}^{grid} + E_{m,h,STB}^{FC} \le M \cdot In_{m,h} \qquad \forall m,h \tag{15}$$

$$E_{m,h,out}^{STB} \le M \cdot Out_{m,h} \qquad \forall m,h \tag{16}$$

$$In_{m,h} + Out_{m,h} \le 1 \qquad \forall m,h \tag{17}$$

where, $E_{m,h,STB}^{FC}$ is battery charged by the FC unit. M is a infinite integer. $In_{m,h}$ and $Out_{m,h}$ represent two non-negative integer variables respectively which are equal to 0 or 1, but cannot be equal to 1 at the same time.

Furthermore, the excessive electricity produced from PV system cannot be sold out to the utility system except for the electricity purchased from utility system is zero which can be described as follows:

$$E_{m,h,STB}^{grid} \le M \cdot In1_{m,h} \qquad \forall m,h \tag{18}$$

$$E_{m,h,self}^{grid} \le M \cdot In2_{m,h} \qquad \forall m,h \tag{19}$$

$$E_{m,h,sal}^{PV} \le M \cdot Out1_{m,h} \qquad \forall m,h \tag{20}$$

$$In1_{m,h} + Out1_{m,h} \le 1 \qquad \forall m,h \tag{21}$$

$$In2_{m,h} + Out1_{m,h} \le 1 \qquad \forall m,h \tag{22}$$

where, M is a infinite integer. $In1_{m,h}$, $In2_{m,h}$ and $Out1_{m,h}$ represent three non-negative integer variables respectively, which are equal to 0 or 1. $In1_{m,h}$ and $Out1_{m,h}$ cannot be equal to 1 at the same time. Also, $In2_{m,h}$ and $Out1_{m,h}$ cannot be equal to 1 at the same time.

4.3.2.3 General View of LINGO Programming

Using mathematical programming method to solve the decision problem consists of two steps: firstly, translating and expressing the actual decision problems into mathematical model using mathematical concepts and language; secondly, choosing optimization software to solve the built mathematical model. Linear Interactive and General Optimizer (LINGO) is widely employed in mathematical modeling, solving of optimization models and some other fields due to its benefits such as convenient and simple programming language, efficient algorithm, and flexible nested performance [1]. It provides a completely integrated package that includes a powerful language for expressing optimization models, a full featured environment for building and editing problems, and a set of fast built-in solvers. Thus, in this study, LINGO is chosen to solve this problem.

4.4 Evaluation methods for distributed energy system

The aim of evaluation is to reach a better decision-making.

4.4.1 Assessment criteria

The selection of criteria is of vital importance for the solution of a given MCDM problem [3]. In this study, three criteria, namely, primary energy savings (PES, index of energy performance), total cost saving (TCS, index of economic performance), and CO2 emissions reduction (CER, index of environmental performance), are selected and calculated according Eqs. (1)-(3), respectively [4].

$$PES = \frac{Q_{ENE,CS} - Q_{ENE,PS}}{Q_{ENE,CS}} \times 100\% \tag{23}$$

$$TCS = \frac{Q_{COST,CS} - Q_{COST,PS}}{Q_{COST,CS}} \times 100\% \tag{24}$$

$$CER = \frac{Q_{CO2,CS} - Q_{CO2,PS}}{Q_{CO2,CS}} \times 100\% \tag{25}$$

where, $Q_{ENE,CS}$ and $Q_{ENE,PS}$ are the primary energy consumptions of the conventional system and the proposed system based on CCHP plant, respectively. $Q_{COST,CS}$ and $Q_{COST,PS}$ denote annual total costs (including both running cost and annualized investment cost) of the conventional system and the proposed system, respectively. $Q_{CO2,CS}$ and $Q_{CO2,PS}$ indicate annual CO2 emissions from the conventional system and the proposed system, respectively.

4.4.2 Unit cost of DER system

The unit cost of DER system can be defined as total cost of unit power generation. It is determined by the initial investment cost as well as maintenance cost, which is irrelevant to the energy demand side. The formulation can be defined as follows:

$$C_{unit} = C / E_{sum} \tag{26}$$

where, C_{unit} is the unit cost of DER system, C is the annual total energy cost, E_{sum} is the annual total power generation. C is combined of two parts: annual average investment cost and annual maintenance cost, which can be described as:

$$C = C_{inv} + C_{o\&m} \tag{27}$$

where, C_{inv} is annual average investment cost, $C_{o\&m}$ is annual maintenance cost. Assuming that the initial investment cost of the DER system is through bank loans, and matching interest repayment way is used. The average annual investment cost can be deduced according to the following formulation:

$$C_{inv} = Q \cdot C_{uni} \cdot \frac{i}{1 - \frac{1}{(1+i)^N}} \tag{28}$$

where, Q is the capacity of the DER system. C_{uni} denotes the price of the DER system per kWh. i is the interest rate of the bank loan, N is the payback period of loan.

Assuming maintenance cost is proportional to the investment cost, which can be calculated according to the following formulation:

$$C_{o\&m} = \alpha C_{inv} \tag{29}$$

where, α is coefficient of maintenance cost.

4.4.3 Dynamic payback period of investment cost

As to the dynamic payback period of investment cost, it is necessary to take inflation and returns into account, thus, the NPV (Net Present Value) is adopted in this paper. NPV is used in capital budgeting to analyze the profitability of an investment or project. It is one of the most reliable measures used in capital budgeting because it accounts for time value of money by using discounted cash inflows. The formula for the calculation of NPV is as follows:

$$NPV = \left[\frac{R^1}{\left(1+i^1\right)} + \frac{R^2}{\left(1+i^2\right)} + \frac{R^3}{\left(1+i^3\right)} + \ldots \right] - initial \quad investment \tag{30}$$

Where, i is the target rate of return per period;
R1 is the net cash inflow during the first period; R2 is the net cash inflow during the second period; R3 is the net cash inflow during the third period and so on. When the NPV value is equal to 0, the corresponding time is the payback period. R can be calculated as follows:

$$R = C_{con}^{ele} - C_{DER}^{ele} + C_{DER}^{sal} - C_{o\&m} \tag{31}$$

where, C_{con}^{ele} is annual electricity cost purchased from the utility grid of the conventional system. C_{DER}^{ele} is the cost of unsatisfied annual electricity purchased from the utility grid of the DER system. C_{DER}^{sal} is the income selling surplus electricity to the utility grid.

4.4.4 Multi-criteria decision aid method

In this study, as one of the most widely used multi-criteria techniques in decision-making processes, the analytic hierarchy process (AHP) method has been employed for the assessment of the proposed system based on CCHP plant. Since its emergence in the 1970s, the AHP method has illustrated its success in organizing various types of complex multi-criteria evaluation problems in a hierarchical structure

[5]. Generally, the concept of AHP method can be realized through the following procedures [6-8].

(1) Structural hierarchy establishment

As the structural skeleton of the AHP method, hierarchy is used to group all the elements according to their influences on the entire system. Generally, at least three hierarchical levels are necessary: the overall goal of the decision, evaluation criteria, and alternative choices, from the top level to the bottom one.

(2) Pair-wise comparison

The purpose of pair-wise comparison is to understand the relative importance of the elements. It can be executed for each hierarchy with the aid of a nominal scale. In a real decision-making problem, the values of various criteria may have different physical meanings. In order to arrange them in the form of a normal scale, in this study, the mean level method as shown in Eq. (32) is employed [38].

$$P_{i,j} = \begin{cases} Roundup\left[\dfrac{Q_i - Q_j}{Q_{max} - Q_{min}} \cdot (N-1) + 1\right] & Q_i > Q_j \\ 1 & Q_i = Q_j \\ \dfrac{1}{Roundup\left[\dfrac{Q_j - Q_i}{Q_{max} - Q_{min}} \cdot (N-1) + 1\right]} & Q_i < Q_j \end{cases} \tag{32}$$

Where, P denotes the item of pair-wise comparison. *Roundup* is a function achieving the least integer value not less than the real one. Q_i and Q_j are the numerical values of the i th and j th alternative system, respectively, for a specific criterion. Correspondingly, $Q_{\max}$ and $Q_{\min}$ are the maximal and minimal values of the criterion, respectively. N is maximal number of scaling ratio, which is 9 according to the theory of AHP method.

(3) Eigenvector and maximum eigenvalue determination

In order to understand the comparative weight amongst various elements of a certain hierarchy, the eigenvector of the established comparison matrix should be derived. Following which, it is also necessary to calculate the maximum eigenvalue, which is used to assess the consistency of the comparative matrix and determine whether to accept the results.

(4) Consistency verification

The difference between maximum eigenvalue and its order is used to judge the degree of consistence. Unless all pair-wise comparisons at each level are proved to be consistent, the judgments cannot be synthesized to find out the final priority ranking for each criterion.

(5) Synthesizing judgment

By weighting all evaluation criteria according to the overall goal of decision, as well as the alternatives from the viewpoint of each assessment criterion, the final scores of the alternatives are determined by aggregating the weights throughout the hierarchy.

4.5 Summary

In this chapter, the optimization and evaluation method is proposed to support the introduction and optimization of the DER system, which is expected to being a prime city infrastructure and will be continuously introduced due to its energy-saving and environmental advantages. The method is used to examine the introduction feasibility of distributed energy resource according to the demand for the region and optimize the economics of the system. In addition, the multi-criteria assessment method is also proposed for the overall assessment of the DER system considering various options.

Reference

[1] Zheng Z, Rong X, Huan Y. Micro-sources design of an intelligent building integrated with micro-grid. Energy and Buildings 2013;57:261-267.

[2] Moghaddas-Tafreshi S, Zamani H, Hakimi S. Optimal sizing of distributed resources in micro grid with loss of power supply probability technology by using breeding swarm optimization. Renewable and Sustainable Energy 2011.

[3] M.D. Catrinu, Decision aid for planning local energy systems — application of multi-criteria decision analysis, Doctoral thesis, Norwegian University of Science and Technology, Norway, 2006.

[4] G. Angrisani, C. Roselli, M. Sasso, Distributed microtrigeneration systems, Progress in Energy and Combustion Science 38(4) (2012) 502-521.

[5] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill, New York, 1980.

[6] J.O. Jaber, Q.M. Jaber, S.A. Sawalha, M.S. Mohsen, Evaluation of conventional and renewable energy sources for space heating in the household sector, Renewable and Sustainable Energy Reviews 12(1) (2008) 278-289.

[7] J.K.W. Wong, H. Li, Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems, Building and Environment 43(1) (2008) 108-125.

[8] M.M. Kablan, Decision support for energy conservation promotion: an analytic hierarchy process approach, Energy Policy 32(10) (2004) 1151–1158.

CHAPTER FIVE: REGIONAL ANALYSIS OF COMBINED COOLING HEATING AND POWER SYSTEMS IN JAPAN AND CHINA

5.1 Introduction

As an efficient approach to generate electrical and thermal energy from a single fuel source, the CCHP (combined cooling, heat and power) plant is considered to be one of the feasible and effective solutions. The CCHP system recovers the waste heat from the electricity generating process, otherwise that would be discarded into the environment. The heat recovered is used to satisfy the thermal demand (cooling, heating, or hot water needs) of an end-user. By recycling the waste heat, the BCHP system can achieve a primary energy efficiency of 60% to 90%, a dramatic improvement over the average 35% efficiency of conventional fossil fuel based power plants. Higher efficiencies can also contribute to the reduction of air emissions including SO2 which is the main component of local air pollutions, and CO2 which is the main threat to the global environment.

Since its first emergence, the CCHP system has spread with varying success to many developed countries, and has played an important role in promoting energy efficiency in these countries. For example, in Japan, CCHP system has been developed rapidly during the last 20 years.

As energy-saving and environmental issues are paid more and more attention, the conventional single-criterion analysis is unsatisfied and the decision problem becomes more challenging. This is because the best system from an economic viewpoint may have more environmental emissions; and contrarily, the promising system from an environmental viewpoint may cost more. Under these backgrounds, the multi-criteria decision making (MCDM) method has been proposed to handle a wide range of variables appraised from different viewpoints. Over the past few decades, it has been employed for the evaluation and determination of energy systems widely [1- 4].

In this chapter, the performances of CCHP systems for various commercial buildings located in different climate zones in Japan and China will be assessed and compared, based on a multi-criteria analysis involving energy, economic and environmental issues.

5.2 Outline of the assessment process

In this study, a multi-criteria decision aid method has been employed, in order to have a comprehensive understanding about the benefits of introducing CCHP systems for commercial buildings located in different regions in Japan.

5.2.1 Assessment process of CCHP system

The whole assessment process can be divided into four phases, as shown in Fig. 5-1 Following the initial collection of building properties (e.g., energy demands) and technical information (e.g., efficiencies), the capacity of the CCHP system can be determined according to the method introduced in the following sub-sections. Based on the instantaneous fraction of the CCHP system (ratio of energy load and its nameplate capacity, θ), its running strategies can be determined. In detail, if the instantaneous fraction is lower than the critical coefficient (σ), the system is out of operation; if the value is larger than 100%, the system will operate at its nameplate capacity; otherwise, the system will operate following the energy (electricity or heat) load. Subsequently, based on the selected assessment criteria, all alternative CCHP systems for various building types located in different regions are evaluated, respectively. After achieving the single-criterion assessment results, the preference values including the scores and the weights can be determined. The scores reflect the preferences a decision-maker has for different achievement levels under each criterion considered, while the weights reflect the preferences for the different criteria. Following which, based on the selected MCDM method, the overall evaluation index can be obtained following the multi-criteria assessment procedure introduced in the following sub-sections. Finally, the ranking of all the CCHP systems can be reported.

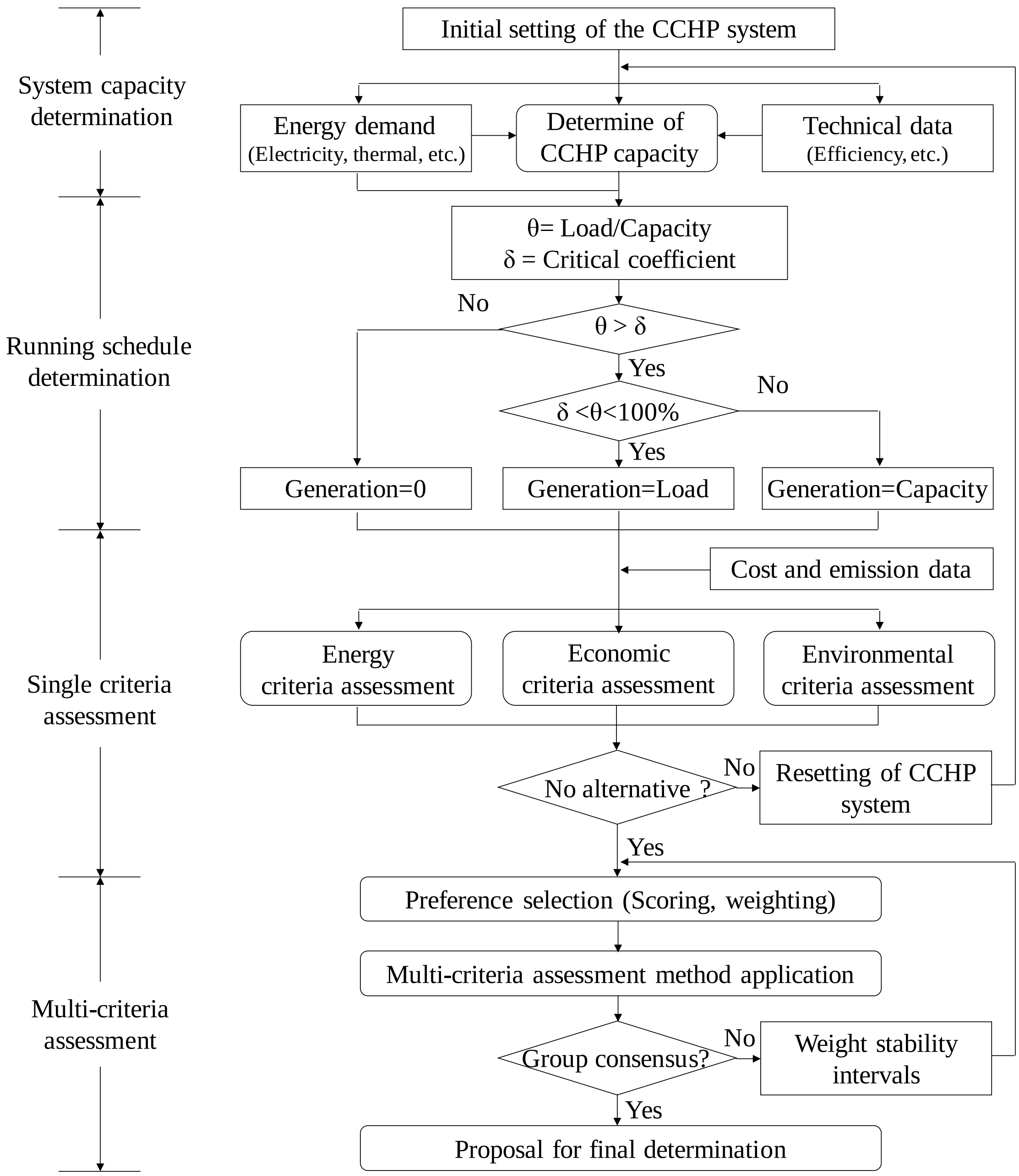


Fig. 5-1 Flow chart of multi-criteria assessment of CCHP systems

5.2.2 Modeling of the CCHP system

To carry out a comparative analysis, a conventional energy supply system which generates electricity and heat separately, is assumed. Fig. 5-2 shows the energy flows of the conventional system and the proposed system based on CCHP plant. On the demand side, four types of energy forms (electricity for lights and equipments, space cooling, space heating and hot-water) has been considered.

As to the conventional system, the electrical demand is totally served by the utility grid. The space heating and cooling loads are supplied by the electric heat pump which is the dominant thermal equipments in commercial buildings. In the CCHP system, both utility grid and on-site CHP plant can be employed to satisfy the electrical demand, and the shares of them are determined according to the running schedules. Similarly, the thermal demand could come from either the recovered heat, or an auxiliary boiler, or a combination of both. In addition, because electricity buy-back from on-site CCHP systems is permitted in Japan, the surplus electricity out of the CCHP system can be sold back to the grid when the generated power exceeds local demands.

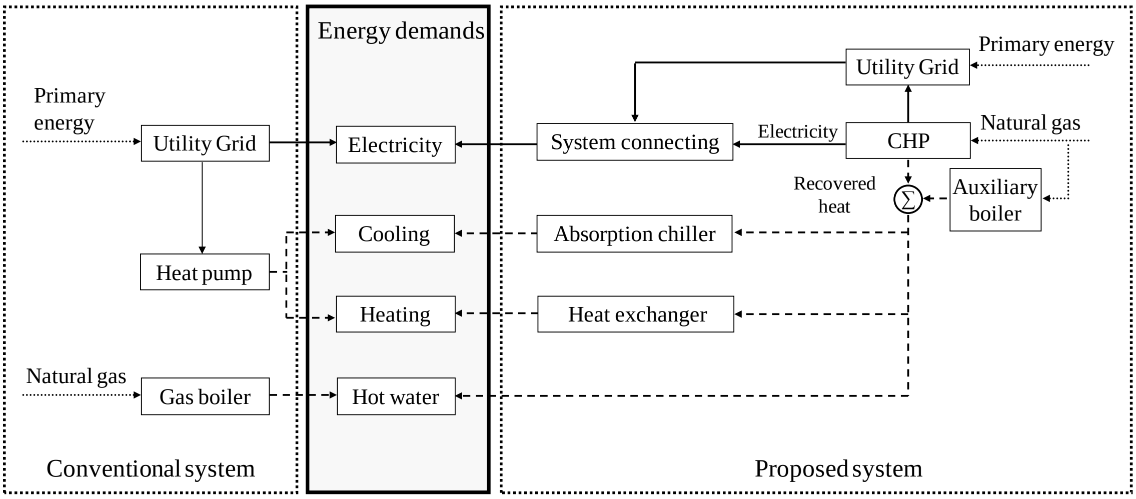


Fig. 5-2 Super structure of the conventional system and the proposed system

5.2.3 Concept for the design and operation of CCHP systems

According to previous studies, the CCHP system may employ three typical operating modes, namely, heat tracking mode, electricity tracking mode and energy island mode; among which, heat tracking mode usually has better performances from either energy, economic or environmental viewpoint [5, 6]. In this study, while considering the feasibility of electricity buy-back, the heating tracking mode is assumed for the following analyses.

Under the heat tracking mode, the CCHP system operates following the thermal load, while the electrical energy produced is determined according to the level of generated thermal energy, as well as the heat-to-power ratio of the CHP plant. Therefore, there will be no excess heat under this operating mode while the surplus electricity may be sold back to the utility grid as mentioned above.

Based on the assumption of heat tracking mode, the capacity of the CCHP system can be determined. Different from many previous studies on the development of optimization models for the determination of the size of the CCHP system [7-13], an intuitional method has been employed in this study. It determines the capacity of a CCHP system based on the concept of maximizing annual total energy (heat, in this study) generation at full load, and can be simply implemented with the aid of the load duration curve [14-15]. In this way, the system ensures the maximum operation time at nominal load (i.e., the maximum thermal energy that is produced with the highest efficiency) and is capable to cover also a great fraction of the energy demand below the rated one. Although there may be several limits of this method, it has been recognized to be a common practice which can give a compromising solution not to undersize or oversize the prime mover of the CCHP system [16].

5.3 Case study in Japan

The investigation of national energy consumption trends showed that the consumption of energy in Japan had grown from 11.1 EJ in 1973 to 14.5 EJ in 2011. The commercial building takes the main responsibility for the high increase, followed by the residential and transport sectors. In Japan, since the 1970s oil crisis, energy-saving regulation in the industry sector has achieved great success, and reduces total industry energy consumption by 14% with increased output (32%) in 2011 compared with that of 1973 [17]. On the contrary, the commercial building sector illustrates an opposite trend, thus, energy-savings received in the industry sector may be offset by the increased consumption in commercial buildings. This situation is due, on the one hand, to the construction of new commercial buildings, and on the other hand, to the search of higher comfort levels. Therefore, energy conservation in commercial buildings is strongly required in Japan.

In addition, at the UN Climate Change Conference (COP 15), Japan had announced an ambitious goal (25% reduction from the 1990 level) to curb the emissions of greenhouse gas (GHG), with 2020 as the target year. However, in the year 2011, total GHG emissions amounted to about 1.3 billion tons of carbon, which increased by about 3.7% in comparison with that of 1990. Among which, along with reduced emissions from the industry sector, the GHG emissions from commercial buildings increased by 11.8% (93 million tons) [18]. Facing such a grim reality, the distributed energy resources (DER), which have been recognized as an important innovation to the conventional energy supply system, are paid more and more attention. Generally, DER means small-scale energy generation units, and is mainly composed of thermal technologies and renewable ones [19-20]. While recognizing the high initial cost and low utilization efficiency of the renewable technologies (e.g., solar, wind energy), the currently feasible DER option is the combined cooling, heating and power (CCHP) system which can acquire three different forms of energy, namely, cooling, heating and power, from a single primary energy source [21].

In Japan, the CCHP system has experienced rapid development during the last decades. The number of CCHP plants had increased from 67 in 1986 to 9350 in 2013, and the total generation capacity had increased from 200 kW in 1986 to 9,852 MW as of March 2013. According to the investigation of Advanced Cogeneration and Energy Utilization Center of Japan (ACEJ), the largest emerging market for CCHP system is the commercial building, which shares more than 75% of existing CCHP applications [22]. However, while considering the vast number of commercial buildings, the share of CCHP systems is far from enough. In order to promote the penetration of CCHP systems in commercial buildings, for a specific case of demand, a comprehensive evaluation of potential benefits with CCHP system adoption is of vital importance. Gamou et al. [23] proposed an optimal unit sizing method for CCHP systems while taking into consideration the uncertainty of energy demands. Yoshida et al. [24] executed a sensitivity analysis of the system structure of the CCHP system for a hospital, while considering feasible technical improvement and cost down. Ruan et al. [25] examined the performances of the CCHP systems for commercial buildings located in Kyushu, from energy, economic and environmental viewpoints. Zhou et al. [26] discussed the economically optimal CCHP systems for five commercial buildings located in Tokyo.

It can be concluded that most of previous studies have focused on the single-criterion evaluation (e.g., annul energy cost) of the CCHP system for a specific customer within a particular location. However, as a demand-side dominated energy system, the performance of a CCHP system is greatly dependent upon the seasonal climate conditions which may determine local energy demands (especially, space heating and cooling loads). Actually, some previous studies have been reported on the influence of climate condition on the energy consumption in buildings in Japan [27-32]. However, further research is escaped. The influence of climate condition on the performance of energy systems (e.g., CCHP system) is uncertain, thus will be one of main topics of the current study.

5.3.1 Description of selected six cities in Japan

A DER generator which means small scale electric generation units located within the electric distribution system at or near the end-users. The generated power or recovered heat are mainly employed for on-site consumption, although sometimes electricity buy-back may be available. Therefore, the design and operation of a DER system is greatly dependent upon local atmospheric conditions, which may determine energy (thermal, especially) demands and other local conditions.

Due to its narrow stretch land shape across a wide range of latitudes, different regions may illustrate distinct climatic features in Japan. In terms of the assessment of energy performance in buildings, according to the current energy efficiency standards in Japan, the whole country is divided into six regions. In this study, six cities (Sapporo, Hachinohe, Sendai, Tokyo, Kagoshima and Naha) within each of the six climate zones. have been selected for following studies.

On the other hand, different types of buildings usually illustrate distinct energy profiles, which may greatly affect the performances of the CCHP systems. In this study, four typical buildings (hotel, hospital, store and office) sharing 56% of the existing

CCHP systems in Japan have been chosen as the representatives of the commercial building [22]. In addition, according to a previous survey [33], the CCHP systems are usually introduced in relatively large-scale commercial buildings with floor areas more than 20,000 m2. Therefore, in this study, all examined commercial buildings are assumed to be the prototype buildings with the same floor area (20,000 m2) and other building characteristics.

As is known to all, both Japan and China are countries with 98% of the land area stretching between latitudes of 20°N to 50°N, from the subtropical zones in the south to the temperate zones in the north. There is a large diversity in climates which determines the necessary energy consumption, especially heating and cooling loads. Therefore, it is critical to take into consideration the climatic conditions while assessing energy related issues at the local scale in both Japan and China.

In the following analysis, for each city (region) and hence each climate zone, four building types are analyzed and compared as to the DER options and corresponding system performances (economic, energy and environmental ones).

5.3.2 Selection of regions

There are various ways to classify climate types according to different criteria using different climatic variables and indices. In Japan, according to the current energy efficiency standards, the whole country is divided into six regions by heating degree days (HDD), as shown in Fig. 5-3. For each region, standard heat transfer coefficients are specified. In addition, there are also requirements for adding air barriers, heat transfer coefficients for doors, and so on. In this study, in order to execute a comparative study with China, five cities (Sapporo, Sendai, Tokyo, Kagoshima and Naha) located within different climate zones have been selected for analysis (see Fig. 5-3). In other words, Sendai is selected as the sample city for regions 2 and 3, while considering the overlapping latitude of these two regions.

Detailed locations and climate conditions of the regions selected in Japan are illustrated in Table 5-1.

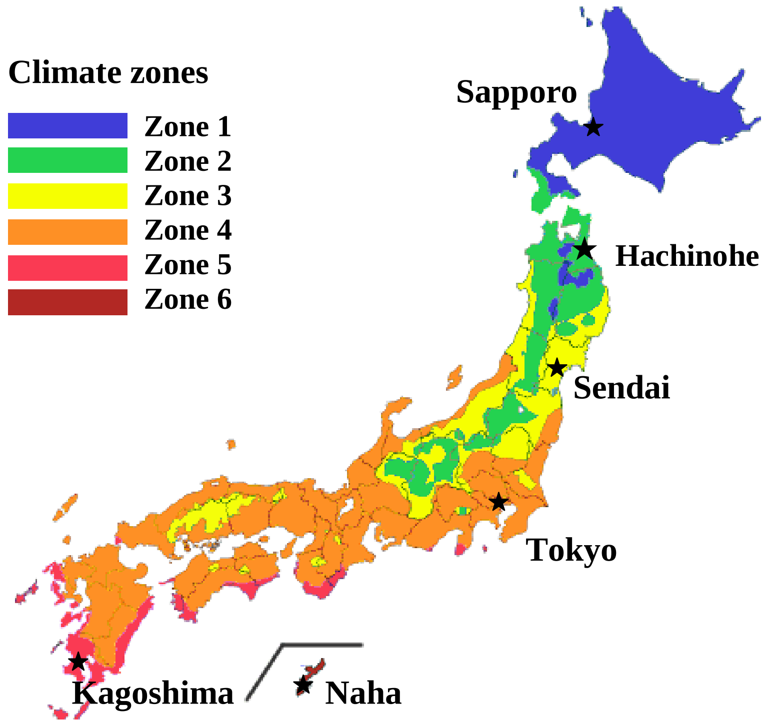


Fig. 5-3 Geographical distribution of major climate zones and six cities in Japan

Table 5-1 Features of selected cities in Japan

Country	City	Coordinates	Annual average temperature	Climate
Japan	Sapporo	E141°21′ N43°04′	8.9 ℃	Cool summer and icy winter
	Hachinohe	E141°28′ N40°33′	10.2 ℃	Cool summer and icy winter
	Sendai	E140°53′ N38°15′	12.4 ℃	Moderate humid summer and cold winter
	Tokyo	E139°76′ N35°68′	16.1 ℃	Hot summer and generally mild winter
	Kagoshima	E130°11′ N31°21′	19.2 ℃	Hot humid summer and relatively mild winter
	Naha	E127°40′ N26°12′	23.1 ℃	Hot humid summer and warm winter

5.3.3 Energy demand profiles

As mentioned above, the design and operation of the DER system is determined based on the energy load profiles. Therefore, in order to achieve satisfied assessment results, it is necessary to understand detailed information about the energy demands. In Japan, according to previous studies [34, 35], the hourly energy intensity (electricity, cooling, heating and hot-water) in terms of the floor area for various building located in Tokyo have been determined based on long-term investigations. However, it is impossible to collect all the data required in every city around the country. Therefore, by using the data of Tokyo as the base scenario, while considering the difference of climatic conditions and other factors, the regional coefficients for the calculation of annual energy consumptions have been deduced, as shown in Table 5-2 [34, 36].

In this study, by using the deduced energy intensity, annual energy consumptions of assumed commercial buildings in selected cities have been calculated and compared, as shown in Fig. 5-4. From the figure, the following characteristics can be concluded:

(1) As to the same region, hotels and hospitals have overwhelmingly larger hot-water and heating loads than stores and offices. For example, in Tokyo, hot-water demand amount to 1.0 GJ/m^2 in hotels, approximately 10 times that of stores and 30 times that of offices. Overall, hotels have the largest thermal demand, followed by hospitals, stores and offices. On the other hand, stores consume more electricity than other buildings, amount to 2.1 GJ/m^2, about 1.5-3 times more than other buildings.

(2) Hotels and hospitals in the northern areas (cold zones) have relatively large energy consumption than the southern areas (hot zones), due to the dominated requirements of thermal energy (heating load, especially). On the contrary, as mentioned above, electricity is the main energy form in stores and offices; thus, Tokyo has relatively higher total energy consumption in these two types of buildings because of its larger regional coefficients for electricity consumption.

Table 5-2 Regional coefficients for the calculation of annual energy consumptions

Climate zone	Selected city	Regional coefficients			
		Electricity	Cooling	Heating	Hot water
Zone 1	Sapporo	0.80	0.50	2.40	1.15
Zone 2	Hachinohe	0.90	0.70	1.40	1.08
Zone 3	Sendai	0.90	0.90	1.40	1.05
Zone 4	Tokyo	1.00	1.00	1.00	1.00
Zone 5	Kagoshima	0.90	1.20	0.70	0.95
Zone 6	Naha	0.90	1.50	0.10	0.84

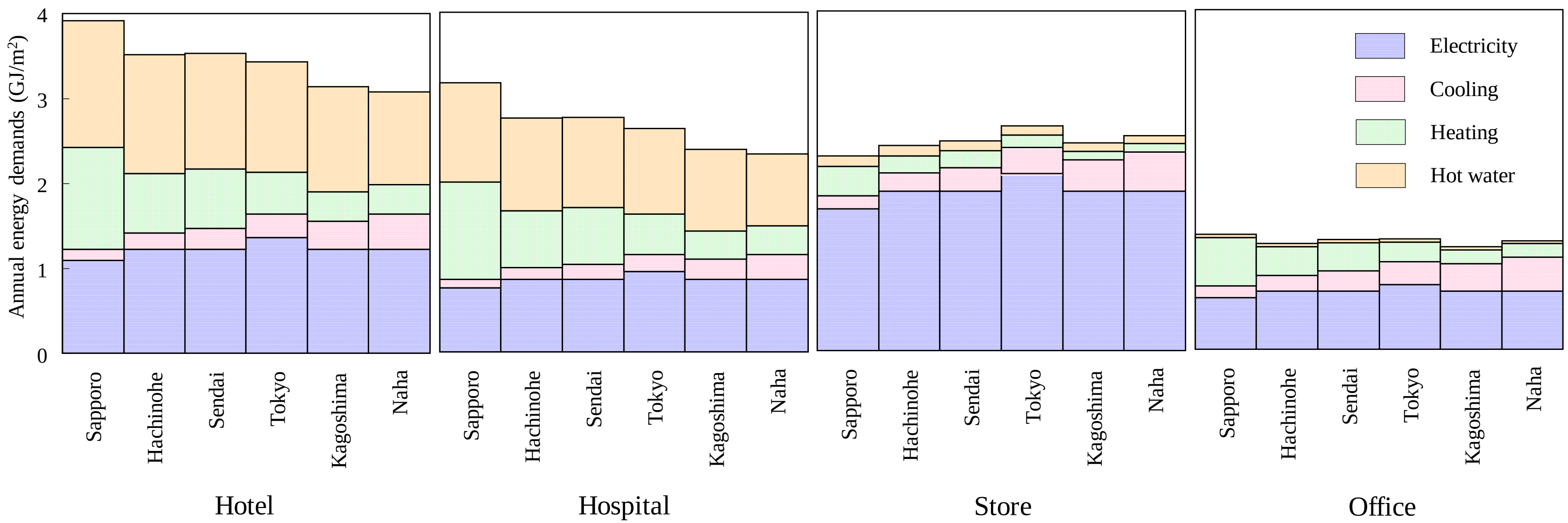


Fig. 5-4 Annual cumulative energy demands of the commercial buildings in selected six cities

5.3.4 Technical features of the CCHP system

Usually, a CCHP system may employ various kinds of prime movers including gas engine, gas turbine, Stirling engine and CHP [35]. According to a previous investigation, gas engine has the largest share (more than 70%) among national total CCHP systems in commercial buildings in Japan [22]. Therefore, in this study, the gas engine unit has been selected for the following analyses. Usually, the rated performance of a gas engine plant may vary with its capacity. In this study, the rated parameters (referred to LHV value) of the gas engine plant with various capacities have been investigated and shown in Table 5-3. Based on the data, the rated electric and thermal efficiencies in association with the capacity (400-2500 kW) can be deduced by the following polynomial fitting functions [37]:

$$\eta_{e0} = 8E^{-10}Cap^3 - 5E^{-6}Cap^2 + 0.0115Cap + 35.135 \tag{1}$$

$$\eta_{h0} = -2E^{-9}Cap^3 + 1E^{-5}Cap^2 - 0.0227Cap + 56.462 \tag{2}$$

where, η_{e0} and η_{h0} denote the rated electric and thermal efficiencies, respectively. Cap denotes the rated capacity of the gas engine unit.

Table 5-3 Rated electric and thermal efficiencies for various gas engine capacities

Capacity (kW)	Rated electric efficiency (%)	Rated thermal efficiency (%)
299	38.2	50.9
526	39.5	47.6
889	42.8	43.4
1191	43.0	43.4
1487	43.0	43.4
2002	45.1	41.6
2679	45.5	41.4

In addition, for a given capacity, the performance of a gas engine unit may change at part-load operation. Therefore, the power generation efficiency and heat recovery efficiency are assumed to change with operating conditions, as functions of the part-load ratio [38]:

$$\eta_e = \eta_{e0} \cdot (0.4812 f_{ge}^3 - 2.4726 f_{ge}^2 + 2.9801 f_{ge} + 0.0113) \tag{3}$$

$$\eta_h = \eta_{h0} \cdot (-1.3476 f_{ge}^3 + 2.8870 f_{ge}^2 - 2.1247 f_{ge} + 1.5853) \tag{4}$$

where, η_e and η_h denote the electric and thermal efficiencies at part-load operation, respectively. f_{ge} is the part-load factor of the gas engine plant.

The recovered heat from the gas engine plant usually includes exhaust gas with relatively high temperature and jacket water with relatively low temperature. The high-temperature exhaust gas can be used to active the absorption chiller directly, or serve the heating load via the heat exchanger; while the low-temperature jacket water may be used directly to serve the hot-water demand. On the other hand, the high-temperature exhaust gas can be firstly transferred to hot water and then used to active the absorption chiller in combination with the low-temperature jacket water. In this way, the coefficient of performance (COP) of the absorption chiller may be relatively high by making full use of the recovered heat. Furthermore, similar to the gas engine unit, the transient operation of the absorption chiller should also be considered, thus its coefficient can be determined as [39] :

$$COP_{abc} = -5.6739 f_{abc}^4 + 15.4539 f_{abc}^3 - 15.3729 f_{abc}^2 + 6.6939 f_{abc} + 0.3981 \qquad (5)$$

where, COP_{abc} denotes the coefficient of performance of the absorption chiller. f_{abc} is the part-load factor of the absorption chiller.

Moreover, the COP of the electric heat pump is recognized as an approximately fixed value of 4. This is because that, instead of the centralized energy centre, multiple electric heat pumps may be employed to supply the heating and cooling demand in the conventional system. In this way, the part-load ratio of the electric heat pump can remain at relatively high level through rational sequencing control strategy. In addition, the performance of auxiliary boiler is also recognized as an fixed value of 90%.

5.3.5 Market information and other assumptions

Energy price is one of the most important factors determining the economic performance of the CCHP system. According to the data shown in Tables 5-4, different cities may have different electricity tariff and natural gas price. Generally, Tokyo and Kagoshima have relatively higher electricity tariff rates and also enjoy high buy-back prices for on-site power generation; while, Sendai has the lowest prices for both ones. As to the natural gas, Hachinohe has the highest price, followed by Naha and Kagoshima. In addition, in order to promote the adoption of CCHP systems, the gas prices for the CCHP systems are relatively lower than that for common gas consumption in most cities except Naha.

Tables 5-5 also show the emission features of grid electricity and natural gas in different cities. Tokyo enjoys the lowest carbon intensity; while Naha in Okinawa has the largest carbon intensity due to the escape of nuclear power plants. In should be indicated that these values may fluctuate year by year due to the variation of local power compositions especially the start and stop of nuclear power plants.

Table 5-4 Prices and technical features of grid electricity in different cities

Item			Sapporo	Hachinohe	Sendai	Tokyo	Kagoshima	Naha
Electricity tariff	Demand charge ($/kW)		22.402	19.898	16.867	20.557	15.813	20.886
	Energy charge for summer ($/kWh)	On-peak	0.184	0.218	0.162	0.245	0.294	0.205
		Mid-peak	0.184	0.200	0.110	0.236	0.245	0.205
		Off-peak	0.109	0.105	0.110	0.152	0.086	0.205
	Energy charge for other seasons ($/kWh)	On-peak	0.184	0.218	0.162	0.245	0.294	0.187
		Mid-peak	0.184	0.187	0.110	0.219	0.233	0.187
		Off-peak	0.109	0.105	0.110	0.152	0.086	0.187
Buy-back price	Summer ($/kWh)	On-peak	0.082	0.074	0.074	0.102	0.094	0.093
		Mid-peak	0.082	0.074	0.074	0.102	0.094	0.093
		Off-peak	0.082	0.074	0.074	0.044	0.045	0.073
	Other seasons ($/kWh)	On-peak	0.082	0.074	0.074	0.090	0.083	0.079
		Mid-peak	0.082	0.074	0.074	0.090	0.083	0.079
		Off-peak	0.082	0.074	0.074	0.044	0.045	0.073
Carbon intensity (kg-CO_2/kWh)			0.688	0.600	0.600	0.525	0.612	0.903
Average power generation efficiency (%)			39.06	44.80	44.80	46.30	43.60	38.17

Table 5-5 Prices and emission features of natural gas in different cities

Item		Sapporo	Hachinohe	Sendai	Tokyo	Kagoshima	Naha
Common customer	Fixed customer charge ($/month)	39.533	118.598	13.178	15.813	19.766	17.131
	Demand charge ($/m^3)	14.433	0.000	14.810	11.590	18.027	12.255
	Energy charge ($/m^3)	1.200	2.312	1.461	1.157	1.509	1.685
CCHP customer	Fixed customer charge ($/month)	98.831	35.579	922.425	237.195	988.313	17.131
	Demand charge ($/m^3)	14.433	0.000	8.499	12.234	9.962	12.255
	Energy charge ($/m^3)	0.647	1.334	0.941	0.821	0.787	1.685
Carbon intensity (kg-CO_2/kWh)		0.180					

5.3.6 Determination of system capacity

In this sub-section, Tokyo is selected as an example to show the means to determine the capacity of a CCHP system. As mentioned in Section 2, the graphical method based on the thermal load (sum of space heating, cooling and hot-water demand) duration curve is employed to determine the capacity of the CCHP system. On the load duration curve as shown in Fig. 5-5, the rectangle with maximum area is found with one vertex lying at the origin and the other constrained on the curve itself. Taking hotels for example, based on maximizing the area below thermal load duration curve, the maximum heat (1,107 kW) recovered from the gas engine unit, and the duration time (4,928 h) are determined. Similarly, in the same way, the thermal capacities of CCHP systems for hospital, store and office can be determined as 1,237 kW, 577 kW and 731 kW, respectively.

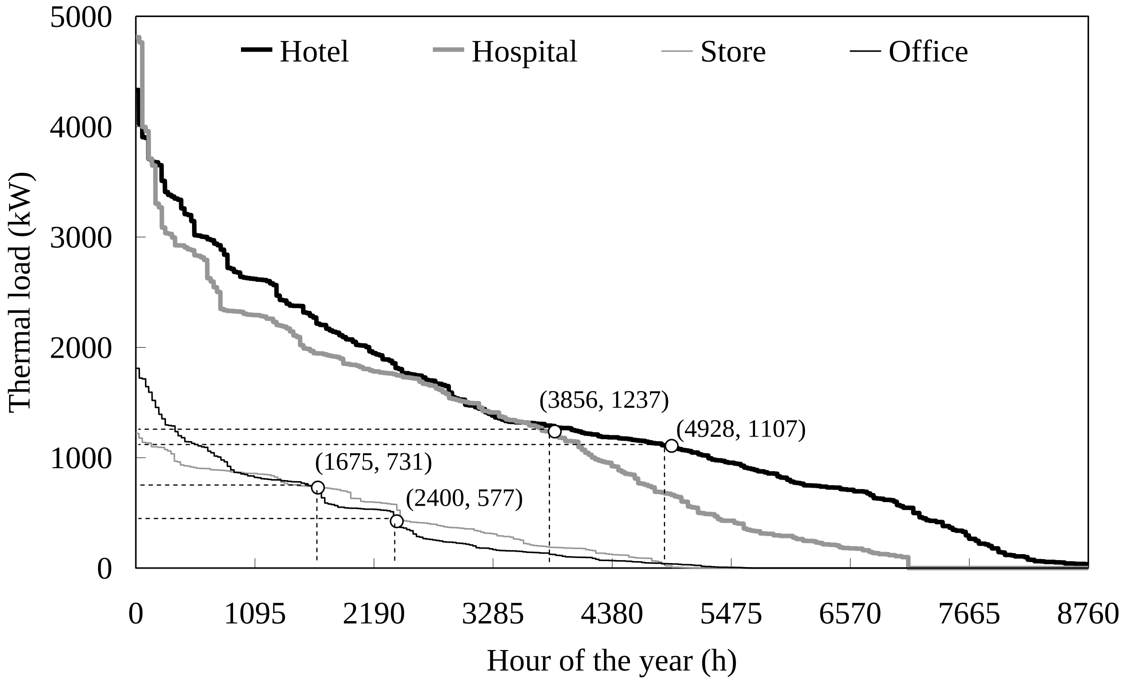


Fig. 5-5 Thermal load duration curves for various buildings in Tokyo

Using the method introduced above, the capacities of CCHP systems in different buildings and regions can be determined and compared, as shown in Table 5-6. Generally, larger system size is preferred by hotels and hospitals due to their relatively higher thermal demands (see Fig. 3). Furthermore, hotels have the longest duration time at rated capacity, followed by hospitals, stores and offices. On the other hand, as to the same building type, Sapporo always introduces the largest CCHP capacity, but encounters relatively short duration time.

Table 5-6 Duration times and capacities of CCHP systems for various buildings in selected cities

City	(Duration time, hour; Capacity, kW)			
	Hotel	Hospital	Store	Office
Sapporo	(3478, 2220)	(3514, 1832)	(1086, 1635)	(1024, 2139)
Hachinohe	(4736, 1382)	(3395, 1741)	(2070, 616)	(1024, 1265)
Sendai	(5378, 1265)	(3488, 1670)	(2100, 749)	(1737, 806)
Tokyo	(4928, 1265)	(3856, 1414)	(2400, 660)	(1675, 835)
Kagoshima	(4172, 1294)	(3373, 1529)	(3081, 455)	(2064, 701)
Naha	(4138, 1304)	(3374, 1167)	(1190, 891)	(1160, 848)

5.3.7 Single criteria assessment

In this sub-section, as one of the main steps in multi-criteria assessment, the assessment results of each alternative based on the criteria introduced in Section 2 are illustrated and discussed.

5.3.7.1 Assessment of energy performance

Fig. 5-6 shows the primary energy saving ratios for various options. As is expected, all examined alternatives enjoy positive PES thanks to the heat tracking operation mode which could fully utilize the recovered heat without electricity losses (surplus electricity can be bought back by the utility). Especially, CCHP systems in hotels and hospitals have relatively high primary energy saving ratios which are 25-56% and 28-47%, respectively. This is because that, on the one hand, they have relatively large and stable thermal demand in coincident with the electrical need, which leads to longer duration time at rated capacities (see Fig. 5-5 and Table 5-6); on the other hand, as indicated in previous studies [9], hotels and hospitals have favorable heat-to-power ratios which are in accordance with that of the gas engine based CCHP system.

As to the same building type, Sapporo always enjoys the best energy performance followed by Naha. However, looking into the figure, it can be found that the ranking orders of the cities may be diverse for different building type. For example, the potential order of energy saving of the CCHP system is Sapporo ≻ Naha ≻ Kagoshima ≻ Hachinohe ≻ Sendai ≻ Tokyo for hotels, hospitals and offices, while Sapporo ≻ Naha ≻ Sendai ≻ Hachinohe ≻ Tokyo ≻ Kagoshima for stores. This is because the energy performance depends not only on the building type and site location, but also on the size of the CCHP system and its operating strategy which is determined according to the thermal duration curve.

5.3.7.2 Assessment of economic performance

Although the introduction of CCHP systems results in satisfied energy performance for all options as discussed above, it may cost more compared with the conventional system, as shown in Fig. 5-7. Especially, the CCHP systems for all examined commercial buildings in Naha has minus TCS values. It means that it is unfeasible to introduce the CCHP system in Naha from the economic point of view. This is mainly due to the relatively lower electricity tariff rate and higher gas price. Furthermore, Naha is the only exception without discounted price for the natural gas consumption of the CCHP system. On the contrary, the CCHP systems in Kagoshima enjoy the best economic performances with relatively high cost saving ratios (more than 10%) for all building types. Moreover, Tokyo also achieves satisfied economic performance with TCS values ranging from 8.4% to 33.0%.

On the other hand, as to the same region, the CCHP systems in hotels enjoy better economic performance than other building types in all cities except Naha; while, the CCHP systems in stores achieve better performance in Naha. This is mainly due to less thermal demand compared with electrical requirement in stores, which results in less natural gas consumption with higher price in Naha.

5.3.7.3 Assessment of environmental performance

Fig. 5-8 shows the CO2 emissions reduction ratio values for various options. Generally, the installation of CCHP systems results in satisfied environmental performances. Sapporo enjoys the best environmental performance due to its great potential of energy-saving (see Fig. 5). Furthermore, the environmental performances of CCHP systems in Naha are also outstanding with relatively high CER values (more than 60%). This is because of the satisfied energy performance as well as the relatively high carbon intensity of the grid electricity (see Table 3).

On the other hand, as to the same region, similar to the energy performance, the CCHP systems in hotels and hospitals achieve better environmental performances than stores and offices. In addition, comparing with the energy performances shown in Fig. 5, it can be concluded that the energy performance and the environmental performance does not necessarily have coherent relationship. In other words, a CCHP system with better energy performance may have less environmental benefit, and vice versa. This is because the CO_2 emissions are calculated by multiplying the primary energy consumption with the corresponding carbon intensity. On the one hand, the carbon intensities of grid electricity may vary in various regions, which may result in different emission values even with the same primary energy consumption; on the other hand, due to the introduction of the CCHP system, the fuel transfer from coal to natural gas may also affect the final emission values. Therefore, a CCHP system with reduced CO_2 emissions may not necessarily achieve the energy-saving benefits. Furthermore, it should be indicated that because of the relatively high share of nuclear power in Japanese power composition, the contribution of fuel transfer is marginal in most regions.

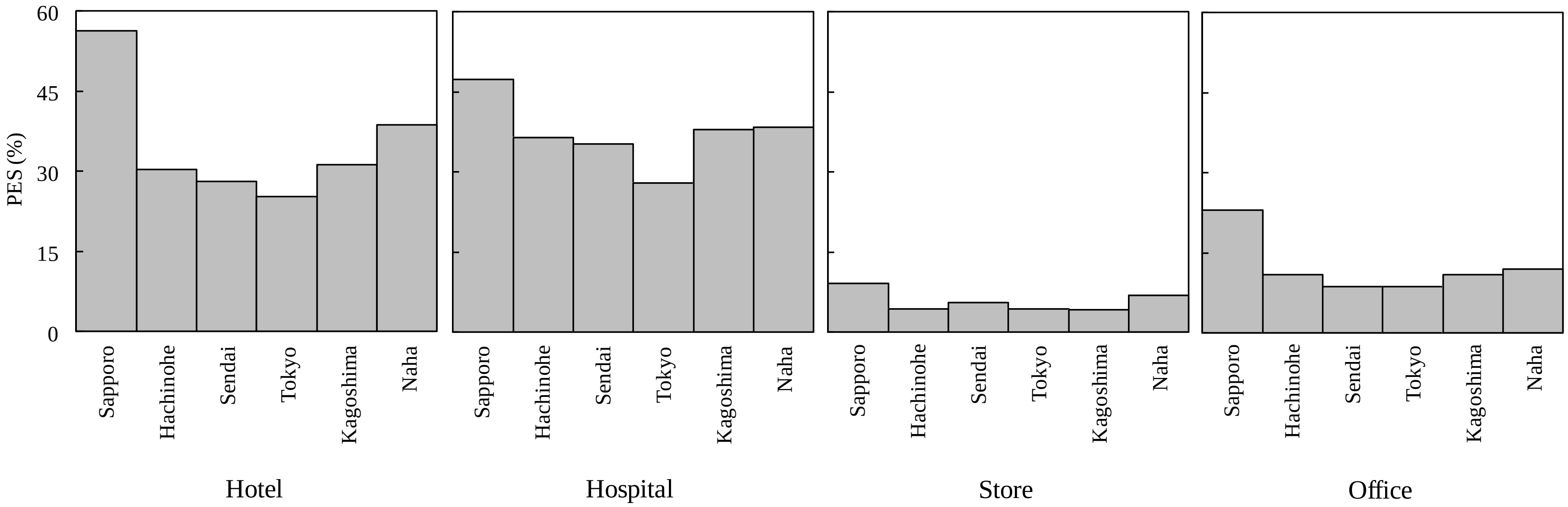


Fig. 5-6 Primary energy saving ratios for various options

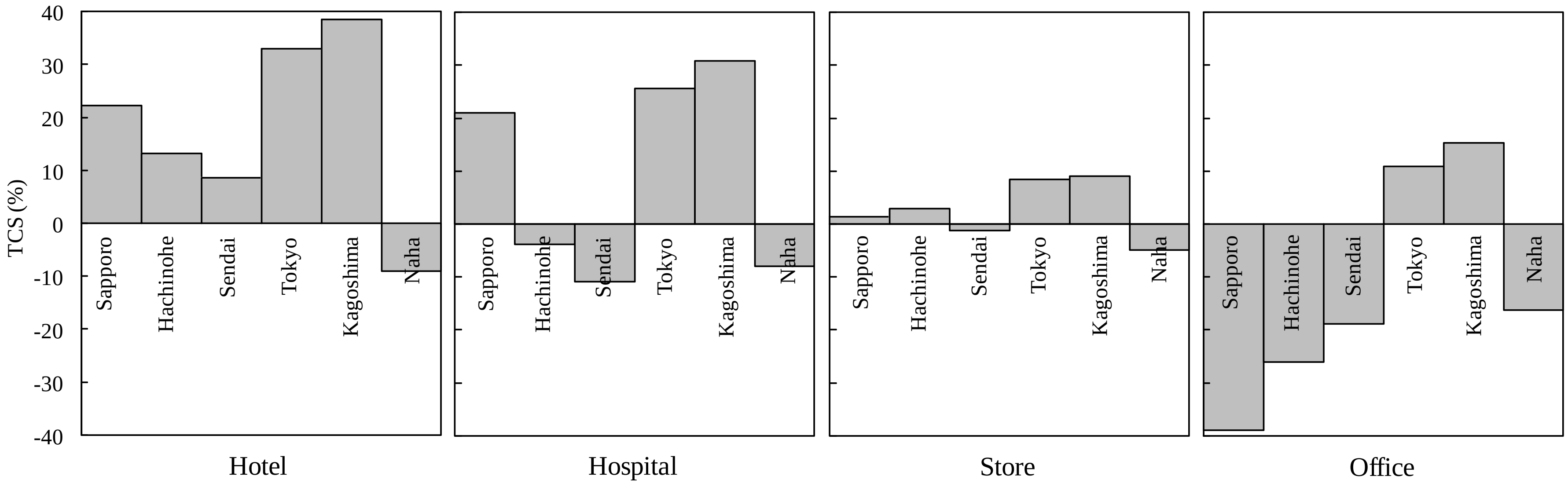


Fig. 5-7 Total cost saving ratios for various options

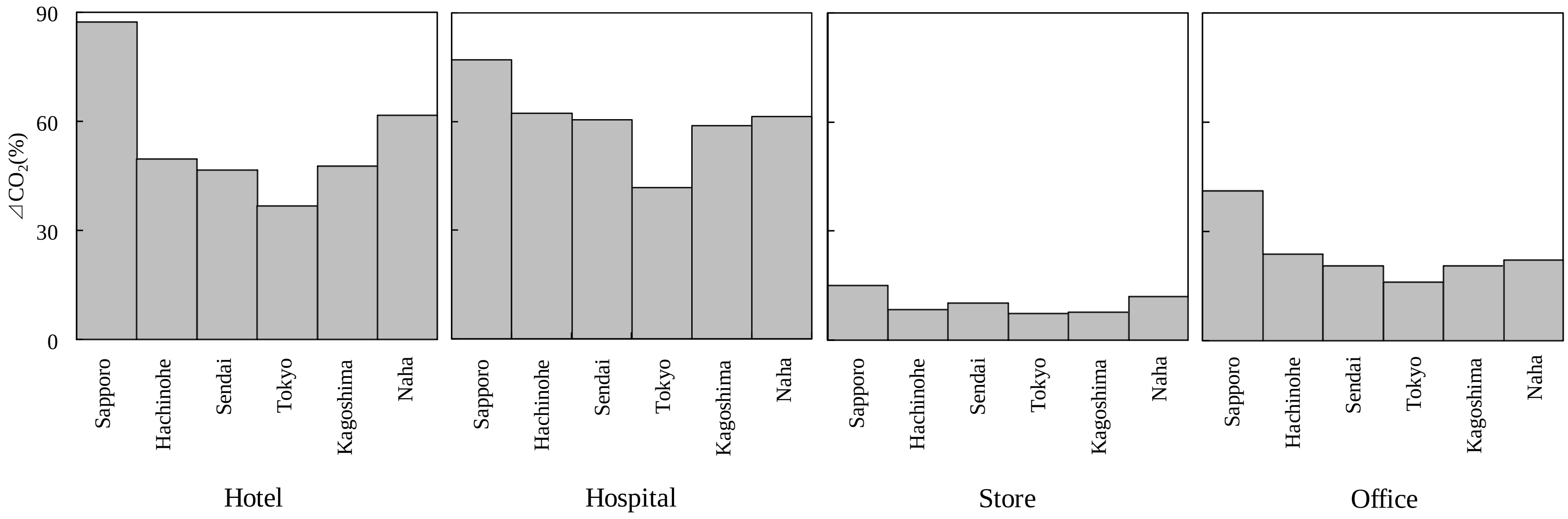


Fig. 5-8 CO_2 emissions reduction ratios for various options

5.3.8 Multi-criteria assessment

In this study, in order to evaluate the CCHP systems for various building types located in different regions, the hierarchical structure of the AHP method is developed firstly. The determination of ranking order of the CCHP systems is given at the top level (Level 0). The elements of PES, TCS and CER are considered in the evaluation criteria level (Level 1). The elements of alternative CCHP systems are included in the alternatives level (Level 2).

According to the concept of AHP method introduced in Section 2, detailed procedures of the case study are illustrated as follows.

5.3.8.1 First level analysis

After developing a hierarchical structure, it is necessary to perform pair-wise comparisons at each level of the hierarchy. To achieve a concise pair-wise comparison, the nominal scale introduced in Section 2 is employed.

According to a previous survey [35], the motivation of introducing CCHP systems may be different for various consumers. In detail, offices, stores and hotels usually select economic benefit as the most important reason for introducing CCHP systems, while energy performance is paid more attention by the hospitals. Taking the stores for example, Eq. (7) illustrates the pair-wise comparison matrix of the three assessment criteria (PES, TCS, CER) in the first level of the hierarchy.

$$M = \begin{vmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 1 \\ 1/2 & 1 & 1 \end{vmatrix} \tag{7}$$

Following which, the synthesized matrix is deduced by dividing each element of the pair-wise comparison matrix by its column total, as shown in Eq. (8).

$$N = \begin{vmatrix} 0.5 & 0.5 & 0.5 \\ 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 \end{vmatrix} \tag{8}$$

Based on the synthesized matrix, the priority vector can be obtained by finding the row average, as shown in Eq. (9).

$$P = \begin{vmatrix} 0.5 \\ 0.25 \\ 0.25 \end{vmatrix} \tag{9}$$

Furthermore, the consistency ratio should be calculated to verify if the judgment is consistent. Following the same way, the priority vectors of the criteria for all building types are determined and the results are shown in Table 5-7.

Table 5-7 The priority vectors of the three criteria for various building types

	Hotel	Hospital	Store	Office
PES	0.60	0.27	0.50	0.40
TCS	0.30	0.46	0.25	0.30
CER	0.10	0.27	0.25	0.30

5.3.8.2 Second level analysis

Firstly, by using the mean level method introduced in Section 2, the numerical values shown in Figs. 5-7 are converted within the normal scale. Following which, the pair-wise comparison matrices of the alternatives in the second level with respect to each criterion in the first level can be deduced.

Finally, based on the synthesizing method, the local priority vectors of the alternatives with respect to each criterion are deduced and displayed in Table 5-8. In the table, R1- R6 indicate the selected six cities, respectively.

5.3.8.3 Synthesizing judgments

Following the determination of alternatives' scoring with respect to each criterion and the weights for each criteria, the overall priority of the alternatives can be deduced as shown in Table 5-9.

The results of the global priority indicate that the rank of regions for the same building type may vary case by case. For example, the ranking order of the overall performances of the CCHP systems in the six cities is Sapporo $\succ$ Kagoshima $\succ$ Naha $\succ$ Tokyo $\succ$ Hachinohe $\succ$ Sendai for hotels while Kagoshima $\succ$ Sapporo $\succ$ Tokyo $\succ$ Hachinohe $\succ$ Sendai $\succ$ Naha for stores. Generally, the CCHP systems in Kagoshima achieve more benefits than other regions for stores and offices; while, as to hotels and hospitals, the systems in Sapporo are preferred. This is because that, the economic performances of the CCHP systems in stores and office in Sapporo are not satisfied; while Kagoshima enjoys relatively good performances for all three criteria although its primary energy saving ratios and CO_2 emissions reduction ratios are lower than Sapporo.

Moreover, looking into the overall ranking of all options, the four most promising CCHP systems are those for hotels in Sapporo (13.45%), hospitals in Sapporo (9.30%), hospitals in Kagoshima (8.10%) and hotels in Kagoshima (7.14%). The CCHP systems in hotels and hospitals enjoy the front half of the overall rank; while the systems in stores and offices take up the remaining half. Therefore, the CCHP system may be recognized to be a satisfying measure for energy conservation in hotels and hospitals.

Table 5-8 Priority vector of the alternatives with respect to each criterion

Criteria	Hotel						Hospital						Store						Office					
	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6
PES	0.16	0.05	0.04	0.03	0.05	0.07	0.11	0.07	0.06	0.04	0.07	0.07	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.02	0.02
TCS	0.07	0.05	0.04	0.10	0.13	0.02	0.06	0.02	0.02	0.08	0.10	0.02	0.03	0.03	0.02	0.04	0.04	0.02	0.01	0.01	0.01	0.04	0.05	0.01
CER	0.16	0.05	0.04	0.03	0.04	0.07	0.12	0.07	0.07	0.03	0.07	0.07	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.02	0.01	0.02	0.02

Table 5-9 Global priority and rank of the CCHP systems with AHP

System	Hotel						Hospital						Store						Office					
	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6
Global priority	13.	4.6	3.9	5.4	7.1	5.7	9.3	4.7	4.2	5.6	8.1	4.7	1.6	1.4	1.3	1.6	1.6	1.3	2.4	1.4	1.3	2.1	2.6	1.5
(%)	45	2	7	9	4	2	0	5	4	5	0	3	3	3	5	2	5	3	5	1	3	5	1	2
Sub rank	1	5	6	4	2	3	1	4	6	3	2	5	2	4	5	3	1	6	2	5	6	3	1	4
Overall rank	1	10	12	7	4	5	2	8	11	6	3	9	17	20	22	18	16	24	14	21	23	15	13	19

5.4 Performance of CCHP system in China

5.4.1 Description of selected five cities in China

In terms of the thermal design of buildings in China, there are five major climate types, namely severe cold (with a very long and cold winter as well as a very short and cool summer), cold (with a cold winter as well as a humid and hot summer), hot summer and cold winter (with a humid and cold winter as well as a long and hot summer), mild (with a warm winter and a cool summer), as well as hot summer and warm winter (with a short and warm winter as well as a very long and hot summer). Fig. 5-9 shows an overall layout of the five major climates.

In this study, a major city within each of the five climate zones has been selected for analysis. The relative locations of the five cities are also marked in Fig. 5-9. Harbin is selected as the representative city within the severe cold zone. The mean temperature in the coldest month is below minus 10 °C; while, the mean temperature in the hottest month is about 24 °C. Beijing is located in the cold zone with a climate of continental type. Shanghai is located in the hot summer and cold winter zone with four distinctive seasons. The mean temperature of the hottest month July is between 25 °C and 30 °C; while, the mean temperature of the coldest month January is between 2 °C and 7 °C. Kunming belongs to the mild zone and is well known as the “spring city”. The average temperatures of the hottest month in July and the coldest month in January are 20 °C and 8 °C, respectively. Guangzhou is located in the hot summer and warm winter zone with a subtropical monsoon climate, which has a feature of high temperature, abundant rainfall and sufficient sunshine.

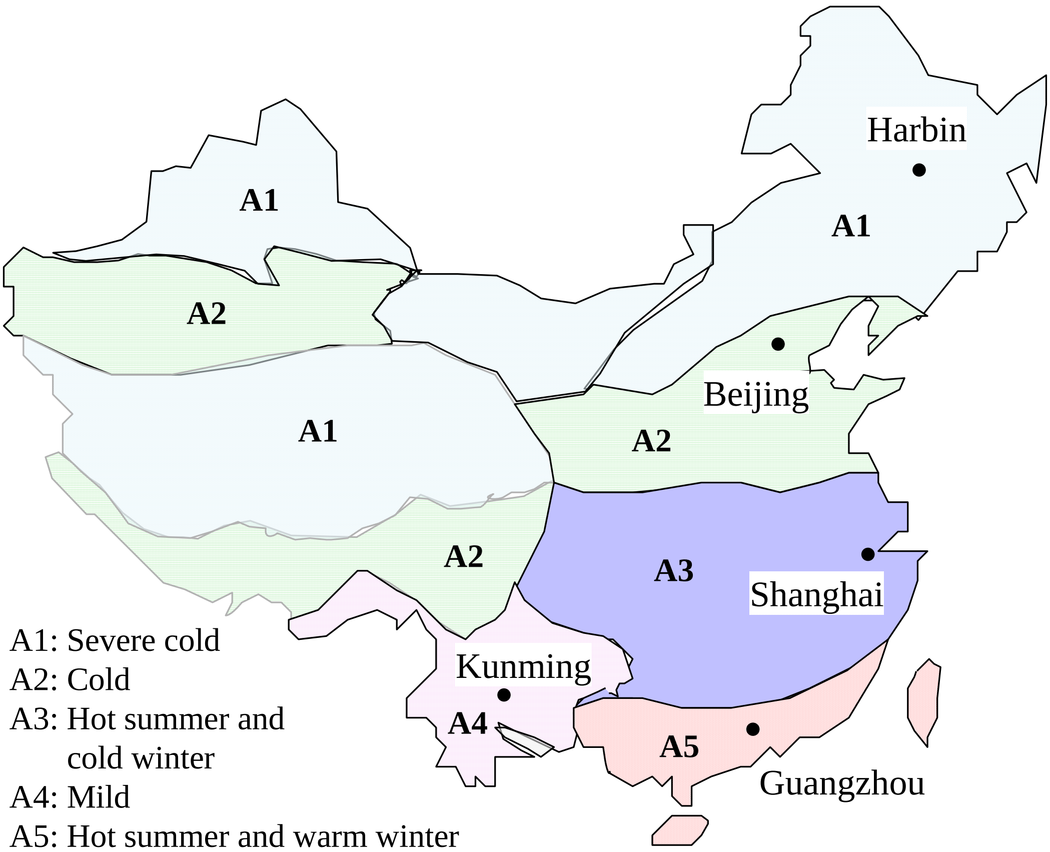


Fig. 5-9 Geographical distribution of five major climates and five cities in China

Detailed locations and climate conditions of the regions selected in China are illustrated in Table 5-10.

Table 5-10 Features of selected cities in China

China	Coordinates	Annual average temperature	Climate
Harbin	E126°40′ N45°48′	5.6℃	Long cold winter, short hot summer
Beijing	E116°23′ N39°54′	12.6℃	Hot and rainy summer, cold and dry winter
Shanghai	E121°30′ N31°14′	15.6℃	Hot summer and cold winter
Kunming	E102°41′ N25°04′	15℃	Four seaons like spring
Guangzhou	E113°20′ N23°10′	22.3℃	Hot summer and warm winter

5.4.2 Energy demand in China

The energy demand in China is deduced as follows: regional annual energy consumption is divided by the value in Tokyo, then the ratios are multiplied by the original energy unit consumption of Tokyo. Table 5-11 shows the regional unit consumption of various building types located in selected five cities.

Table 5-11 Regional annual energy consumption (kWh/m^2)

Building type	City	Electricity	Cooling	Space-heating	Water-heating
Hotel	Harbin	40.76	5.21	246.40	49.07
	Beijing	88.99	56.16	120.12	154.21
	Shanghai	107.29	58.48	38.60	175.57
	Kunming	24.12	2.16	0.00	27.93
	Guangzhou	47.13	35.72	10.55	87.65
Hospital	Harbin	17.47	6.40	410.67	38.90
	Beijing	58.26	68.99	200.89	70.46
	Shanghai	113.46	71.84	64.33	40.14
	Kunming	19.27	2.65	0.00	13.89
	Guangzhou	55.40	43.88	17.58	13.34
Store	Harbin	33.02	4.22	41.07	7.19
	Beijing	58.15	59.50	38.78	22.30
	Shanghai	86.99	47.43	6.43	25.15
	Kunming	19.55	1.75	0.00	4.05
	Guangzhou	38.23	28.97	1.76	12.52
Office	Harbin	30.25	3.94	136.89	0.77
	Beijing	66.40	42.50	66.00	1.21
	Shanghai	80.86	44.26	21.44	0.43
	Kunming	18.06	1.63	0.00	0.24
	Guangzhou	35.63	27.03	5.86	0.06

Fig. 5-10 shows annual cumulative energy demands of the assumed four buildings in four kinds of buildings in the selected five cities in China. According to the profiles shown in the figure, the following conclusions can be deduced.

In China, as to the same building types, annual energy demand of Harbin is the largest one and of which space-heating occupies a large ratio because its severe cold weather in winter; and Kunming is the least one because its suitable climate all the year round. On the other hand, as to the same city, Hotel and hospital consume larger energy consumption than other three building categories, and followed by office, commerce and apartment. In addition, energy unit demand of water-heating in both commerce and office are very low and below 2kWh/m2 per year. However, water-heating consumption in Hospital and Hotel are relatively high, but is still far below the value in Japan (see Fig. 4-2).

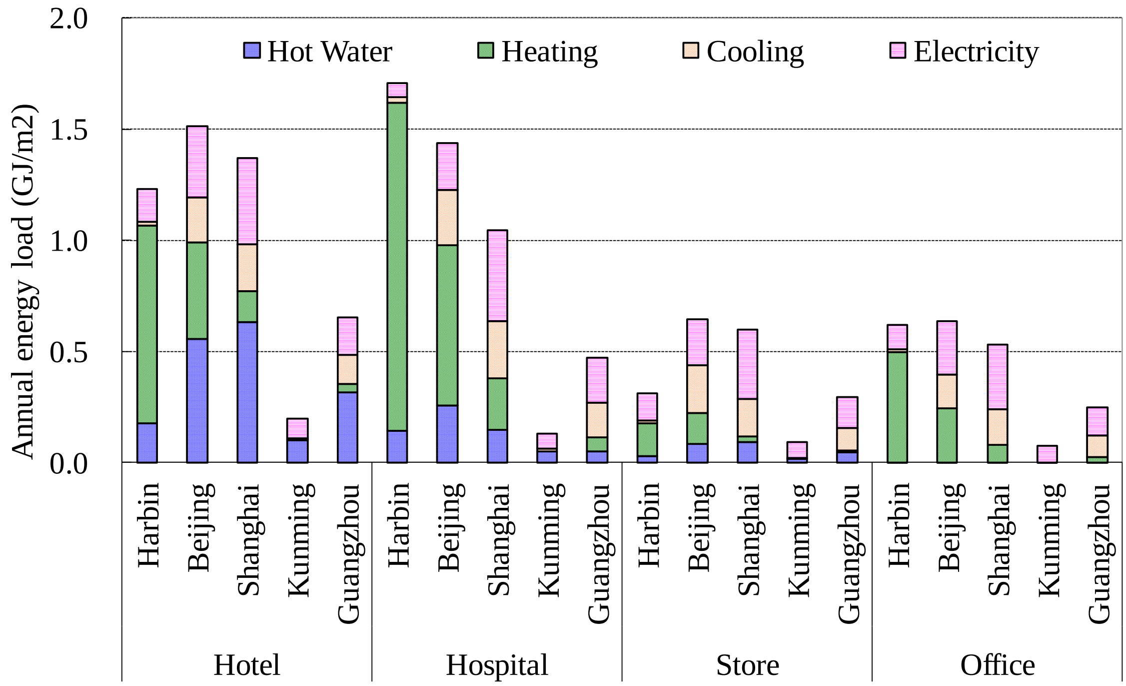


Fig. 5-10 Annual cumulative energy demands of the commercial buildings in selected five cities in China

5.4.3 Market information and technical assumptions

As shown in Table 5-12, the electricity and gas prices in different cities illustrate more or less difference in China. Undoubtedly, the same with Japan, different cities have different electricity tariff and natural gas price. Generally, except Shanghai, there is no demand charge in other cities. For the time of use electricity tariff have not adopted in all cities around the country of China, thus, different from Beijing, Shanghai and Kunming, a flat electricity tariff is adopted in Harbin and Guangzhou.

As to the natural gas price, the southern areas (Kunming and Guangzhou) have higher prices, which are about 70% higher than that in the northern areas. This may be partly due to the harder access to the natural gas in the southern areas. Although it is believed that the readjustment of energy prices may promote the introduction of energy conservation and distributed energy technologies, detailed analysis is out of the scope of this study.

Furthermore, carbon intensities of grid electricity and natural gas are important parameters for the assessment of the environmental performance of the CCHP system. As shown in Table 5-13, the mean carbon intensities of local electric utilities have been employed. Generally, Harbin has the largest intensity value and Shanghai has the lowest one. As to the natural gas, a mean value is assumed for all five cities in China.

Table 5-12 Electricity tariffs

	Item		Harbin	Beijing	Shanghai	Kunming	Guangzhou
Electricity tariff	Demand charge ($/kW)		0	0	6.863	0	0
	Summer ($/kW)	On-peak	0.140	0.187	0.196	0.167	0.162
		Mid-peak		0.126	0.120	0.113	
		Off-peak		0.048	0.047	0.059	
	Other seaons ($/kW)	On-peak		0.187	0.191	0.167	
		Mid-peak		0.120	0.114	0.113	
		Off-peak		0.057	0.058	0.059	
Carbon intensity	(kg-CO2/kWh)		1.13	1.01	0.88	1.00	1.00

Table 5-13 Natural gas prices

	Item	Harbin	Beijing	Shanghai	Kunming	Guangzhou
Natural gas	($/m3)	0.745	0.528	0.587	0.788	0.792
Carbon intensity	(kg-CO2/kWh)	0.22				

5.4.4 Determination of CCHP system capacity in China

In China, Shanghai is selected as an example to show the means to determine the capacity of a CCHP system. The same as Japan, the graphical method based on the thermal load (sum of space heating, cooling and hot-water demand) duration curve is employed to determine the capacity of the CCHP system. Fig. 5-11shows the thermal load duration curves for various buildings in Shanghai. As the figure shows, based on maximizing the area below thermal load duration curve, the maximum heat (626 kW) recovered from gas engine unit, and the duration time (4379h) are determined in Shanghai hotel. Similarly, the thermal capacities of CCHP systems for hospital, store and office can be determined as 465 kW, 189 kW, 297kW respectively.

The capacities of CCHP in China in different buildings and regions are showed in Table 5-14. Generally, for the thermal demand is less than that in Japan, the CCHP capacity is far away from Japan. Undoubtedly, the capacity of CCHP system enjoys large size both in hotels and hospital because of their relatively higher thermal demand. Again, Harbin has the largest capacity in all build types, whereas, Kunming enjoys the lowest one which is also corresponding to their thermal demand. As to the duration time, hotels always have the longest one.

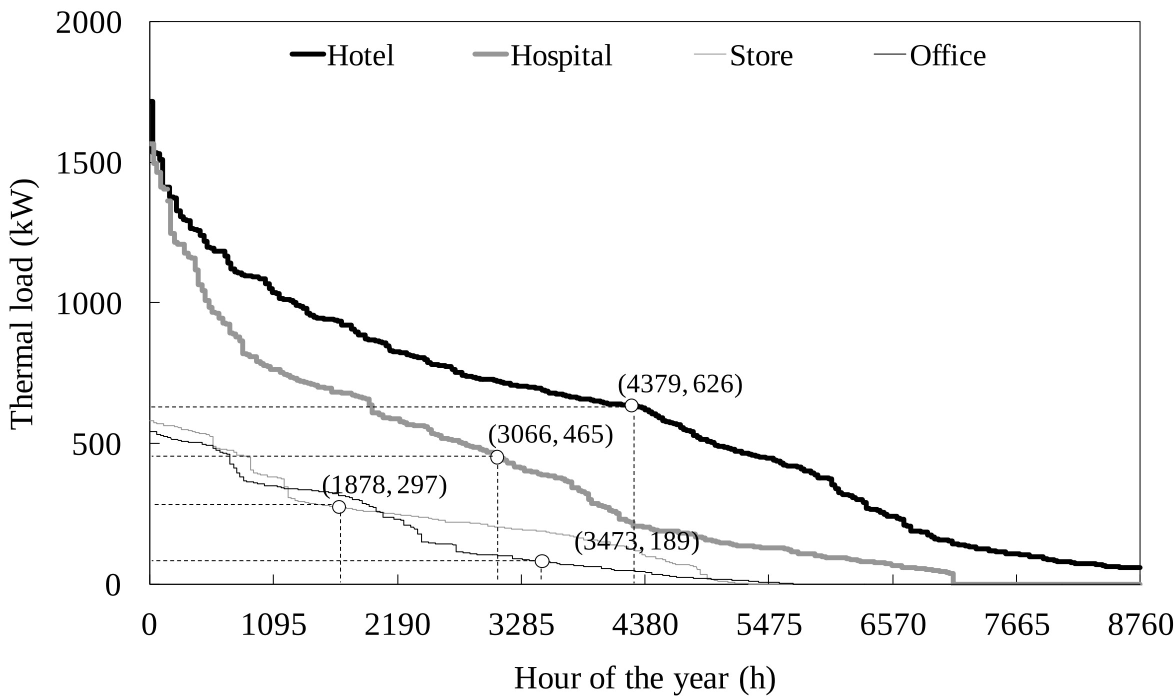


Fig. 5-11 Thermal load duration curves for various buildings in Shanghai

Table 5-14 Optimal capacity and duration time

City	(Duration time, hour; Capacity, kW)			
	Hotel	Hospital	Store	Office
Harbin	(2266, 1174)	(1446, 2523)	(1084, 508)	(1022, 1437)
Beijing	(5406, 563)	(3302, 752)	(2036, 529)	(1766, 453)
Shanghai	(4379, 626)	(3066, 465)	(3473, 189)	(1878, 297)
Kunming	(4405, 67)	(3250, 55)	(3951, 19)	(1158, 13)
Guangzhou	(4349, 320)	(3030, 164)	(3861, 83)	(1098, 200)

5.4.5 Single criteria assessment

The assessment results of each factor in China are illustrated and discussed as follows.

5.4.5.1 Assessment of energy performance

Fig. 5-12 shows the primary energy consumption reduction rate in China. Generally, energy-saving performance is satisfied in all examined alternatives especially in Harbin and Beijing. Except store, Harbin always has the highest reduction ratio which is even reach to 66% in hospital, whereas Kunming always has the lowest one. Similar to Japan, the ranking orders of the cities may be diverse for different building type. For example, the potential order of energy saving of the CCHP system is Harbin > Shanghai > Guangzhou > Beijing > Kunming for hotel, whereas in hospital, the order is Harbin > Beijing > Kunming > Shanghai > Guangzhou.

Furthermore, as to the same city, CCHP systems in hospital and hotel have better energy performance, and the reason has been analyzed in Japan. Except Harbin, hotel always enjoys the highest ratio which is flowed by hospital, store and office respectively.

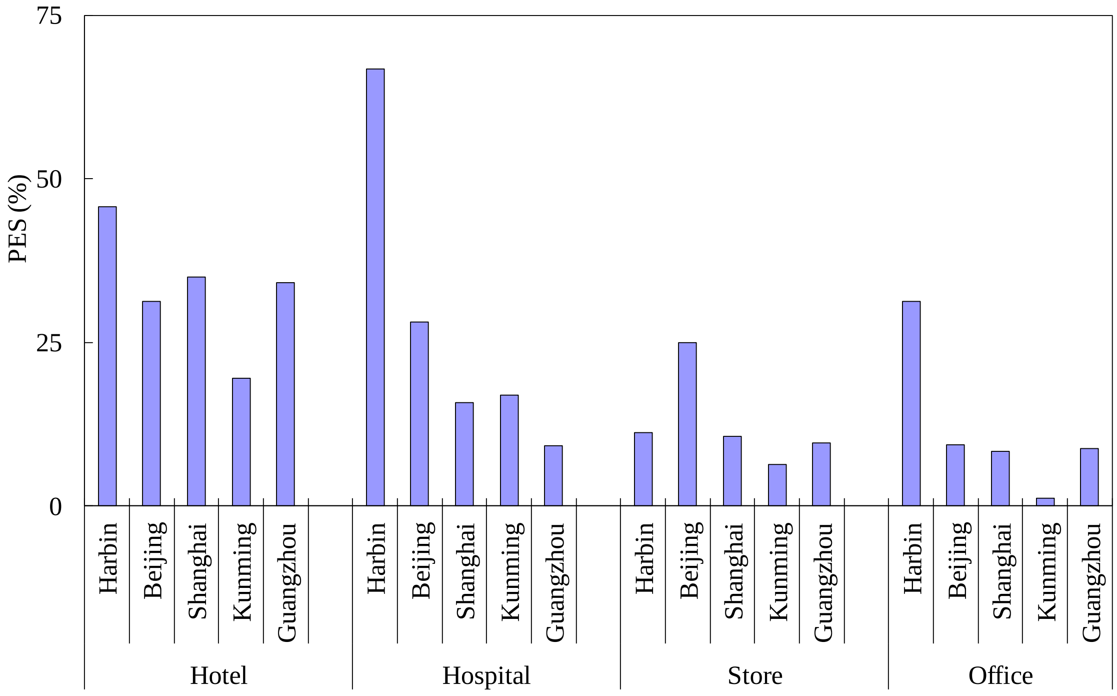


Fig. 5-12 Primary energy saving ratios for various options

5.4.5.2 Assessment of economic performance

Fig. 5-13 shows total cost saving ratios for various options. Note that, different from Japan, there is no discount price for the natural gas consumption of CCHP system in China. Therefore, generally, the annual cost reduction ratio is worse than that in Japan, which is unsatisfied in all cities. Especially in Harbin, the CCHP system for all examined commercial building has minus TCS values which is due to its relatively high initial investment cost of relatively large CCHP system capacity. The situation is a little better in Shanghai, Kunming and Guangzhou, the TCS values are all positive except in office. Furthermore, the CCHP system in hotels enjoy better economic performance than other building types, followed by hospital, store and office respectively.

5.4.5.3 Assessment of environmental performance

Fig. 5-14 shows the CO2 values for various option in China. Generally, the CCHP system adoption shows a better environmental performance than that in Japan. Harbin enjoys the best environmental performance due to its great potential of energy-saving, which is as high as from 141% to 285%, and followed by Beijing. Generally, hotel and hospital show better environmental performance than other two building type.

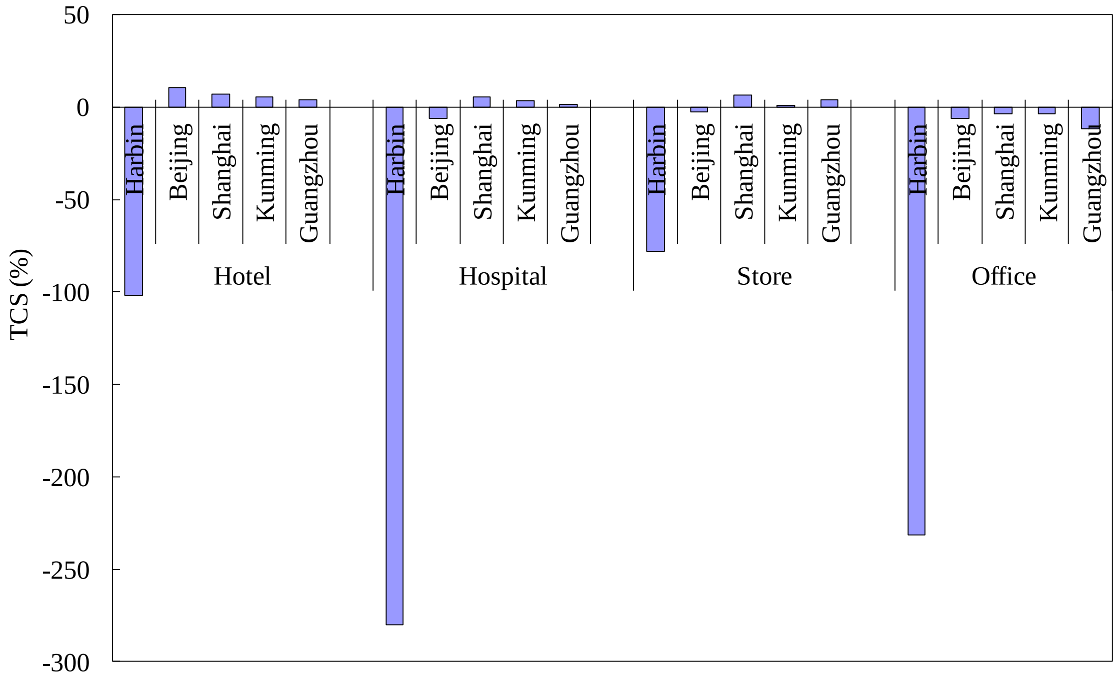


Fig. 5-13 Total cost saving ratios for various options

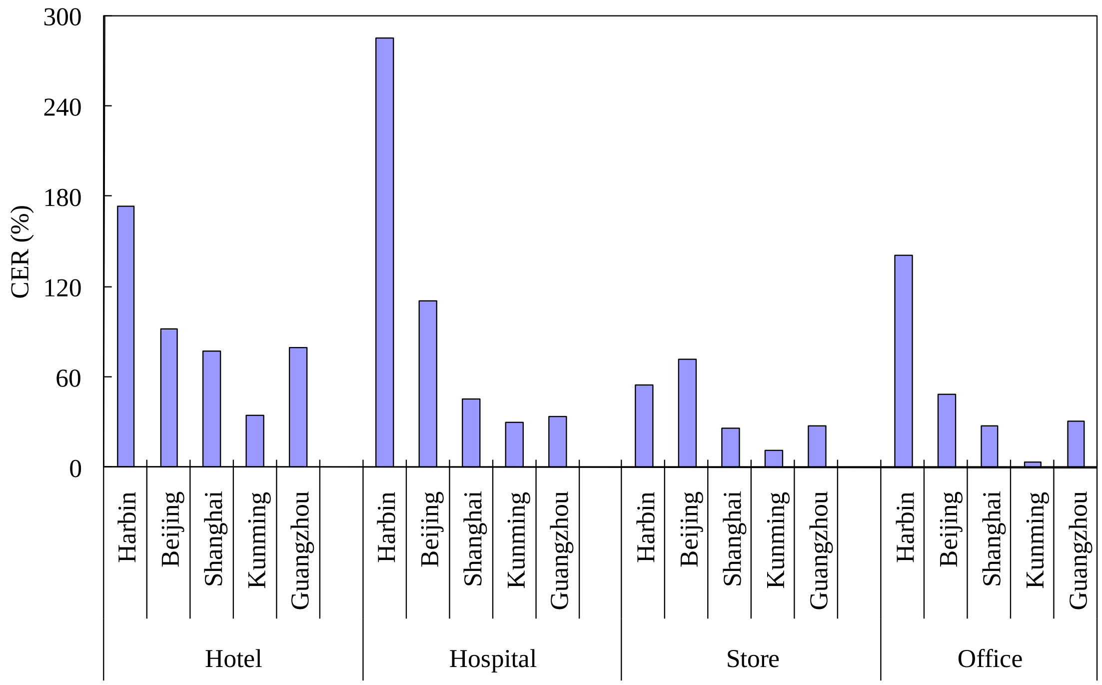


Fig. 5-14 CO_2 emissions reduction ratio for various options

5.4.6 Multi-criteria assessment

Similar to Japan, based on the same synthesizing method, the local priority vectors of the alternatives with respect to each criterion are deduced and displayed in Table 5-15. In the table, R1-R5 indicate the selected five cities, respectively.

Following the determination of alternatives scoring with respect to each criterion and the weights for each criteria, the overall priority of the alternatives can be deduced as shown in Table 5-16.

The results of the global priority indicate that the rank of regions for the same building type may vary case by case. For example, the ranking order of the overall performance of the CCHP system in the five cities is Harbin > Beijing > Shanghai > Kunming > Guangzhou for hospital, while Harbin > Beijing > Shanghai > Guangzhou > Kunming for both hotel and office.

Table 5-15 Local priority vectors of the alternatives with respect to each criterion

Criteria	Hotel					Hospital					Store					Office				
	R1	R 2	R 3	R 4	R 5	R1	R 2	R 3	R 4	R 5	R1	R 2	R 3	R 4	R 5	R1	R 2	R 3	R 4	R 5
PRS	0.12	0.07	0.08	0.04	0.08	0.22	0.06	0.03	0.03	0.02	0.02	0.05	0.02	0.02	0.02	0.07	0.02	0.02	0.01	0.02
TCS	0.02	0.07	0.07	0.06	0.06	0.01	0.05	0.06	0.06	0.06	0.02	0.05	0.07	0.06	0.06	0.01	0.05	0.05	0.05	0.05
CER	0.12	0.06	0.05	0.02	0.05	0.24	0.07	0.03	0.02	0.02	0.03	0.04	0.02	0.02	0.02	0.09	0.03	0.02	0.01	0.02

Table 5-16 The overall priority of the alternatives

System	Hotel					Hospital					Store					Office				
	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
Global priority (%)	9.23	6.18	5.54	3.72	5.50	12.92	5.76	4.51	4.26	3.86	2.73	4.69	3.18	2.67	3.09	6.02	3.29	2.96	2.56	2.80
Sub rank	1	2	3	5	4	1	2	3	4	5	4	1	2	5	3	1	2	3	5	4
Overall rank	2	3	6	12	7	1	5	9	10	11	18	8	14	19	15	4	13	16	20	17

5.5 Summary

In order to cope with the continually increasing energy consumption in commercial buildings, the CCHP systems are expected to play a bigger role in the coming years. In this chapter, the performances of CCHP systems for prototype commercial buildings (hotel, hospital, store and office) have been examined for a major city within each of the six major climate zones in Japan, as well as five major climate zones in China. The computed results have been analyzed and compared with the assistance of the AHP method using energy, economic and environmental performances as the assessment criteria. The criteria weights are assessed based on a previous investigation on a large number of existing CCHP systems. According to the assessment results, the following conclusions can be deduced.

(1) Generally, the introduction of CCHP systems results in satisfied energy and environmental performances in all examined commercial buildings in both Japan and China. The average primary energy saving ratios for all options are 21.2% in China and 22.6% in Japan. However, the mean CO2 emissions reduction ratios in China and Japan are 70.3% and 37.4%, respectively. This is mainly due to the relatively high carbon intensity of electricity from conventional power plant in China.

(2) The situation is different as to the economic performance which is affected by not only the system itself, but also financial and political conditions. The average total cost saving ratio for all options in China is -33.8%. Although the average value is 4.3%, it cannot be recognized as a satisfied value. For example, from the economic point of view, Tokyo and Kagoshima are the most attractive regions for the installation of CCHP systems; while it is hard to be introduced in Naha.

(3) Different building types illustrate distinguishing energy, economic and environmental performances. Hotels and hospitals are popular customers of the CCHP system from either viewpoint, although the economic performance is not satisfied; on the contrary, the adoption of CCHP systems in offices results in marginal benefits mainly due to their weak energy intensity especially thermal demands.

(4) Although the variation of climate condition leads to decreased cooling load and increased heating load from Southern area to Northern area, the total energy demand does not illustrate obvious regularity because electricity and hot-water demands (having weak relationship with the climate condition) are the dominant energy forms for all examined four types of buildings. Therefore, the influence of climate condition on the performances of the CCHP systems is inexplicit. Generally, the cold and hot zones enjoys better energy and environmental performances, while the mild climate zones enjoy better economic performances.

(5) By using the multi-criteria method, a comprehensive evaluation of the CCHP systems can be realized. For example, in Japan, the systems in Kagoshima achieve the most benefits for the stores and offices; while, as to the hotels and hospitals, the systems in Sapporo are more preferred. Overall, hotels and hospitals are recognized to be the potential customers of the CCHP systems from an integrated viewpoint.

(6) Weak economic performance is considered to be the main barrier against the penetration of CCHP systems in commercial buildings in both Japan and China. Besides the technical improvement of the CCHP system itself, incentives including the regulation of the electricity and natural gas prices should be paid more and more attention.

Reference

[1] C. Dinca, A. Badea, P. Rousseaux, T. Apostol, A multi-criteria approach to evaluate the natural gas energy systems, Energy Policy 35(11) (2007) 5754-5765.

[2] T. Buchholz, E. Rametsteiner, T.A. Volk, V.A. Luzadis, Multi Criteria Analysis for bioenergy systems assessments, Energy Policy 37(2) (2009) 484-495.

[3] P.A. Pilavachi, S.D. Stephanidis, V.A. Pappas, N.H. Afgan, Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies, Applied Thermal Engineering 29(11-12) (2009) 2228-2234.

[4] K. Alanne, A. Salo, A. Saari, S. Gustafsson, Multi-criteria evaluation of residential energy supply systems, Energy and Buildings 39(12) (2007) 1218-1226.

[5] Y. Ruan, Q. Liu, W. Zhou, R. Firestone, W. Gao and T. Watanabe, Optimal option of distributed generation technologies for various commercial buildings, Applied Energy 86(9) (2009) 1641-1653.

[6] J. Wang, C. Zhang, Y. Jing, Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China, Applied Energy 87(4) (2010) 1247-1259.

[7] M.A. Lozano, J.C. Ramos, L.M. Serra, Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints, Energy 35 (2) (2010) 794-805.

[8] G. Pagliarini, C. Corradi, S. Rainieri, Hospital CHCP system optimization assisted by TRNSYS building energy simulation tool, Applied Thermal Engineering 44 (2012) 150-158.

[9] H. Ren, W. Gao, Y. Ruan, Optimal sizing for residential CHP system, Applied Thermal Engineering 28(5-6) (2009) 514-523.

[10] P.J. Mago, L.M. Chamra, Analysis and optimization of CCHP systems based on energy, economical, and environmental considerations, Energy and Buildings 41(10) (2009) 1099-1106.

[11] A.T Rezvan, N. S. Gharneh, G.B. Gharehpetian, Robust optimization of distributed generation investment in buildings, Energy 48(1) (2012) 455-463.

[12] A.T Rezvan, N. S. Gharneh, G.B. Gharehpetian, Optimization of distributed generation capacities in buildings under uncertainty in load demand, Energy and Buildings 57(2013) 58-64.

[13] R. Ooka, K. Komamura, Optimal design method for building energy systems using genetic algorithms, Building and Environment 44(7) (2009) 1538-1544.

[14] E. Cardona, A. Piacentino, A methodology for sizing a trigeneration plant in mediterranean areas, Applied Thermal Engineering 23(13) (2003) 1665-1680.

[15] Q. Gu, H. Ren, W. Gao, J. Ren, Integrated assessment of combined cooling heating and power systems under different design and management options for residential buildings in Shanghai, Energy and Buildings 51 (2012) 143-152.

[16] A. Piacentino, F. Cardona, An original multi-objective criterion for the design of small-scale polygeneration systems based on realistic operating conditions, Applied Thermal Engineering 28(17-18) (2008) 2391-2404.

[17] Agency for Natural Resources and Energy, Fiscal 2012 Annual Energy Report, Ministry of Economy, Trade and Industry, Japan, 2013.

[18] National Institute for Environmental Studies, National greenhouse gas inventory report of Japan, Ministry of the Environment, Japan, 2013.

[19] "2050 Japan Low-Carbon Society" scenario team, Japan Scenarios and Actions towards Low-Carbon Societies, National Institute for Environmental Studies, Japan, 2008.

[20] H. Ren, W. Gao, A MILP model for integrated plan and evaluation of distributed energy systems, Applied Energy 87(3) (2010) 1001-1014.

[21] D.W. Wu, R.Z. Wang, Combined cooling, heating and power: A review, Progress in Energy and Combustion Science 32(5-6) (2006) 459-495.

[22] Advanced Cogeneration and Energy Utilization Centre Japan. http://www.ace.or.jp/web/works/works_0010.html (last accessed: 08.04.2014).

[23] S. Gamou, R. Yokoyama, K. Ito, Optimal unit sizing of cogeneration systems in consideration of uncertain energy demands as continuous random variables, Energy Conversion and Management 43(9-12) (2002) 1349-1361.

[24] S. Yoshida, K. Ito, R. Yokoyama, Sensitivity analysis in structure optimization of energy supply systems for a hospital, Energy Conversion and Management 48(11) (2007) 2836-2843.

[25] Y. Ruan, Q. Liu, W. Zhou, R. Firestone, W. Gao and T. Watanabe, Optimal option of distributed generation technologies for various commercial buildings, Applied Energy 86(9) (2009) 1641-1653.

[26] N. Zhou, C. Marnay, R. Firestone, W. Gao, Masaru Nishida, An analysis of the DER adoption climate in Japan using optimization results for prototype buildings with U.S. comparisons, Energy and Buildings 38(12) (2006) 1423-1433.

[27] Geospatial Information Authority of Japan.

[28] http://www.gsi.go.jp/KOKUJYOHO/center.htm (last accessed: 01.04.2014).

[29] Y. Takuma, H. Inoue, F. Nagano, A. Ozaki, H. Takaguchi, T. Watanabe, Detailed research for energy consumption of residences in Northern Kyushu, Japan, Energy and Buildings 38(11) (2006) 1349-1355.

[30] Y. Yamaguchi, Y. Shimoda, T. Kitano, Reduction potential of operational carbon

dioxide emission of Nakanoshima business/cultural area as a model for low-carbon districts in warm climates, Building and Environment 59 (2013) 187-202.

[31] Y. Tonooka, Oki Fukasawa, Y. Murahashi, Syuichi Miura, A detailed energy demand estimation and CO2 emission inventory of residential house by prefecture and hosing type in Japan, Journal of Environmental Engineering (Transactions of AIJ) 592 (2005) 89-96.

[32] K. Murakami, M. Kanaumi, Investigation on influence for electric consumption of city and consuming structure of public facilities, Journal of Environmental Engineering (Transactions of AIJ) 584 (2004) 69-74.

[33] H. Takaguchi, S. Izutsu, S. Washiya, Development and analysis of DECC (Date-base for energy consumption of commercial building) (Part 1): Development on basic database of DECC, Journal of Environmental Engineering (Transactions of AIJ) 678 (2012) 699-705.

[34] Y. Ruan, W. Gao, H. Li, T. Ojima, Investigation on the situation of combined heating and power system in Japan, Journal of Asian Architecture and Building Engineering 4(1) (2005) 245-251.

[35] T. Kashiwagi, Natural Gas Cogeneration Plan/Design Manual 2002, Japan Industrial Publishing Co., Ltd, Tokyo, 2002.

[36] Y. Ruan, Integration study on distributed energy resource and distribution system, Doctoral thesis, The University of Kitakyushu, Japan, 2006.

[37] Architectural Institute of Japan, Data book for solar building designs, Ohmsha Ltd., Tokyo, 2004.

[38] J. Wang, J. Wu, C. Zheng, Analysis of tri-generation system in combined cooling and heating mode, Energy and Buildings 72 (2014) 353-360.

[39] TRNSYS, TRNSYS 17 transient system simulation TYPE902.

[40] S. Jayasekara, S.K. Halgamuge, Mathematical modeling and experimental verification of an absorption chiller including three dimensional temperature and concentration distributions, Applied Energy 106 (2013) 232-242.

CHAPTER SIX: REGIONAL ANALYSIS FOR PHOTOVOLTAIC SYSTEM ADOPTION IN JAPAN AND CHINA

6.1 Introduction

In recent years, the searching for a substitute for fossil energy sources has increased the interest in photovoltaic (PV) system as a friendly and reliable energy technology which has been proved to be an effective option in helping countries to meet their CO2 reduction and renewable energy generation targets [1]. However, because of the high initial investment cost compared with the conventional power supply system, PV system has had extremely limited deployment, making up far less than one percent of the global electricity generation due primarily to economics (JM Pearce). Based on this background, some countries have made various polices to promote the PV system adoption (eg. subsidy and FIT (feed-in tariff) in Japan [2], FIT in Germany) and realized commercialization.

There has been significant growth in the number of residential solar photovoltaic (PV) adoptions over the past few years. The policies and incentives on solar energy indicate that PV is likely to become increasingly popular.

The PV module was put on the roof of the building directly in earlier time, whereas, Building Integrated Photovoltaic (BIPV) are taken into consideration at present. BIPV means except for electricity generation, the system is constructed as one part of the building structure, taking place of traditional roof, window or rain shelter etc. There are two main style of BIPV: PV roof and PV wall. BIPV is the development directions in the future, whereas needing the support of government.

The capacity of residential PV system is always 1-5 kW, and it can be set flexibly based on the situation of customer demand and roof area. The generated electricity of PV system can be selected in three models: all grid-connected, all self-use or surplus electricity grid-connected [3].

As we all know, the power generation of PV technology, which converts sunlight directly into electricity, is mainly affected by the solar irradiation, thus, the performance of PV unit will be compared and analyzed within various cities located in different climate zones in Japan and China respectively. In addition, different electricity demands also affect the performance of PV system. Therefore, four building types: store, office, hospital and hotel will be selected to do the research.

In this chapter, a full electrification building with four building types (store, office, hospital and hotel) located in different climate zones in Japan and China respectively was assumed, and the total area is 10000m2. The energy demand (electricity, cooling, heating and hot water) has been introduced in chapter 5. Furthermore, the performance of PV unit will be investigated from three aspects: unit cost of PV system, payback time, and annual cost reduction rate compared with conventional system.

6.2 Block diagram of PV system

Figure. 6-1 shows block diagram of the PV system. As the figure shows, electricity demand is supplied by the PV system, and the deficiency is satisfied by local utility grid. Similarly, cooling and space-heating is assumed to use electricity through an air conditioner. In addition, an air-source heat pump will meet hot water demand. Note that, there is no battery within the system, and the surplus electricity will be sold out to the utility grid depending on a certain FIT (feed in tariff) according to the government policy, which will bring benefit for the customers.

Furthermore, as to the schematic of grid-connected PV system which is shown in Fig. 6-2, the key components of a grid connected PV system include solar panels, inverter, electrical panel, disconnect switch and a meter that facilitates grid integration. The array is composed of a series of PV modules which themselves are composed of numerous PV cells, the cells are made mostly of silicon or another semiconducting material that converts incoming light energy into electricity; An inverter is a power-conditioning device that converts the incoming direct current (DC) power from the PV array into alternating current (AC) power that most home electronic devices are designed to use; The users can buy power from the central utility when needed or supply surplus home-generated power back to the utility, and through a meter the power brought in and sold out can be metered respectively [4-5].

The algorithm of PV system analysis procedure is shown in Figure 6-3. After setting the capacity of PV unit, initial values including load data, technical data, climate data are given to the PV system at the beginning and the electricity generated can be deduced. If load demand is more than electricity generated, the insufficient electricity will satisfied by utility grid, on the contrary, if load demand is less than electricity generated, the surplus electricity generated will be sold back to the utility grid which is named FIT subsidy system. Based on the above principle, the operational strategy is assessed and the annual energy charge is evaluated by the comprehensive relationships of load demands, PV system performance characteristics and energy balance of the whole system. In addition, given a specific PV capacity, the economic and environmental characteristics of the whole energy system can be evaluated. Furthermore, the sensitivity analysis can be easily executed to understand the influence factors relating to the economic adoption of PV system.

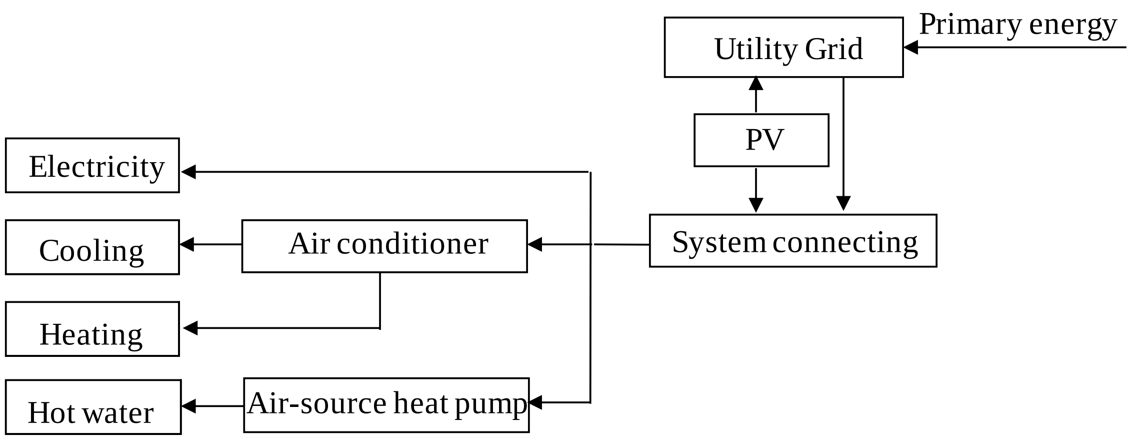


Fig. 6-1 Block diagram of PV system

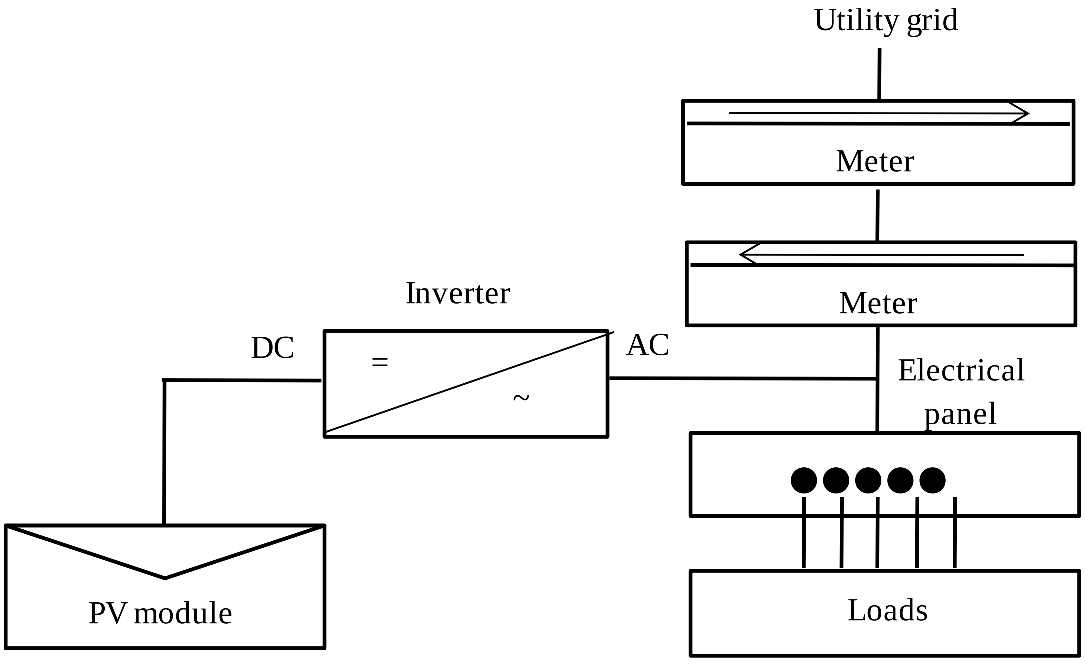


Fig. 6-2 Schematic of grid-connected PV system

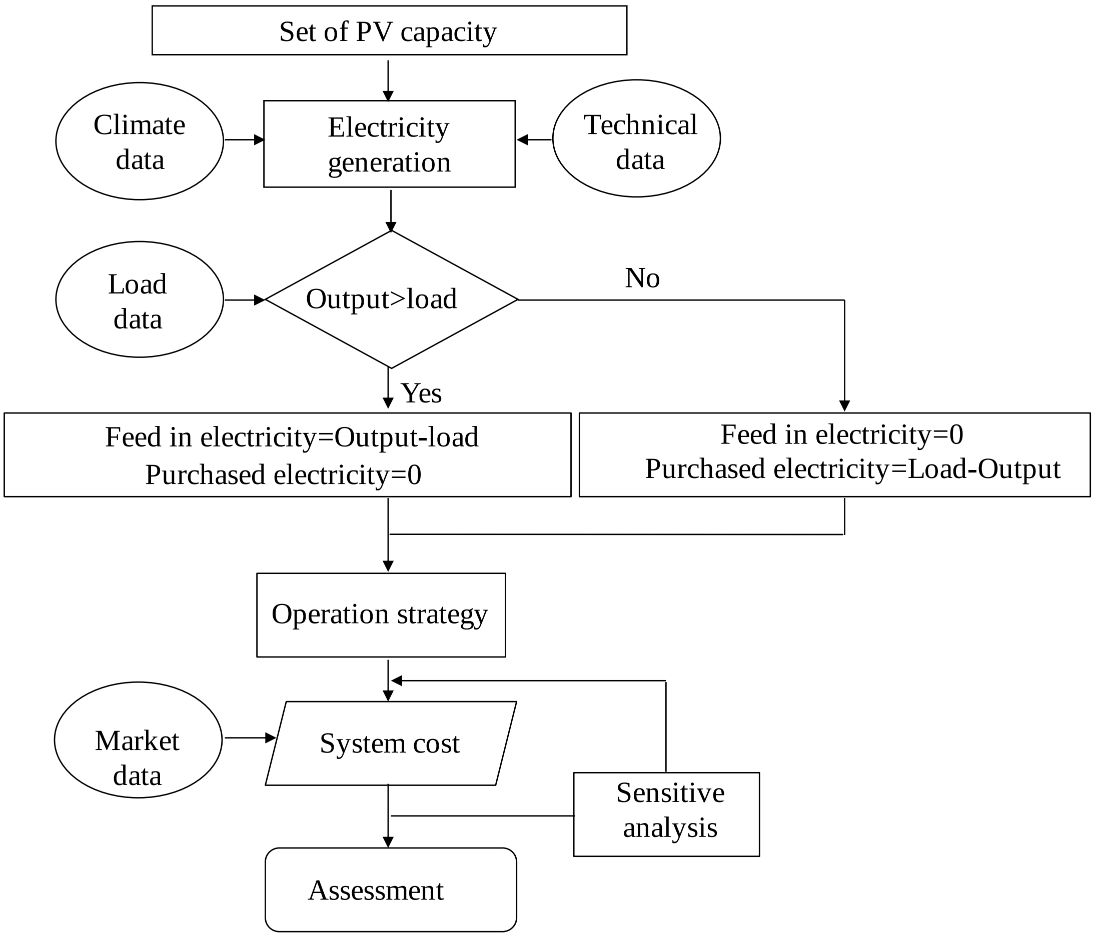


Fig. 6-3 The algorithm of PV system analysis procedure

6.3 Description of research objects and numerical study in Japan

6.3.1 Economic and technical assumptions

In this study, limited by the floor area of the building, assuming the capacity of PV system is 130kW. According to the policies made by state grid, FIT will be executed as long as 20 years since the PV system is installed. Therefore, assuming the cost payback time is within twenty years. In addition, it is necessary to take inflation and returns into account, so the NPV (Net Present Value) is adopted in this paper. NPV is used in capital budgeting to analyze the profitability of an investment or project. It is one of the most reliable measures used in capital budgeting because it accounts for time value of money by using discounted cash inflows. i is target rate of return per period which is assumed as 0.015 in Japan according to the investigation of Japanese market information.

Furthermore, as to the initial investment of PV system, based on the average value of investigated market price, the PV module is 1557.2 $/kWh. Again, the PV module accounts for 60% of total PV system, thus, the ancillary equipment is 1038.1 $/kW. As to annual the maintenance cost, assuming the maintenance cost is α times of investment cost, which is set as 0.5% in this paper [6-8].

Table 6-1 Economic and technical assumptions in Japan

Item	Japan
i	0.015
N（year）	20
Maximum capacity (kW)	130
PV modules ($/kW)	1557.2
Ancillary equipment ($/kW)	1038.1
Maintenance ($/kW)	15.12
Power generation efficiency (%)	14.8
Total initial investment ($/kW)	2595.3
Annual investment cost ($/kW)	151.9

6.3.2 Load demand

As has been introduced before, the building is assumed as using electricity for all energy demand, thus, it is necessary to transfer all demand to electricity which is shown in Fig. 6-4. It can be found out that, generally, store enjoys the largest energy consumption, followed by hotel, hospital and office respectively. As to the same building type, Tokyo always has the largest electricity load except in hospital. In addition, it can be found out that, the energy consumption order is always different in various building types. For example, office and hospital have the same order which is Tokyo > Sapporo > Hachinohe > Sendai > Kagoshima > Naha.

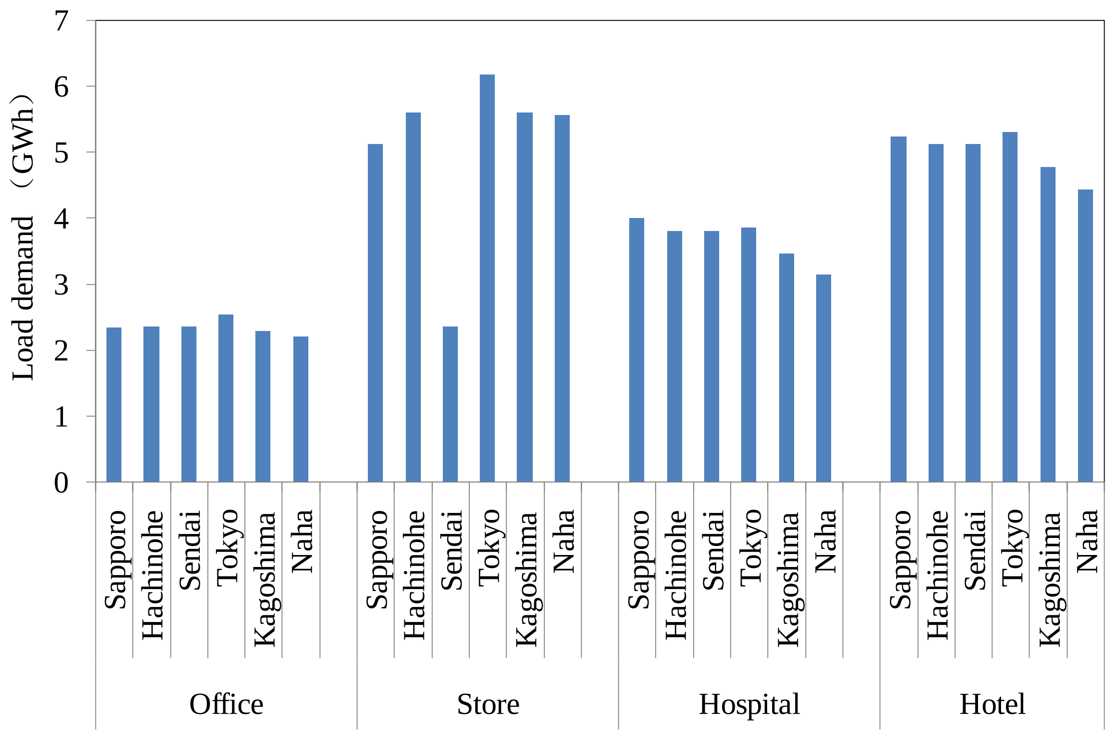


Fig. 6-4 Electrification load of various building type in six cities

6.3.3 Climate data

Solar irradiation is the main factor affecting the electricity generation of PV system. In this study, to be simple, 45 degree has been selected to be the solar incident angle for all cities. Taking January in Tokyo as an example to show the daily solar irradiation (see Fig. 6-5). The peak time is at am 11, which is 0.4 kWh/m2. And the solar irradiation is almost 0 from AM 1 to AM 7 and PM 6 to PM 12.

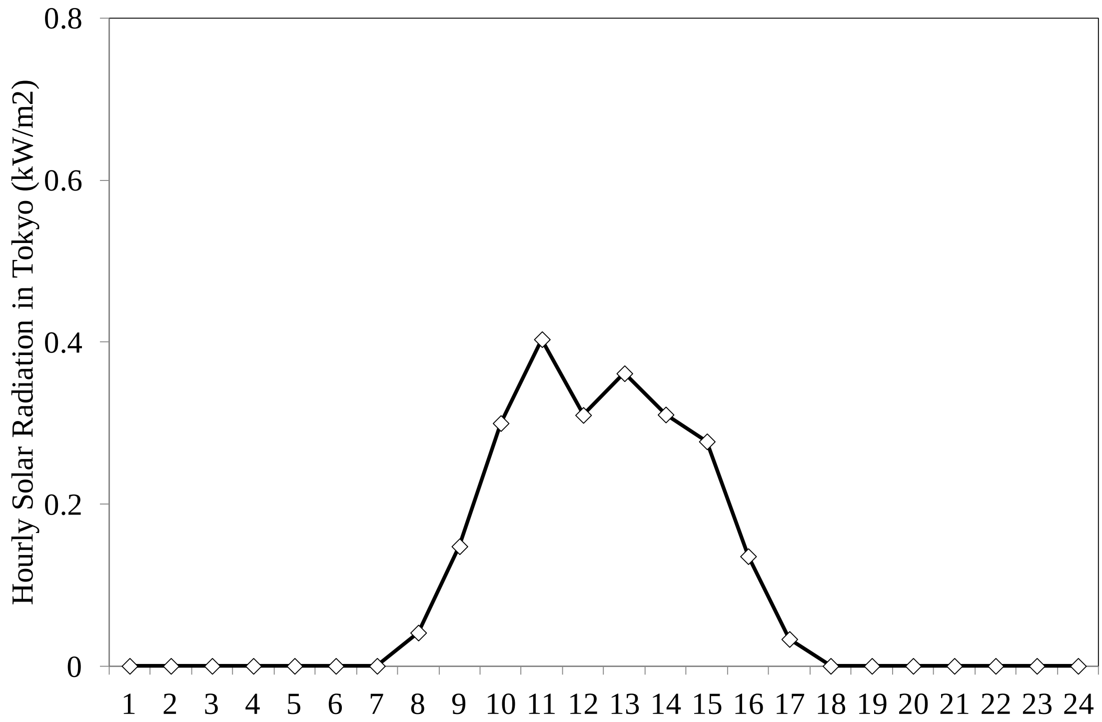


Fig. 6-5 Hourly solar irradiation in Tokyo

Fig. 6-6 shows the annual solar daily radiation in selected six cities in Japan. Before July, the solar irradiation in Naha is not the largest, while from July to December, as is expected, Naha enjoys the highest solar irradiation and followed by Kagoshima. In addition, it can be concluded that the peak solar irradiations do not appear in the same month in different cities. For example, solar irradiation peaks at June in Sapporo and Hachinohe, while peaks at August in Kagoshima.

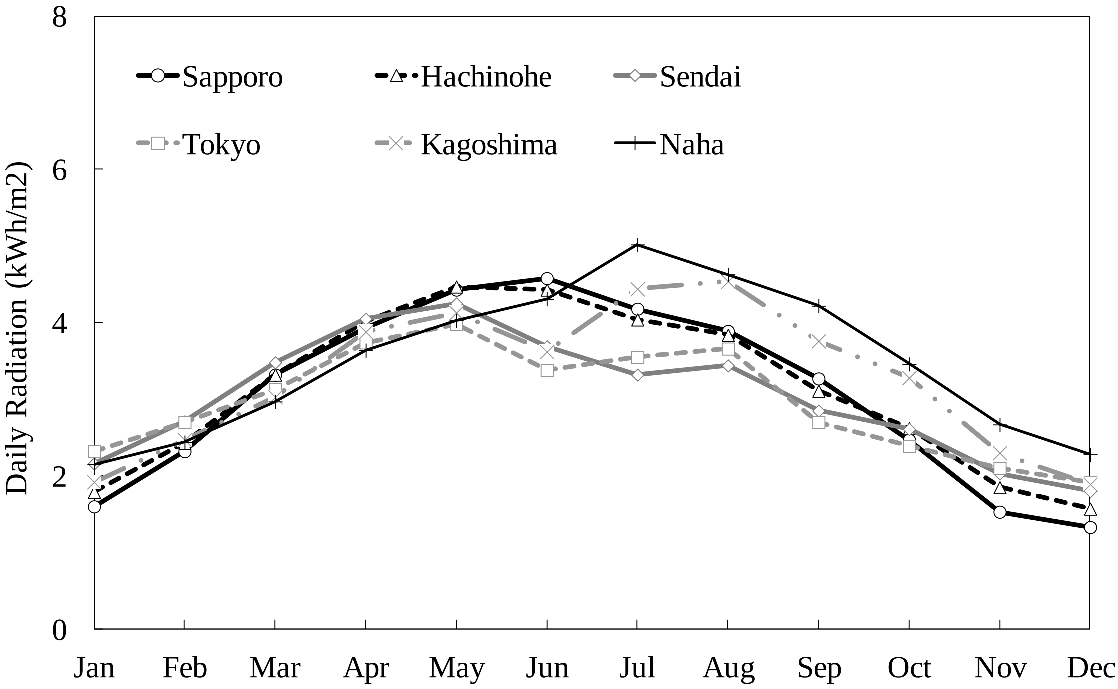


Fig. 6-6 Annual solar daily radiation in selected six cities in Japan

6.3.4 Performance of PV unit in Japan

6.3.4.1 Unit cost of PV system

Fig. 6-7 shows unit costs of PV system in different cities. As has been introduced above, unit cost of PV system is determined by both the investment of PV system and total electricity generated. Generally, Tokyo has the highest PV unit cost with 0.162 $/kWh and followed by Sendai, Sapporo, Hachinohe, Kagoshima and Naha, respectively.

In order to compare the unit cost of PV system with the conventional utility electricity price, Fig. 6-8 shows the gap between the two systems in commerce, which can be deduced by conventional electricity price minus PV system unit cost. Note that, the flat utility electricity price is adopted here for comparison convenience. It is interesting to find out that PV system shows lower unit price than utility price especially in Naha, which means that from the view of unit cost point, it is available to adopt the PV system in Japan.

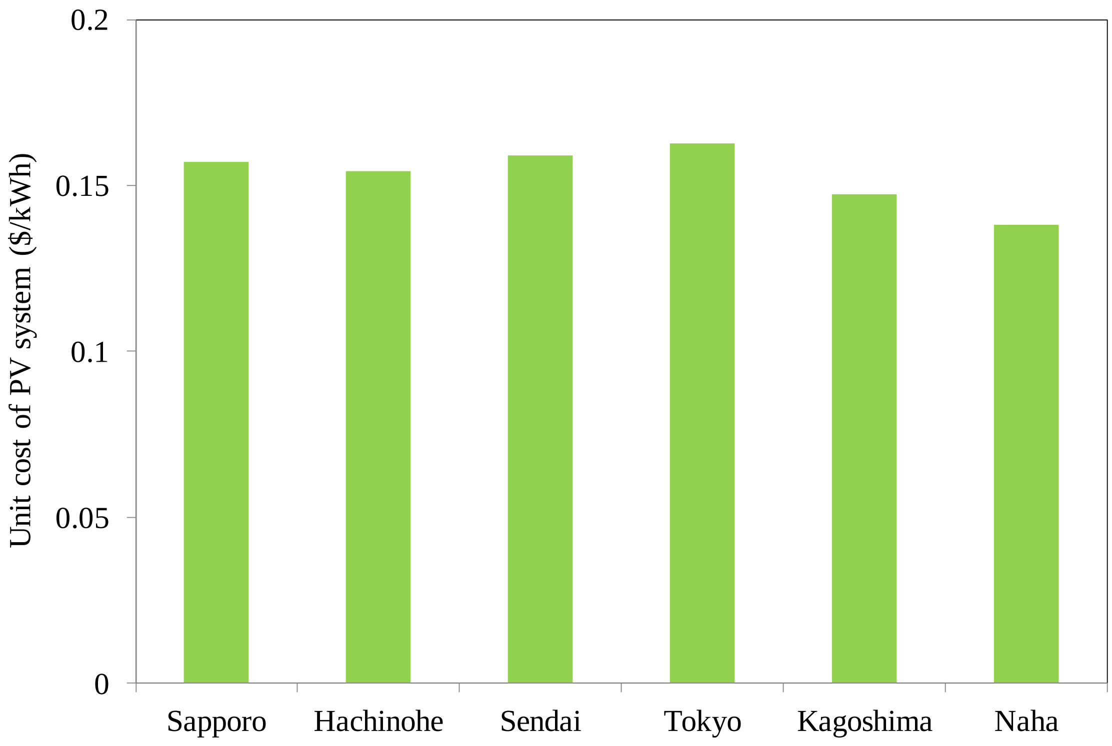


Fig. 6-7 Unit cost of PV system ($/kWh)

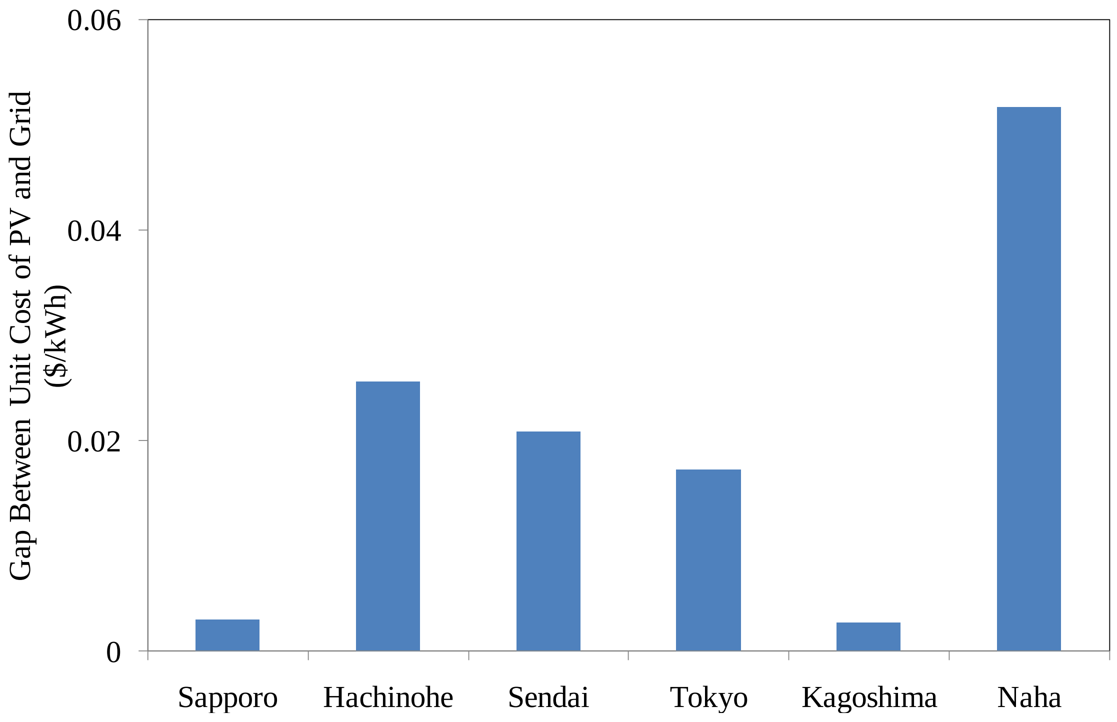


Fig. 6-8 Gap between cost of PV and gird price per kWh ($/kWh)

As an example, Fig. 6-9 shows the operation strategy of the PV system in six selected cities in official sector. The electricity load is equal to electricity produced by PV system plus brought from grid, subtracting electricity sold out [3]. As has introduced before, the studied building is assumed electrification, which means there is only electric demand which is supplies by PV unit as well as purchased electricity from the utility grid. As the figure shows, the PV electricity sold out is almost zero in all cases for high energy demand and low electricity generated. However, although almost all of the PV system electricity generation is supplied to the load demand, the proportion is less than 20%, because of high electricity demand, which is largest in Naha due to its relatively low electricity demand and larger amount electricity generation from PV system. It can be concluded that the order is in accordance with the load demand and other than the PV electricity generated amount.

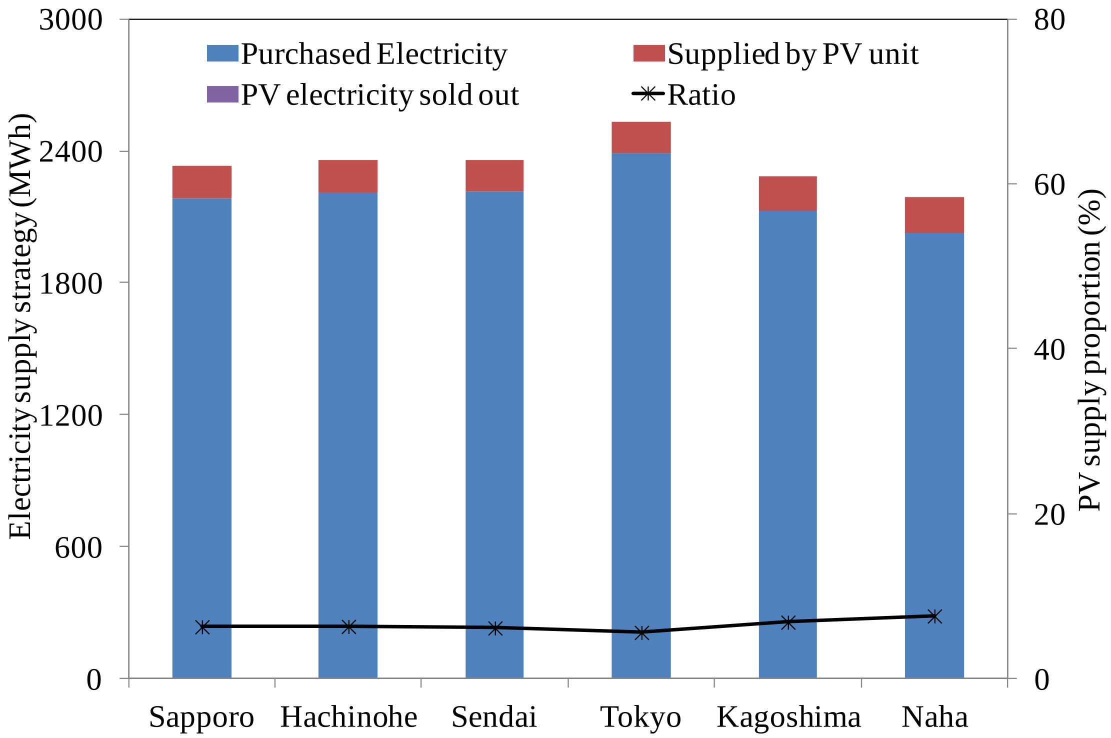


Fig. 6-9 Annual operation strategy of PV system

Economic performance is the most important factor when consumers adopt renewable energy system. Fig. 6-10 shows the annual cost reduction ratio as well as payback year of the PV system in selected six cities. Generally, office has the best economic performance, and followed by hospital, hotel and store which is in accordance with the electricity demand. In addition, Kagoshima always occupies the highest cost reduction in commerce, while Tokyo is the lowest one.

As to the payback year, generally, the value is the same in one city for all commercial building types due to the same electricity price, same FIT. Payback year in Kagoshima for commerce is shortest which is only 11 years, and followed by Naha, Tokyo, Sendai, Hachinohe and Sapporo, respectively. Furthermore, it can be concluded that the payback years is in accordance with the annual cost reduction rate for the net cash flow of the system is the same for each building type for commerce.

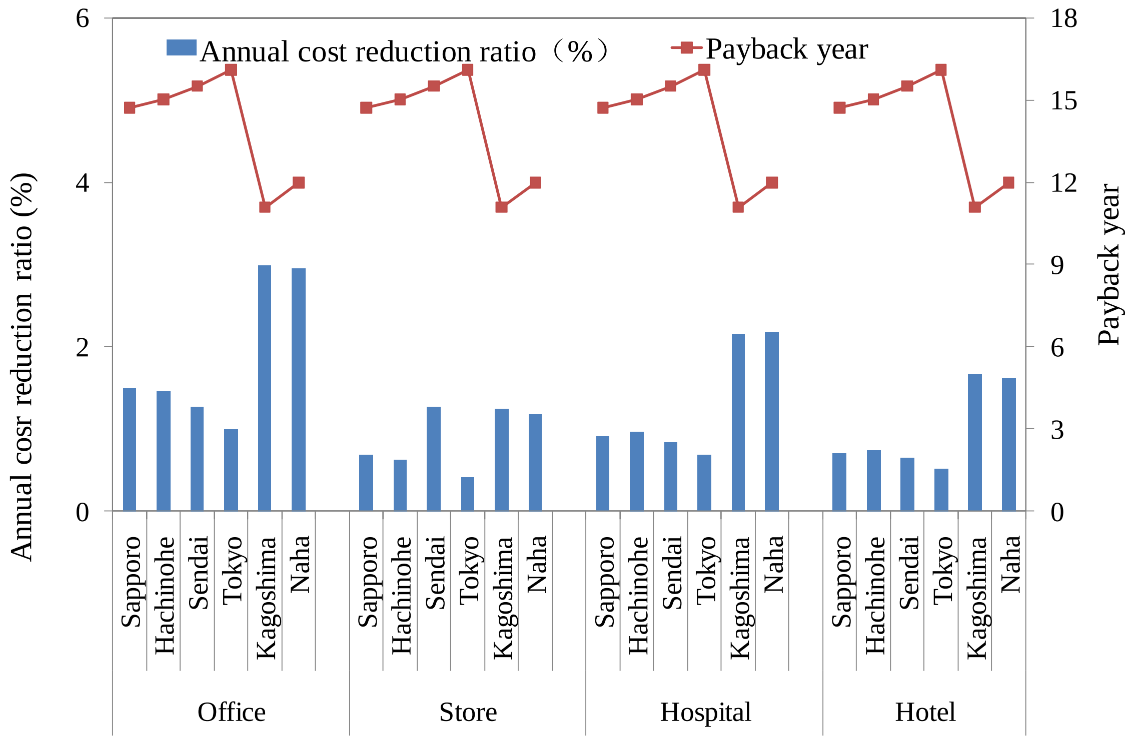


Fig. 6-10 Annual cost reduction ratio and payback year

Fig. 6-11 shows the annual CO_2 reduction rate of various building types in various countries which represents the environmental performance of the PV system. Generally, Naha has the best environmental performance both in commerce, except store, while Tokyo is the worst. As to the same city, generally, office has the highest CO_2 reduction rate, and followed by hospital, hotel and store, respectively.

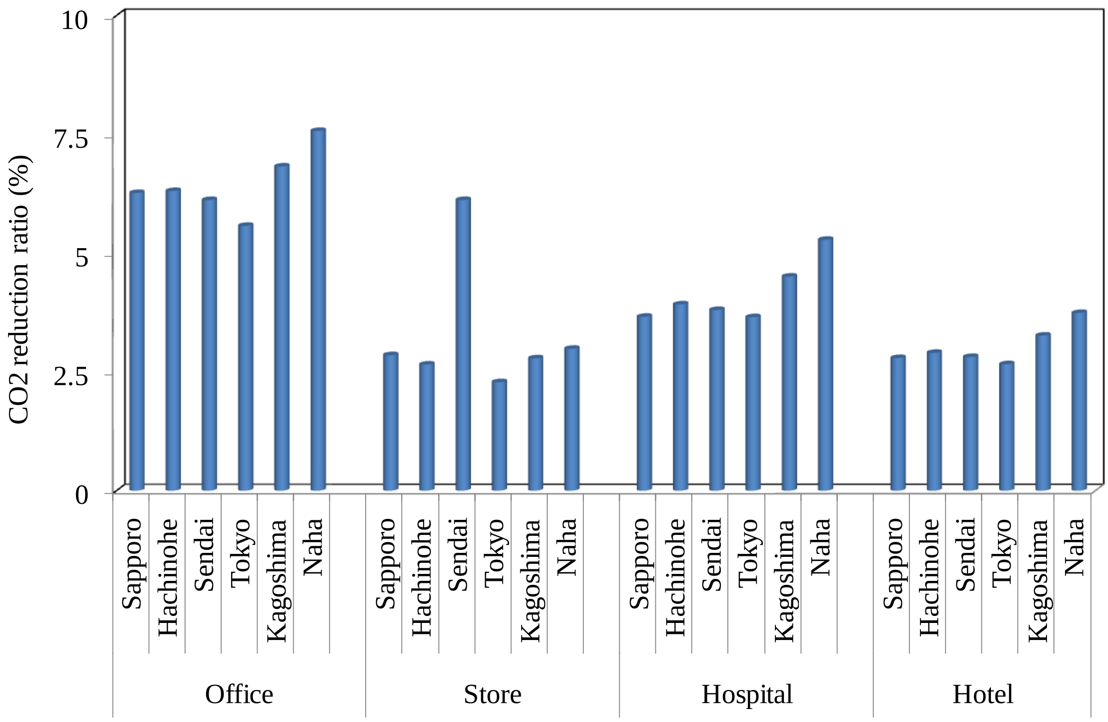


Fig. 6-11 Annual CO2 reduction rate

6.4 Description of research objects and numerical study in China

6.4.1 Economic and technical assumptions

Using the same way with Japan, the economic and technical assumptions of PV system in China are presented in Table 6-2 [9-12].

Table 6-2 Economic and technical assumptions of PV system in China

Item	China
i	0.06
N（year）	20
Maximum capacity (kW)	130
PV modules ($/kW)	987.4
Ancillary equipment ($/kW)	658.2
Maintenance ($/kW)	0.72
Power generation efficiency (%)	12.0
Total initial investment ($/kW)	1645.6
Annual investment cost ($/kW)	143.5

Fell behind some developed countries, PV system in China is far from commercialized and still at the stage of case studies. Similar with Japan, FIT system is the main incentive for PV unit popularization. In 2012, "The distributed grid-connected photovoltaic (PV) service work opinion" was presented by Sate grid which indicated that the utility would purchase the surplus electricity produced by PV system as long as twenty years, providing investors a reasonable return on their investments. As to the electricity produced by the PV system, customers have three choices: all self-used, full internet access (sell all electricity out of the PV system to the grid) or partly internet access (only sell the surplus electricity to the grid).

Table 6-3 shows the different FIT system in selected five cities in China. Except for the subsides (0.069 $/kWh of total PV electricity generated) supplied by the state, the surplus electricity generated from PV unit can be sold back to local utility grid with an additional FIT subsidy, and the FIT is equal to electricity tariff of local coal-fired units. For example, the consumer in Beijing will receive 0.069 $/kWh of total generated electricity (include self-use and surplus electricity), and as to the surplus part of electricity which will be sold back to the utility grid, an additional 0.064 $/kWh will be subsidized to the customer. Note that, in order to promote the adoption of PV unit, an additional subsidy is promoted in Shanghai which is 0.065 $/kWh and 0.04 $/kWh in residential and commercial sector respectively. In addition, from the table, it can be concluded that Shanghai has the highest FIT both in residence and commerce, and followed by Guangzhou, Harbin, Beijing and Kunming respectively.

Table 6-3 FIT system in different cities in China

Item / City	Electricity tariff of coal-fired power plant ($/kWh)	Government subsidy ($/kWh)	Local subsidy ($/kWh)	Self-use subsidy ($/kWh)	FIT ($/kWh)
Shanghai	0.075	0.069	Residence 0.065	0.134	0.209
			Commerce 0.040	0.109	0.185
Beijing	0.064	0.069	0	0.069	0.133
Harbin	0.066	0.069	0	0.069	0.135
Kunming	0.061	0.069	0	0.069	0.130
Guangzhou	0.082	0.069	0	0.069	0.151

6.4.2 Load demand

As has been introduced above, the building is assumed as all electrification, thus the load demand indicates only the electricity demand. Fig. 6-12 shows the electricity demand in various building types within different cities. Generally, Kunming has the lowest demand because of its warm seasons around the whole year. As to the same city, generally, hospital and hotel has larger electricity demand because their high heat demand, while office has lowest electricity demand.

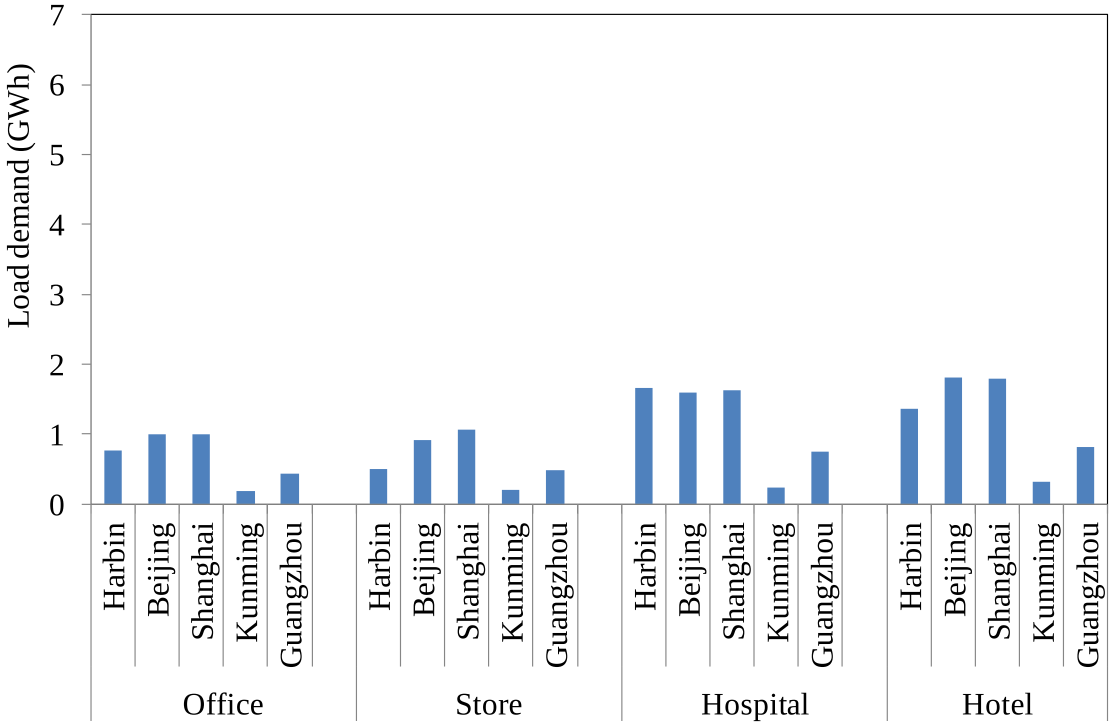


Fig. 6-12 Annual electricity demand of the electrification building in selected cities

6.4.3 Climate data

The power generation out of the PV system is mainly depended on the solar radiation. Fig. 6-13 shows hourly solar irradiation in August in Shanghai. The solar radiation is almost zero during the night time from 19:00 to 5:00 of the next day, while, during the daytime, the peak value is 13:00 which is 0.603 kW/m2.

Fig. 6-14 shows the monthly mean daily solar radiation in selected five cities. From the curve, it can be found that except Guangzhou, the solar radiation has a similar curve in other four cities and in all of them the peak values are around May. In addition, the curve of PV irradiation is relatively smooth in Kunming but intense in Harbin.

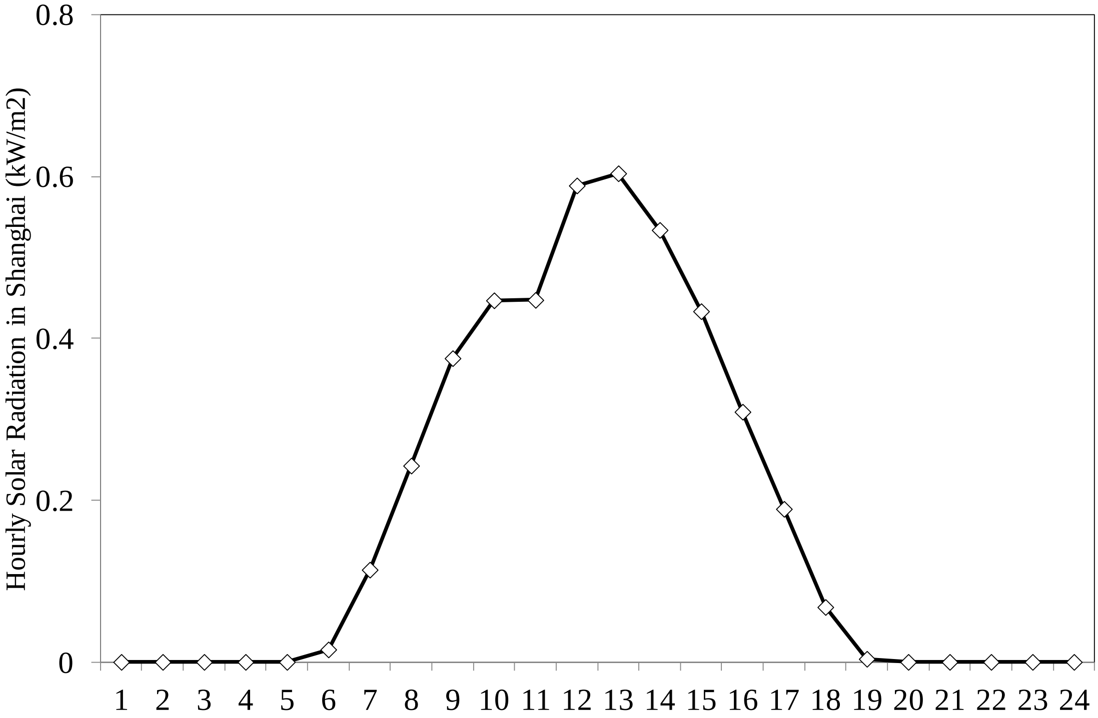


Fig. 6-13 Hourly solar irradiation in August in Shanghai (kW/m^2)

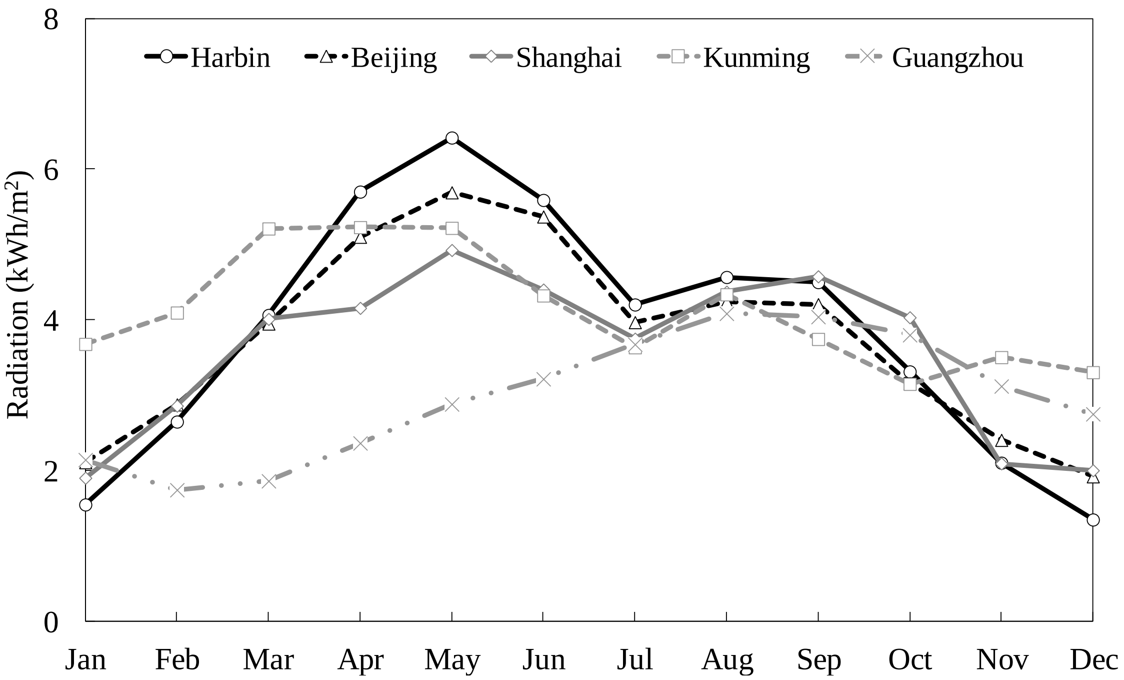


Fig. 6-14 Monthly mean daily solar radiation in selected five cities

6.4.4 Performance of PV unit in China

6.4.4.1 Unit cost of PV system in China

As is introduced in chapter 4, unit cost is determined by total cost of PV unit as well as total amount of electricity generated in the whole life cycle. Fig. 6-15 shows unit cost of PV system of selected five cities in China. Generally, Guangzhou has the highest unit cost with 0.156 $/kWh, which is due to the lowest electricity generation, and followed by Shanghai, Beijing, Harbin and Guangzhou, with the value of 0.143 $/kWh, 0.123 $/kWh, 0.121 $/kWh and 0.156 $/kWh respectively. In order to compare the unit cost of PV system with the conventional system.

Fig. 6-16 shows the gap between cost of PV and gird price per kWh in commercial sector which is deduced through grid cost minus unit cost of PV. For the convenience of comparison, flat grid price is adopted here other than time of use price. Different from Japan, it is not economic efficiency to adopt PV system in China especially in Beijing for its lowest conventional grid price.

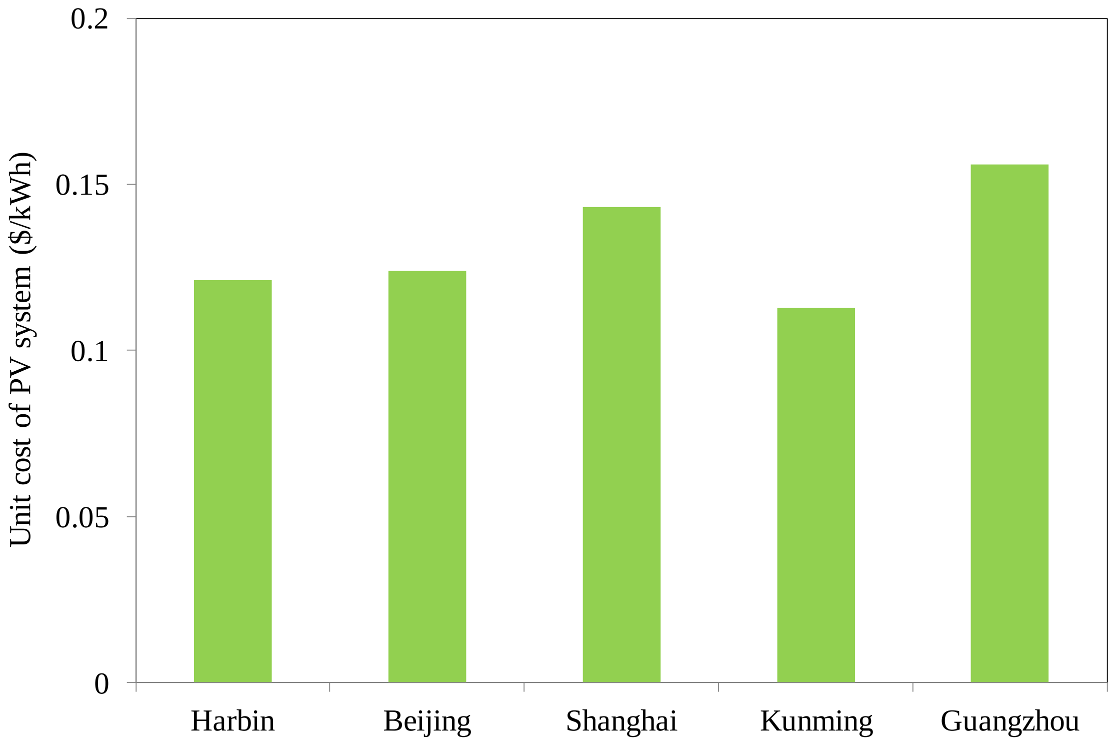


Fig. 6-15 Unit cost of PV system ($/kWh)

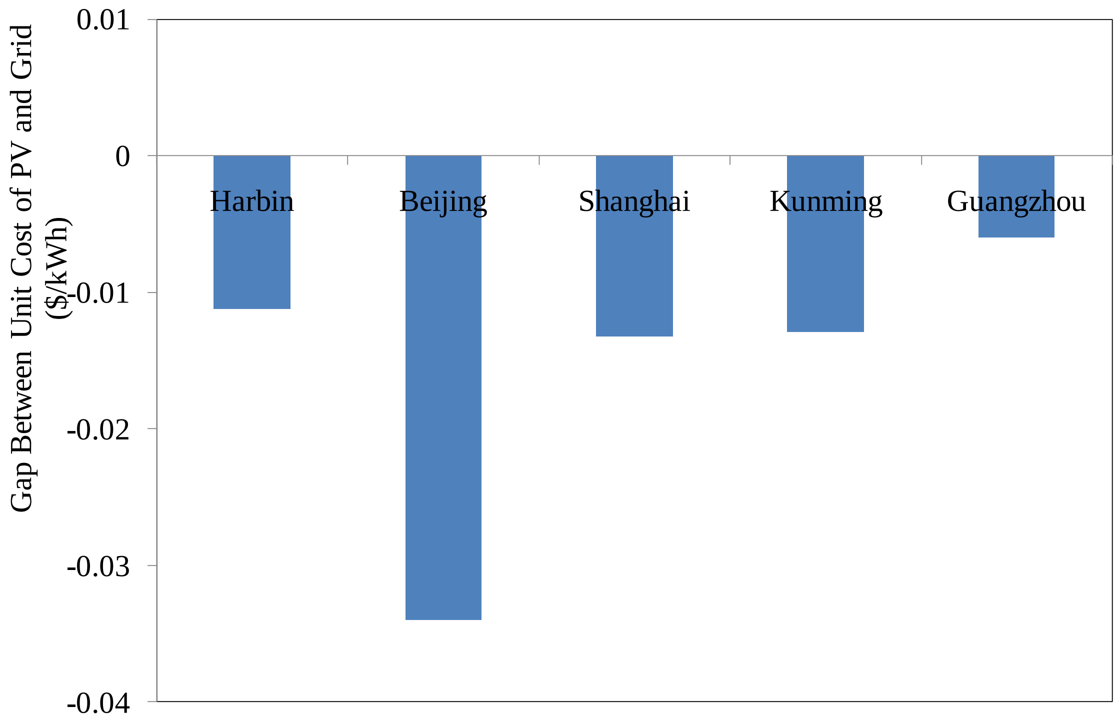


Fig. 6-16 Gap between cost of PV and gird price per kWh ($/kWh)

Fig. 6-17 shows the operation strategy of the PV system in five selected cities in official sector. As has introduced before, the studied building is assumed electrification, which means there is only electric demand which is supplies by PV unit as well as purchased electricity from the utility grid. Although the amount of electricity supplied by PV is smallest in Kunming, the proportion is highest because of relatively low electricity, and followed by Guangzhou, Shanghai, Beijing and Harbin respectively. It can be concluded that the order is in accordance with the load demand and other than the PV electricity amount. As to the surplus PV electricity which is sold out to the utility grid, Kunming has the largest demand because of its low electricity demand and high PV electricity generation, and followed by Harbin, Guangzhou, Beijing and Shanghai respectively.

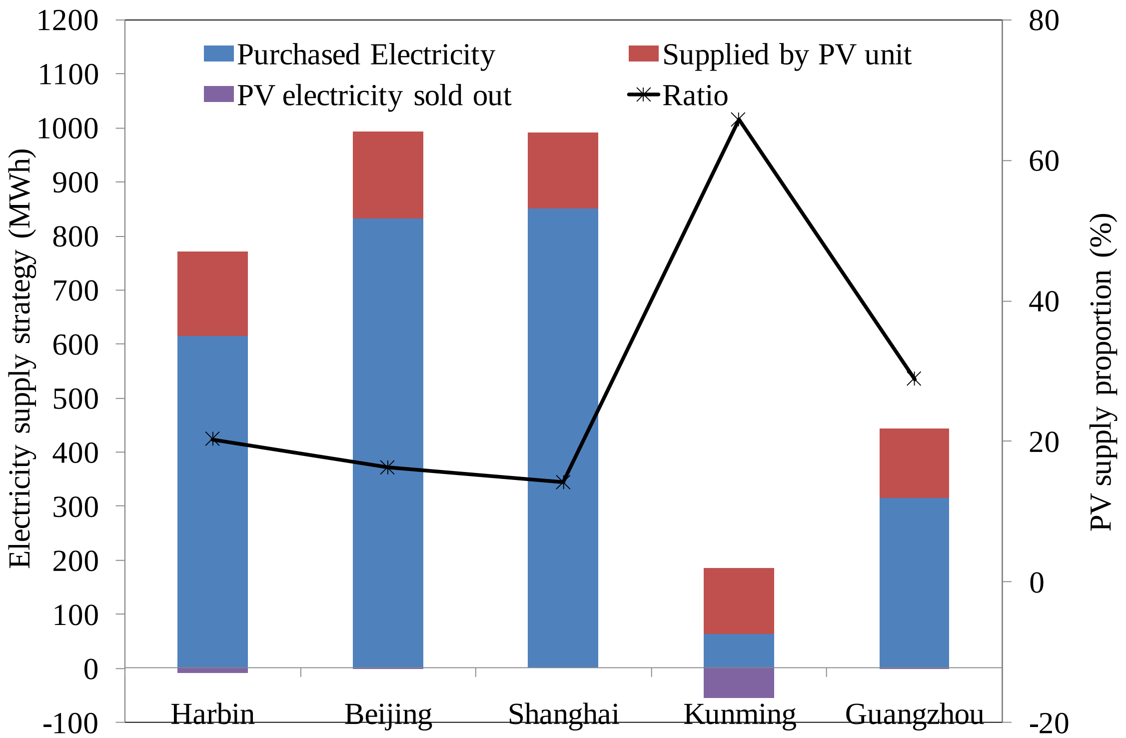


Fig. 6-17 Operation strategy of PV system

Economic performance is the most important factor when consumers adopt renewable energy system. Fig. 6-18 shows the annual cost reduction ratio as well as payback year of the PV system. Generally, the annual cost reduction ratio is satisfied in all building types within selected five cities especially in Kunming, the value is as high as about 40%. In addition, it is interesting to find out that the cost reduction ratio is in accordance with the order of electricity demand (see Fig. 6-12). For example, as to the same city, generally, the economic performance is worse both in hospital and hotel which is because of their higher load demand compared with other building types.

As to the payback year, as to the same building types, Guangzhou always has longer pay back years than other cities which are about 10 years in commercial sector. Furthermore, it can be concluded that the payback years have no relationship with the annual cost reduction rate, which are affected by both net cash flow of the system and bank loan interest rates.

Fig. 6-19 shows the annual CO_2 reduction rate of various building types in various countries which represents the environmental performance of the PV system. Generally, Kunming has the best environmental performance which has the CO_2 reduction ratio of more than 40% in commerce.

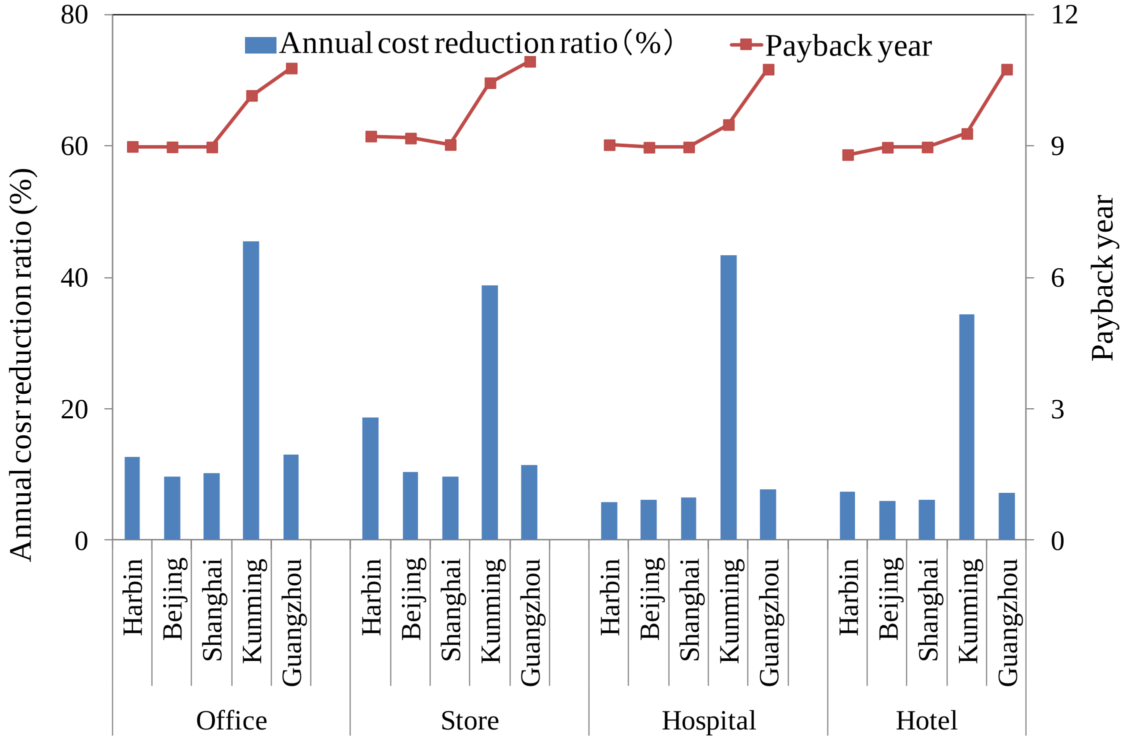


Fig. 6-18 Annual cost reduction ratio and payback year

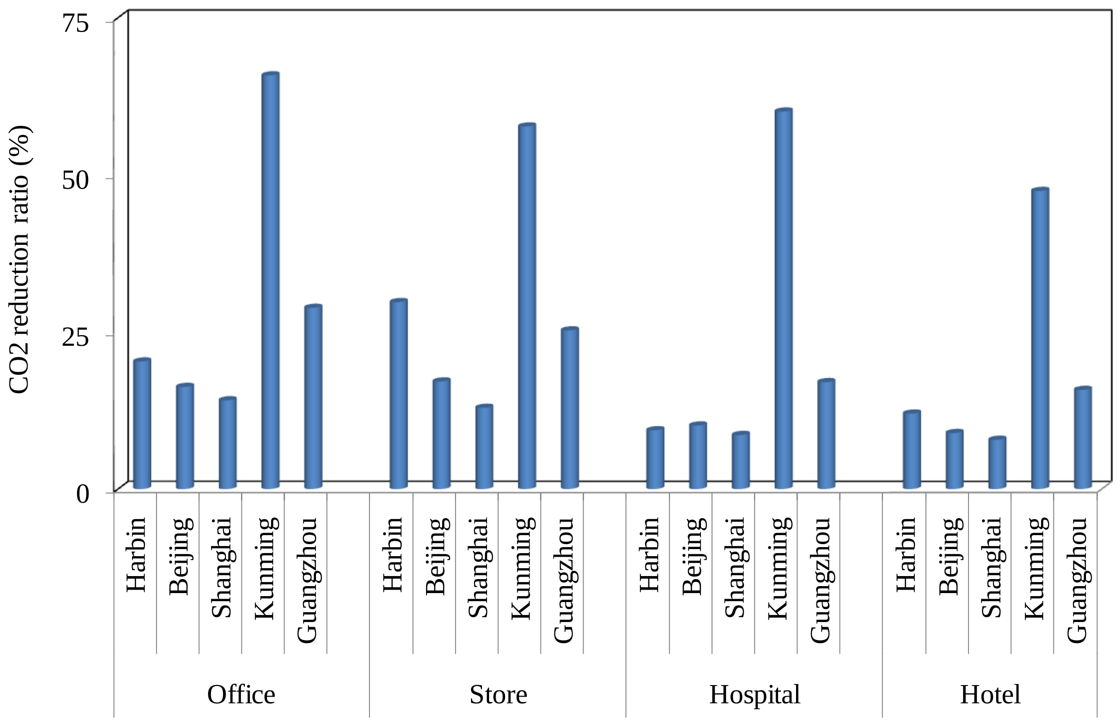


Fig. 6- 19 Annual CO2 reduction rate

6.5 Summary

In this chapter, the same as CCHP system studied in Chapter five, the hourly operation strategy as well as energy, economic and environmental performance of PV system are assessed within various building types of different cities located in Japan and China. According to the analysis, the following conclusions are deduced:

①The unit cost of PV system in China still higher than conventional utility unit cost per kWh both in commercial sector, whereas, the situation is contrary in Japan, which means as the decreasing of PV module price, improving electricity transfer efficiency of PV cell the unit cost of PV has been lower than conventional unit cost which is relatively higher in Japan.

②Because of the large electricity demand in Japan, the electricity sold out is almost 0 which is totally contributed to supply the load demand. However, in China, during the solar irradiation peak time, the electricity generated from the PV system is larger than the electricity demand during that time, thus, the surplus electricity demand can be sold out to the utility gird.

③As to the economic performance, the result is satisfied both in Japan and China. Which means the annual cost with the PV system is lower than conventional annul cost.

④The system which has a higher annual reduction ratio always has a shorter payback year. While, this is not definitely right, for the payback year is determined by the net cash flow of the system as well as total initial cost of the PV system.

⑤As is expected, the environmental performance is satisfied because of 0 emission during the electricity generation of the PV system.

References

[1] The expert group on renewable energy convened by the United Nations department of economic and social affairs: Increasing global renewable energy market share: recent trends and perspectives, U.S.A.: the United Nations, 2005.12

[2] New energy and industrial technology development organization (NEDO): Overview of "PV Roadmap Toward 2030", Japan: NEDO, 2004.6

[3] Robort Foster: Japan Photovoltaic market overview, U.S.A.: New Mexico State University, pp.1-10, 2005.10

[4] Qingrong Liu, Yuji Ryu, Weijun Gao, Yingjun Ruan: Field study and sensitive analysis of PV system by multiple regression method, Journal of Asian Architecture and Building Engineering, Vol.3(2), pp. 247-252, 2004.11

[5] Ministry of the Environment: Concrete idea about environmental tax, Japan, 2005

[6] Carbon tax research committee: Towards the early introduction of carbon tax, Japan: Japan Center for a Sustainable environment and Society, 2006

[7] José L. Bernal-Agustín and Rodolfo Dufo-López: Economical and environmental analysis of grid connected photovoltaic systems in Spain, Renewable Energy, Vol.31(8), pp.1107-1128, 2006.7

[8] M. Oliver and T. Jackson: Energy and economic evaluation of building-integrated photovoltaics, Energy, Vol.26(4), pp. 431-439, 2001.4

[9] J. Byrne: Evaluating the economics of photovoltaics in a demand-side management role, Fuel and Energy Abstracts, Vol.37(2), pp.118, 1996.2

[10] R. Goto, Y. Hamada, H. Kubota, M. Nakamura, K. Ochifuji and M. Murase: Study on hybrid utilization of renewable energy and fuel cell for residential energy system Part 3— Experiments and analyses on hybrid system using solar

[11] Hongbo Ren, Weijun Gao and Yingjun Ruan: Optimal sizing of grid connected photovoltaic systems for residential application, The Yellow Sea Rim International Exchange Meeting on Building environment and Energy 2007, pp.175-183, 2007.1

[12] Qingrong Liu: Research on the high efficiency energy utilization and supply system for residence, Ph.D. thesis, The University of Kitakyushu, 2007.3

CHAPTER SEVEN: INTEGRATED ASSESSMENT FOR HYBRID CHP, PV AND BATTERY DISTRIBUTED ENERGY SYSTEM ADOPTION: JAPAN-CHINA COMPARISON

7.1 Introduction

As the improvement of people's living quality and the acceleration of urbanization process, residential sector occupied the second largest, accounted for about 10.6% of China's total energy consumption in 2010, followed by industry sector (71.12%). The value was projected to increase to an even higher value in the coming future [1].

In the last decades, widespread researches on the accessibility of renewable energy sources (RES) such as photovoltaic (PV) arrays and wind turbines (WTs) have been done in numerous literatures, which is due to their in-exhaustible, zero greenhouse gas emissions and site-dependent advantages [2-4]. However, RES have their extremely limited deployments. For instance, the PV system subjects to the change of weather conditions and solar radiation which cannot produce electricity continually, similarly, the WTs is strongly dependent on wind speed. As an alternative way, storage devices have been adopted which can be used later to supply the load during the periods of low or no power output and improve system reliability. Whereas, literature shows that the design of a standalone RES generation plant can lead to an over sizing of the batteries [5]. On the other hand, though still in early stages of adoption, CHP (combined heat and power) systems are becoming a focus of interest due to their potential for high efficiency, low emissions and low noise [6]. The CHP system recovers the waste heat from the electricity generating process which can be used to satisfy the thermal demand (cooling, heating, or hot water needs) of an end-user. By recycling the waste heat, the system can achieve a primary energy efficiency of 60% to 90%, a dramatic improvement over the average 35% efficiency of conventional fossil fuel based power plants [7]. However, the CHP system has a poor response to instantaneous power demands.

These disadvantages of each alternative way introduced above can be limited during a combination of CHP system and a renewable unit, which creates a distributed network hybridizing different micro-sources and is usually a balanced and optimal solution [5]. This system can supply reliable power regardless of time and location overcoming the above mentioned various problems within single systems which lead to a deep study of the hybrid system for supplying residential load. Under these backgrounds, in recent years, a new concept named residential distributed energy system established on end-users has been proposed [8], which integrates various micro-sources simutaneously, such as, PV arrays, WTs, CHPs, battery, etc. from the technical points of view. Based on the theory described above, a CHP/PV/battery hybrid residential energy system has been put forward in some developed countries such as Japan, etc. [9]. The CHPs will be connected to the PV system in parallel in order to not only smooth the output power which changes steeply with the change of the solar radiation intensity, but also contribute to expand the PV penetration level [10]. Also, a electric energy storage system is added within the PV and CHP systems. The integrated use of a PV unit, a CHP system and a battery will realize the interaction of different energy supply system in time and space. However, the incorporation of a hybrid system is not an easy task [11]. It is worth noting that a well designed system should not only cover the load demand without shortages but also can limit the annual energy cost [12]. Thus, the system should be optimized by a robust running strategy in a way to minimize the total operation cost with regard to satisfy constraints.

Currently, a number of research have been done on distributed hybrid residential energy system. Ranjbar et al. [12] developed an evolutionary programming based approach to do the economic analysis of combining CHP and wind hybrid system for supplying grid-parallel residential load. Nosrat and Pearce [13] demonstrated a new simulation algorithm and dispatch strategy for the modeling of hybrid PV-CHP systems for a typical home in Vancouver. Hamada et al. [14] described field experiments and numerical simulations on hybrid utilization of solar PV and CHP for a residential energy system. Hosseini et al. [15] analyzed the energy and exergy efficiency of hybrid solar-CHP combined heat and power systems for residential applications. It can be found that current researches mainly focus on domestic PV-CHP or wind-CHP hybrid systems, while merely coupling storage device to the hybrid system and there have been no detailed study on the impact of different cities within different climate zones upon the hybrid energy system within a international comparison.

In this study, an optimization model is developed for the CHP/photovoltaic (PV)/battery based residential energy system. While satisfying residential electrical and thermal demands, the model may determine the optimal running strategies with the annual running cost as the objective function to be minimized. Furthermore, besides the energy flows among the equipments in the energy system, the financial information including electricity tariff and natural gas price, as well as some policy issues (e.g., buy-back price) is also accounted for in the model. Therefore, as the results of the model, besides the optimal electrical and thermal balances, the optimal utilization forms of PV cells and battery can be also deduced. Again, performance of hybrid system within six cities selected from Japan and five cities selected from China within different climate zones will be compared to do the research.

7.2 System overview

The energy flow chart of CHP/PV/battery based residential energy system is shown in Fig 7-1. It can be found that the system is defined as a grid-connected one as grid connecting may be always necessary from the economic viewpoint, although energy can be generated on site [16]. To be detailed, the system consists of a CHP plant, a PV unit, a back-up burner as well as a storage battery which must be used to deliver the required power at peak time and charged either by the excessive power energy output from the CHP plant or the relatively cheap grid electricity during the midnight.

In this system, the electric power demand will be supplied by on-site power generator (CHP plant and PV unit), the storage battery and the utility grid, whereas the recovered heat from CHP unit and the backup boiler will meet the domestic heating and hot water requirements. However, most noteworthy is that the energy demand can be served by either combined system preferentially as there is no priority on energy supply order within the optimization model which will be introduced detailed later. In addition, electricity buy-back is taken into consideration and the surplus electricity output from PV unit can be delivered back to the grid creating profits for the end-users. Furthermore, the surplus recovered thermal energy from FC unit is neglected other than stored or sold out. Again, it should be pointed out that, the electricity load in the system not only includes the direct demand for lighting and power equipment, but also contains the cooling load with the use of air conditioner; the thermal load includes heating and hot water.

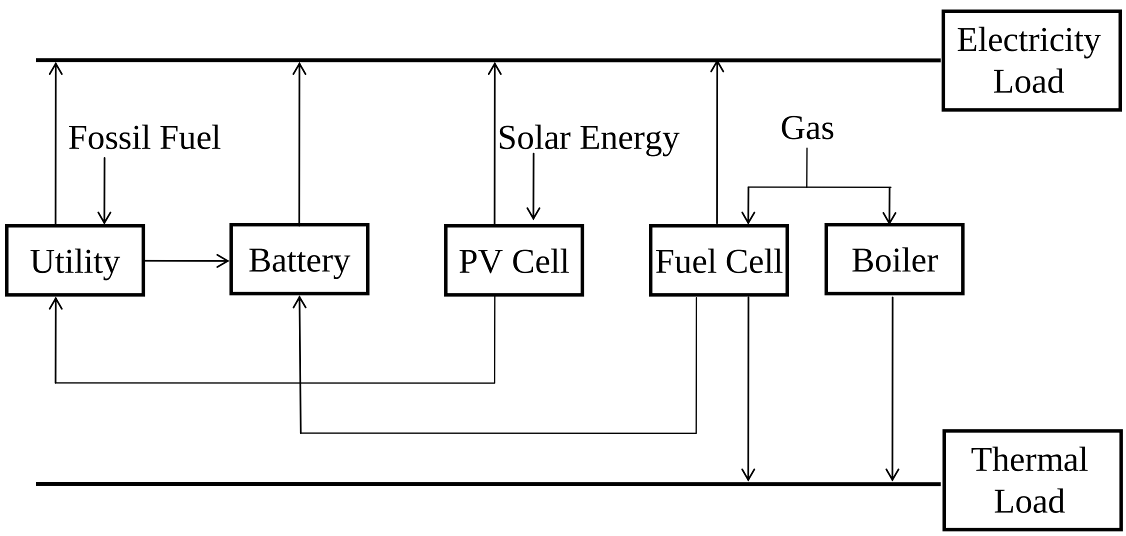


Fig. 7-1 Energy flow of the hybrid PV/CHP/battery system

7.3 Technical parameters of system components

In this paper, a numerical example is utilized to verify the feasibility of the proposed optimization model. The proposed CHP/PV/battery based residential energy system will be adopted in a assumed two floor household located in Japan and China respectively, of which the total area is 150 m2. As we all know, heat and electric load profile, tariff structure, available solar insolation, and installed DG equipment all have strong effects on the sites achievable energy cost [18]. In the following, firstly, some necessary data (e.g. energy load, fuel price) as the inputs to the model will be introduced or assumed. Then the results from the optimization process will be analyzed and discussed in detail.

Table 7-1 shows the system components assumed in this study and their technical parameters. Data includes equipment capacity, electrical and thermal production efficiencies as well as heat recovery efficiency according to the investigation of the current market [17].

Table 7-1 Technical parameters of system components

Types	Item	Values
PV unit	Capacity	4kW
	Area	28m2
	Electricity efficiency	0.148
CHP unit	Capacity	0.7kW
	Electricity efficiency	0.42
	Heat recovery efficiency	0.392
	Backup boiler efficiency	0.9
Battery	Capacity	2kWh
	Charging efficiency	0.95
	Discharging efficiency	0.95
Air conditionor	ccop	4

7.4 Performance of hybrid system in Japan

7.4.1 Energy load

Detailed knowledge about energy loads for at least a year is important for accurate design of the PV/CHP/battery distributed residential energy system. In this study, the hourly load demands of a typical household in Tokyo (Japan) have been calculated according to energy consumption intensities of residential building type [19, 20]. As the energy load varies widely among different seasons, to be simplicity, three periods (winter, summer and autumn-spring) have been selected to represent the load profile of the whole year as shown in Fig. 7-2 (note that January and August were selected for the winter and summer period, respectively, while the mid period is the average of April and November). It can be observed that, generally, the peaks of electric consumption are between 8AM and 9PM in all three periods. In addition, it can be found that although the electric demand varies little among different seasons, the value in summer is relatively high due to the larger amount of cooling demands because of the really hot weather. Comparatively, the relative change in thermal load throughout the year is much larger. Compared with other seasons, the value in winter changes more sharply and peaks from 6PM to 11PM and 4AM to 12AM. The mean annual electrical (control direct demands for lighting and power equipment, the cooling load with the use of air conditioner) and thermal (heating and hot water) demands are 13,074 kWh/year and 12,491 kWh/year respectively, which means each one occupies about 50% of total energy consumption.

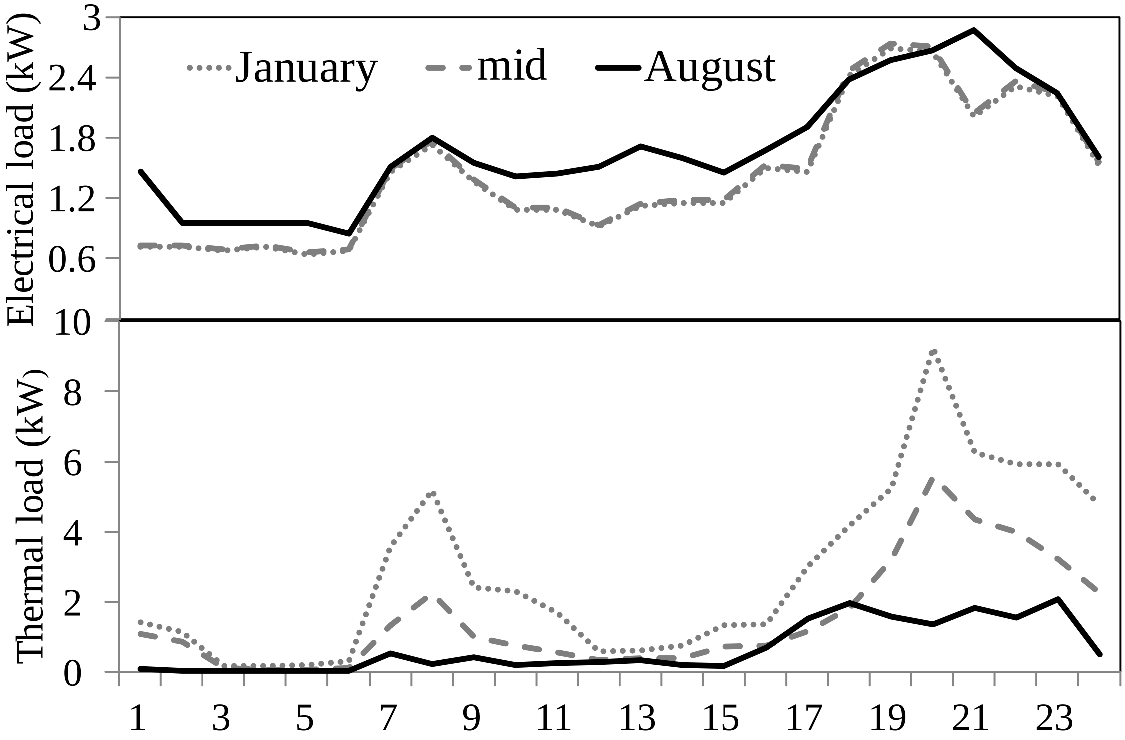


Fig. 7-2 Hourly electrical and thermal loads of the residential building

7.4.2 Supply strategy

In this study, annual running cost is set as the objective function to be minimized in this optimization model, thus, the energy price is another important input and has been introduced above in a detail way.

Using the optimization method, the case study described in the previous sections has been solved. In the following, three typical days in January, April and August which represent winter, spring & autumn as well as summer will be selected as examples to discuss the optimal operation strategy of the PV/CHP/battery residential energy system. The situation in Tokyo, Japan will be selected as an example to show the optimization result.

（1）Power supply strategy

Fig. 7-3 shows the electricity balance of the residential building. Positive values represent domestic electric demand, PV and CHP outputs, battery outputs as well as utility power supply, whereas the battery inputs and sold electricity generated from PV unit are indicated on the negative side. From this figure, the following conclusions can be deduced.

(a) During the night time, purchasing electricity tariff from grid is relatively low then the management strategy order CHP to be off and supply electrical load from local grid mainly which is more economical than generating power by CHP unit during this period.

(b) From 9 AM to 4 PM period, the electricity demand is almost satisfied by CHP unit and battery, PV unit meet the deficiency other than purchasing electricity from utility grid. It is not only due to the electricity price is almost high during this period, but also because the customer is not allowed to sell and buy electric power at the same time according to Japan's current electric power standard.

(c) As aforementioned, storage battery which is used as a supplement is charged either by the electricity purchased from the utility grid or by the generated electricity from the CHP unit. In addition, the battery is charged almost when the purchasing tariff is low and discharged during the peak period.

(d) Furthermore, most of the electric energy generated from PV unit is sold out to the local grid for the relatively high selling price (32 yen/kWh) compared with the purchasing tariff. Because if selling price is higher than purchasing price then it encourages customers to adopt renewable energy systems such as PV unit which are environment friendly.

（2）Thermal supply strategy

The thermal balance of the residential building is depicted in Fig. 7-4 and from which the following conclusions can be observed.

(a) Compared with the electricity balance, the thermal supply strategy is relatively simple. In this study, thermal energy is recovered from CHP unit as a by-product, thus, to be economic, the strategy order the recovered heat from CHP unit to meet the heat demand firstly, then the deficiency can be compensated by a backup boiler otherwise the surplus recovered thermal energy from CHP unit is neglected.

(b) The thermal demand during valley time can be totally satisfied by the CHP unit which is in accordance with the electric supply strategy (see Fig. 7-3). Again, the demand during the daytime can be matched by CHP unit and backup furnace.

(c) In addition, it is interesting to found that to minimize the total annual operation cost, there is no surplus recovered thermal energy from the CHP unit.

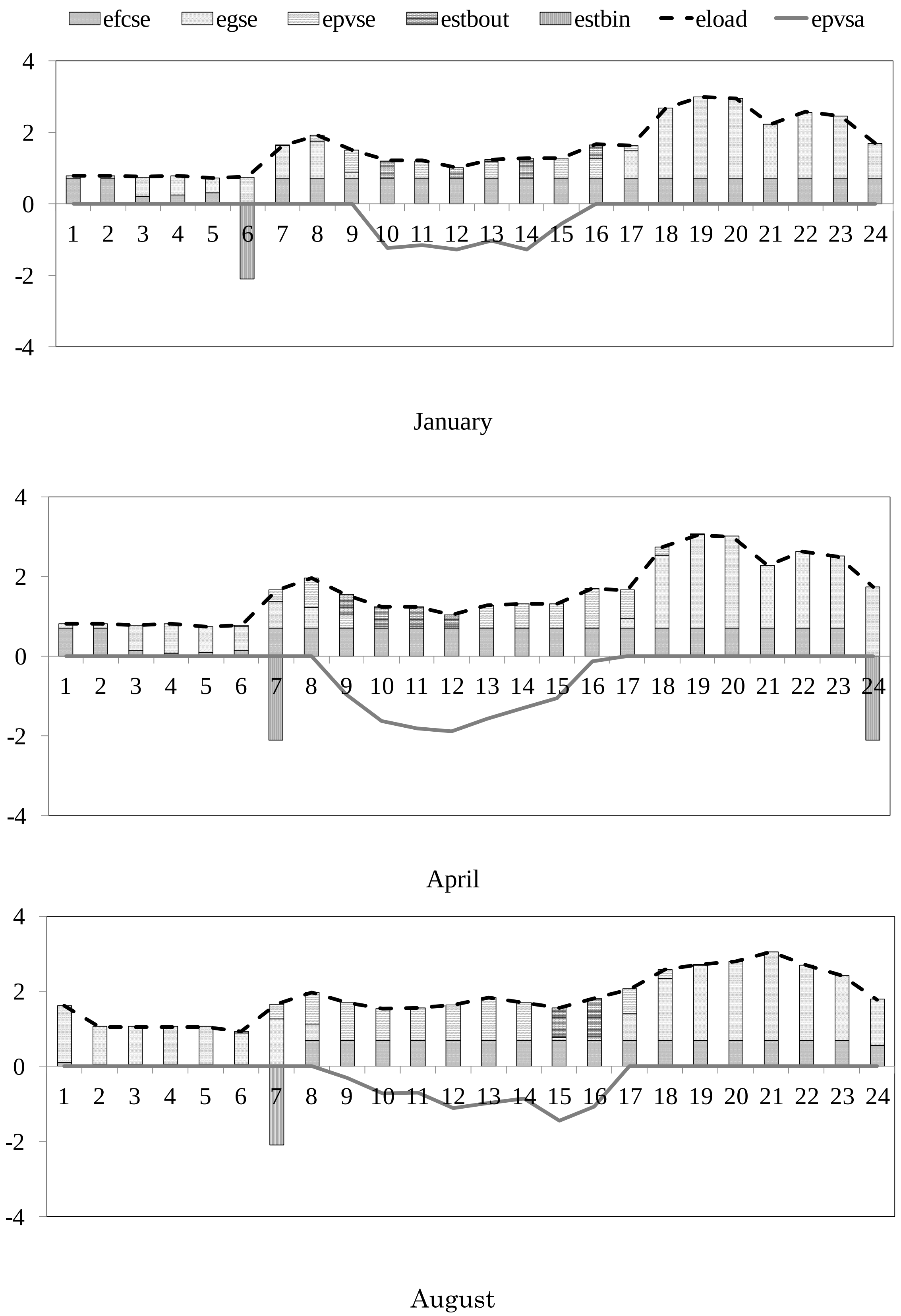


Fig. 7-3 Diurnal electricity pattern（kW）

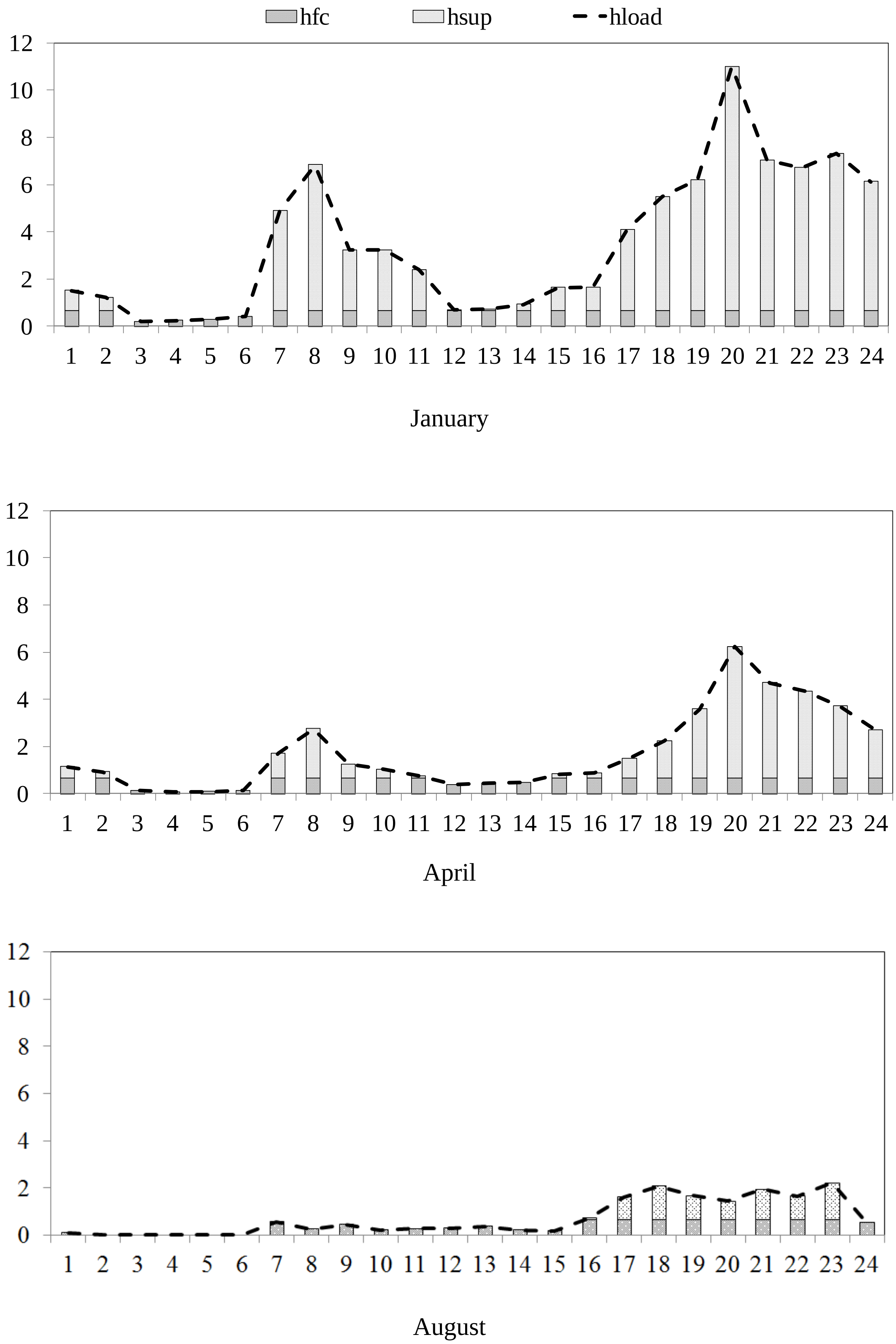
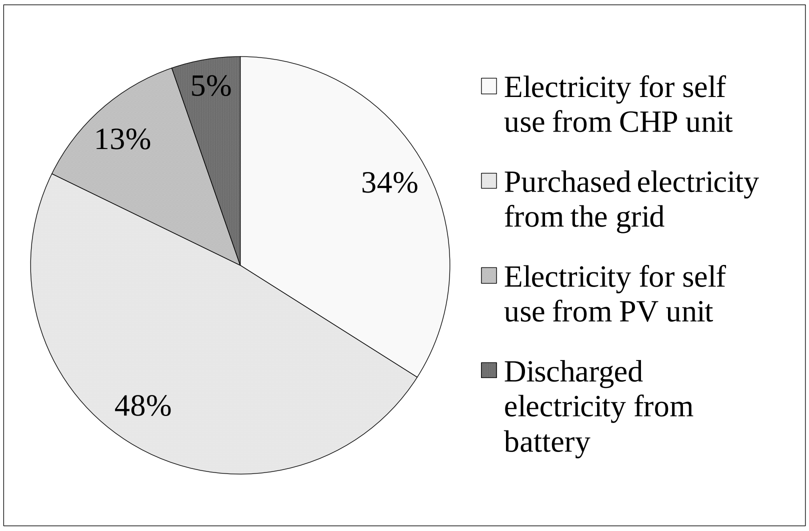


Fig. 7-4 Diurnal heat pattern（kW）

7.4.3 Strategy of each system

Fig. 7-5 summarizes the electricity and thermal balance considering a full calendar year minimizing the total annual running cost of the distributed residential energy system in Tokyo, Japan. Generally, the utility grid supplies the largest amount of electricity demand of the assumed typical residential building with 48%, and followed by CHP unit, PV cell as well as battery, which is 34%, 13%, 5% respectively. As to the thermal supply balance, backup boiler is the main supplier other than the CHP unit which accounted for as much as 71%.

Fig. 7-6 illustrates the optimal utilization forms of different micro-sources within the distributed residential energy system. For the CHP unit, the electricity is mainly used to supply the electricity load with 95.9%, and the rest is used to charge the battery. As to the PV unit, more than half of the electricity produced is sold out to the utility grid with 59.8%, taking advantage of the relatively high FIT rate. In addition, the battery is mainly charged by the utility grid which accounted for as much as 75.1% annually which indicates that supplying battery by generating extra power from FC unit is not cost-effective, unless the thermal energy generated simutaneously will be useful other than be neglected.



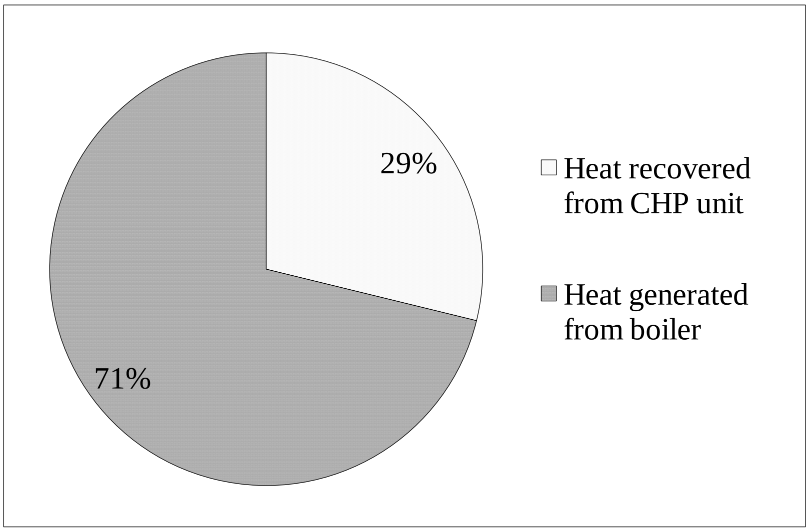
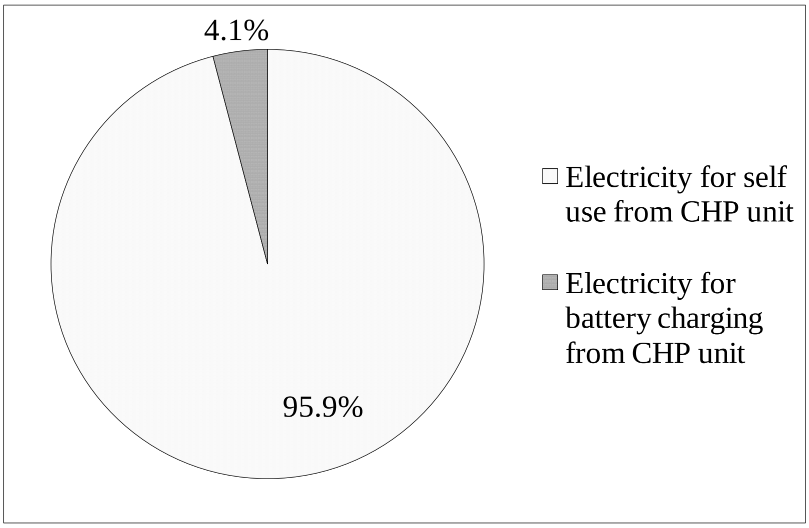
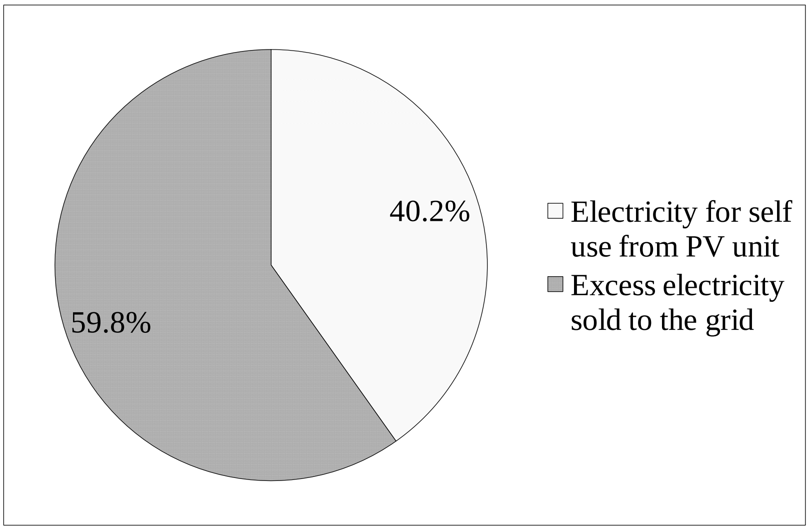


Fig. 7-5 Optimal electricity and thermal balance in Tokyo throughout the year





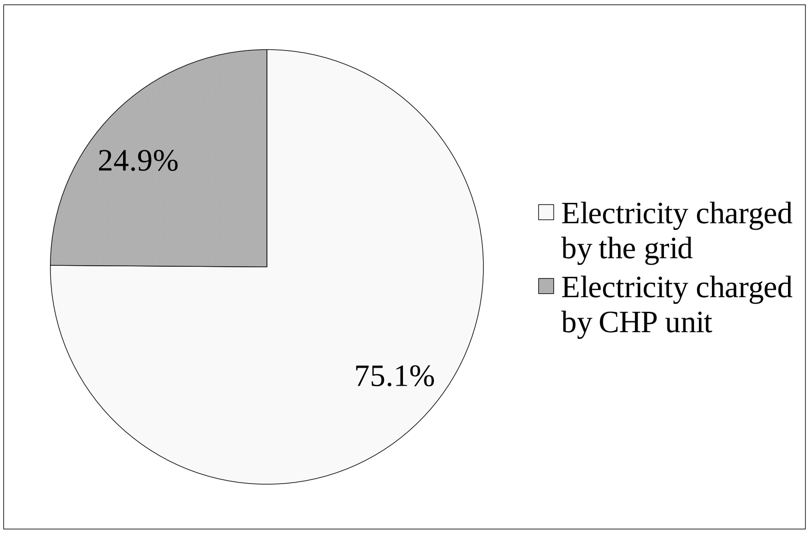


Fig. 7-6 Optimal utilization forms of PV cells, CHP unit and battery

Fig. 7-7 shows the optimal operation strategy of the hybrid PV, CHP and battery energy supply system in selected six cities in Japan. It can be found out that, except Sapporo, utility grid is the main electricity supplier in other five cities, followed by CHP system, PV system as well as discharged electricity from battery. As to the heat supply, boiler is the main supplied, which accounts for more than 70% in all cities.

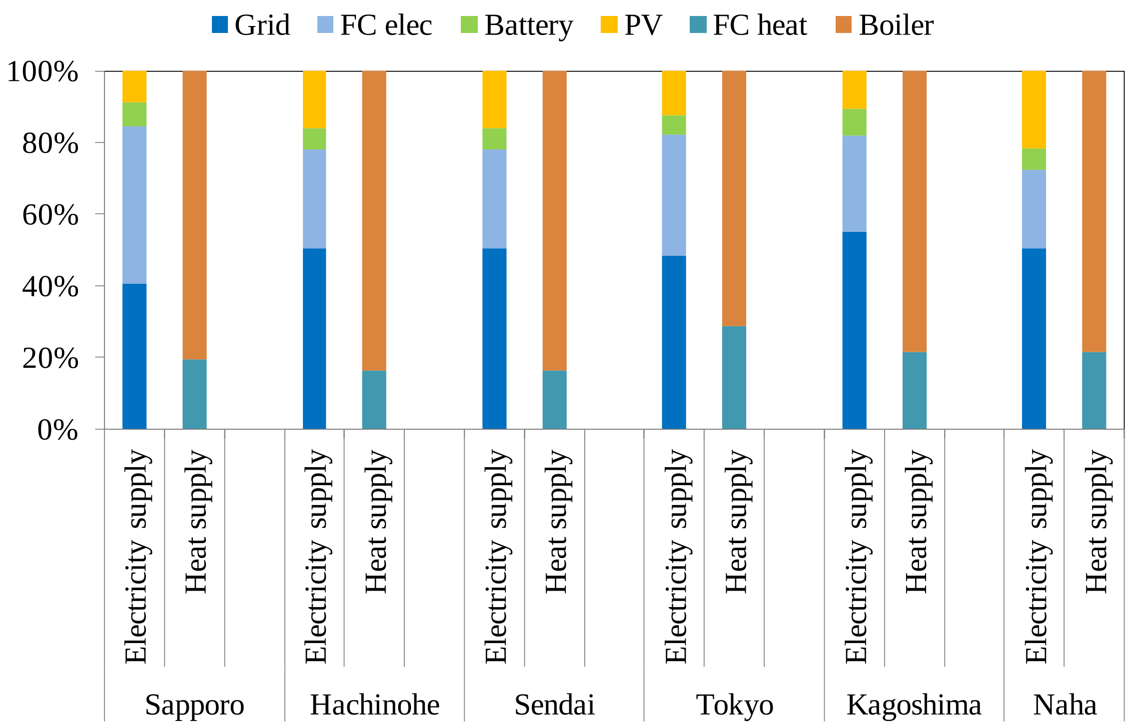


Fig. 7-7 Optimal operation strategy of the hybrid system

7.4.4 Cost reduction compared with conventional system

Fig. 7-8 shows the energy cost of conventional system as well as hybrid CHP, PV & battery system. Surplus electricity generated from PV system which is sold back to the utility grid is showed on the negative axis. The cost of hybrid system includes electricity bought cost, gas cost for CHP and backup boiler and subtract economic profit from selling excess electricity from PV.

Fig. 7-9 shows energy cost reduction ratio compared with the conventional system. costs are reduced by 65% in Kagoshima, followed by Sapporo (64.5%), Hachinohe (53.5%), Sendai (52.8%), Tokyo (51%), and Naha (35%).

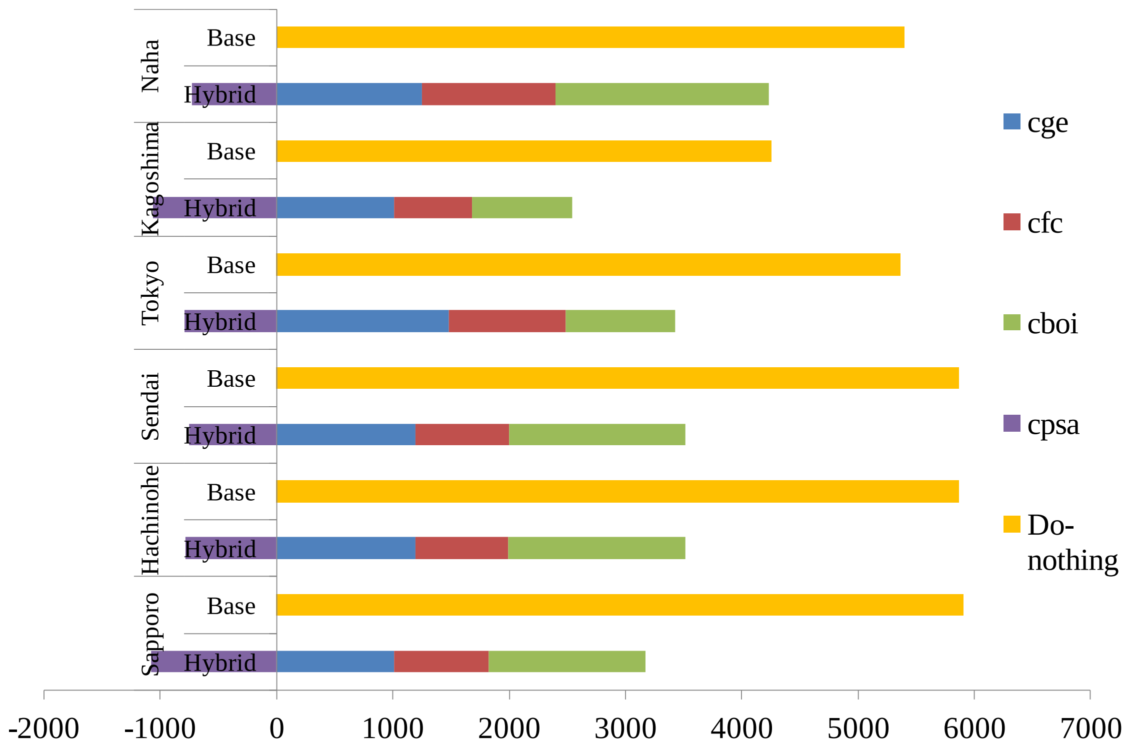


Fig. 7-8 Energy bill savings

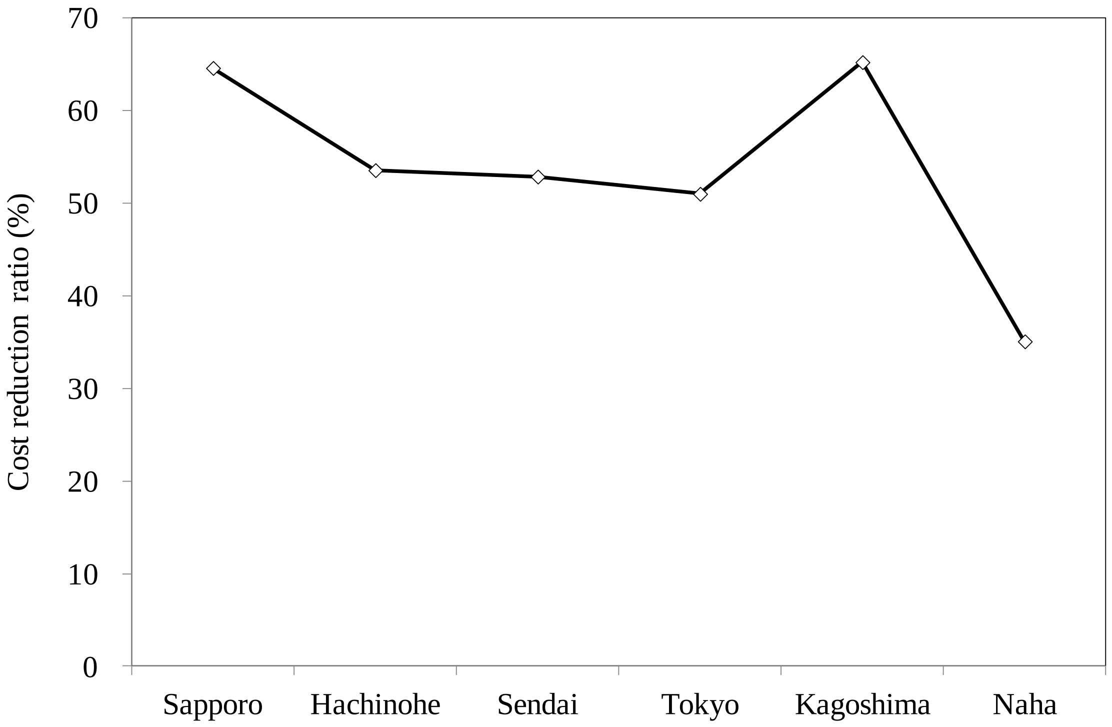
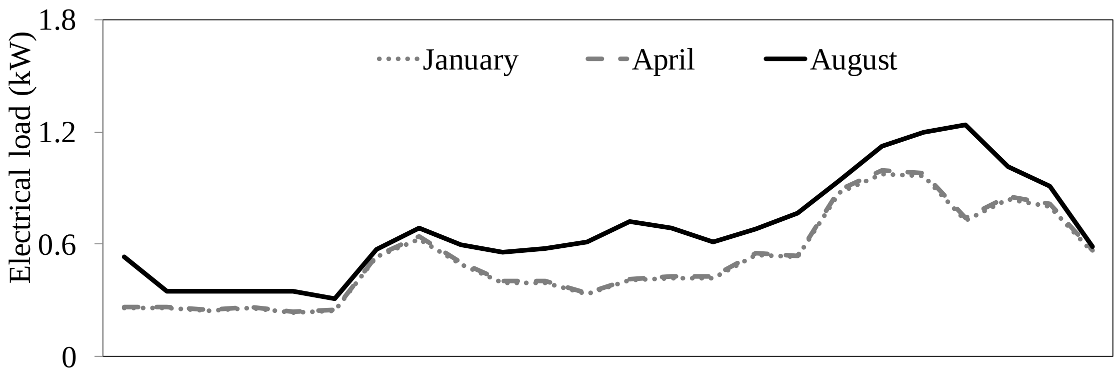


Fig. 7-9 Energy cost reduction ratio

7.5 Performance of hybrid system in China

7.5.1 Energy load

Detailed knowledge about energy loads for at least a year is important for accurate design of the PV/CHP/battery distributed residential energy system. In China, the hourly load demands of a typical household in Shanghai have been calculated according to energy consumption intensities of residential building type [19,20]. As the energy load varies widely among different seasons, to be simplicity, three periods (winter, summer and autumn-spring) have been selected to represent the load profile of the whole year as shown in Fig. 7-10 (note that January and August were selected for the winter and summer period, respectively, while the mid period is the average of April and November). It can be observed that, generally, the peaks of electric consumption are between 8AM and 9PM in all three periods. In addition, it can be found that although the electric demand varies little among different seasons, the value in summer is relatively high due to the larger amount of cooling demands because of the really hot weather. Comparatively, the relative change in thermal load throughout the year is much larger. Compared with other seasons, the value in winter changes more sharply and peaks from 6PM to 11PM and 4AM to 12AM. The mean annual electrical (control direct demands for lighting and power equipment, the cooling load with the use of air conditioner) and thermal (heating and hot water) demands occupy about 50% of total energy consumption.



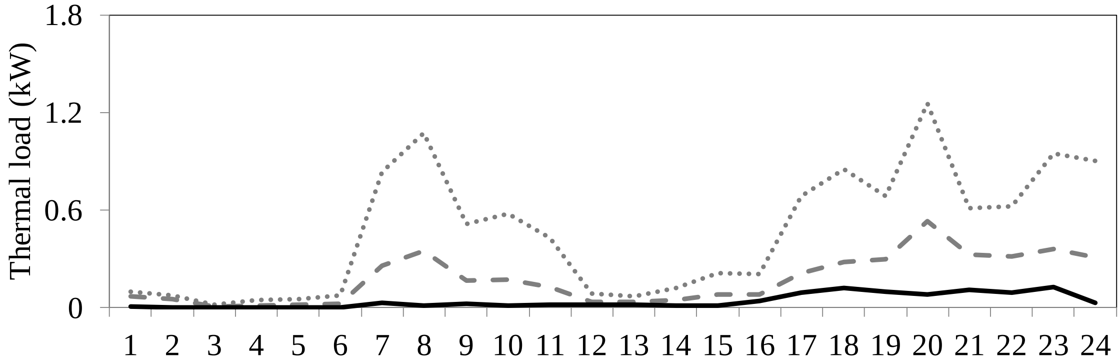


Fig. 7-10 Hourly electrical and thermal loads of the residential building in Shanghai

7.5.2 Optimal running strategy

Similar to Japan, annual running cost is set as the objective function to be minimized in this optimization model in China.

In the following, three typical days in January, April and August which represent winter, spring & autumn as well as summer will be selected as examples to discuss the optimal operation strategy of the hybrid PV/CHP/battery residential energy system. The situation in Shanghai, China will be selected as an example to show the optimization result.

（1）Power supply strategy

Fig. 7-11 shows the electricity balance of the residential building. Positive values represent domestic electric demand, PV and CHP outputs, battery outputs as well as utility power supply, whereas the battery inputs and sold electricity generated from PV unit are indicated on the negative side. From this figure, the following conclusions can be deduced.

(a) During the night time, generally from 1 AM to 6 AM and 11 PM to 12 PM, purchasing electricity tariff from grid is relatively low then the management strategy order CHP to be off and supply electrical load from local grid mainly which is more economical than generating power by CHP unit during this period both in January and April. While, in August, from early at PM 8 the hybrid system cannot satisfy all electricity demand which should buy electricity from utility gird. In addition, as to August, although electricity demand is large because of hot weather, electricity is most supplied by PV unit, other than CHP system during the daytime.

(b) Similar with Japan, from 7 AM to 8 PM period, the electricity demand is almost satisfied by CHP unit and battery, PV unit meet the deficiency other than purchasing electricity from utility grid. It is not only due to the electricity price is almost high during this period, but also because the customer is not allowed to sell and buy electric power at the same time according to China's current electric power standard.

(c) As aforementioned, storage battery which is used as a supplement is charged either by the electricity purchased from the utility grid or by the generated electricity from the CHP unit. In addition, the battery is charged almost when the purchasing tariff is low and discharged during the peak period. It can be found out that, the battery is charged at 6 AM in January and August, 6AM and 12 PM in April.

(d) Furthermore, most of the electric energy generated from PV unit is sold out to the local grid for the relatively high selling price compared with the purchasing tariff. Because if selling price is higher than purchasing price then it encourages customers to adopt renewable energy systems such as PV unit which are environment friendly.

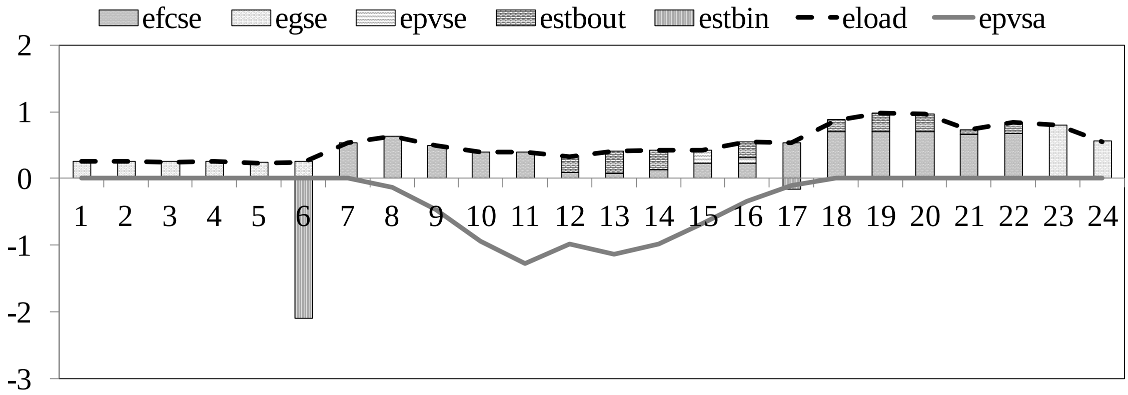
（2）Thermal supply strategy

The thermal balance of the residential building in Shanghai is depicted in Fig. 7-12 and from which the following conclusions can be observed.

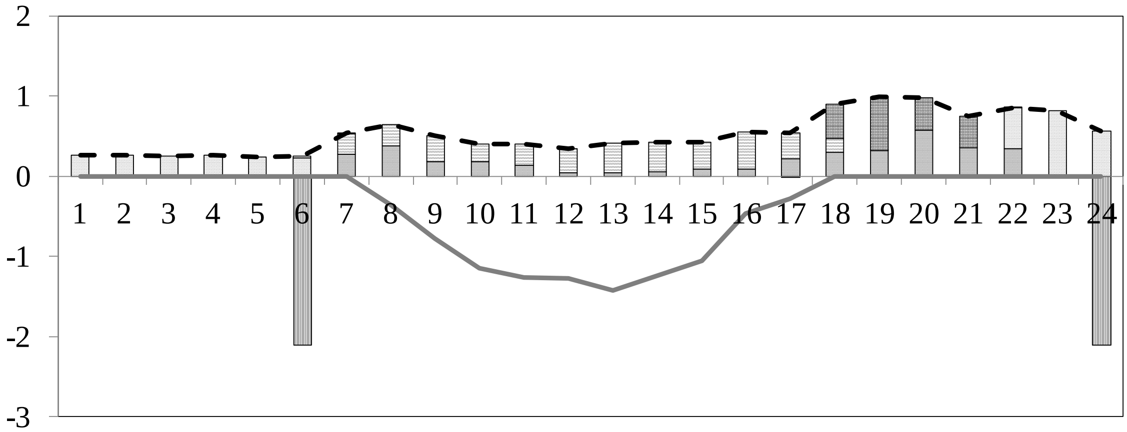
(a) Compared with the electricity balance, the thermal supply strategy is relatively simple. In this study, thermal energy is recovered from CHP unit as a by-product, thus, to be economic, the strategy order the recovered heat from CHP unit to meet the heat demand firstly, then the deficiency can be compensated by a backup boiler otherwise the surplus recovered thermal energy from CHP unit is neglected.

(b) Different from Japan, the hot demand is generally supplied by FC unit, for the relatively low heat demand in China.

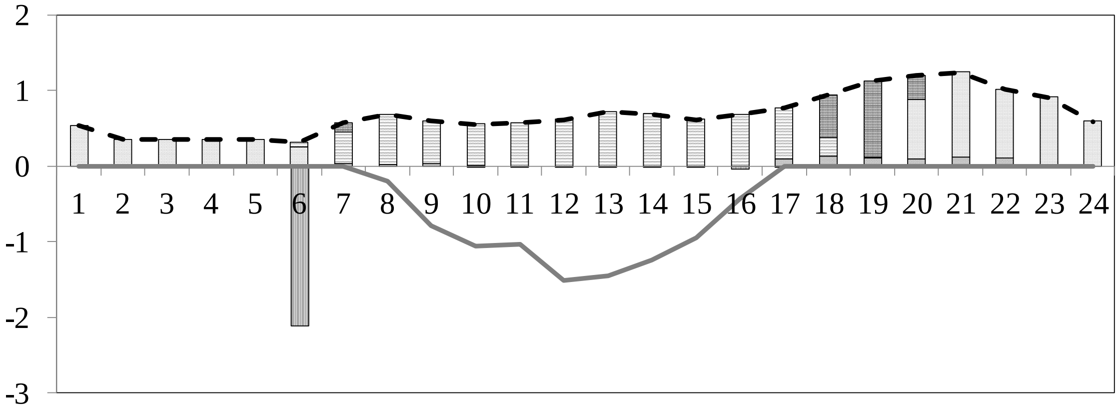
(c) In addition, it is interesting to found that to minimize the total annual operation cost, there is no surplus recovered thermal energy from the CHP unit.



January

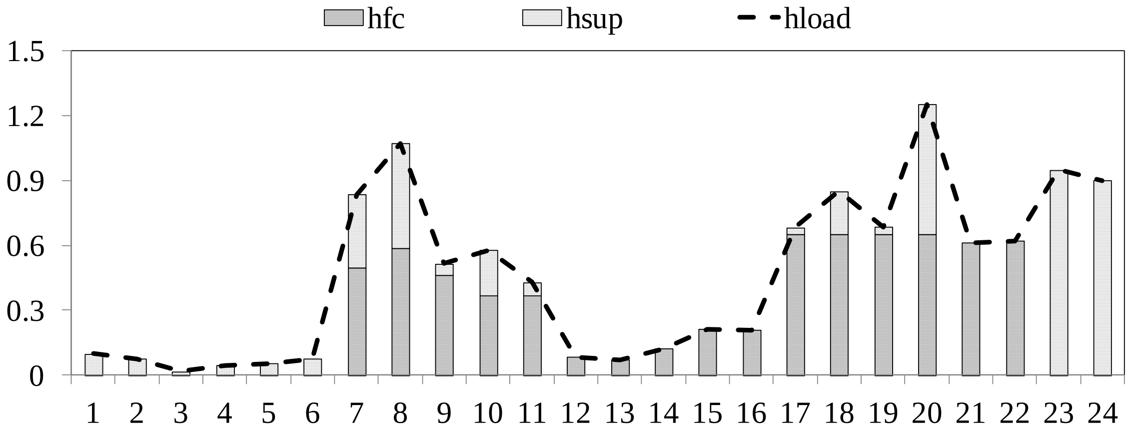


April

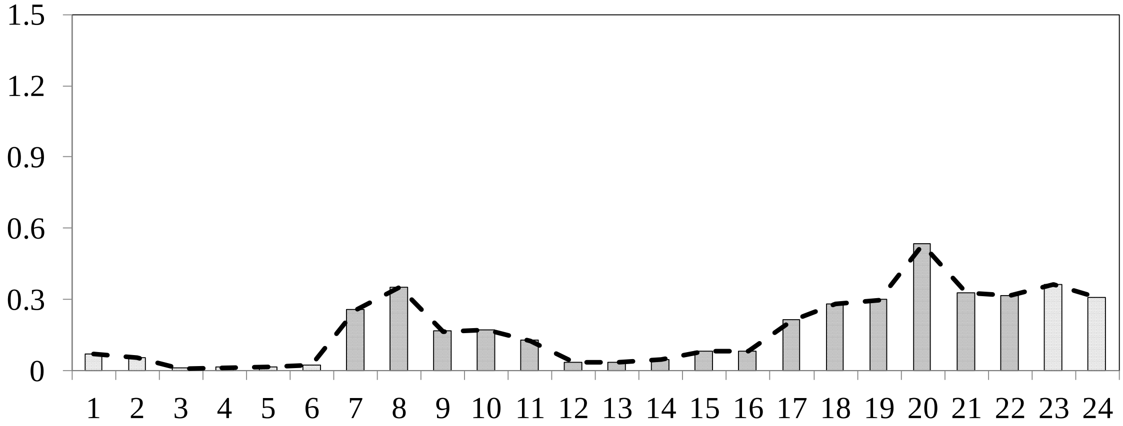


August

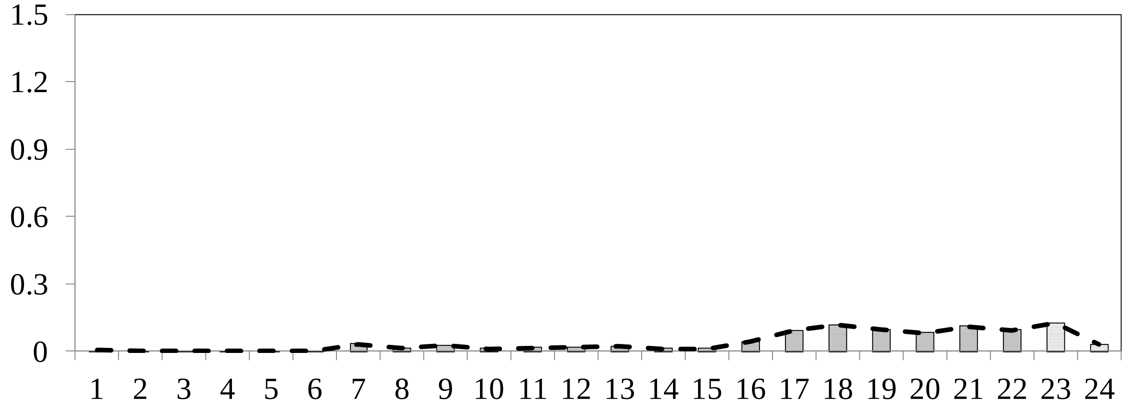
Fig. 7-11 Diurnal electricity pattern（kW）



January



April



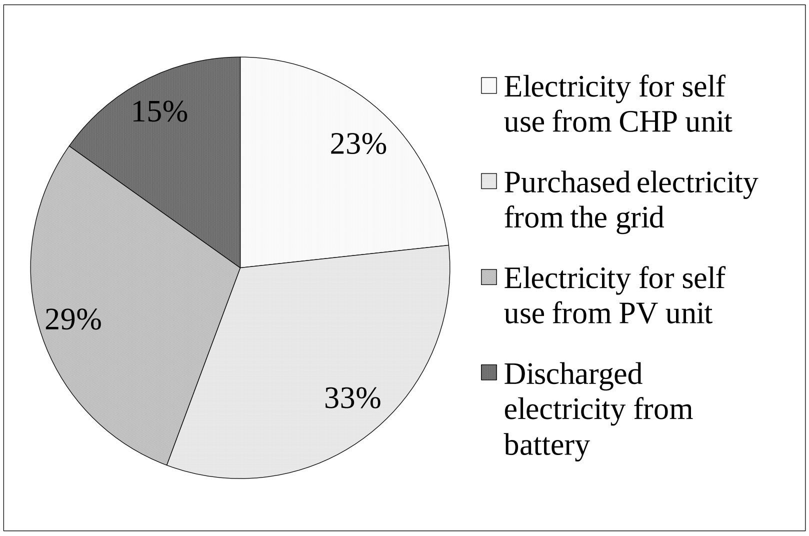
August

Fig. 7-12 Diurnal heat pattern（kW）

7.5.3 Strategy of each system

Fig. 7-13 summarises the electricity and thermal balance considering a full calendar year minimizing the total annual running cost of the distributed residential energy system in Shanghai, China. Generally, the utility grid supplies the largest amount of electricity demand of the assumed typical residential building with 33%, and followed by PV cell, CHP unit, as well as battery, which is 29%, 23%, 15% respectively. As to the thermal supply balance, backup boiler is the main supplier other than the CHP unit which accounted for as much as 72%.

Fig. 7-14 illustrates the optimal utilization forms of different micro-sources within the distributed residential energy system. For the CHP unit, the electricity is mainly used to supply the electricity load with 96.2%, and the rest is used to charge the battery. As to the PV unit, more than half of the electricity produced is sold out to the utility grid with 64.8%, taking advantage of the relatively high FIT rate. In addition, the battery is mainly charged by the utility grid which accounted for as much as 94.5% annually which indicates that supplying battery by generating extra power from CHP unit is not cost-effective, unless the thermal energy generated simutaneously will be useful other than be neglected.



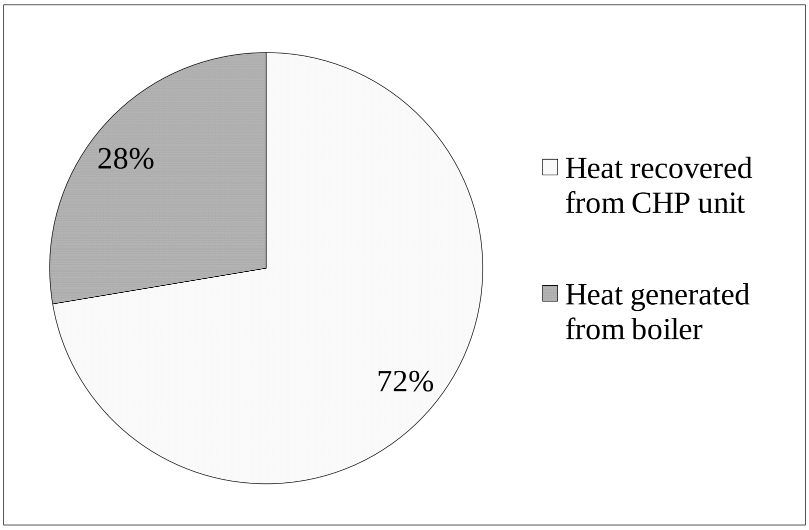
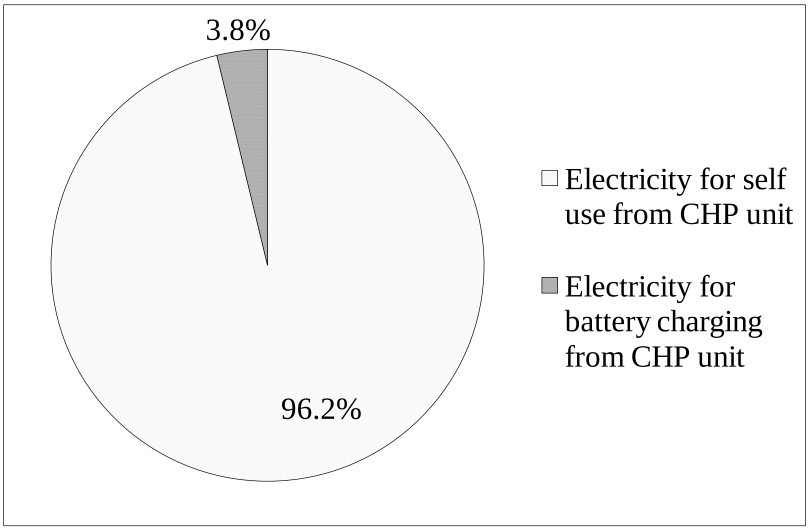
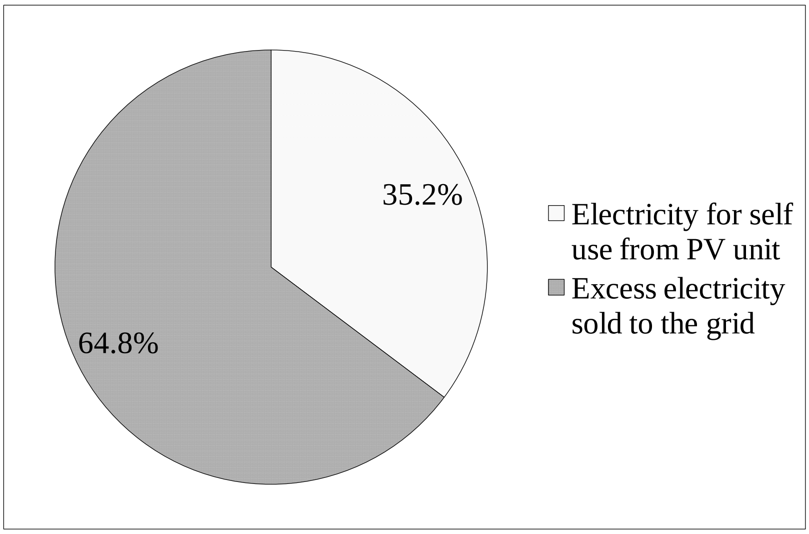


Fig. 7-13 Optimal electricity and thermal balance in Tokyo throughout the year





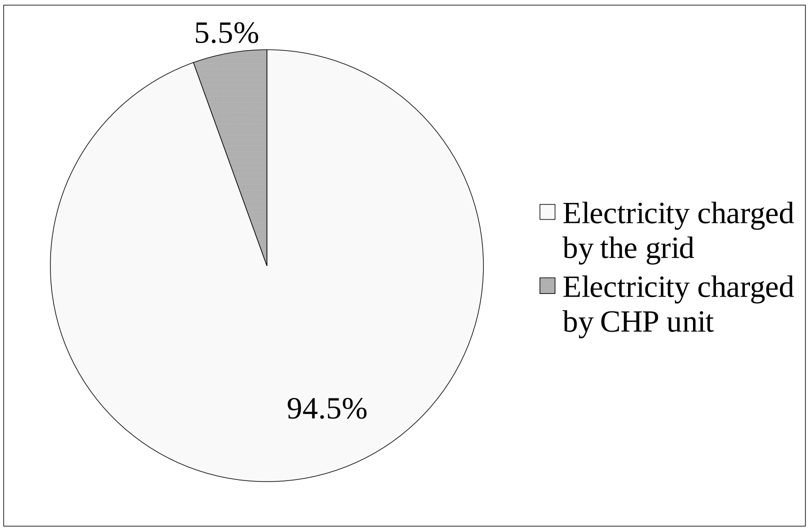


Fig. 7-14 Optimal utilization forms of PV cells, CHP unit and battery

Fig. 7-15 shows the optimal operation strategies of the hybrid PV, CHP and battery energy supply system in selected five cities in China. It can be found out that, in Harbin and Beijing, CHP supplies the main electricity and followed by PV. However, in Shanghai, Kunming and Guangzhou, PV is the main electricity supplier. As to the heat supply, in Harbin and Beijing, because of their large thermal demand, boiler is the main supplier, which accounts for 95% in Harbin and 75% in Beijing, while in other three cities, CHP is the main supplier, which occupies 72%, 100%, 86% in Shanghai, Kunming and Guangzhou.

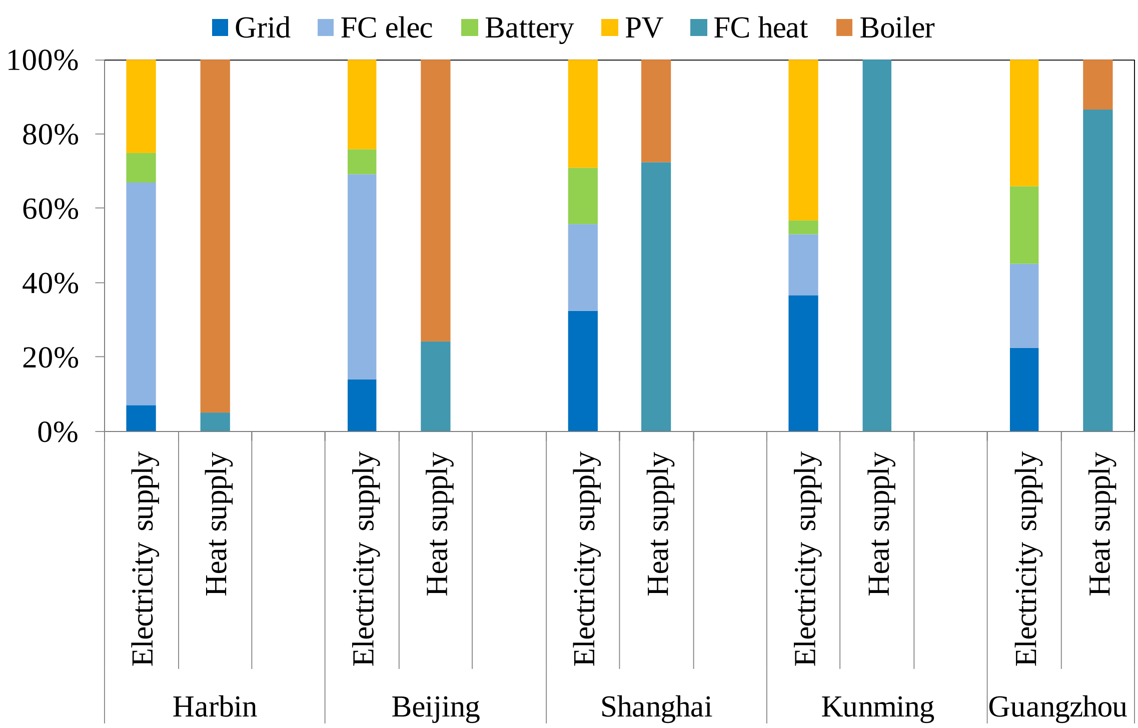


Fig. 7-15 The optimal operation strategy of the hybrid PV, CHP and battery energy supply system

7.5.4 Cost reduction compared with conventional system

Fig. 7-16 shows the energy cost of conventional system as well as hybrid CHP, PV & battery system. Surplus electricity generated from PV system which is sold back to the utility grid is showed on the negative axis. The cost of hybrid system includes electricity bought cost, gas cost for CHP and backup boiler and subtract economic profit from selling excess electricity from PV.

Fig. 7-17 shows energy cost reduction ratio compared with the conventional system. Generally, the cost reduction ratio is high in all selected cities in China, due to high profit from selling surplus electricity generated by PV system as well as self-use part. The costs are reduced by 445% in Kunming, followed by Shanghai (175%), Guangzhou (157%), Beijing (105%), and Harbin (54%).

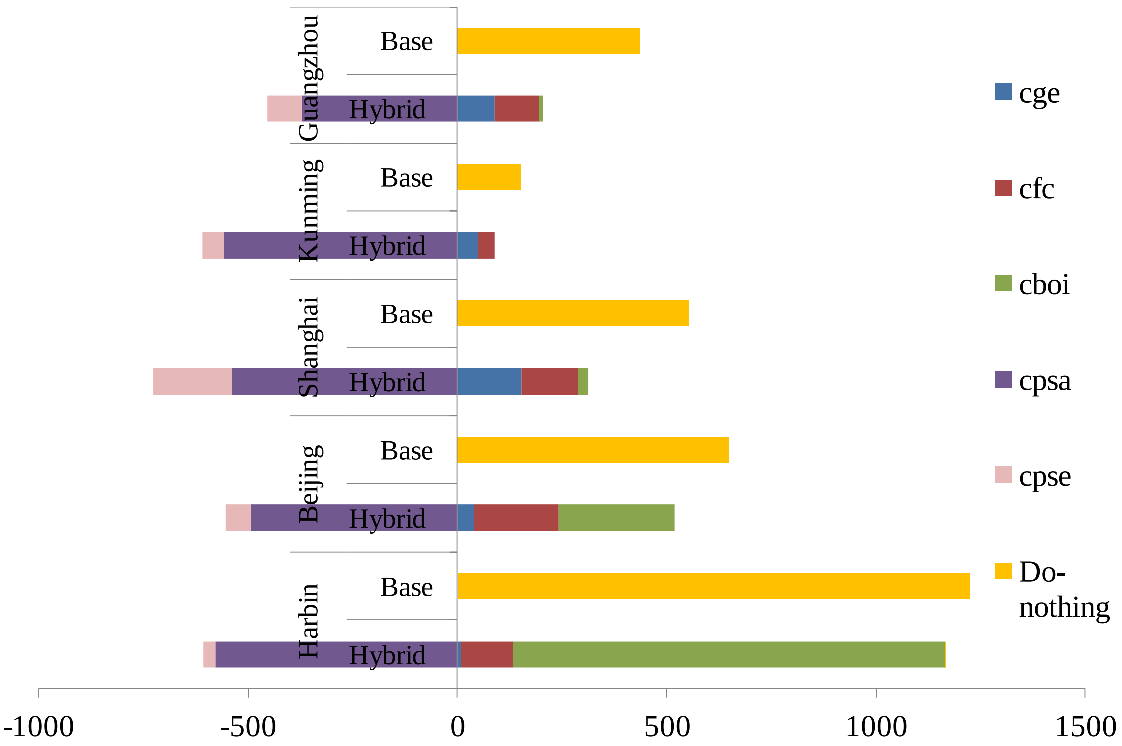


Fig. 7-16 Energy bill savings

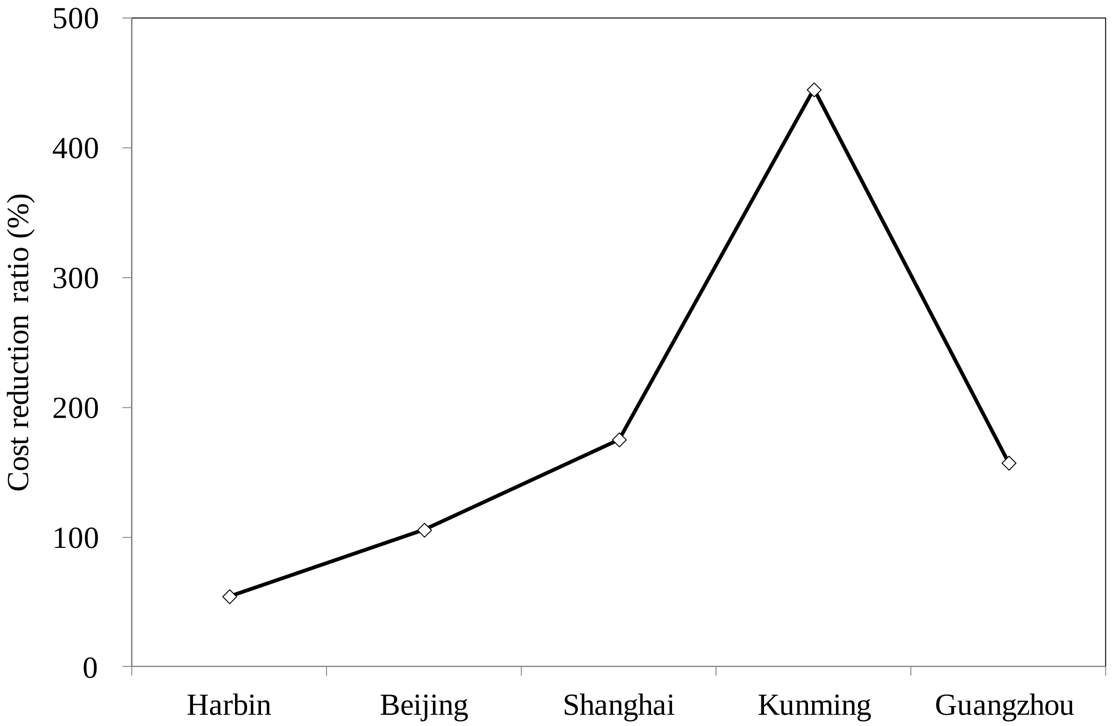


Fig. 7-17 Energy cost reduction ratio

7.6 Summary

In this chapter, by employing the aforementioned optimization method, the hourly running strategies of residential hybrid PV/CHP/battery energy supply system located in different climate zones in Japan and China are compared and analyzed. Again, the environmental and economical performance of the hybrid system are assessed in a detail way. According to the analysis, the following conclusions can be deduced:

(1) As to the optimal running strategy, the battery is always charged at AM 6 or AM 7 as well as PM 24 when the electricity tariff is relatively low both in Japan and China. During the daytime, hybrid PV/CHP/battery can satisfy the electricity demand without buying electricity from utility grid, whereas, during the night time, to be economic, the system usually order CHP to be off, and utility gird will supply the electricity due to the cheap price. Due to the relatively low heat demand of China, the heat demand is mainly supplied by CHP unit, whereas backup boiler is the main supplier in Japan.

(2) In China, cities in cold climate zones with high heat demand always have low cost reduction ratios. This is because, there is no incentives for CHP using gas price. Thus, the optimization method order the CHP to run only if thermal energy and electricity energy can be well matched, and the unsatisfied part of thermal demand will be supplied by the boiler which cost more than the warm area where the electricity and thermal demand matched perfect and the heat recycled from the CHP system can satisfy totally or most of the heat demand.

(3) In Japan, the situation is more complex because there is a subsidy for CHP use gas price for all selected cities except Naha, thus, the cost reduction ratio of Naha is lowest.

(3) The economic performance of hybrid PV/CHP/battery in China is much better than Japan, which is even higher than 100%. This is because the cities in China got a lot profit from self-use and selling out surplus electricity generated from PV system due to the strong subsidy launched by the Chinese government.

References

[1] Zheng Z, Rong X, Huan Y. Micro-sources design of an intelligent building integrated with micro-grid. Energy and Buildings 2013;57:261-267.

[2] Shaahid S, Elhadidy M. Economic analysis of hybrid photovoltaic-diesel-battery power systems for residential loads in hot regions—A step to clean future. Renewable and Sustainable Energy Reviews 2008;12:488-503.

[3] Zhang H, Li L, Zhou D, Zhou P. Political connections, government subsidies and firm financial performance: Evidence from renewable energy manufacturing in China. Renewable Energy 2014;63:330-336.

[4] Oh S, Lee Y, Yoo Y, Kim J, Kim S, Song S, Kwak H. A support strategy for the promotion of photovoltaic uses for residential houses in Korea. Energy Policy 2013;53:248-256.

[5] Panapakidis I, Sarafianos D, Alexiadis M. Comparative analysis of different grid-independent hybrid power generation systems for a residential load. Renewable and Sustainable Energy Reviews 2012;16:551-563.

[6] Ozlu S, Dincer I, Naterer G. Comparative assessment of residential energy options in Ontario, Canada. Energy and Buildings 2012;55:674-684.

[7] Michael Angelo A. Pedrasa, Ted D. Spooner, Iain F. MacGill. A novel energy service model and optimal scheduling algorithm for residential distributed energy resources [J]. Electric Power Systems Research，2011， 81(12)：2155-2163.

[8] Pearce J. Expanding photovoltaic penetration with residential distributed generation from hybrid solar photovoltaic and combined heat and power systems. Energy 2009;34:1947-1954.

[9] Mehleri E, Sarimveis H, Markatos N, Papageorgiou L. Optimal design and operation of distributed energy system: Application to Greek residential sector. Renewable Energy 2013;51:331-342.

[10] Ranjbar M, Mohammadian M, Esmaili S. Economic analysis of hybrid system consists of CHP and wind based CHP system for supplying grid-parallel residential load. Energy and Buildings 2014;476-487.

[11] Nosrat A, Pearce J. Dispatch strategy and model for hybrid photovoltaic and trigeneration power systems. Applied Energy 2011;88:3270-3276.

[12] Hamada Y, Takeda K, Goto R, Kubota H. Hybrid utilization of renewable energy and CHPs for residential energy systems. Energy and Buildings 2011;43:3680-3684.

[13] Hosseini M, Dincer I, Rosen M. Hybrid solar-CHP combined heat and power systems for residential applications: Energy and exergy analysis. Journal of Power Sources 2013;221:372-380.

[14] Ren H, Gao W. A MILP model for integrated plan and evaluation of distributed energy systems 2010; 87:1001-1014.

[15] Moghaddas-Tafreshi S, Zamani H, Hakimi S. Optimal sizing of distributed resources in micro grid with loss of power supply probability technology by using breeding swarm optimization. Renewable and Sustainable Energy 2011.

[16] Marnay C, Stadler M, Aki H, Coffey B, Firestone R, Lai J, Siddiqui A. Microgrid Selection and Operation for Commercial Buildings in California and New York States. The 4th European PV-Hybrid and Mini-Grid Conference. May 2008.

[17] Kashiwagi T. Natural Gas Cogeneration plan/design manual 2002. Japan Industrial Publishing Co., Ltd.; 2002.

[18] Ojima Lab. Consumption unit of electricity, heating, cooling and hot water. Waseda University; 2002.

[19] Ren H, Gao W, Ruan Y. Economic optimization and sensitivity analysis of photovoltaic system in residential buildings. Renewable Energy 2009;34:883-889.

[20] Kyushu Electric Power Co., Inc.http://www.kyuden.co.jp/index.html.

[21] Saibu Gas Co., Ltd. http://www.saibugas.co.jp

CHAPTER EIGHT: CONCLUSIONS AND PROSPECTS

The energy consumption is increasing gradually all over the world. In 2009, world energy consumption decreased for the first time in 30 years as a result of the financial and economic crisis. However, by the end of 2013, the energy consumption has increased by more than 7% compared with 2009. In addition, energy consumption growth vigorous in several developing countries, specifically in Asia (e.g. China and India). Fossil energy use increased most in 2000-2008. In October 2012 the IEA noted that coal accounted for half the increased energy use of the prior decade, growing faster than all renewable energy sources. The dependent on fossil fuel energy has brought out not only greenhouse gasses but also produced large amounts of pollutants such as sulphurous oxides (SOx), nitrous oxides (NOx), and particulate matter (PM). Based on this background, each country has been making great effort to all kinds of researchers and activities to save energy and seek new energy source. More concerns have brought the traditional centralized and fossil-based energy paradigm towards the decentralization energy supply system. Thus, distributed energy resources (DER) comprising of small, modular, electrical renewable or CHP electricity generation units placed at or near the point of energy consumption has gained much attention as a viable alternative or addition to the current energy system. Distributed energy source is the utilization of an on-site energy source to provide electricity and other energy to one or more buildings or facilities. Compared with traditional central energy supply, distributed energy source not only can utilize a wide range of energy source, but also environmentally friendly as well as supplying electricity high-quality and reliably.

While adopting the DER system, to holistically achieve the most cost or carbon effective building energy efficiency and on-site generation combination, multiple technology options and their operating schedules need to be optimized simultaneously. In addition, to assess the performance of the DER system, a set of effective assessment method is also needed. Furthermore, building sector has become the largest energy consumer compared with industry and transport which occupied 34% of total globally final energy consumption in 2012. Thus, it is of vital importance to introduce the DER system to the building sector. Again, climate weather largely affect the electricity load as well as electricity generated from DER system (e.g. PV unit). Therefore, in this study, five building types (hotel, hospital, store, office and residence) located in different climate zones in Japan and China (two main countries in Asia) have been selected to do the research which includes three kinds of DER systems: single CHP system, single PV system, as well as hybrid CHP/PV/battery distributed energy supply system.

The main works and results can be summarized as follows:

In chapter one, current energy and environmental situations, as well as the feasibility and necessity to introduce the distributed energy system are presented. In addition, current situation of global distributed energy system (CHP and PV mainly) adoption were investigated briefly. Based on the background, the purpose of current research is proposed.

In chapter two and chapter three, the supply and consumption of energy and electricity in Japan and China are summarized and compared. In addition, current status of CHP system as well as PV system adoption in Japan and China are investigated respectively. Moreover, currently, in both Japan and China, governments have promoted various policies to provide incentives for the DER system adoption. Therefore, the policies for CHP system and PV system adoption so far in the selected two countries are summarized.

In chapter four, firstly, based on a mathematical optimization approach where the design and structure of the energy system as well as the operation of each component are optimized, a MILP (mixed integer linear programming) problem of a distributed energy system was formulated and presented minimizing annual operating cost while guaranteeing resilience of the electricity and heating demand. The model is used to analyze the optimal design, running strategy of the DER system.

Secondly, various kinds of assessment methods adopted in this paper were presented detailed, which include multi-criteria analysis, net present value and so on.

In chapter five, in order to cope with the continually increasing energy consumption in commercial buildings, the CCHP systems are expected to play a bigger role in the coming years. In this chapter, the performances of CCHP systems for prototype commercial buildings (hotel, hospital, store and office) have been examined for a major city within each of the six major climate zones in Japan, as well as five major climate zones in China. The computed results have been analyzed and compared with the assistance of the AHP method using energy, economic and environmental performances as the assessment criteria. The criteria weights are assessed based on a previous investigation on a large number of existing CCHP systems. According to the assessment results, the following conclusions can be deduced.

(1) Generally, the introduction of CCHP systems results in satisfied energy and environmental performances in all examined commercial buildings in both Japan and China. The average primary energy saving ratios for all options are 21.2% in China and 22.6% in Japan. However, the mean CO2 emissions reduction ratios in China and Japan are 70.3% and 37.4%, respectively. This is mainly due to the relatively high carbon intensity of electricity from conventional power plant in China.

(2) The situation is different as to the economic performance which is affected by not only the system itself, but also financial and political conditions. The average total cost saving ratio for all options in China is -33.8%. Although the average value is 4.3% in

Japan, it cannot be recognized as a satisfied value. For example, from the economic point of view, Tokyo and Kagoshima are the most attractive regions for the installation of CCHP systems; while it is hard to be introduced in Naha.

(3) Different building types illustrate distinguishing energy, economic and environmental performances. Hotels and hospitals are popular customers of the CCHP system from either viewpoint, although the economic performance is not satisfied; on the contrary, the adoption of CCHP systems in offices results in marginal benefits mainly due to their weak energy intensity especially thermal demands.

(4) Although the variation of climate condition leads to decreased cooling load and increased heating load from Southern area to Northern area, the total energy demand does not illustrate obvious regularity because electricity and hot-water demands (having weak relationship with the climate condition) are the dominant energy forms for all examined four types of buildings. Therefore, the influence of climate condition on the performances of the CCHP systems is inexplicit. Generally, the cold and hot zones enjoys better energy and environmental performances, while the mild climate zones enjoy better economic performances.

(5) By using the multi-criteria method, a comprehensive evaluation of the CCHP systems can be realized. For example, in Japan, the systems in Kagoshima achieve the most benefits for the stores and offices; while, as to the hotels and hospitals, the systems in Sapporo are more preferred. Overall, hotels and hospitals are recognized to be the potential customers of the CCHP systems from an integrated viewpoint.

(6) Weak economic performance is considered to be the main barrier against the penetration of CCHP systems in commercial buildings in both Japan and China. Besides the technical improvement of the CCHP system itself, incentives including the regulation of the electricity and natural gas prices should be paid more and more attention. In summary, the CCHP systems are more suitable for a certain type of building in a certain region than others. Careful technology selection and system design is required for each application.

In chapter six, the same as CCHP system studied in Chapter five, the hourly operation strategy as well as energy, economic and environmental performance of PV system are assessed within various building types of different cities located in Japan and China. According to the analysis, the following conclusions are deduced:

(1) The unit cost of PV system in China still higher than conventional utility unit cost per kWh both in residential and commercial sector, whereas, the situation is contrary in Japan, which means as the decreasing of PV module price and improving electricity transfer efficiency of PV cell, the unit cost of PV has become lower than conventional unit cost which is relatively higher in Japan.

(2) Because of the large electricity demand in Japan, the electricity sold out is almost 0 which is totally contributed to supply the load demand. However, in China, during the solar irradiation peak time, the electricity generated from the PV system is larger than the electricity demand during that time, thus, the surplus electricity demand can be sold out to the utility gird.

(3) As to the economic performance, the result is satisfied both in Japan and China. Which means the annual cost of the PV system is lower than conventional annul cost.

(4) The system which has a higher annual reduction ratio always has a shorter payback year. While, this is not definitely right, for the payback year is determined by the net cash flow of the system as well as total initial cost of the PV system.

(5) As is expected, the environment performance is satisfied because of 0 emission during the electricity generation of the PV system.

In chapter seven, by employing the aforementioned optimization method, the hourly running strategies of residential hybrid PV/CHP/battery energy supply system located in different climate zones in Japan and China are compared and analyzed. Again, the environmental and economical performance of the hybrid system are assessed in a detail way. According to the analysis, the following conclusions can be deduced:

(1) As to the optimal running strategy, the battery is always charged at AM 6 or AM 7 as well as PM 24 when the electricity tariff is relatively low both in Japan and China. During the daytime, hybrid PV/CHP/battery can satisfy the electricity demand without buying electricity from utility grid, whereas, during the night time, to be economic, the system usually order CHP to be off, and utility gird will supply the electricity due to the cheap price. Due to the relatively low heat demand of China, the heat demand is mainly supplied by CHP unit, whereas backup boiler is the main supplier in Japan.

(2) In China, cities in cold climate zones with high heat demand always have low cost reduction ratios. This is because, there is no incentives for CHP using gas price. Thus, the optimization method order the CHP to run only if thermal energy and electricity energy can be well matched, and the unsatisfied part of thermal demand will be supplied by the boiler which cost more than the warm area where the electricity and thermal demand matched perfect and the heat recycled from the CHP system can satisfy totally or most of the heat demand.

(3) In Japan, the situation is more complex because there is a subsidy for CHP use gas price for all selected cities except Naha, thus, the cost reduction ratio of Naha is lowest.

(4) The economic performance of hybrid PV/CHP/battery in China is much better than Japan, which is even higher than 100%. This is because the cities in China got a lot profit from self-use and selling out surplus electricity generated from PV system due to the strong subsidy launched by the Chinese government.

履　歴　書

フリガナ	ゴ　　ケイ	性　　別
氏　　　名	呉　瓊　（Qiong Wu）	女
生 年 月 日	昭和 62 年 8 月 17 日	
所　　　属	北九州市立大学大学院 ・ 国際環境工学研究科	
専　　　攻	環境工学	
研究テーマ	地域別分散型エネルギーシステムの総合評価に関する日中比較研究	
連　絡　先	〒808-0135 福岡県北九州市若松区ひびきの 1-1・高研究室	
電　　　話	093-695-3234	
E－MAIL	wuqiongrff＠163.com	

学　　　歴		
2002 年 9 月	中国 ・ 泰州市明星高校	入学
2005 年 7 月	中国 ・ 泰州市明星高校	卒業
2005 年 9 月	中国 ・ 南京師範大学 ・ 電力システム学科	入学
2009 年 7 月	中国 ・ 南京師範大学 ・ 電力システム学科	卒業
2009 年 9 月	日本 ・ 京都文化日本語学校	入学
2010 年 3 月	日本 ・ 京都文化日本語学校	卒業
2010 年 4 月	日本 ・ 北九州市立大学大学院 ・ 環境工学専攻 博士前期課程	入学
2012 年 3 月	日本 ・ 北九州市立大学大学院 ・ 環境工学専攻 博士前期課程	卒業
2012 年 4 月	日本 ・ 北九州市立大学大学院 ・ 環境工学専攻 博士後期課程	入学
2015 年 3 月	日本 ・ 北九州市立大学大学院 ・ 環境工学専攻 博士後期課程	卒業見込

職　　　歴		
2013 年 2 月	中国 ・ 上海電力学院	実験係

賞　　　罰	
2010 年	北九州学術研究都市奨学金
2012 年	北九州学術研究都市奨学金

論 文 目 録

1. 学術雑誌論文

1) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao and Jianxing Ren, Multi-criteria Assessment of Combined Cooling Heating and Power Systems Located in Different Regions in Japan, Applied Thermal Engineering 73(1), pp 658-668, 2014
2) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao and Jianxing Ren, Influence of FIT Rate on the Adoption of Residential PV System in China, Advanced Materials Research Vols. 805-806, pp 121-124, 2013
3) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao and Jianxing Ren, Economic assessment of residential photovoltaic system based on dynamic load characteristics, Renewable Energy Resources, 32(2), pp 133-137, 2014 (In Chinese)
4) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao and Jianxing Ren, Current Situation of Residential Micro-CHP System in Japan and the Revelation to China, Applied Energy Technology, 11, pp 1-6, 2013 (In Chinese)
5) Hongbo Ren, **<u>Qiong Wu,</u>** Jianxing Ren, Weijun Gao, Cost-effectiveness Analysis of Local Energy Management Based on Urban-rural Cooperation in China, Applied Thermal Engineering 64(1-2), pp224-232, 2014
6) Hongbo Ren, **<u>Qiong Wu</u>**, Yinyin Ban, Jian Yang, Game theory based profit allocation method for users within a regional energy interchanging system, Communications in Computer and Information Science 463, pp 341-348, 2014

2. 国際会議論文

1) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao, Jianxing Ren, Investigation and analysis of electricity tariffs in Japan, China and Thailand, Proceedings of The 2nd Asia Future Conference (AFC), Bali, Aug. 2014
2) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao, Integrated Assessment of BCHP System Adoption for Different Building Types in China, The 1st Asia Future Conference (AFC) "Asia in the World--- Potentials of Regional Cooperation", Thailand, Mar. 2013
3) **<u>Qiong Wu</u>**, Hongbo Ren, Weijun Gao, Jianxing Ren, Influence of Building Type and Climate Condition on the Adoption of BCHP Systems in

Japan, The Eighth International Conference of the Yellow Sea Rim International Exchange Meeting on Building Environment and Energy (YSRIM2013), Suzhou, Jan. 2013

4) **Qiong Wu**, Weijun Gao, Hongbo Ren, A simulation-based analysis of photovoltaic system adoption for residential buildings in Asian countries, Proceedings of AIRAH Building Simulation Conference 2011: driving better design through simulation, Australia, Nov. 2011