博 士 論 文

Study on Equipment Maintenance and System Optimization of Distributed Energy Resource

分散型エネルギーシステムにおける設備保全とシステム最適化に関する研究

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Study on Equipment Maintenance and System Optimization of Distributed Energy Resource

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Preface

Distributed energy resource (DER) system can save energy costs and reduce environmental impact. However, the investment is large, the capacity is unreasonable, the economic benefits are poor, and equipment failures are frequent. In this paper, the maintenance management and configuration optimization of DER system is analyzed. This study investigated the DER system in Kitakyushu Science and Research Park, Japan, and proposed a new maintenance priority index. Meanwhile, a life cycle assessment (LCA) of the DER system is analyzed and a comprehensive performance assessment method is proposed to analyze the development potential of the DER system.

Acknowledgements

This work could not have been completed without the support, guidance, and help of many people and institutions, for providing data and insights, for which I am very grateful.

First of all, I would like to give my sincere thanks to my supervisor Professor Weijun Gao has given me invaluable guidance and constant support and encouragement throughout the whole processes. During my study in these five years and the writing of this thesis, he has always been generous to offer me useful suggestions, answer my question and discuss research questions with me. He details guidance and helpful comments on my thesis encourage me to overcome difficulties and think more critically during the processes of writing.

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ABSTRACT

Owing to the continuous growth in the world's energy demand, the problems of energy consumption, greenhouse gas emission, and environmental pollution have become increasingly prominent. At present, countries all around the world have implemented energy-saving and emission reduction measures to achieve carbon neutralization. The distributed energy resource (DER) system is a high-efficiency energy system that can promote energy-saving and decrease carbon emissions. However, the implementation of DER is still hindered, mainly due to improper maintenance management and unsuitable installed capacity. Maintenance management is a key element for the equipment or system to complete its function during the production cycle. Each component has a different operation and maintenance mode. Inadequate resources for maintenance management or poor maintenance strategies will lead to equipment or system failures and losses. The choice of installed capacity and operating strategy affects the economy, energy efficiency and environmental protection of DER. If the installed capacity is too large, it will lead to higher investment costs and energy consumption. If the equipment capacity is too small, it will lead to high system operation cost. Therefore, it is necessary to select the appropriate equipment capacity according to the energy demand of the user. Therefore, the focus of this research is on the equipment maintenance and system optimization of DER. In the maintenance optimization stage, a maintenance priority assessment method is used to allocate maintenance management resources based on the assessment results to help managers develop reasonable maintenance strategies and reduce maintenance costs. In the system design optimization stage, the capacity and operation strategy of the system is optimized for the energy demand of users to achieve the purpose of improving economic benefits and promoting energy saving and emission reduction.

In Chapter 1, REASEARCH BACKGROUND AND PURPOSE OF THE STUDY. The present situation of DES is investigated and the technologies that can be applied to DES are introduced. And the purpose of this study is proposed.

In Chapter 2, LITERATURE REVIEW OF THE DISTRIBUTED ENERGY RESOURCE SYSTEM. Research advances in the evaluation performance and maintenance management of DER systems are reviewed. DER is a complex system consisting of multiple devices that can provide multiple energy sources, and its configuration design and maintenance management determine the performance of the system and are the main research focus of DER. Therefore, the previous literature is reviewed.

In Chapter 3, THEORIES AND METHODOLOGY OF THE STUDY. In this section,

the methodological study and the mathematical model were presented. And the system models are established. Also, the economy benefit, energy consumption, carbon emission reduction and maintenance management of the equipment of DER are analyzed. In addition, the simulation models and algorithms used in the follow-up study are provided.

In Chapter 4, INVESTIGATION ON REAL OPERATION DATA OF DISTRIBUTED ENERGY RESOURCE SYSTEM. The management of DER system in Kitakyushu Science and Research Park (KSRP) were investigated and analyzed in terms of operation status and maintenance management strategy.

In Chapter 5, LIFE CYCLE ASSESSMENT ANALYSIS OF DISTRIBUTED ENERGY RESOURCE SYSTEM. Based on the analysis of the operation status of the DER system in chapter 4, this section proposed a life cycle assessment method to evaluated the DER system performance. The comprehensive benefits of DERs were analyzed in terms of economic benefit, energy consumption and environmental performance compared with conventional energy systems (CES), respectively.

In Chapter 6, STUDY ON MAINTENANCE OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM. The maintenance strategy of the DES system in KSRP is analyzed and optimized. The main power generation units of the DER system in KSRP includes fuel cell and gas engine. Each generator has associated equipment, absorption chiller, heat exchanger, cooling tower, cooling pump, etc. The failure modes, failure causes, and failure effects of the components were investigated; and severity (S), occurrence (O), and detection (D) factors were evaluated. The maintenance strategy was optimized to improve maintenance and reduce the risk priority number (RPN). The results can be used as a reference for component maintenance optimization.

In Chapter 7, COMPREHENSIVE PERFORMANCE ASSESSMENT AND OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM. Different configurations of equipment will affect the performance of DER. In this section, a comprehensive performance assessment based on the economy, energy and environmental performance was proposed to optimize the system to find the optimal capacity. And discussed the impact of different electricity price mechanisms on the development of DER. The comprehensive evaluation index (CPI) was established based on economy, energy and environment performance, and a configuration optimization model of the DER with the maximum CPI as the goal was established by genetic algorithm (GA). Then, the development potential of the DER was evaluated by analyzing the economic saving, energy saving and carbon reduction performances.

In Chapter 8, CONCLUSION. The whole thesis of each chapter has been presented

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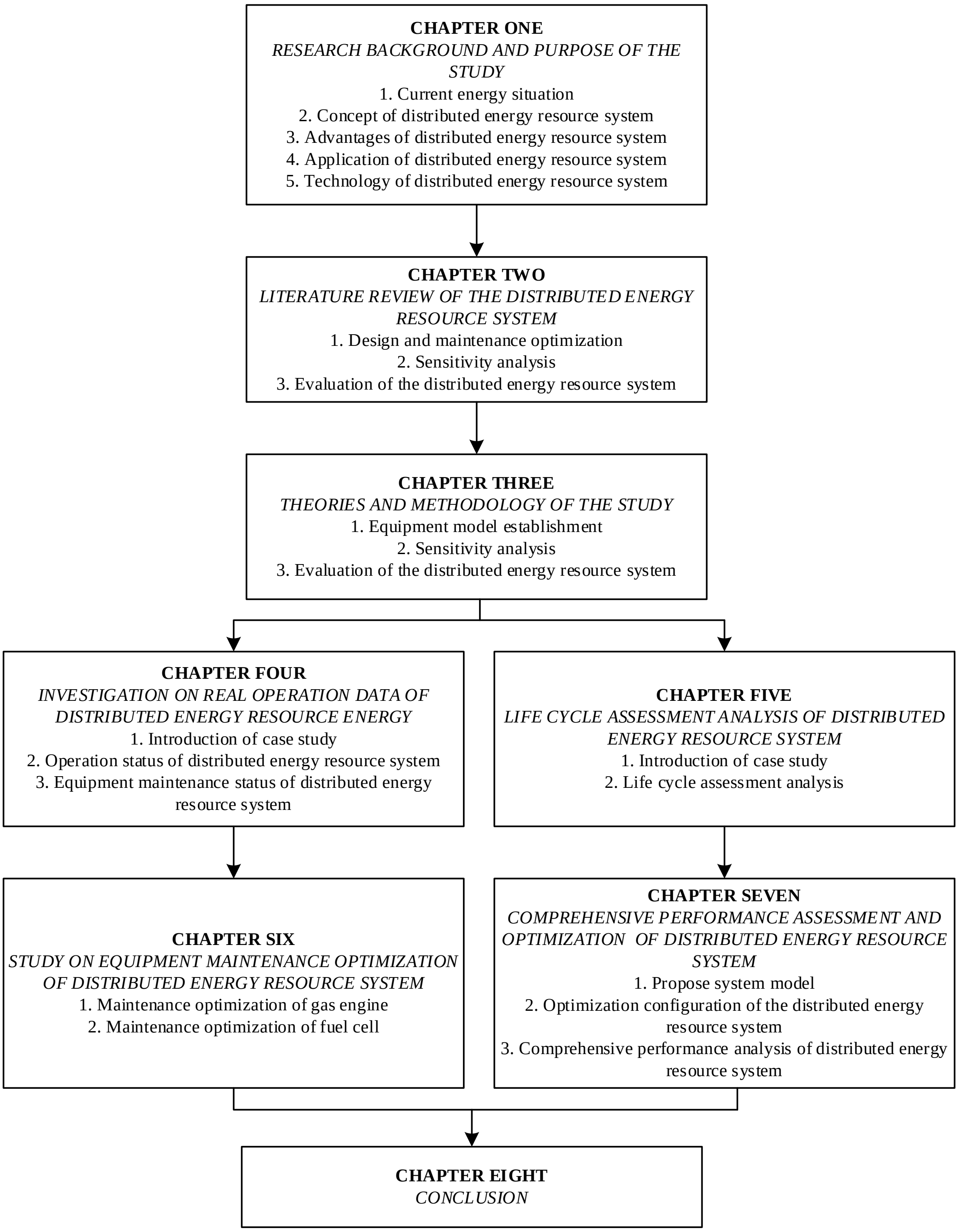
STUDY ON EQUIPMENT MAINTENANCE AND SYSTEM OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE



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THE NOMENCLATURE

Nomenclature	
AIC	annual investment cost ($/year)
AMC	annual maintenance cost ($/year)
AOC	annual operating cost ($/kWh)
ATC	annual total cost ($/year)
C	cost ($)
CCHP	combined cooling heating and power
CDE	carbon dioxide emission
CDER	carbon dioxide emission reduction
CHP	combined cooling and power
COP	coefficient of performance
CO_2	carbon dioxide
CPI	comprehensive performance index
CSR	cost-saving ratio
DER	distributed energy resource
DES	distributed energy system
E	electricity demand (kWh)
F	fuel consumption (m^3)
FTL	following the thermal load
GA	genetic algorithm

I	investment cost ($)
KSRP	Kitakyushu Science and Research Park
M	maintenance cost ($)
N	capacity of the equipment (kWh)
PEC	primary energy consumption
PESR	primary energy consumption ratio
PGU	power generation unit
Q	heat (kWh)
SP	separated production
STOU	seasonal time-of-use
TOU	time-of-use
Greek letter	
η	efficiency
μ	CO_2 emission conversion factor
ω	weight vector
Subscript	
ab	auxiliary boiler
ac	absorption chiller
b	boiler
c	cooling
e	electricity

ec	electric chiller
f	fuel
$grid$	electricity grid
h	heating
he	heat exchanger
m	equipment number
pgu	power generation unit
r	recovery heat
rh	recovery heat supplied to heat exchanger
t	hours
$total$	total amount of fuel
tr	transmission of power grid

Chapter 1

BACKGROUND AND PURPOSE OF THE STUDY

CHAPTER ONE: RESEARCH BACKGROUND AND PURPOSE OF THIS STUDY

1.1 Background

1.1.1 Situation of international energy development

In recent years, coal and oil-based fossil energy sources are facing increasing depletion; and global climate change and environmental pollution have also caused serious impact on human survival. In this context, countries all over the world are considering the sustainable development of energy and environment in their countries, and they all regard energy conservation, environmental protection and the search for new energy sources as the key development strategies in the national energy field.

Global energy demand in 2020 fell by 4%, the largest decline since World War II and the largest ever absolute decline. The latest statistical data for energy demand in the first quarter of 2021 highlights the continued impacts of the pandemic on global energy use. Building on Q1 data, projections for 2021 indicate that as Covid restrictions are lifted and economies recover, energy demand is expected to rebound by 4.6%, pushing global energy use in 2021 0.5% above pre-Covid-19 levels. The outlook for 2021 is, however, subject to major uncertainty. It depends on vaccine rollouts, the extent to which the Covid-19-induced lockdowns scarred economies, and the size and effectiveness of stimulus packages. Current economic outlooks assume global GDP will surpass 2019 levels, lifting demand for goods, services and energy. However, transport activity and, particularly, international travel remain severely suppressed. If transport demand returns to preCovid levels across 2021, global energy demand will rise even higher, to almost 2% above 2019 levels, an increase broadly in line with the rebound in global economic activity (Fig.1-1).

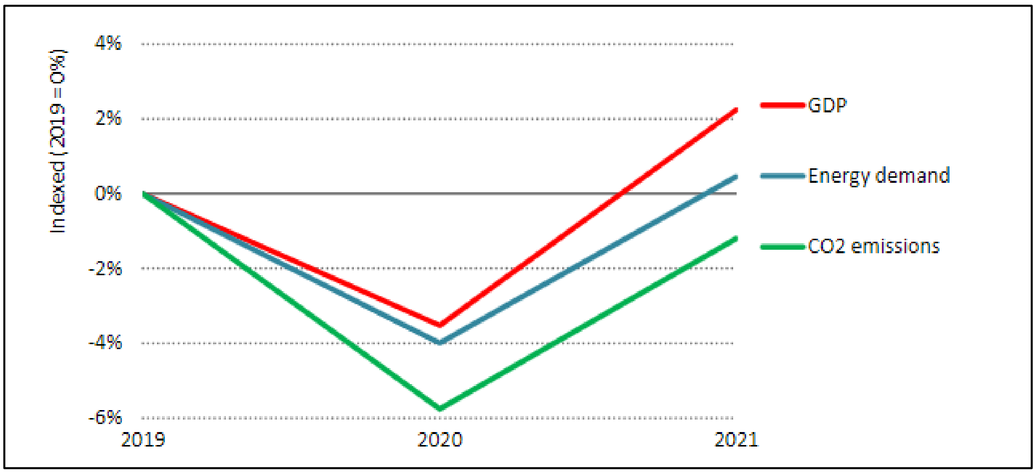

Fig.1-1 Evolution of global GDP, total primary energy demand, and energy-related CO_2 emissions, relative to 2019 [1].

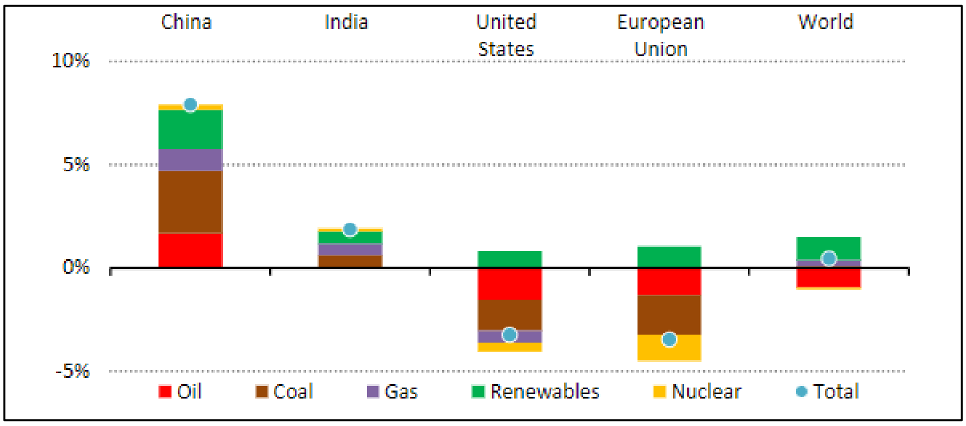

Fig.1-2 Change of primary energy demand by region and by fuel in 2021 relative to 2019 [1]**.**

The drop in demand in 2020 did not affect all fuels evenly. Oil was by far the hardest hit, with restrictions on mobility causing demand for transport fuels to fall by 14% from 2019 levels. At the peak of restrictions in April, global oil demand was more than 20% below pre-crisis levels. Overall, oil demand was down by almost 9% across the year (Fig.1-2).

In 2021, oil demand is expected to rebound by 6%, faster than all other fuels. The last time oil demand increased this rapidly was in 1976. Despite the strong rebound, oil demand remains 3% (3.1 mb/d) below 2019 levels. Road transport activity has remained subdued through much of the year, expected to recover to pre-Covid-19 levels only in the last months of 2021, while air transport demand is on track to remain markedly below 2019 levels for all of 2021. Only in Asia and, notably, in China does oil demand climb well above pre-Covid-19 levels. In 2020, coal demand dropped by 220 million tons of coal equivalent (Mtce), or 4%. The largest declines in coal use for electricity generation were in advanced economies, down 15%, which accounts for more than half of coal's global decline. Coal was particularly squeezed in the power mix by lower electricity demand, increasing output from renewables, and low gas prices.

In 2021, coal demand has rebounded strongly, reversing all of the declines in 2020, though with major geographic variations. The decline in 2020 was concentrated in the United States and Europe, and demand in advanced economies is expected to recover only onequarter of its 2020 drop, curtailed by renewables deployment, lower gas prices and phase-out policies. Meanwhile, China is projected to account for 55% of the 2021 increase.

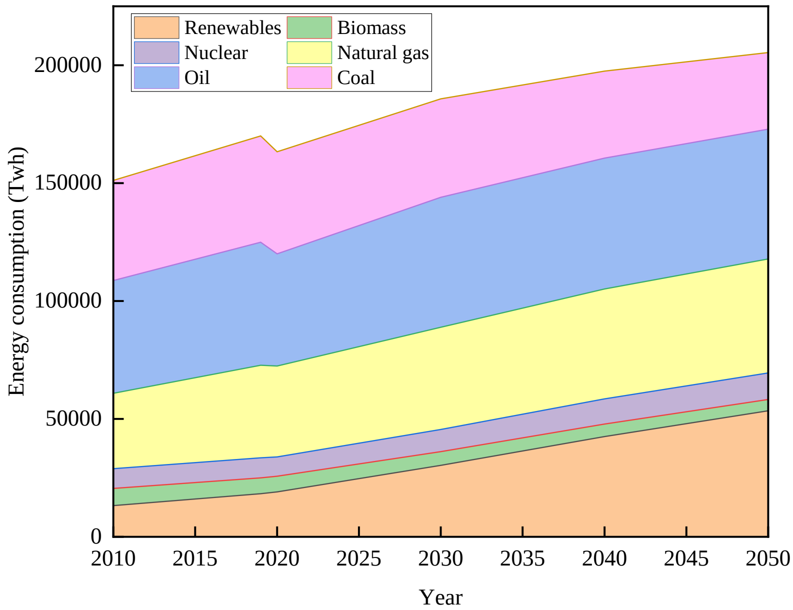

Fig.1-3 Global energy consumption [2].

According to BP's "Energy Outlook 2021" forecast for the future energy development trend, coal demand rises slightly by 2025, but falls below 2020 levels by 2030, while oil and gas demand increases: demand growth for fossil fuels and renewables is roughly flat, with the share of fossil fuels in the global energy mix falling only slightly from 79% today to 75% in 2030. In the Asia-Pacific region, coal demand falls by 10% by 2030, oil and gas demand grow at half the rate of these steps, and nearly 85% of demand growth is met by renewables, so that the share of nuclear and renewables rises from 17% to 24% in 2030, while the share of fossil fuels in the global energy mix falls to 72% (Fig.1-3).

Primary energy consumption decreased by 4.5% last year, the first decline in energy consumption since 2009. The decline was driven largely by oil (-9.7%), which accounted for almost three quarters of the decrease. Consumption for all fuels decreased, apart from renewables (+9.7%) and hydro (+1.0%). Consumption fell across all the regions, with the largest declines in North America (-8.0%) and Europe (-7.8%). The lowest decrease was in Asia-Pacific (-1.6%) due to the growth in China (+2.1%), the only major country where energy consumption increased in 2020. In the other regions, the decline in consumption ranged between -7.8% in South and Central America to -3.1% in the Middle East.

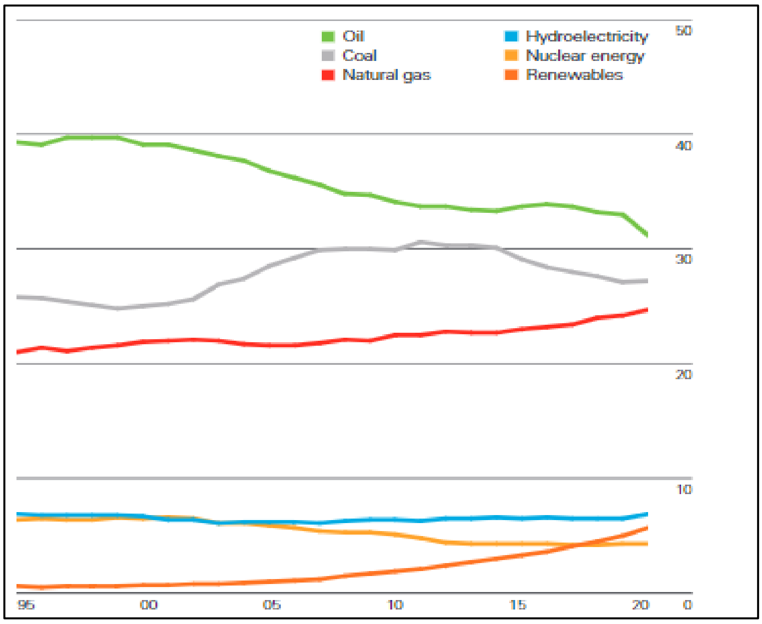

Fig.1-4 Shares of global primary energy [2]**.**

Oil continues to hold the largest share of the energy mix (31.2%). Coal is the second largest fuel in 2020, accounting for 27.2% of total primary energy consumption, a slight increase from 27.1% in the previous year. The share of both natural gas and renewables rose to record highs of 24.7% and 5.7% respectively. Renewables has now overtaken nuclear which makes up only 4.3% of the energy mix. Hydro's share of energy increased by 0.4 percentage points last year to 6.9%, the first increase since 2014 (Fig.1-4).

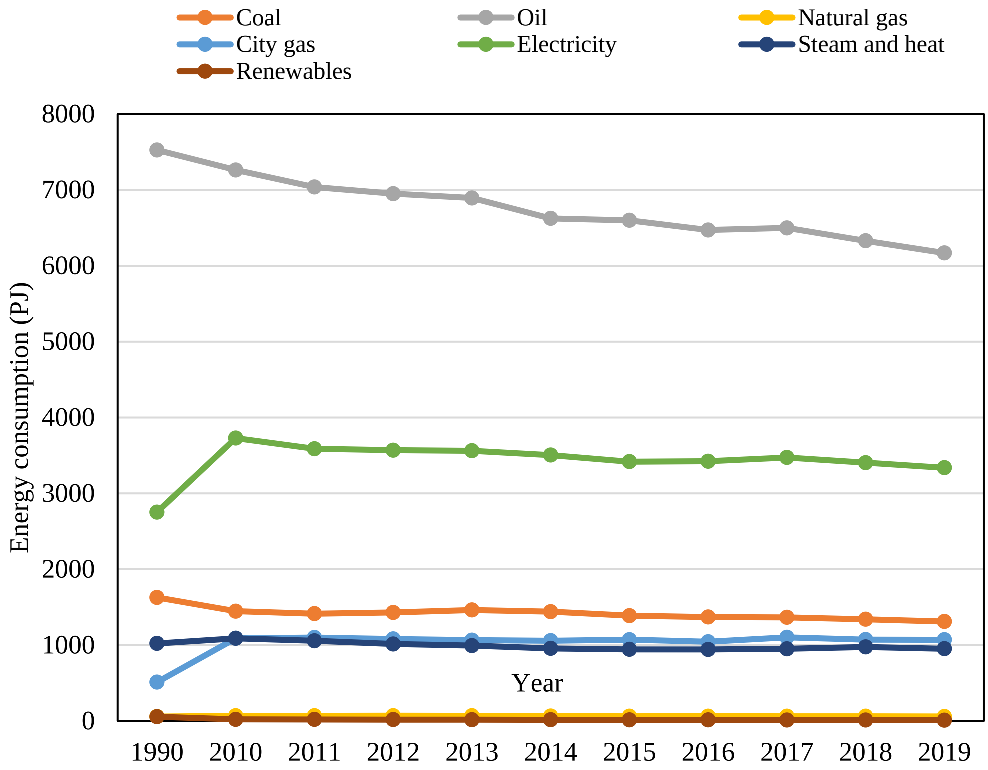

Fig.1-5 Energy classification final energy consumption in Japan [3]

Although city gas showed an increasing trend after Heisei 2 (1990 year) in Japan, it peaked in Heisei 19 (2007 year) and tended to be flat or slightly decreasing thereafter. in 2019 year, although the livelihood sector (household sector, business other sectors) increased, the manufacturing sector showed a larger decrease of 0.2% from the previous year to 1,070 PJ. Electricity consumption decreased by 1.9% from the previous fiscal year to 338 PJ due to a decrease in demand for heating and cooling caused by cold summers and warm winters. despite this, the proportion of electricity in final energy consumption (electrification rate) increased from 20.3% in fiscal 1990 to 25.8% in 2019 year. Coal (including coal products) decreased in manufacturing industries (mainly steel and kiln earth and stone) by 2.1% from the previous fiscal year to 1,311 PJ, the sixth consecutive year of decrease. However, it is the third source of energy after oil and electricity in final consumption (Fig.1-5).

1.1.2 Impact of energy on the environment

Energy and the environment have a very close relationship, on the one hand, in the process of obtaining and using energy, human beings will change the original natural environment or produce a large amount of waste, if not handled properly, it will make the environment on which human beings depend to survive is damaged and polluted, on the other hand, energy and economic development, and the improvement of the environment plays a huge role in promoting. Since 2007, China has become the world's second largest energy producer and consumer, and the world's second largest emitter of carbon dioxide. Due to the unreasonable energy structure and low utilization rate of energy in China, it has caused serious waste of resources, which in turn has a serious impact on the environment, mainly urban air pollution, greenhouse effect, acid rain, nuclear waste problems, etc.

Fig.1-6 shows the global annual fossil CO_2 emissions. Global fossil CO_2 emissions in 2021 are set to rebound 4.9% after a record 5.4% drop in 2020. This follows a decade of strong and growing energy decarbonization which reduced the growth of emissions. Coal and gas use grow more in 2021 than they fell in 2020. Oil use remains below 2019 levels (Fig.1-7).

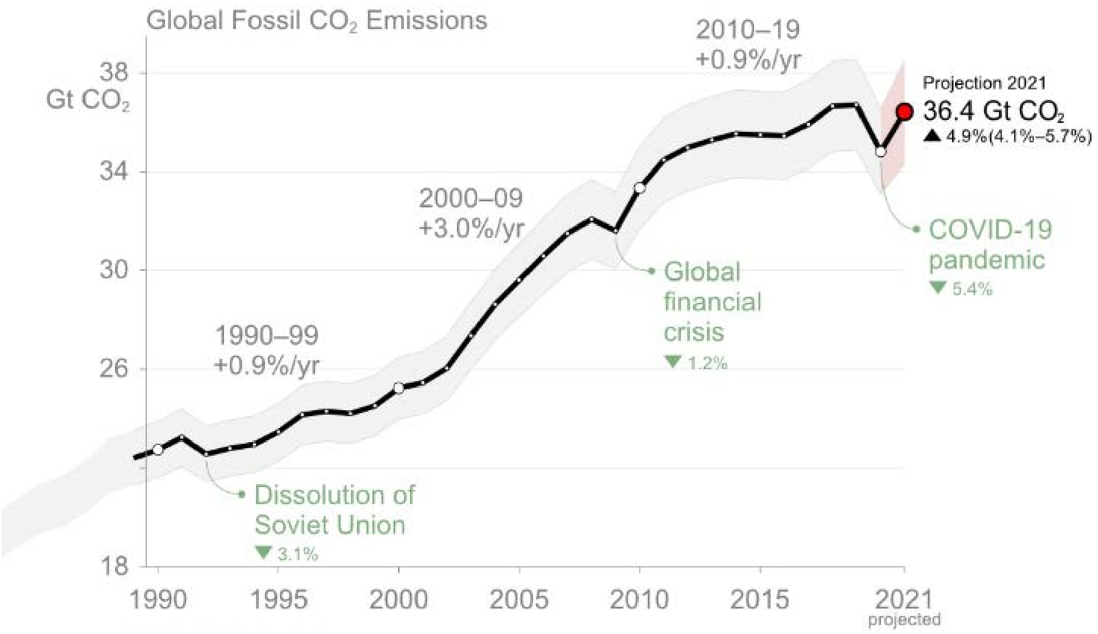

Fig.1-6 Global fossil CO_2 emissions [4]

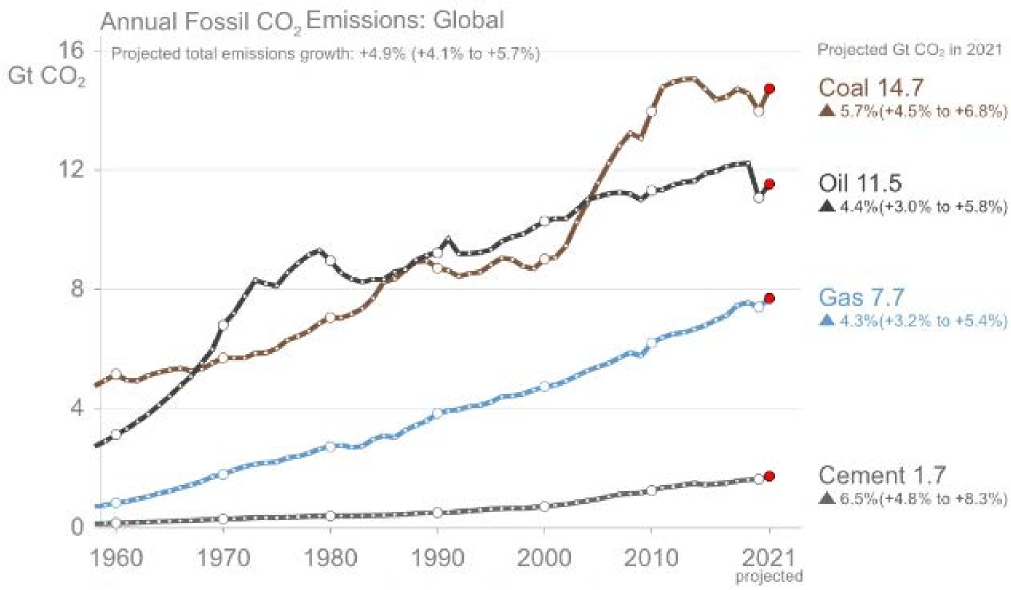

Fig.1-7 Global annual fossil CO_2 emissions [4]

1.2 Distributed energy resource (DER) system

1.2.1 Concept of DER system

In recent years, fossil fuels have been rapidly depleted and environmental pollution has been severe. Therefore, there is an urgent need to find alternatives to fossil fuels and to utilize state-of-the-art technologies to improve energy efficiency. Distributed energy resource (DER) system has now attracted widespread attention. Unlike conventional energy supply systems where production is usually far from the user. DER refers to an energy system where energy is produced close to end use, typically relying on a number of modular and small-scale technologies [5]. The ploy-generation systems can be Combined Heating and Power (CHP) system, Combined Cooling, Heating and Power (CCHP) system, and so on [6]. CCHP systems use waste heat from on-site electricity generation to meet the thermal demand of the facility [7]. Energy cascading utilization can be realized as possible by the poly-generation process in DER [8].

DER is a faster, less expensive option to the construction of large, central power plants and high-voltage transmission lines. They offer consumers the potential for lower cost, higher service reliability, high power quality, increased energy efficiency, and energy independence. The use of renewable distributed energy generation technologies and "green power" such as wind, photovoltaic, geothermal, biomass, or hydroelectric power can also provide a significant environmental benefit. Fig.1-8 shows the schematic diagram of DER system.

The new paradigm calls for use of local resources, such as rooftop solar, small natural gas generators, and microgrids that combine several electricity solutions. Rather than being in another city or even state, these are resources located within neighborhoods, businesses, college campuses, hospitals, and government complexes-near the communities they serve. The proximity of electrical energy consumption prevents the loss of electricity as it passes through the wires. This translates into higher efficiency, which in turn can reduce energy costs while achieving more sustainable electricity. But this reconfiguration has implications beyond geography. It can change who is in charge of the electricity. Electricity, once almost entirely in the hands of utilities, can now be generated and controlled by independent companies as well as those that use it. Consumers and businesses can produce their energy and, in some cases, sell excess energy back into the market, something that once was only possible for energy companies.

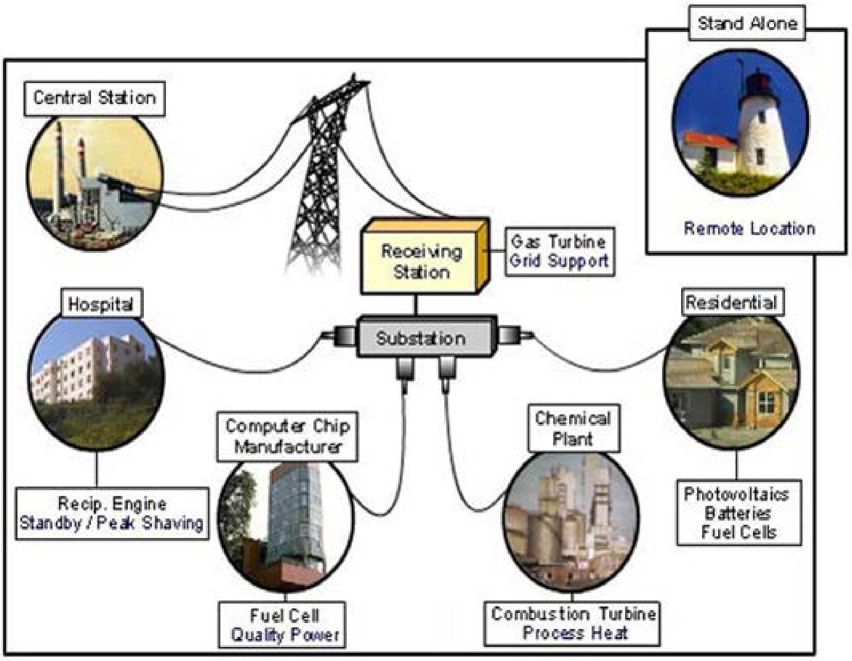

Fig.1-8 Schematic diagram of DER system [9].

1.2.2 Advantages of DER system

DER system can provide a range of benefits, and a good policy and regulatory environment is needed to ensure that distributed energy systems actually realize these possible benefits. Moreover, the combination of DES with large-scale centralized systems is often a smart combination to help maximize benefits.

1) Close to the demand users

According to the definition of distributed energy sources, they are located near the customer's load. This not only distinguishes them from centralized supply, but also brings many benefits:

a. Localization of energy development

Depending on local resource availability, climate and geographical conditions, DES can optimize the supply mix. Various energy sources (e.g., natural gas, wind, solar, geothermal, biomass, ocean and industrial waste heat) can be integrated to best meet local demand. This can also help improve energy security, as natural disasters that cause massive power outages often have serious and even life-threatening impacts on people's lives; Hurricane Sandy on October 29, 2012 caused 7.4 million power outages in the U.S., preventing banks, exchanges, hospitals, and security agencies from operating normally. At this time, if a distributed energy system was used instead of a centralized power supply system, the impact of natural disasters in terms of power outages would be minimized.

In addition, the localization of DER brings the potential for small businesses to play an active role in energy supply, giving electricity users greater ownership of the energy system. Of course, this can be a huge challenge to the traditional business model of large utilities.

b. Reduce transmission and distribution costs

Transmission and distribution cost costs are an important part of the total cost of the power system, typically accounting for about 30% of the final electricity bill. The supply of locally distributed generation can significantly reduce transmission losses. If local supply and demand are balanced, it is possible to move closer to demand and minimize the use of the transmission and distribution network. Such a system can save considerable money, labor and time in building and maintaining large scale infrastructure. Increased DER usage can reduce revenues from large-scale infrastructure, so grid tariffs need to be set in a way that reflects the overall value of the DER system.

c. Improve understanding of customer needs

DER can be tailored to local energy needs, which vary greatly depending on the end-user profile, from industrial parks, commercial centers, data centers, office buildings, medical facilities and transportation hubs to cultural and sports facilities. Fully understand the load characteristics (including their temporal characteristics), heating and cooling requirements and desired reliability levels and use this data to optimize the energy supply for the purpose of building a reliable DER. A good example is the Shanghai Tower, a 128-story skyscraper in the Lujiazui area of Shanghai, which is 632 meters tall. The building has installed a DER with two 1,165 kW gas-fired generators, two 1,047 kW lithium bromide absorption chillers and two 1,368 kW heat exchangers and auxiliary systems. The DES is connected to the municipal grid, as well as an ice storage system, boilers and electronic cooling plants to create a complete energy system for the building, providing a total area of 279,700 m2 with heating, cooling and electrical services. During the heating season, the maximum thermal load is 10 MW in January and a minimum of 6.1 MW in December. The annual utilization time is not less than 5,360 hours, with a generation capacity of 12,489 MWh, a heat supply of 16,651 GJ and an annual cooling supply of 31,729 GJ.

2) High energy efficiency

High energy efficiency is a key advantage driving the continued deployment of distributed energy globally. High energy efficiency can be achieved through three applications: multi-energy and multi-stage energy use, multi-energy complementarity, and the use of waste heat and pressure.

a. Multi-energy and multi-level energy use

Multi-stage energy utilization requires the use of waste heat from power generation for further power generation as well as cooling and heating services. The efficiency performance of the whole system can reach 70-90%. DES can implement this approach very well, as heating and cooling products are best suited for short transport distances.

One of the typical cases is the natural gas distributed energy station project in the core area of Shanghai International Tourism Resort. This project provides five kinds of loads, including cooling, heating, electricity, domestic hot water and compressed air, to the core area of Shanghai International Tourism Resort (Disneyland) by consuming a single clean energy source, natural gas, realizing the five kinds of energy supply, and the comprehensive utilization rate of primary energy reaches 83.41%, which is much higher than the conventional distributed The comprehensive utilization rate of primary energy reaches 83.41%, which is much higher than the requirement that the primary energy utilization rate of conventional distributed energy supply system is more than 70%, and has reached the world advanced level. Through the efficient tertiary utilization of natural gas clean energy, it not only meets all the energy needs in the core area of 3.9 square kilometers, but also builds a low-carbon and energy-saving tourist resort (21,883.08 tons of standard coal can be saved each year, and the annual CO_2 emission reduction is 75,541.87 tons, which is equivalent to 40,000 tons less wood cut each year).

b. Multi-energy complementary

Distributed energy can combine and optimize a variety of energy sources, including wind, solar, natural gas, biomass and other options, including hydrogen energy. The optimal mix can be chosen based on the end-user's geographic location, resource endowment and consumption patterns. When such optimization is well implemented, high overall system efficiency can be achieved by leveraging complementary energy resources and technologies.

c. Utilization of waste heat and pressure

Waste heat and pressure can be an important source of unconsumed energy for various industries such as steel, non-ferrous metals, chemicals, cement and ceramics. For example, flue gases in carbon calcination plants can reach temperatures of 850°C to 900°C. Providing heating, cooling and electrical excess heat and residual pressure not only helps to reduce energy consumption and improve energy efficiency, but also reduces industrial pollution and provides energy-saving options for industry.

3) Use of clean and low carbon energy

Distributed energy can help transform a fossil fuel-based centralized energy system into a cleaner, more diverse energy system that includes a variety of energy sources including wind, solar photovoltaic, solar thermal, renewable energy such as biomass and geothermal, as well as low-carbon fossil fuels such as natural gas. This can have many benefits. These benefits may be direct - such as providing cleaner generation - or indirect, such as providing the flexibility to integrate a higher share of variable generation.

a. Integration of variable renewable energy sources

Variable Renewable Energy Sources (VRE), especially solar photovoltaic and wind power, have characteristics that require multiple specific measures to integrate them into the power system. Most importantly, their maximum output at any given moment is limited by the immediate availability of sunlight and wind. As a result, their output often fluctuates, and these fluctuations can only be predicted to a certain level of accuracy.

DER can provide solutions for the cost-effective and secure integration of wind and solar energy in several ways. First, VRE generation can be included in a DER, geographically extending its deployment and thus smoothing the overall output (when considering multiple DERs). Second, by combining wind and solar in an optimized ratio, their combined variability can be lower (there is typically more wind when there is less sunlight and vice versa). Third, modern DER can dynamically adjust energy consumption to better match wind and solar availability using digital monitoring and control devices. Fourth, other generation sources such as flexible gas generators can balance the remaining variability. Fifth, end-use electrification devices such as electric vehicles can help create new, flexible demand that absorbs potential wind and solar surpluses.

b. Reduction of air pollutant emissions

Compared to centralized coal-based generation systems, distributed energy sources can significantly reduce sulfur dioxide, nitrogen oxide and particulate matter emissions as natural gas generators plow the ground with emissions, while distributed solar PV and wind have zero emissions. For example, the Shanghai Tower project reduced 38 tons of sulfur dioxide emissions per year, and the Guiyang project successfully reduced 498 tons of sulfur dioxide emissions and 249 tons of dust emissions. Modern DER also avoids the particulate emissions associated with the traditional use of biomass.

c. Reduction of carbon emissions

DER can reduce CO_2 emissions by relying on low or no carbon energy supply. the heating and cooling decarbonization capability of DER is also a significant benefit: heating demand accounts for about 30% of global energy-related CO_2 emissions, half of which are used in buildings. Carbon emissions from heating demand can be reduced using CHP systems based on natural gas, biomass, biogas or low-carbon electricity. For example, the Shanghai Tower project reduces CO_2 emissions by 4,855 tons per year, the Gui'an project by 61,464 tons, and the Shanghai Disneyland project by 75,542 tons.

d. Reduction of fossil fuel consumption

Using clean and renewable resources, distributed energy helps reduce fossil fuel consumption, thereby indirectly reducing energy consumption and ecosystem damage associated with fossil fuel extraction and transportation activities. For example, the Shanghai Tower project saves 1,890 tons of standard coal per year, the Gui'an project 24,884 tons, and the Shanghai Disneyland project 21,883 tons.

1.2.3 Application of DER system

Qingmei Wen et al. [10] presented a block diagram of the application level of DER system is shown in Fig.1-9. In the individual building level, the public building involves hospitals and education buildings, etc., and the commercial building usually involves hotels, commercial office buildings and shopping complex, etc. [11]. In district level, the neighborhood can be residential neighborhood [12] and mixed-used neighborhood [13], while the community can be residential community [14], university campus [15] and mixed-use community [16].

1) Building level

The applications of residential-grade and industrial building-grade DER were analyzed, and Li et al. [17] and Isa et al. [11] provided excellent evaluations of large residential building-grade DER, public building-grade DER, and commercial building-grade DER, respectively.

2) District level

Neighborhood-level DES applications are more complex than individual building-level applications for two reasons. First, the design of neighborhood-level DER more often involves distributed generation scheduling than building-level DER. Second, the design of neighborhood-level DER involves energy supply network planning, whereas building-level DER does not. Community-level DER applications typically emphasize renewable energy development aimed at achieving energy self-sufficiency and/or generating positive economic effects.

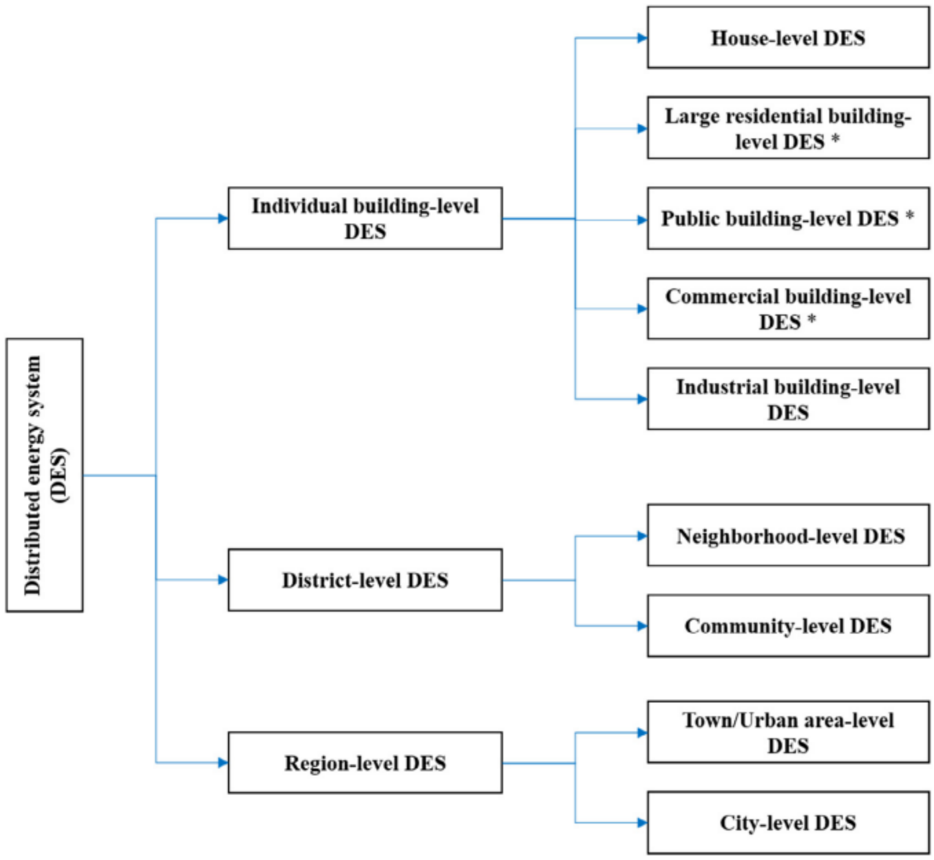

Fig.1-9 Block diagram of the application level of DER system [10]**.**

3) Region level

Currently, the application of regional-level DER is not as mature as the application of building-level and regional-level DER. Some studies have been conducted on the planning of regional-level DER applications. Dou et al. [18] explored the feasibility of developing a heat exchange network between incineration facilities and industry in the Tokyo metropolitan area using a four-step model that included heat mapping and network analysis, hydraulic calculations of the heat supply network, evaluation, and decision making. To reduce the computational complexity of the DER design model, Falke et al. [19] decomposed the design problem into three subproblems, including heat network planning, generator unit design and retrofit measures, and operation simulation. Fonseca et al. [20] presented City Energy Analyst, a tool for analyzing and optimizing energy systems at the community and city level, and tested its applicability with an industrial site in the city of Zug, Switzerland.

1.2.4 Technologies of DER system

The term “distributed energy resource” encompasses a variety of the distributed technologies such as CHP, Renewable generation, Energy storages and Fuel cells as shown in Fig.1-10 [21].

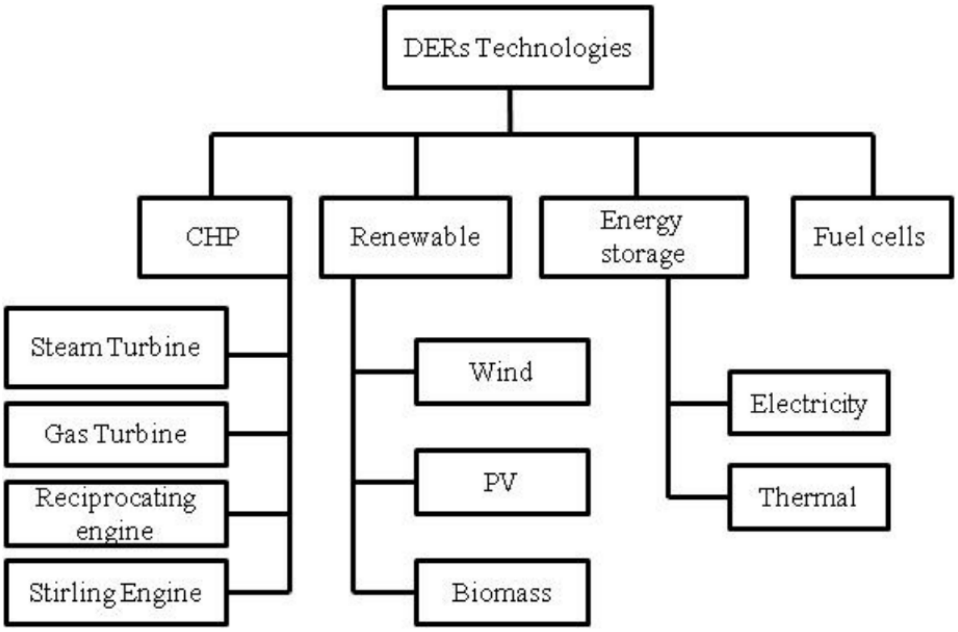

Fig.1-10 Technologies of DER system [21]**.**

1) CHP technologies

Steam turbine is also known as steam turbine engine, is a rotary steam power plant, high temperature and high-pressure steam through a fixed nozzle into an accelerated airflow and then injected into the blades, so that the rotor equipped with blade row rotating, while doing external work. The layout of the steam turbine as shown in Fig.1-11. Steam turbine is the main equipment of modern thermal power plant, also used in metallurgical industry, chemical industry, naval power plant. Steam turbine is a kind of steam as the power, and the steam heat energy into mechanical work of the rotating machinery, is the most widely used in modern thermal power plants in the prime mover. The turbine has the advantages of high single-unit power, high efficiency and long life. Due to the continuous development of metallurgical technology, the turbine structure has also been greatly improved. Large units generally use the double-layer structure of high and medium pressure combined cylinder, high and medium pressure rotor using a rotor structure, high, medium and low-pressure rotor all use the whole forging structure, bearing more tiltable tile structure. All countries are developing and designing large-capacity and high-parameter units, such as the 2000MW turbine being developed in Russia. Japan is developing a new alloy material, which will make it possible to integrate high, medium and low-pressure rotors.

The gas turbine is an internal combustion type power machine that uses continuously flowing gas as the working mass to drive the impeller to rotate at high speed to transform the energy of the fuel into useful work, and is a rotary impeller type heat engine. The typical configuration of the single-shaft gas turbine and the measurement points are shown in Fig.1-12. The compressed air is pressed into the combustion chamber and mixed with the injected fuel to generate high temperature and high-pressure gas; then it enters the turbine to expand and do work, driving the turbine to drive the compressor and external load rotor to rotate together at high speed to realize the partial conversion of chemical energy of gas or liquid fuel into mechanical work. into mechanical work and output electrical work. The exhaust gas from the turbine is discharged to the atmosphere for natural exotherm. In this way, the gas turbine converts the chemical energy of the fuel into thermal energy and part of the thermal energy into mechanical energy. Usually in a gas turbine, the compressor is driven by the expansion of the gas turbine to do work, which is the load of the turbine. In a simple cycle, about 1/2 to 2/3 of the mechanical work from the turbine is used to drive the compressor, and the remaining 1/3 is used to drive the generator. When the gas turbine starts, it first needs external power, usually the starter drives the compressor, until the mechanical work issued by the gas turbine is greater than the mechanical work consumed by the compressor, the external starter is decoupled and the gas turbine can work independently by itself.

Reciprocating engine, also called piston engine, is an engine that uses one or more pistons to convert pressure into rotational kinetic energy, and is also a machine that converts the kinetic energy of the pistons into other mechanical energy, mainly by using the thermal energy generated by the combustion of fuel through the expansion of liquid (such as water) or gas, thus pushing the pistons and converting thermal energy into kinetic energy. The schematic of reciprocating engine is shown in Fig.1-13.

Stirling engine, which is appropriate for a domestic environment with a small capacity, has a high theoretical efficiency and the low emissions of NO_X [21]. Stirling engine is the British physicist Robert Stirling invented in 1816, so named "Stirling engine". Stirling engine is through the cylinder working medium (hydrogen or helium) after cooling, compression, heat absorption, expansion for a cycle to output power, so also known as the hot gas engine. Stirling engine is an external combustion engine, its effective efficiency is generally between the gasoline engine and diesel engine. Stirling engine is the British physicist Robert Stirling invented in 1816, so named "Stirling engine". Stirling engine is through the cylinder working medium (hydrogen or helium) after cooling, compression, heat absorption, expansion for a cycle to output power, so also known as the hot gas engine. Stirling engine is an external combustion engine, its effective efficiency is generally between the gasoline engine and diesel engine.

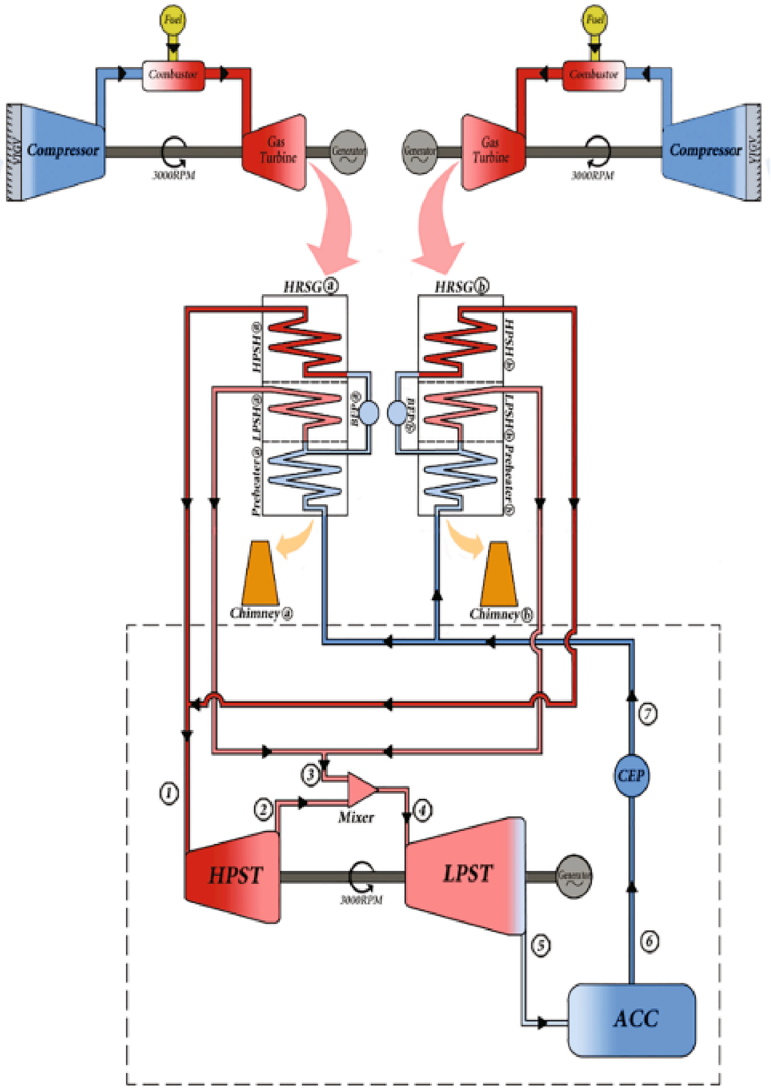

Fig.1-11 The layout of the steam turbine [22].

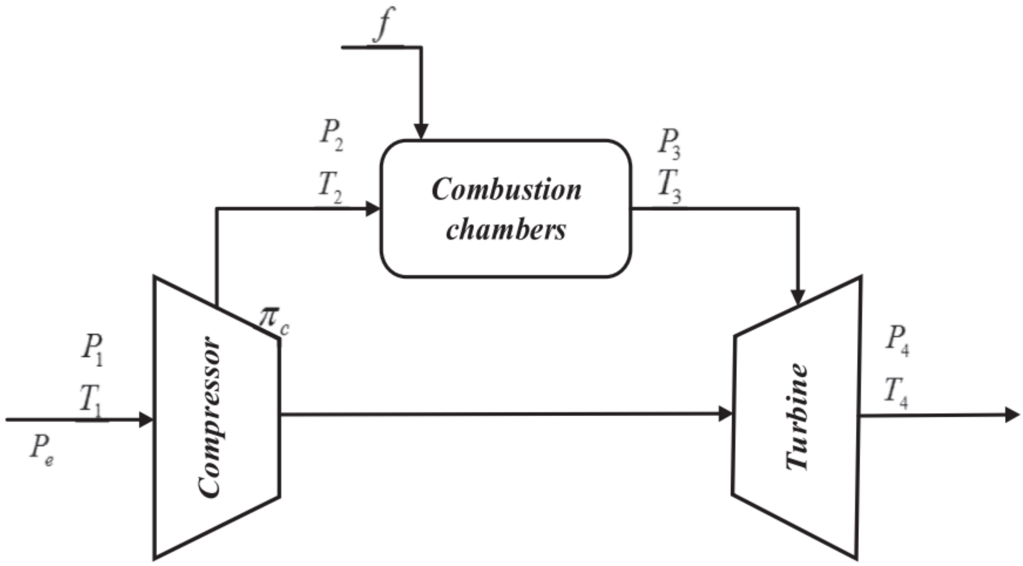

Fig.1-12 Typical configuration of gas turbine [23].

(Notes: T_0: Ambient temperature; f: Fuel coefficient; P_e: Power output; T_4': Turbine exhaust temperature; T_2: Compressor outlet temperature; p_2: Compressor outlet pressures; π_c: Pressure ratio)

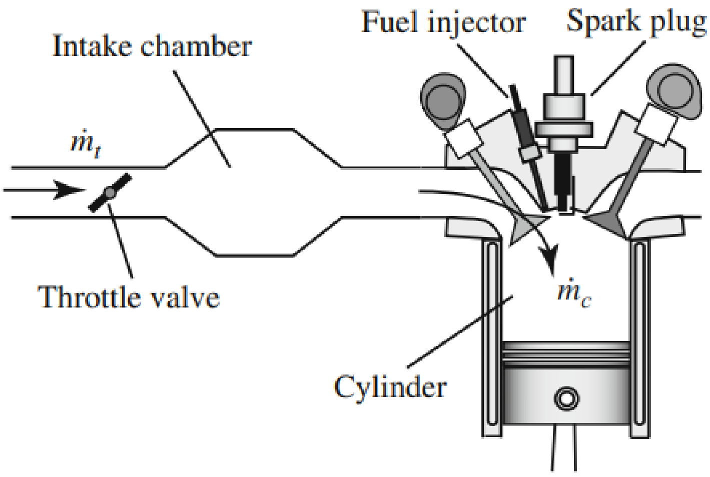

Fig.1-13 Schematic of reciprocating engine [24]**.**

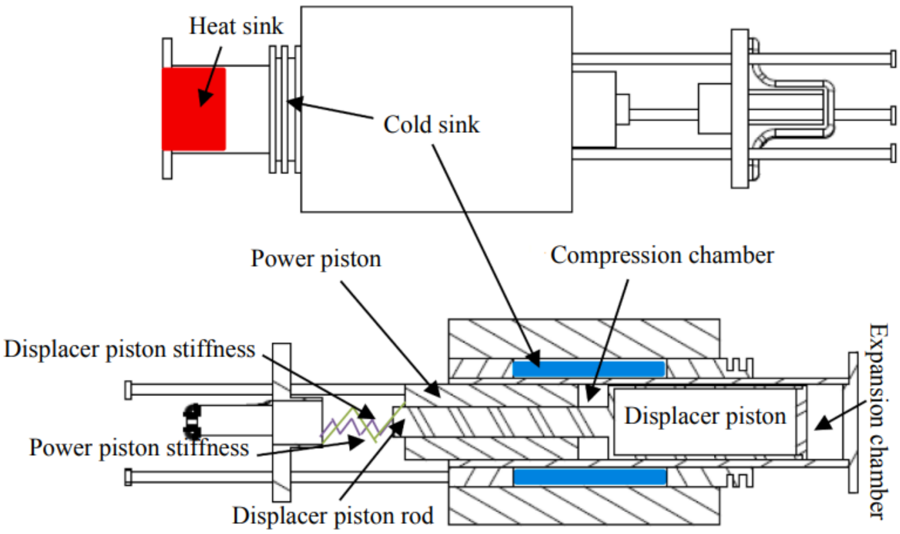

Fig.1-14 Schematic of Stirling engine [25]**.**

2) Renewable technologies

Renewable energy refers to non-fossil energy such as wind, solar, hydro, biomass and geothermal energy, which are clean energy sources. Renewable energy is a green and low-carbon energy source, an important part of China's multi-wheel drive energy supply system, which is important for improving energy structure, protecting ecological environment, coping with climate change, and achieving sustainable economic and social development.

A wind turbine is a type of turbine that uses wind energy for power. An aerospace research facility in Wilbraham, Massachusetts, has developed a wind turbine that generates electricity at half the cost of a conventional turbine. The wind resource in the cold climate is beneficial to the increase of wind power generation, due to higher wind speed and denser cold air [26]. Wind turbine, the new design produces electricity comparable to conventional wind turbines, but the blades are only half the diameter. The smaller blade size and other factors allow the new turbine to be clustered more closely than conventional turbines, increasing the amount of electricity produced per acre of land.

Solar energy is energy from celestial bodies outside the earth (mainly solar energy), is the sun's hydrogen atomic nuclei at ultra-high temperatures when the fusion of the release of enormous energy, the vast majority of human energy needs are directly or indirectly from the sun. The fossil fuels such as coal, oil, and natural gas that we need to live are formed by various plants through photosynthesis after converting solar energy into chemical energy stored in plants and then by buried plants and animals over a long period of geological time. In addition, water, wind, wave and ocean current energy are also converted from solar energy.

Biomass is the use of the atmosphere, water, land, etc. through photosynthesis to produce a variety of organisms, that is, all living organic matter that can grow collectively referred to as biomass. Biomass energy, is the form of energy that solar energy is stored in biomass in the form of chemical energy, that is, energy in the form of biomass as a carrier. It comes directly or indirectly from the photosynthesis of green plants, and can be converted into conventional solid, liquid and gaseous fuels, which are inexhaustible and a renewable energy source, as well as the only renewable carbon source. The conversion technologies of biomass energy mainly include direct oxidation (combustion), thermochemical conversion and biological conversion. Biomass power generation technology is a thermal power generation technology using biomass and its processing into solid, liquid and gas as fuel. Its generators can be gas engine, Stirling engine, gas turbine and steam turbine depending on the fuel, temperature and power respectively.

3) Energy storage

Even in ancient times, mechanisms for storing energy for delayed use were known. These were, of course, the classic types and methods, such as preventing wood from getting wet at night and during rainy season burning. However, due to the development of technology, methods and devices continue to change and improve in different times. The first system device was the battery, which is still the most commonly used technology for energy storage because its output exceeds 90%. Volta's battery was the first one invented in 1800. This original battery was made of zinc and copper sheets that alternated with each other, but had a wire separating them. The energy storage technologies and devices can be classified on various bases. The categorization of EES technologies may be functions-based, time of response or storing periods as shown in Fig.1-15.

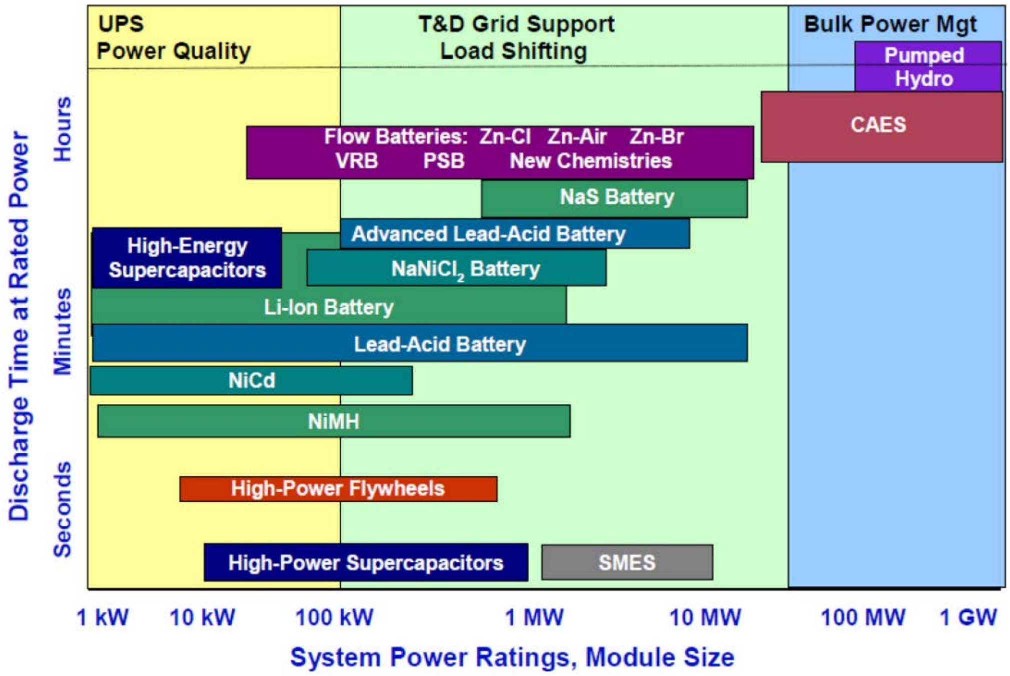

Fig.1-15 Energy storage technologies [27].

4) Fuel cells

Fuel cell is a chemical device that converts the chemical energy of fuel directly into electrical energy, also known as electrochemical generator. It is the fourth power generation technology after hydroelectric power, thermal power and atomic power. In addition, fuel cells use fuel and oxygen as raw materials and have no mechanical transmission parts, so they emit very few harmful gases and have a long service life. Thus, from the perspective of energy saving and ecological environment protection, fuel cell is the most promising technology for power generation. The principle of fuel cell is an electrochemical device with the same composition as a general battery. Its single cell is composed of positive and negative electrodes (negative electrode, i.e., fuel electrode, and positive electrode, i.e., oxidizer electrode) and electrolyte. The difference is that the active material of the general battery is stored inside the battery, thus limiting the battery capacity. In contrast, the positive and negative electrodes of a fuel cell do not contain active material per se, but are only catalytic conversion elements. Therefore, the fuel cell is a veritable energy conversion machine that converts chemical energy into electrical energy. When the cell works, the fuel and oxidizer are supplied externally to carry out the reaction. In principle, as long as the reactants are continuously fed and the reaction products are continuously removed, the fuel cell can continuously generate electricity. Fuel Cell Power Plants (FCPP), particularly Proton Exchange Membrane Fuel Cells (PEMFCs), generated tremendous interest for electricity and heat generation due to its low operating temperature, fast start up characteristics and environmental cleanness [28].

1.3 Research purpose

1.3.1 Research purpose and core content

The research purpose and logic of the research is shown in Fig.1-16. Below. In order to deal with energy depletion and environmental problems, this study focuses on the development potential of distributed energy resource (DER) system. Equipment maintenance management and system design are important factors affecting the economic and environmental benefits of the DER system. Therefore, this paper first analyzed the operation and maintenance status of the DER system, and established the life cycle assessment model of the DER system, analyzed the economy, energy consumption and environment performance of the DER system. Through the analysis of the system operation and maintenance status, we optimized the equipment maintenance management, and established a comprehensive performance index method to optimize the capacity configuration and operation strategy of the DER system. The development potential of DER system is analyzed by comparing the three indexes of cost saving, energy saving and carbon emission reduction with the conventional energy system. It is hoped that this research can improve the core competitiveness of DER system and promote its development.

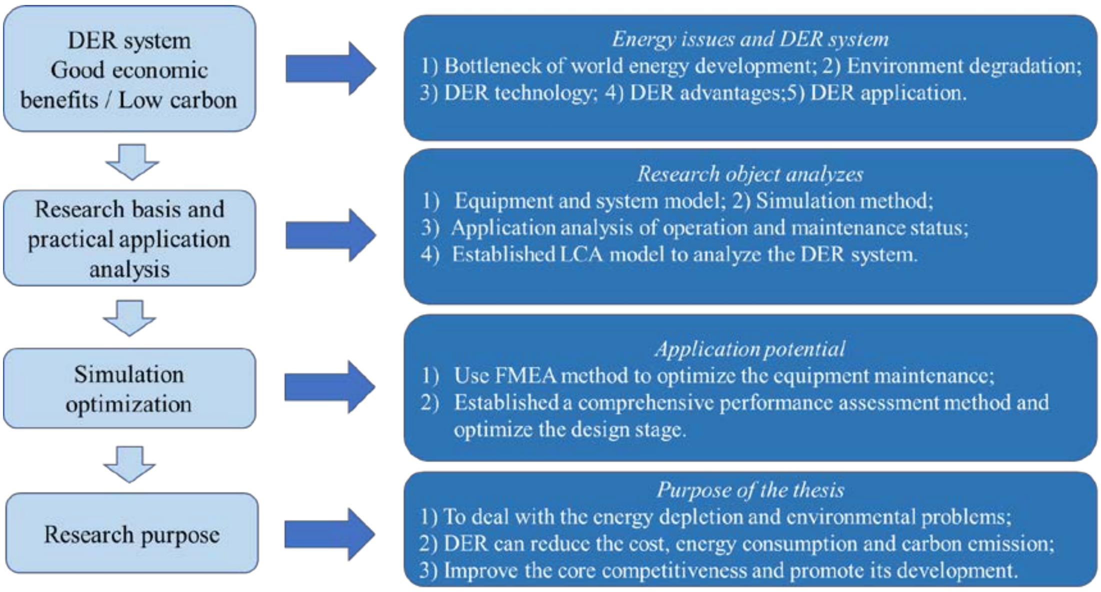

Fig.1-16 Research logic of the article.

1.3.2 Chapter content overview and related instructions

The chapter names and basic structure of the article are shown in Fig.1-17. The brief chapters introduction are shown in Fig.1-18.

Research background	**CHAPTER ONE** Background and purpose of the study	
Previous study	**CHAPTER TWO** Literature review of the distributed energy resource system	
Method	**CHAPTER THREE** Theories and methodology of the study	
Investigation and analysis	**CHAPTER FOUR** Investigation on real operation data of distributed energy resource system	**CHAPTER FIVE** Life cycle assessment analysis of distributed energy resource system
Optimization analysis	**CHAPTER SIX** Study on maintenance optimization of distributed energy resource system	**CHAPTER SEVEN** Comprehensive performance assessment and optimization of distributed energy resource system
Conclusion	**CHAPTER SEVEN** Conclusions	

Fig.1-17 Chapter name and basic structure

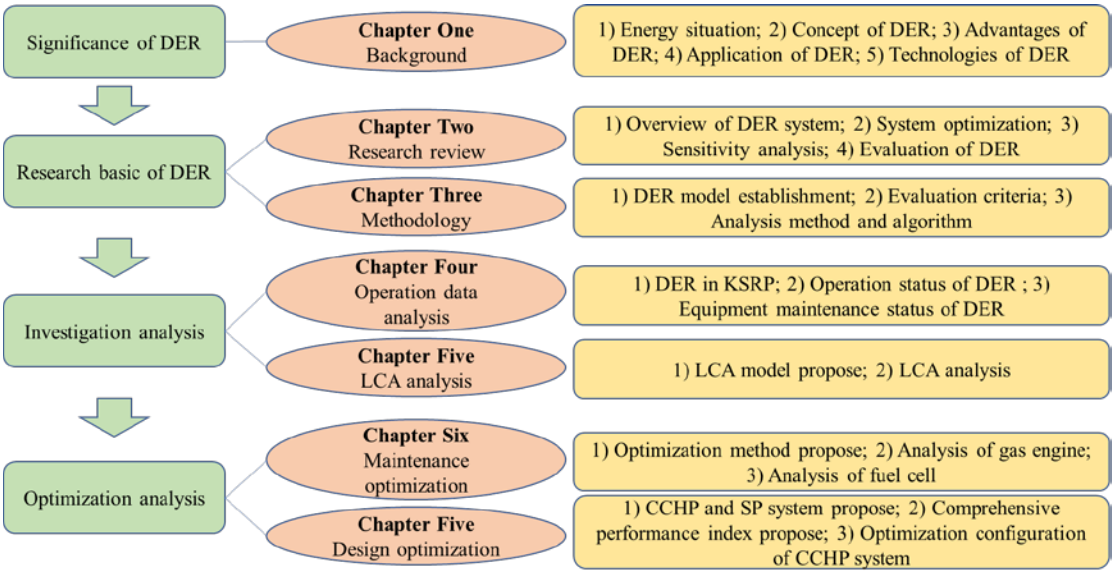

Fig.1-18 Brief chapter introduction

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

Owing to the continuous growth in the world's energy demand, the problems of energy consumption, greenhouse gas emission, and environmental pollution have become increasingly prominent. At present, countries all around the world have implemented energy-saving and emission reduction measures to achieve carbon neutralization. The distributed energy resource (DER) system is a high-efficiency energy system that can promote energy-saving and decrease carbon emissions. Given the current energy problems, this chapter discussed the significance of DER system for future energy development. In addition, the current state of development of DER system is examined, and technologies that can be applied to distributed energy systems are presented.

In Chapter 2, Literature review of the distributed energy resource system:

Research advances in the evaluation performance and maintenance management of DER systems are reviewed. DER is a complex system consisting of multiple devices that can provide multiple energy sources, and its configuration design and maintenance management determine the performance of the system and are the main research focus of DER. Therefore, the previous literature is reviewed.

In Chapter 3, Theories and methodology of the study:

In this section, the methodological study and the mathematical model were presented. And the system models are established. Also, the economy benefit, energy consumption, carbon emission reduction and maintenance management of the equipment of DER are analyzed. In addition, the simulation models and algorithms used in the follow-up study are provided.

In Chapter 4, Investigation on real operation data of distributed energy resource system:

In this chapter, the management of DER system in Kitakyushu Science and Research Park (KSRP) were investigated and analyzed in terms of operation status and maintenance management strategy.

In Chapter 5, Life cycle assessment analysis of distributed energy resource system:

Based on the analysis of the operation status of the DER system in chapter 4, this section proposed a life cycle assessment method to evaluated the DER system performance. The comprehensive benefits of DERs were analyzed in terms of economic benefit, energy consumption and environmental performance compared with conventional energy systems (CES), respectively.

In Chapter 6, Study on maintenance optimization of distributed energy resource system:

The maintenance strategy of the DES system in KSRP is analyzed and optimized. The main power generation units of the DER system in KSRP includes fuel cell and gas engine. Each generator has associated equipment, absorption chiller, heat exchanger, cooling tower, cooling pump, etc. The failure modes, failure causes, and failure effects of the components were investigated; and severity (S), occurrence (O), and detection (D) factors were evaluated. The maintenance strategy was optimized to improve maintenance and reduce the risk priority number (RPN). The results can be used as a reference for component maintenance optimization.

In Chapter 7, Comprehensive performance assessment and optimization of distributed energy resource system:

Different configurations of equipment will affect the performance of DER. In this section, a comprehensive performance assessment based on the economy, energy and environmental performance was proposed to optimize the system to find the optimal capacity. And discussed the impact of different electricity price mechanisms on the development of DER. The comprehensive evaluation index (CPI) was established based on economy, energy and environment performance, and a configuration optimization model of the DER with the maximum CPI as the goal was established by genetic algorithm (GA). Then, the development potential of the DER was evaluated by analyzing the economic saving, energy saving and carbon reduction performances.

In Chapter 8, Conclusion:

This part summarizes the research of previous chapter.

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Chapter 2

LITERATURE REVIEW OF THE DISTRIBUTED ENERGY RESOURCE SYSTEM

CHAPTER TWO: LITERATURE REVIEW OF THE DISTRIBUTED ENERGY RESOURCE SYSTEM

2.1 Overview of DER system

Recent years have witnessed a rapid depletion of fossil fuels and severe environmental pollution. Therefore, there is a desperate need to find alternatives to fossil fuels and take advantage of state-of-the-art techniques to enhance energy efficiency. Currently, the DES has attracted much attention. Different from conventional energy supply systems where productions are usually distant from users, DES is defined as a kind of energy system located at or near its end-users and characterized with high efficiency poly-generation systems, distributed renewable energy technologies, and smaller energy transmission network(s) than the conventional one. The poly-generation systems can be Combined Heating & Power (CHP) system, Combined Cooling, Heating & Power (CCHP) system, and so on [1,2].

Energy cascading utilization can be realized as possible by the poly-generation process in DES [3]. The renewable energy resources utilized by DES usually involve solar energy [4,5], wind energy [6], bioenergy [7,8], geothermal energy (in form of ground-source heat pump) [9]. Therefore, DES has been widely recognized as a promising scenario to fully use local resources and renewable energy resource, and thus avoids energy loss during transmission and reduces emissions as much as possible [10]. The main equipment applied in DES involves prime mover, heat recovery device, thermally activated facility (e.g., absorption chiller) [11] and heat exchanger, and electrical chiller and energy storage device are also often applied to improve the comprehensive efficiency of DES [12,13]. Fig.2-1 [10] shows the schematic diagram of DES. The local heating pipeline network and/or electricity transmission network is also concerned in large DES. The prime mover applied in DES mainly consists of internal combustion engine [14], gas turbine [15], gas engine [16], steam turbine [17], fuel cell [18] and Stirling engine [19], etc.

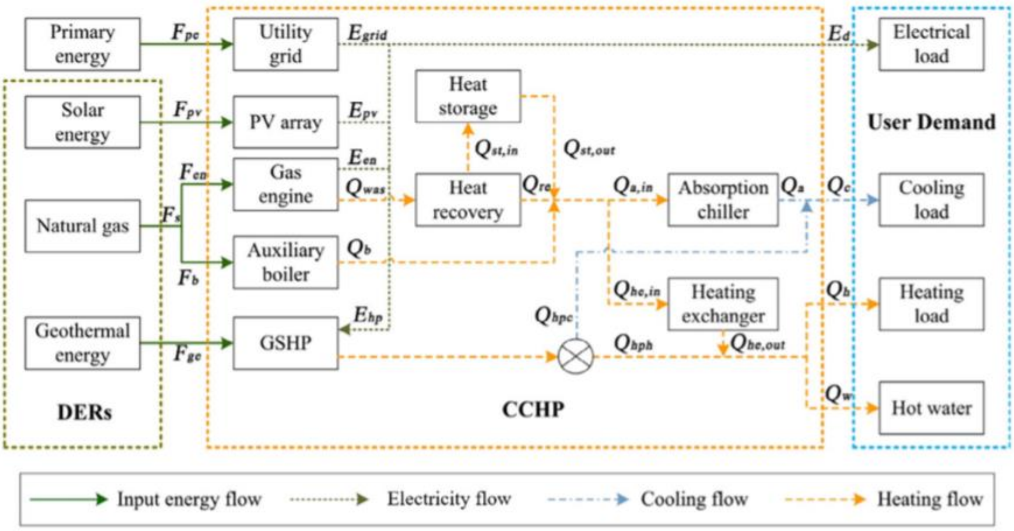

Fig.2-1 Schematic diagram of DES [10].

Recently some reviews of DES development have been done. Han et al. [1] reviewed the DES status in China from four aspects including system optimization, development influence factor, application, and polices. Ma et al. [20] focused on the district load forecast modeling for a distributed energy system. However, neither the level of DES application nor the method of performance evaluation has been discussed clearly. Besides, DES also has been developing rapidly in some African countries [21], apart from China and the developed countries. Therefore, further work is needed to analyze DES development from the application, performance evaluation, and polices. The necessity is also illustrated by Fig.2-2, which shows that the sum of the published articles is 311 and the sum of citations is up to 2 885 in Web of Science when ‘‘distributed energy system” is set as search and timespan is set as 2010–2019. Specifically, the sum of published articles within 2014–2019 is up to 222, accounting for 71% of the total articles published within 2010–2019.

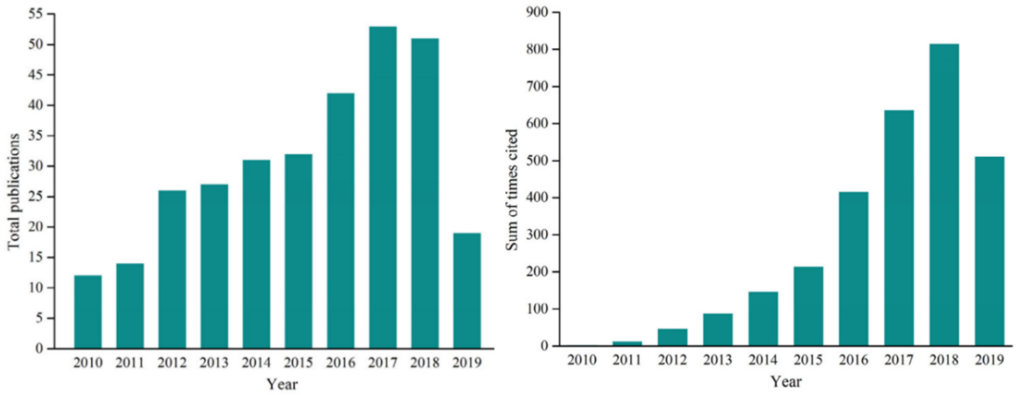

Fig.2-2 Distribution of SCI papers with the topic of “distributed energy system” [21]**.**

There is no consensus definition of distributed energy system yet. However, based on the relationships among CCHP, distributed energy resources (DER), on-site renewable energy system and distributed CCHP system offered by Wu et al. [22], and consideration of the change of energy production ways caused by the advancement of renewable energy utilization technologies, the relationship among multi-generation system (including CHP and CCHP), renewable energy system and DES is clarified (see Fig.2-3). The coverage of DES is various: it can be a typical residential home and the small DES used combines rooftop solar PV cells, CHP and battery [23]. It also can be an industrial site and the DES under construction considers the use of rooftop PV, GSHP, CHP unit, waste heat-based heat pump, etc [24]. In summary, DES includes the multigeneration system and renewable energy system.

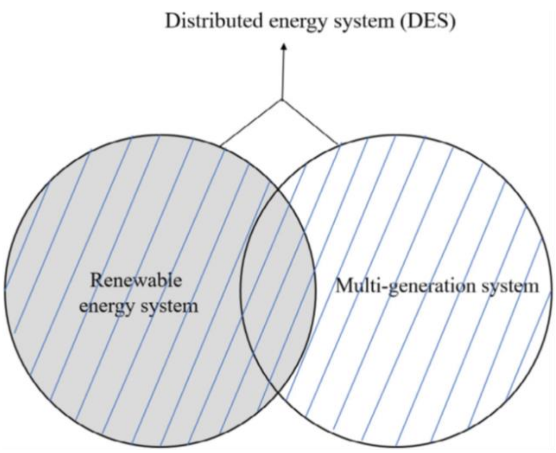

Fig.2-3 Relationships among renewable energy system, multi-generation system and DER [25]**.**

Due to its various advantages, both developed and developing countries increase their attention to DES. Series of strategies thus have been used by them. These strategies directly or indirectly facilitate the further application of DES, and simultaneously evince governmental bodies' appreciations to distributed energy technologies. Based on the application of DES in different countries, in order to specify the strategies in different regions, America, Japan and four developed European countries are selected for the developed country, while Iran, China and two African countries are selected for the developing country, herein.

Before 2015, America took several measures to promote the development of CHP and renewable energy utilization. Aimed at more CHP applied to newly-built commercial buildings and existing ones, the U.S. Department of Energy proposed the "Building Combined Heating & Power 2020 vision" early in 1999. According to the White Paper on CHP in a Clean Energy Standard, an 11% increase of CHP share of the U.S electric power by 2030 is expected to be achieved. Further, the Department of Energy and Environmental Protection Agency jointly determined the strategy that the old equipment in the industrial sector is replaced by effective and clean distributed energy equipment [23]. To control the price increase of natural gas, America launched the Shale Gas Revolution in 2000, resulting in a price decrease of shale gas from $8.86 in 2008 to $4 per million Btu in 2013. It definitely improves the economic competitiveness of natural gas-fired DES. Clean energy is emphasized for sustainable development during 2008–2015. Several related policies thus have been issued. For example, the Blueprint for a Secure Energy Future has been issued in 2011 [26]. It stipulates that the dependence on oil will be reduced by exploiting cleaner alternative energy. Subsequently, the Clean Power Plan has been published in 2015 to promote renewable energy power [27].

Because of the scarcity of energy resources, the Japanese government not only encourages the relevant enterprises, like Yanmar Diesel, MHI and Fiji Electric, to devote to Research & Development of the key equipment of distributed energy, but also stipulates that the distributed energy application must be market-oriented. Following the adjustment in 2007, 2010 and 2014, the fourth adjustment of the Basic Energy Plan has been finished in 2018. In the latest version, the medium-term plan (by 2030) and long-term plan (by 2050) is proposed, based on scientific evaluations of CHP potential in both domestic and industrial sectors. And it is projected that the ratio of renewable energy resource power to total power will be up to 22–24%, while that of nuclear power and fossil fuel power will be reduced to 20–22% and 56% respectively. Aimed at breaking up the power monopoly to give consumers freedom of choice of power supplier, Electrical Business Law was passed and put into effect quickly in 2015. As a result, Japanese energy enterprises have successfully developed several DESs, including Tokyo Gas Kumagaya Branches Heat Interchange Network, Iwasaki Smart Energy Internet in Osaka [28] and Senju Mixing-function District Energy Internet. By taking the 2020 Tokyo Summer Olympics as an opportunity, now Tokyo Metropolitan Government proposed its development vision, of which one target is to construct smart energy for cities. To realize the periodical target, Tokyo Metropolitan Government launched a subsidy program named as Promotion of Smart Energy District Establishment, through which 5.5 billion JPY is projected to be used as a subsidy for the investment in DES based on electricity and heat interchanges. In addition, relevant economic development plans were adjusted and technological measures, like net metering, were taken by the Japanese government to facilitate the DES application.

Germany has been fulfilling its obligation to reduce greenhouse emission and has taken a series of actions, in which specific targets have been determined. In 2012, Germany revised the law named Combined Heat and Power, through which the government set a legally binding development target that the electricity generated by CHP is expected to account for 25% of the total generation by 2025 [28]. According to this law, the electricity from CHP would receive a higher subsidy and have a priority to connect to public grid, the term of validity of incentive scheme for CHP would be extended to 2016, and the limit on CHP capacity would be eliminated. Further, a range of policies including Law on Renewable Energies (2012), Renewable energy heat Act and Micro CHP Incentive Plan have been released. Specifically, the Law on Renewable Energies (2012) stipulates that the biomass-based power plant is obligated to facilitate the development of the CHP project and its preferential policies for renewable energy are also applicable to CHP. Further, Germany in 2015 declared the nuclear power phase-out by 2022, which offers a favorable opportunity for the development of CHP. Now Germany shares the largest part of CHP market among EU members. In 2016, the government modified the Law on Renewable Energies again and proposed energy transition scheme, which is that by 2020 the electricity generated by renewable energy accounts for 35% of the total generation, and this proportion is expected to be 50% by 2030 and over 80% by 2050. Based on these strategies, 75% of capital in the renewable energy sector has been invested in small-scale renewable energy-based projects, such as rooftop solar PV systems. Lately, German Climate Law Draft calls for a net-zero emission by 2050 and subtasks will be assigned to energy, environment and industry sectors.

According to European Regulation 2009/28/EC, the proportion of renewable energy in the total primary energy consumption of Italy should account for 17% by 2020 [29]. Therefore, many supporting strategies have been carried out to realize the target. By 2011, the net metering policy had been adopted in Italy, which allowed the deduction of purchased grid electricity by on-grid electricity generated by solar PV systems. This policy also had been adopted by other countries, like Japan and Denmark. In 2013, Italy issued the National Energy Strategy, which determined the main target of the energy sector in the future is to improve the efficiency of energy utilization and renewable energy should play a significant role in it [30]. In National Energy Strategy, the proportion of renewable energy in the total primary energy consumption in 2020 should be increased to 19–20% from the target proposed by EU (i.e., 17%) and the proportion of fossil fuel should be decreased to 76% from 86%. These targets yielded a widespread renewable energy-based distributed generation. To facilitate the grid connection of distributed renewable electricity, Italy not only upgraded its traditional medium-voltage public grid but also emphasized more the research of terminal equipment of the smart grid. Enel, the largest producer and supplier of electricity in Italy, attaches great importance to the distributed PV system and the new energy storage technology. It has applied the new energy storage technology and distributed PV system to areas with high commercial potential by cooperation with advanced enterprises in the two fields. Then, in 2015 Enel highlighted the application of energy storage technologies in residential buildings in its sustainability report [31]. Furthermore, in 2017 the National Energy Strategy was amended. In the new National Energy Strategy, the proportion of renewable energy in the total primary energy should reach 28% by 2030 and the thermal power plant is planned to be phased out by 2025. The National Integrated Plan for Climate and Energy was published in 2019, where the proportion of renewable energy should be increased to 30%. In addition, Italy has implemented other measures for renewable energy electricity including feed-in tariffs, tax breaks and fiscal stimulus in the construction industry. The fiscal stimulus in the construction industry aims to supply financial support for distributed energy technologies, including solar power, high-efficiency heat pumps, low-enthalpy geothermal application and biomass-based electricity generation, etc. Through these supportive strategies, renewable energy-based distributed generation is predicted to be widely deployed, especially solar power. In the first half of 2020, Italy published the Eco bonus, based on which the tax break of distributed PV project and the energy storage system related to building retrofitting projects is increased to 110%. The new fiscal measure is expected to greatly improve the efficiency of energy utilization.

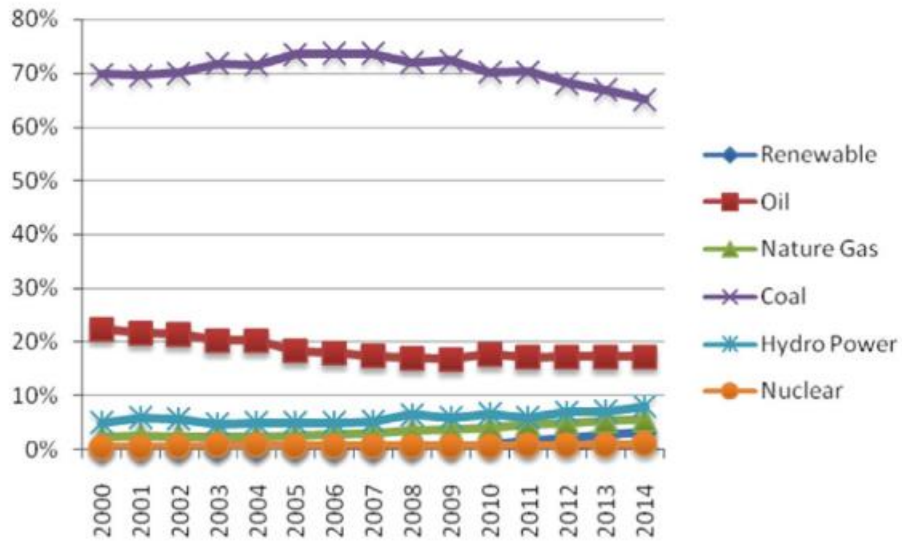

Fig.2-4 Energy consumption of China from 2000 to 2014. Note: data from BP Statistical Review of World Energy (2015).

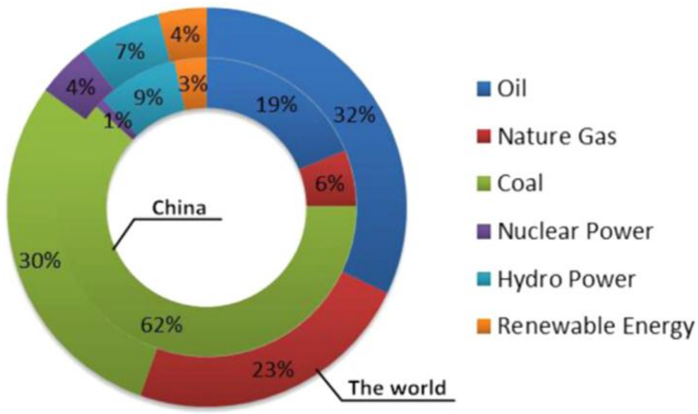

Fig.2-5 Energy consumption structures of China and the World [17].

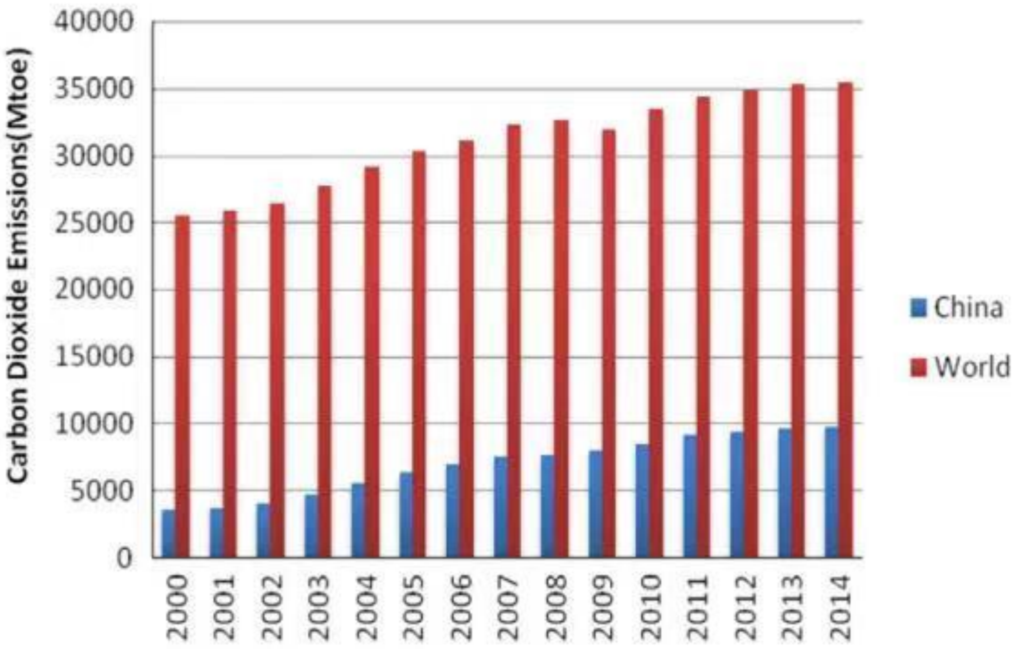

Fig.2-6 China and the world's carbon dioxide emissions Note: data from BP Statis- tical Review of World Energy (2015).

Fig.2-4 shows the percentages of China's primary energy consumption from 2000 to 2014. It can be found hat the percentages of coal in primary energy consumption, decreased slowly from 69.86% in 2000 to 65.10% in 2014, are still much higher than the average level of the world. In addition, natural gas and renewable energy in consumption have a small rise of 3.2%, 3.26%, respectively. And the energy consumption structure of China and the world in 2014 is shown by Fig.2-5 It can be found that the ratio of coal is still higher than the average level of the world and the clean energies vice versa. As everyone knows, when the coal is burned, more CO_2 is released than oil and NG burned for generating equal amount of energy. China emitted 9.76 billion tones CO_2 in 2014, accounting for 27.5% of the world total and ranks 1st in the word [1]. Fig.2-6 shows China's and world's CO_2 emissions from 2000 to 2014. At present, China is the largest developing country and will continue its industrialization and urbanization. Plenty of CO_2 will be emitted in the next 10–20 years, which leads to great burden on CO_2 emission reduction. Therefore, it is necessary for China to seek clean energies and low carbon technologies.

In recent years, DES is becoming a more attractive options worldwide because of its high overall efficiency, low greenhouse gas (GHG) emissions, high reliability, cost saving of grid construction and shortened transport distances, etc. A DES, including high efficiency cogeneration systems and distributed renewable energy technologies, sited at or near the end users and can realize the cascade utilization of energy [32-35]. Compared with conventional centralized energy system (CES), a DES employs a wider range of technologies, including prime movers, waster heat recovery, energy storage, heat pump, solar photovoltaic, small- scale wind turbines, and other equipment that use renewable energy resource [36,37].

2.2 System optimization

2.2.1 Design optimization

The distributed energy system (DES), also known as combined cooling, heating and power (CCHP) system, is composed of three parts, namely power generation unit, refrigeration unit and heating unit. The power generation unit (PGU) is driven by fuel and pro- duces the electricity on site to satisfy power demand of terminal users. Simultaneously, the waste heat rejected from the PGU is utilized for cooling and heating demand, which avoids energy waste. Compared with the traditional separation production (SP) system, DES is installed flexibly near the users in a more compact and decentralized form, satisfying different energy demands. Because of high energy efficiency, significant effect of energy saving and emission reduction, countries around the world have made great efforts to spread DES in recent years, in order to make the entire energy industry economic, safe, efficient and environmentally friendly [38,39].

Li et al. [40] based on the framework of simple cycle gas turbine, an optimization model of DES is built for multiple building complexes in this paper, where the minimum performance factor indicator (PFI) is taken as the objective function and the hourly energy balance between supply and demand is chosen as constraint. Not only the problem of the configuration for installation capacity can be solved, but the concept of time scale is introduced in the process of operation optimization, to minimize energy waste and achieve maximum economic and environmental benefits. Furthermore, an illustrative case study about capacity design and operation strategy of DES in one financial center is given to present the effectiveness of the proposed model. The result shows that the optimal installation capacity is 23.77 MW while satisfying the energy demand of the terminal users. In comparison to separation production system, the primary energy consumption and carbon dioxide emission can be significantly reduced and the overall economy is improved when the DES adopts optimal installation capacity and operation strategy, which can provide theoretical reference for the actual design and operation of DES.

Arcuri et al. [41] built a mixed integer programming model for optimal design of trigeneration in a hospital complex, which could determine the optimal designed capacity and optimal operation strategy simultaneously. There are two different plants are proposed to meet the energy demands of the hospital as shown in Fig.2-7. Plant A is cogeneration plant only and plant B is trigeneration configuration integrating a cogeneration plant with compression and absorption heat-pumps.

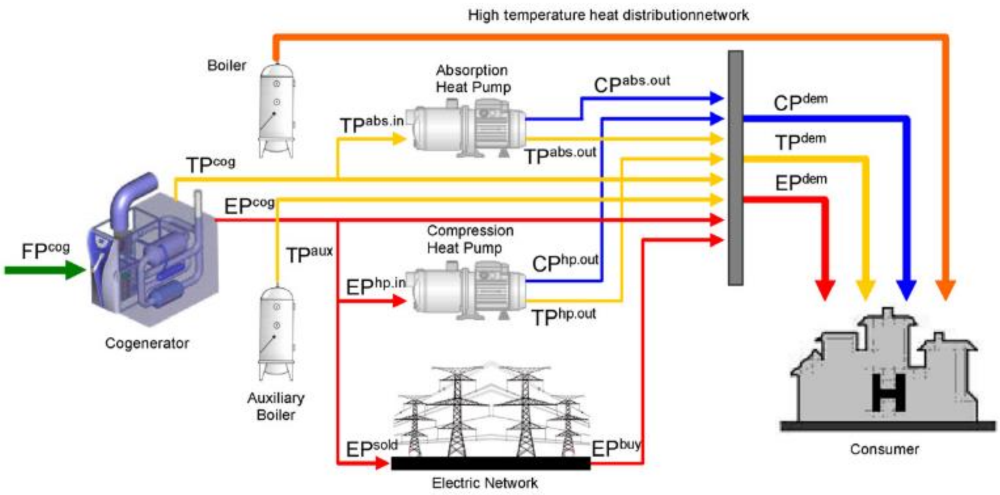

Fig.2-7 Plant diagram [41]**.**

Ren et al. [42] studied the optimal design of CCHP systems for building complexes in five major climate regions of China, taking maximum economic benefit as the optimization target. On the other hand, market-based policy innovations such as carbon tax can promote the introduction of some renewable energies (biomass specially) to a large extent.

Cardona et al. [43] proposed two main procedures to address the problem, a simplified design optimization and a detailed integrated optimization of plant lay-out and operation. The former approach, based on the use of aggregate consumption data, is described more in detail and finally applied to a trigeneration plant serving a 300-bed hospital, situated in a Mediterranean area.

Yang et al. [44] focused on the optimal design of DER (distributed energy resource) systems. The optimization function is the annual total cost for investing, maintaining, and operating the system. All above studies optimized the design and operation strategy of CCHP system based on minimal annual total cost. While some researchers considered maximum NPV (net present value) as another economic optimization objective.

Li et al. [12] presents optimization of CCHP system on their design and operation from energetic analysis, economic operation and environment effect viewpoints. CCHP system for hotels, offices and residential buildings in Dalian (China) is given to ascertain the effectiveness of the model. Weighting method and fuzzy optimum selection theory are employed to evaluate the integrated performances of CCHP systems with various operation strategies. Results show that: (1) Hotels have the greatest contribution (42.28%) to the energy savings based on energetic analysis sub-model because of their relatively stable electricity loads. (2) CCHP systems reduce the annual total costs for all operation cases compared with the reference system for hotels and offices. However, CCHP system achieves no economic merits for residential buildings. (3) The applications of the CCHP system decrease pollutant emissions in all operation cases for the studied buildings. (4) CCHP system driven by gas engine has better performance than driven by gas turbine. Coupled with renewable energy sources and with thermal storage tank are mostly optimum operation cases from energetic, economic and environment criteria. Fig.2-8 shows the basic structure of the CCHP system model.

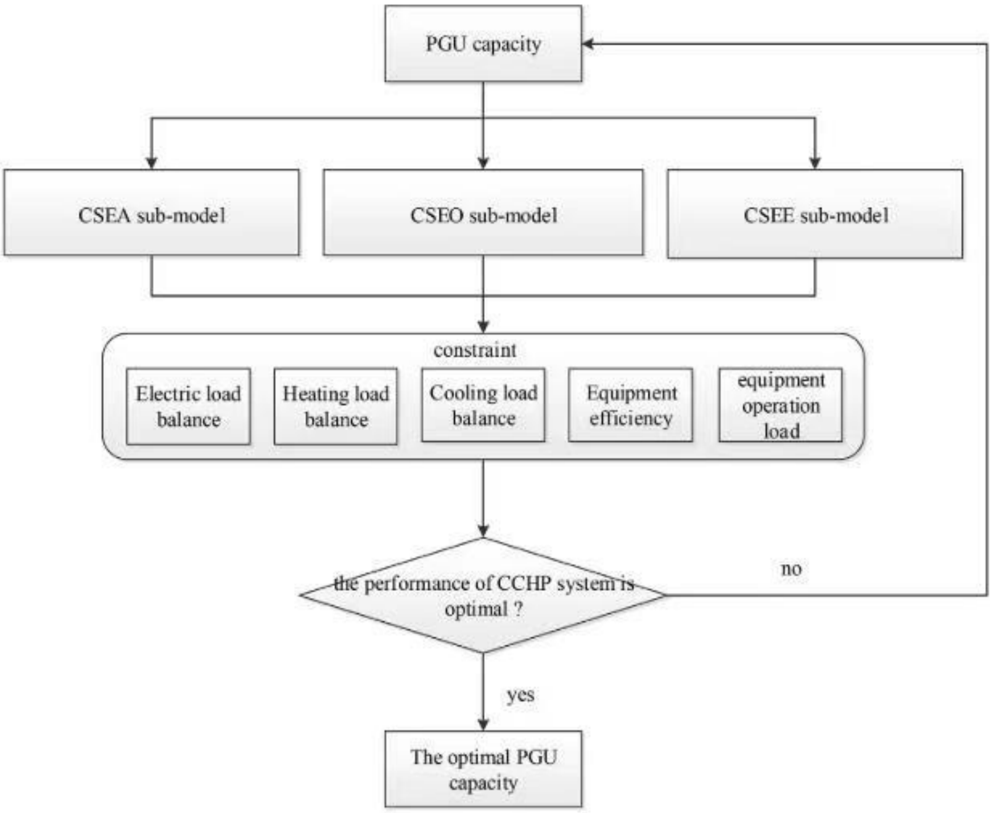

Fig.2-8 Basic structure of the CCHP system model [12]**.**

Omu et al. [45] created a MILP model for the design of a CHP system to meet the electricity and heating demands of a cluster of commercial and residential buildings. The proposed optimization algorithm permits the se- lection of equipment type, size, and location and determination of their operation strategies as well as heating and power distribution network structures.

Cardona et al. [46] have suggested that the PGU optimal capacity can be determined by the ratio of the PGU capacity to the peak value of the user's power demand, and the absorption chiller optimal capacity can be determined by the ratio of the absorption chiller capacity to the peak value of the user's cooling demand. Nowadays the designers tend to make the system-installed capacity as small as possible so that the CCHP system runs with longer time, higher efficiency, and faster return on the initial investment.

Farahnak et al. [47] selected a sample residential building in Mashhad city (Iran) has been selected as a case study to investigate feasibility of employing CCHP systems to meet the energy demands for various buildings sizes. An optimization algorithm is developed to find the best operation point of the Power Generation Unit (PGU) at minimum energy cost. The algorithm optimizes the operation of the CCHP systems at first step. The results of the algorithm implementation for different PGU capacities and various buildings sizes, demonstrate the performance of the operationally optimized CCHP systems at second step.

Bianchi et al. [48] analyses carried out in the paper provide guidelines to select the proper prime mover technology and size and thermal storage system size, with reference to prime mover operating hours and produced electric and thermal energy. Moreover, both primary energy saving and profitability of the CHP system compared to the separate production of electricity and heat are also evaluated. The aim of this paper is to provide general guidelines for the design of micro-CHP systems for the heating of residential buildings.

Martínez-Lera et al. [49] developed a new method to evaluate the thermal contribution of TES based on simple procedures. Comparisons with detailed simulations for a range of situations confirm the ability of this method to predict the effect of TES on CHCP systems with good approximation, as well as to find the optimal size in a relatively simple manner and with few required data. The case studies show a strong dependence of the TES contribution on the demands profile and the operation strategy. However, adequately sized TES are proven to bring relevant energy savings as well as economic profit to CHCP plants. Fig.2-9 shows the process of the method.

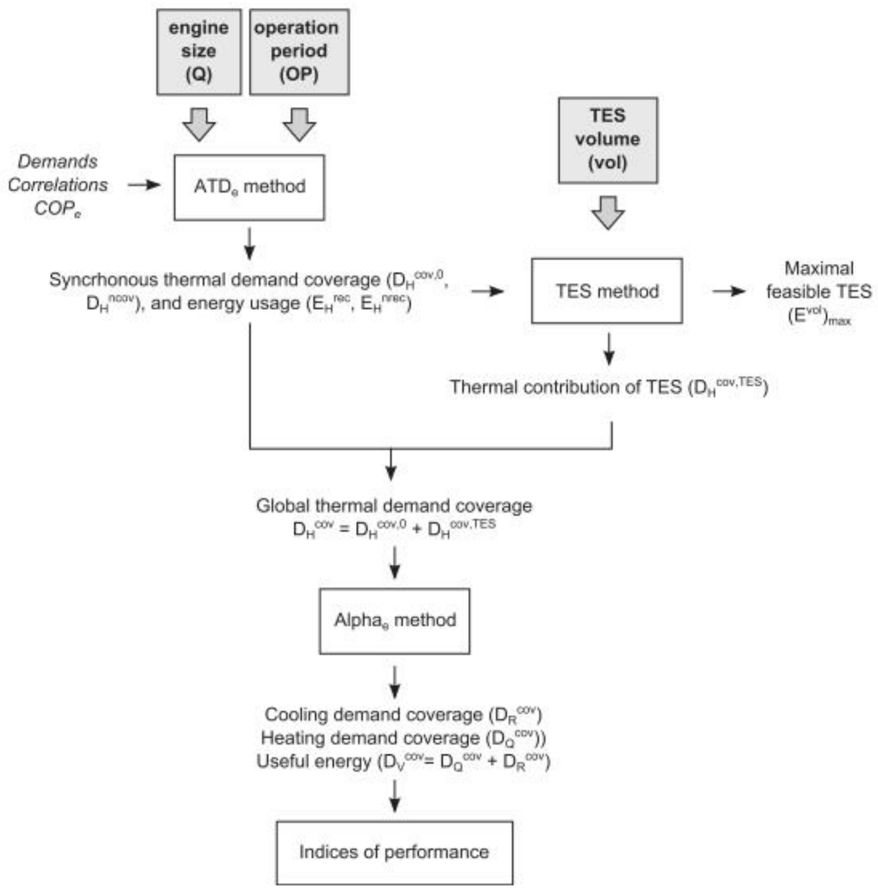

Fig.2-9 Diagram of the extended ATDe method, indicating its main procedures and results [49]**.**

Zhou et al. [36] provided a generic energy systems engineering framework toward the optimal design of DES in China, with the purpose of obtaining optimal combination of technologies and capacity of equipment for a given area with given energy demands. A hotel in Beijing is selected as an illustrative example to demonstrate the key steps and features of the proposed approach. Results show that the optimal configuration of such a DES is a rather complex system equipped with various technologies. It is more efficient and economic than conventional centralized energy systems as well as distributed combined cooling, heating and power systems.

Liu et al. [50] introduced an energy systems engineering framework towards the optimal design of such energy systems with improved energy efficiency and environmental performance. The framework features a superstructure representation of the various energy technology alternatives, a mixed-integer optimization formulation of the energy systems design problem, and a multi-objective design optimization solution strategy, where economic and environmental criteria are simultaneously considered and properly traded off. A case study of a supermarket energy systems design is presented to illustrate the key steps and potential of the proposed energy systems engineering approach.

Liu et al. [51] proposed a structural configuration of the CCHP system with hybrid chillers, consisting of a combined electric and absorption chiller, whose electric cooling to cool load ratio varies according to different electric and thermal loads in every hour. A new operation strategy, based on the variational electric cooling to cool load ratio, for the CCHP system with unlimited and limited power generation unit (PGU) capacity is investigated. Given the proposed operation strategy, an optimization algorithm is adopted to determine the optimal PGU capacity. In addition, a case study of a hypothetical hotel in Victoria, BC, Canada is con- ducted to verify the feasibility of the proposed CCHP system structure and the corresponding optimal operation strategy. Fig.2-10 shows the CCHP system with hybrid chillers implemented.

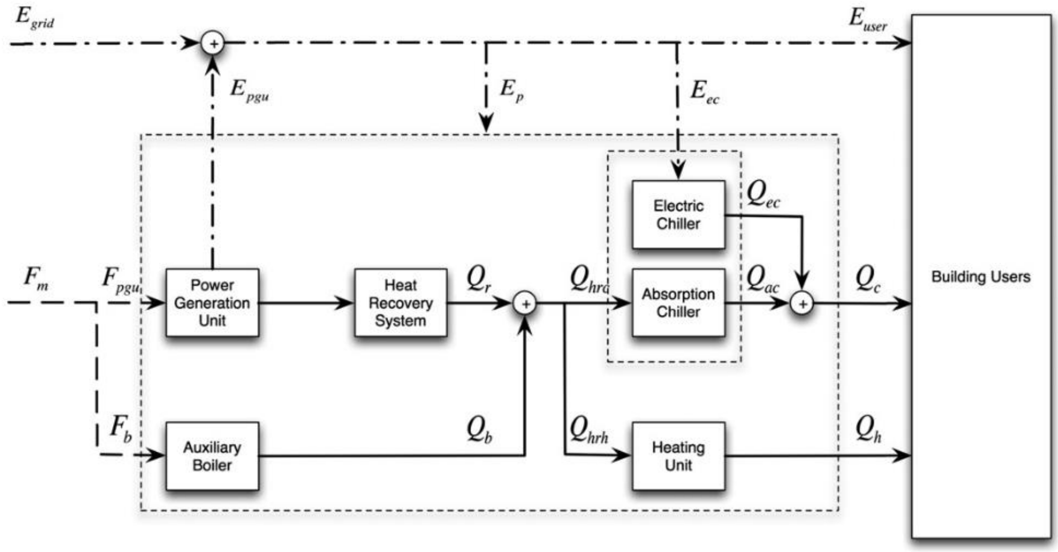

Fig.2-10 The CCHP system with hybrid chillers implemented [51].

Wang et al. [52] optimized life cycle performance of a hybrid combined cooling heating and power (CCHP) system incorporating with solar energy and natural gas. A basic natural gas CCHP system containing power generation unit, heat recovery system, hybrid cooling system and storage tank, is integrated with solar photovoltaic (PV) and/or heat collector. LCA optimization methodology is proposed to optimize the configuration and variable load operation of the solar-assisted CCHP system to minimize the life cycle environmental impact. CCHP schemes in following electrical load (FEL) and following thermal load (FTL) strategies are optimized by different objectives respectively. Analysis and comparison are performed on life cycle environmental impacts caused by global warming potential, acidification potential and respiratory effect potential. The influences of main independent decision variables are discussed to discover the generic configuration rules for hybrid CCHP system. The results indicate that FTL strategy is superior to FEL strategy at taking the environmental compensation of surplus products from the hybrid CCHP system into consideration.

Cao et al. [53] proposed an energy flow for CCHP system to decrease the main power consumption based on a building thermal demand in Kerman area, Iran. The method introduced a developed version of the owl search algorithm to increase the efficiency of the CCHP system in comparison with the separation production system. Final simulations declare well efficient results for the presented method.

Khodaei et al. [54] introduced a two-layer programming technique to optimal designing the dispatch problem for a CCHP of a hospital in Chongqing, China. The first layer used non-dominated sorting genetic algorithm-II (NSGA-II) and stochastic selection algorithm (SSA) to minimize the total life- cycle cost and the pollutant emissions. The second layer was to use the mixed-integer linear programming (MILP) algorithm to achieve a dynamic optimal scheduling scheme and achieve the lowest operating costs.

Tian et al. [55] proposed an optimized operation strategy for the distributed system (DES) for a research station in Antarctica. MILP method was used for optimizing the system efficiency and for decreasing the primary energy consumption of the DES over a year. The system was modeled by the GAMS platform. The results showed about a 12% decrease for the optimized primary energy consumption due to the optimization strategy compared with the original operation strategy.

Lu et al. [56] introduced an optimized configuration for buildings energy systems. The optimal scheduling of the case study was performed by an improved nonlinear programming method including a mixed-integer mechanism. For performance evaluation of the proposed scheduling, four scenarios were studied. Finally, the method was applied to a real case study, the Hong Kong Zero Carbon Building. They declared that the presented method can decrease the cost of operation energy, especially in the presence of thermal energy storage.

Huang et al. [57] proposed a complex hybrid nonlinear integer model to optimize the energy management of a residential area. The method was used for solving the non-convex MINLP to obtain the pseudo-optimal solution. The results showed that using the proposed algorithm gives better results of demand response toward the commercial solver Knitro.

Abbasi et al. [58] proposed for the optimal design and deployment of the CCHP systems for usage in a residential building, considering their application in various climatic conditions. Energy demands of the building were estimated at six different climatic zones. The preliminary CCHP plant based on different prime-movers, including internal-combustion engine, gas turbines, Stirling-engine, and the molten carbonate fuel cell was modeled. Multi-objective optimizations based on energy, economic and environmental (3E) objective functions were implemented to determine the optimal capacity of prime-movers. The final solution at each area was obtained in two steps. First, multi- criteria decision-making techniques (Fuzzy, TOPSIS, and LINMAP) were used to select the best CCHP configurations among the Pareto optimal sets. Second, a new class of the analytic hierarchy process (AHP) was employed to prioritize the optimal solutions based on each prime-mover in any zone. Results show that the ICE-based CCHP system was the most beneficial alternative for use in the residential sector at all climates. CCHP systems based on GTs and SEs come as the next priorities, respectively. It was found that in determining an appropriate CCHP system, the type of technology is more important than the climatic conditions.

Jayasekara et al. [59] proposed a two-stage method to solve both tasks. The operation of large thermal power plants must be altered smoothly, as quick changes in system settings may result in cascade tripping of subsystems, ultimately leading to a complete shutdown. This work uses graphical representation of the operational space of the system, which helps in tracking the operation along its optimum trajectory smoothly. The daily energy demands of a five-star hotel, collected over a year, were used to demonstrate the applicability of the proposed method. Using the proposed method reduced the total annual cost over 7% and 13% in Australia and Sri Lanka respectively, compared to the conventional method of following thermal load. Fig.2-11 shows the block flow diagram of energy cost optimization algorithm.

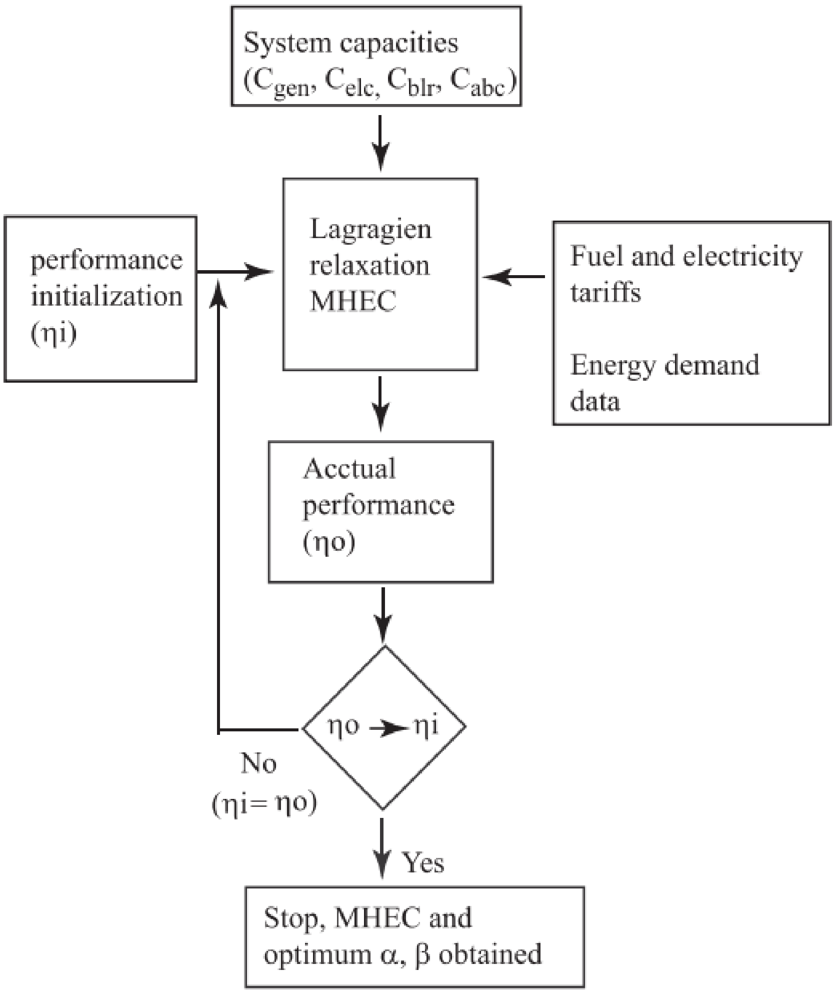

Fig.2-11 Block flow diagram of energy cost optimization algorithm [59].

In literature [60], the configuration was optimized by adding an air-conditioning system and a heat storage tank in residential and office buildings sequentially and the optimal problem was formulated as a nonlinear programming problem.

2.2.2 Operation strategy optimization

To make rational use of the DES, many researchers have been devoted to relevant studies, and proposed many optimization models of DES with different optimization targets or objects. Through optimization models, these studies aim to obtain the rational equipment capacity and optimal operation strategy of DES, so as to fully achieve its advantages of being economic, environmentally friendly and efficient. As for strategy optimization, there are several operation strategies for CCHP system, mainly including following the electric load (FEL) model and following the thermal load (FTL) model.

Kang et al. [61] proposed which consists of a power generation unit (PGU), an absorption chiller, a storage tank and a ground source heat pump (GSHP) to substitute conventional electric chiller and auxiliary boiler to supply the deficient cooling or heating load. In the study, three basic load following strategies: following electric load (FEL), following thermal load (FTL) and following hybrid load (FHL) are employed to analyze the annual total cost (ATC), operational cost (COST), carbon dioxide emissions (CDE) and primary energy consumption (PEC) based on a case study of a regional energy system in Sino-Singapore eco-city. For the evaluated case, carbon tax and electricity feed in tariff are both considered to compare with the performances of following maximum electric efficiency of the PGU (Max-eff) strategy. Fig.2-12 shows the schematic diagram of the CCHP system and the separate system.

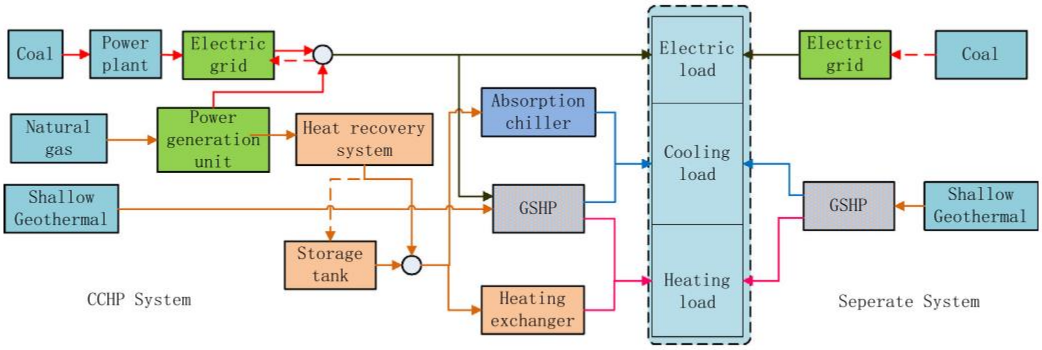

Fig.2-12 Schematic diagram of the CCHP system and the separate system [61].

Li et al. [62], the performance of CCHP system operating under five different strategies: FEL, FTL, two types of following the hybrid electric- thermal load (FHL1 and FHL2), and following the maximum efficiency of power generation unit were compared and analyzed. It was found that whether it is possible to sell electricity to the grid is a key factor for selecting the optimal strategy. In Region (1) in Fig. 2-13(a), the electricity demand cannot reach the starting condition of the PGU and the electricity, heating, and cooling demands will be met by the power grid, the gas-fired boiler, and the electric chiller. Region (2) signifies that PGU operates following the electric load. For load point A or B, the PGU will operate at A' or B'. The surplus heat (A) is stored in the heat storage tank, and the insufficient heat (B) will be supplied by the heat storage tank or the gas-fired boiler. Region (3) means that the PGU operates at full load (C') to meet the electrical demand and the surplus heat (C) or insufficient heat (D) can be stored in the storage tank or imported from the boiler.

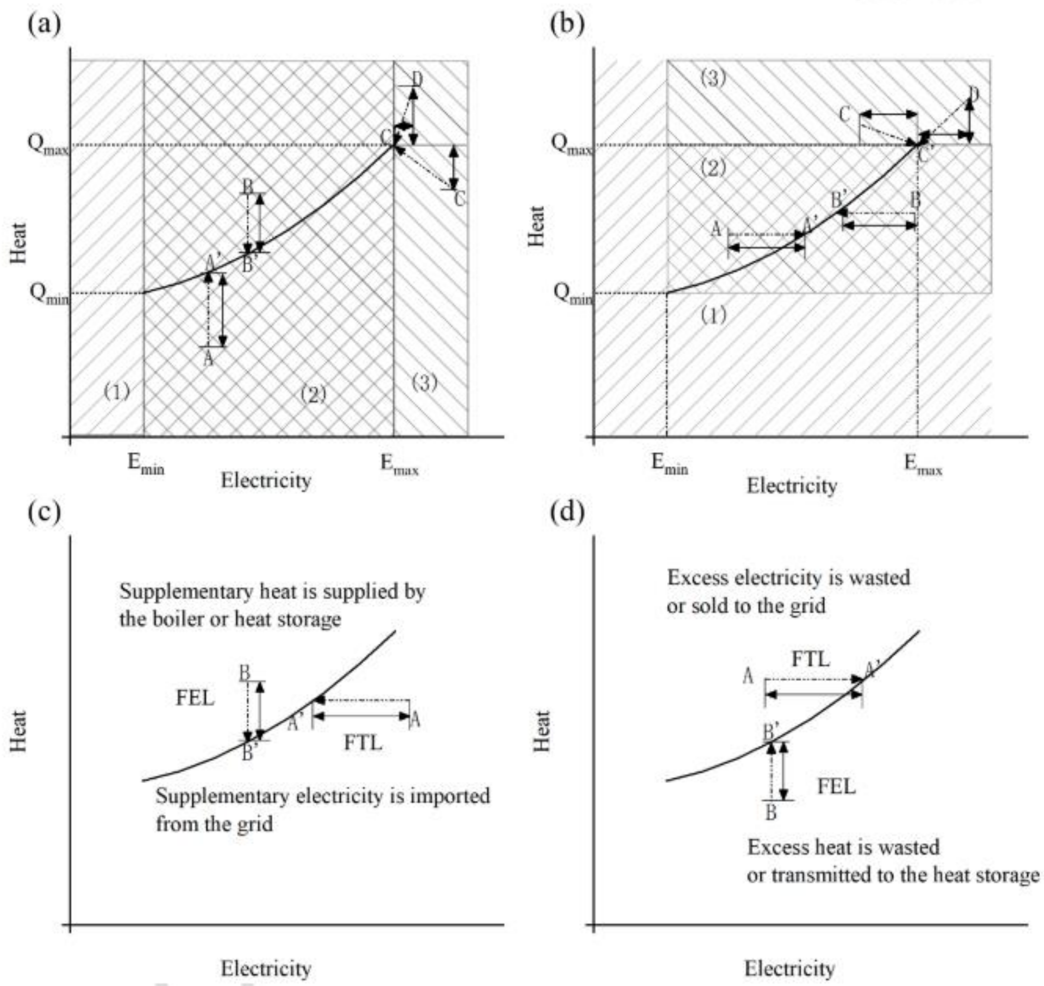

Fig.2-13 Operation strategies of the CCHP system :(a) FEL operation strategy; (b) FTL operation strategy; (c) FHL1 operation strategy; (d) FHL2 operation strategy [62]**.**

Lorestani et al. [63] used FEL and FTL operational strategies and analyzed the economic and reliability bene- fits of each of them for CCHP systems.

Han et al. [64] and Wang et al. [65] proposed the compressor inlet air throttling (IAT) operation method combined with FEL, FTL and FHL and evaluated the off-design performance.

Calise et al. [66] proposed three different operating strategies were evaluated in order to minimize the plant cost and maximize the performance of the system, namely: Thermal Load Tracking mode (TLT), Maximum Power Thermal Load Tracking mode (MPTLT) and Electricity Load Tracking mode (ELT).

Rong et al. [67] applied the Tri- Commodity Simplex algorithm to optimize the CCHP system, which minimized the costs of production and carbon dioxide emission to the largest extent.

Biezma et al. [68] compared a variety of building energy schemes based on the economic and energy consumption evaluation criteria. The results showed that the optimal energy scheme under different evaluation criteria would be different.

Arcuri et al. [41] built a mixed integer programming model for optimal design of trigener- ation in a hospital complex, which could determine the optimal designed capacity and optimal operation strategy simultaneously.

Lozano et al. [69] developed an optimization model using Mixed Integer Linear Programming (MILP) to determine the type, number and capacity of equipment in CHCP systems installed in the tertiary sector as well as to establish the optimal operation mode for the different plant components on an hour-by-hour basis throughout the year. The objective function to be minimized is the annual total cost. The optimization model considers the legal constraints imposed to feed the surplus autogenerated electricity into the grid at a regulated feed-in tariff. The optimization model is applied to design a system providing energy services for a hospital located in the city of Zaragoza (Spain). The effects of the financial market conditions and energy prices in the optimal structure of the system are analyzed. Fig.2-14 shows the trigeneration system.

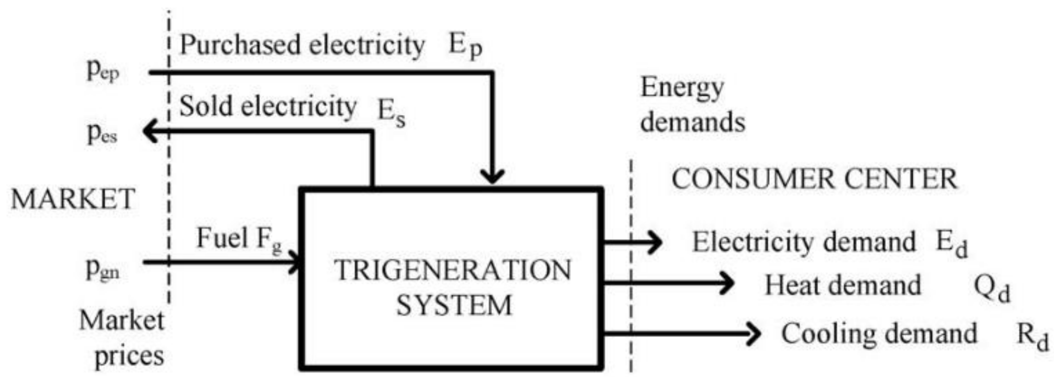

Fig.2-14 Trigeneration system [69].

Ren et al. [42] studied the optimal design of CCHP systems for building complexes in five major climate regions of China, taking maximum economic benefit as the optimization target.

Tichi et al. [70] focused on energy price policies so that they examined the effects of current and future energy price policies on optimal configuration of CHP and CCHP systems in Iran, based on particle swarm optimization algorithm.

Mago et al. [39] analyzed the performance of CCHP and CHP systems operating following the electric load (FEL) and operating following the thermal load (FTL), based on primary energy consumption (PEC), operation cost, and carbon dioxide emissions (CDE) for different climate conditions. Results show that CCHP and CHP systems operated FTL reduce the PEC for all the evaluated cities. On the other hand, CHP systems operated FEL always increases the PEC. The only operation mode that reduces PEC and CDE while reducing the cost is CHP-FTL.

Wu et al. [71] established a comprehensive micro-CCHP system is built, basing on gas engine and adsorption chiller. Auxiliary devices, such as gas boiler, heat pump and electric chiller, are also considered in the study of operational optimization. In order to find the optimal operation strategies and discuss why they are the optimal ones, a mixed-integer non-linear programming model is developed. Energy saving ratio and cost saving ratio are chosen as the objectives and they are calculated hierarchically. Operation strategies under various load conditions are analyzed in detail and two-dimensional distributions of system performance are presented. Results show that, optimal operation strategy changes with load conditions for energy saving optimization while it also changes with energy prices for cost saving optimization. For energy saving optimization, micro-CCHP system is always superior to conventional separated system when the heating load is over 12 kW in CHP (combined heating and power) mode or over 21 kW in CCHP mode. For cost saving optimization, micro-CCHP system can be superior to conventional separated system when the dimensionless energy price ratio is less than 0.45.

Operation strategy is one of the critical factors that can affect the energy saving, economic, and environ- mental performance of a combined cooling, heating, and power (CCHP) system. Li et al. [72] models a CCHP system to investigate its annual total cost reduction, primary energy saving, and carbon dioxide emission reduction with respect to a reference system under five different operation strategies as follows: following the electric load (FEL), following the thermal load, following a hybrid electric–thermal load, following the seasonal operation strategy, and following the electric–thermal load of buildings (FLB). All the different operation strategies were optimized considering the part-load conditions for office and residential buildings in Dalian, China. The results indicate that the FLB and FEL yielded better performance than the other strategies. Furthermore, the redundant electricity and heat generated by CCHP systems were analyzed. The CCHP system operating under the strategies that produce less redundant electricity or heat may not yield better performance. However, the CCHP system operating under the strategies that produce huge redundant energy may achieve good integrated performance.

Mago et al. [73,74], an optimized operation strategy, FHL, was applied. The PGU efficiency was assumed to be a constant and the linear relationship between the electricity produced by PGU and the heat recovered by the CCHP system was established. Therefore, the constant was used to determine whether the CCHP system operated following the electric load or thermal load. If a CCHP system operated following this strategy, the energy waste could be avoided under ideal conditions that the efficiency of PGU is constant. The CCHP system yielded the best performance in general offices under the FHL strategy than the FEL and FTL strategies.

Amanda et al. [75] proposed two basic load-following methods following the thermal load (FTL) and following the electric load (FEL), are compared with a hybrid method which either follows the thermal or the electric demand in a given time period, within a specified operating range, in order to minimize the amount of excess electrical or thermal energy produced by the CHP system. These methods are implemented on an hour-by-hour basis for a large hotel benchmark building which is modeled in 16 cities located in different climate zones using EnergyPlus building simulation software. The hybrid method results in a higher total CHP system efficiency than either the FTL or FEL methods, with CHP system efficiency values from 71% to 87%. The power-to-heat ratio of the building (PHRb), which describes the relationship between electrical and thermal demand for the given facility, is found to predict the maximum possible CHP system efficiency using the hybrid method on an hourly basis. Buildings with lower PHRb values, corresponding to higher relative thermal demands, have the highest possible CHP system efficiency values. The hybrid operational method is also implemented on a monthly basis, where the building's average monthly demands are used to set the operating condition of the prime mover for the entire month. The building is then simulated on an hour-by-hour basis to determine the system's performance with only monthly changes in the loading conditions. This monthly method produces similar results to the hybrid method when it is implemented on an hourly basis, with CHP system efficiency values from 74%

to 86%.

2.2.3 Maintenance optimization

Distributed energy system is a complex system which can provide the electricity, heating, cooling at the same time, and composed of power generation system, cooling system, storage system, heating recovery system, heat boiler and so on. Among them, the power generation system is the core of the distributed energy system. Because of is should produce the electricity and the waste heat od power generation system can be recovery to meet the heating or cooling demand. Thus, it is very important that power generation system can have a good operation and maintenance for the distributed energy system.

Reliability and maintenance, health management and security are closely related. Inspection ana maintenance are necessary methods to keep the reliability of the distributed energy system. Reliability analysis is a process to make the quantitative reliability requirements into the product design through reliability prediction, allocation, analysis and improvement of a series of reliability engineering technology, so as to form the inherent reliability of the product. It is a kind of reliability engineering. The reliability analysis runs through the whole life cycle of products, and the methods of reliability analysis in different stages of products are different. The distributed energy system especially the gas engine and fuel cell has been development near 20 years, a lot of application program of distributed energy system is close to the design life of the distributed energy system. Considering the high cost of investment for a new power generation system, the maintenance and replacement a part of old equipment to prolong the service life for the whole system is the best way to improve the energy efficiency and reduce the cost.

Kang et al. [76] conducted risk assessment through a modified Failure Modes and Effects Analysis (FMEA) method, named correlation-FMEA, to study the connection between failure modes and its effect on the failure probability of the entire system. A series of failure modes with high priority were determined by conventional FMEA, and the corresponding connections were analyzed to obtain the correlation coefficients using the reliability index vector method. The data used in our research comes from field operation in China. Probability Network Evaluation Technique (PNET) was used to get the weakest failure modes set of the system based on those coefficients. With the results, suggestions for floating wind turbine design were provided regarding aspects of safety and reliability.

Hoseynabadi et al. [77] applied that method to a wind turbine (WT) system using a proprietary software reliability analysis tool. Comparison is made between the quantitative results of an FMEA and reliability field data from real wind turbine systems and their assemblies. These results are discussed to establish relationships which are useful for future wind turbine designs. The main system studied is an existing design 2 MW wind turbine with a Doubly Fed Induction Generator (DFIG), which is then compared with a hypothetical wind turbine system using the Brushless Doubly Fed Generator (BDFG) of the same rating.

Tavner et al. [78] concerned with understanding the historic reliability of modern wind turbines. The prime objective of the work is to extract information from existing data so that the reliability of large wind turbines can be predicted, particularly when installed offshore in the future. The article uses data collected from the Windstats survey to analyses the reliability of wind turbine components from historic German and Danish data. Windstats data have characteristics common to practical reliability surveys; for example, the number of failures is collected for each interval but the number of turbines varies in each interval. In this article, the authors use reliability analysis methods which are not only applicable to wind turbines but relate to any repairable system. Particular care is taken to compare results from the two populations to consider the validity of the data. The main purpose of the article is to discuss the practical methods of predicting large-wind-turbine reliability using grouped survey data from Windstats and to show how turbine design, turbine configuration, time, weather and possibly maintenance can affect the extracted results.

Feili et al. [79] utilized of Failure Modes and Effects Analysis (FMEA) as a convenient technique for determining, classifying and analyzing common failures in typical GPPs is considered. As a result, an appropriate risk scoring of occurrence, detection and severity of failure modes and computing the Risk Priority Number (RPN) for detecting high potential failures is achieved. In order to expedite accuracy and ability to analyze the process, XFMEA software is utilized. Moreover, 5 major parts of a GPP is studied to propose a suitable approach for developing GPPs and increasing reliability by recommending corrective actions for each failure mode. Fig.2-15 shows the suggested FMEA process in a GPP.

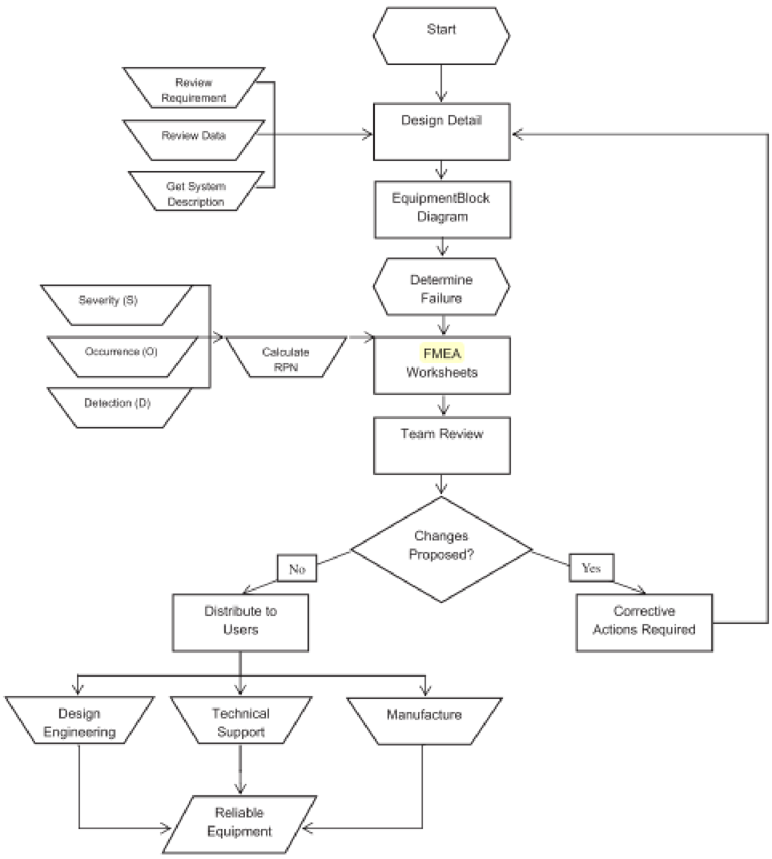

Fig.2-15 Suggested FMEA process in a GPP [79].

Xiao et al. [80] extended the definition of RPN by multiplying it with a weight parameter, which characterize the importance of the failure causes within the system. Finally, the effectiveness of the method is demonstrated with numerical examples.

Pickard et al. [81] introduced a useful method to simultaneously analyze multiple failures for complex systems. However, they did not indicate which failures need to be considered and how to combine them appropriately. This paper extends Pickard's work by proposing a minimum cut set-based method for assessing the impact of multiple failure modes. In addition, traditional FMEA is made by addressing problems in an order from the biggest risk priority number (RPN) to the smallest ones. However, one disadvantage of this approach is that it ignores the fact that three factors (Severity (S), Occurrence (O), Detection (D)) (S, O, D) have the different weights in system rather than equality. For examples, reason- able weights for factors S, O are higher than the weight of D for some non-repairable systems.

Mazure et al. [82] proposed A last stage (L-0) turbine blades failure was experienced at a 28 MW geothermal unit after seven years of operation period. This unit has one flow intermediate/low-pressure turbine composed of nine stages with 25-in./3600 rpm last stage blades. The last stage row contains 62 free standing blades. Visual examination indicated that the 37 L-0 blades had cracks in their airfoils initiating at the trailing edge, near the blade platform. Laboratory evaluation of the cracking indicates the failure mechanism to be high cycle fatigue (HCF), and the cracks initiation was accelerated by erosion picks on the blade surface due to steam recirculation flow and corrosion. A last stage blade failure evaluation was carried out. The investigation included a metallographic analysis of the cracked blades, natural frequency analysis, blade stress analysis, unit operation parameters, history of events analysis and crack initiation and propagation analysis. This paper provides an overview of the failure investigation, which led to the identification of some operation periods with low load as the primary contribution to the observed failure.

Gao et al. [83] proposed a cost-effective two-stage optimization model for microgrid (MG) planning and scheduling with compressed air energy storage (CAES) and preventive maintenance (PM). In the first stage, we develop a two-objective planning model, which consists of power loss and voltage deviation, to determine the optimal location and size of MG. Then, a stochastic scheduling model is presented in the second stage to balance outputs of distributed generations (DGs), charging and discharging power of CAES, power exchange costs of MG and PM costs of DGs. Whilst we derive a credibility assessment-based risk aversion model, named conditional value-at- credibility (CVaC), to hedge against uncertain wind power. The proposed model has been evaluated on the IEEE testing system and numerical results demonstrate the effectiveness of the model by providing the optimal trade- off solution in terms of the economy and security. The Fig.2-16 shows the typical configuration of MG.

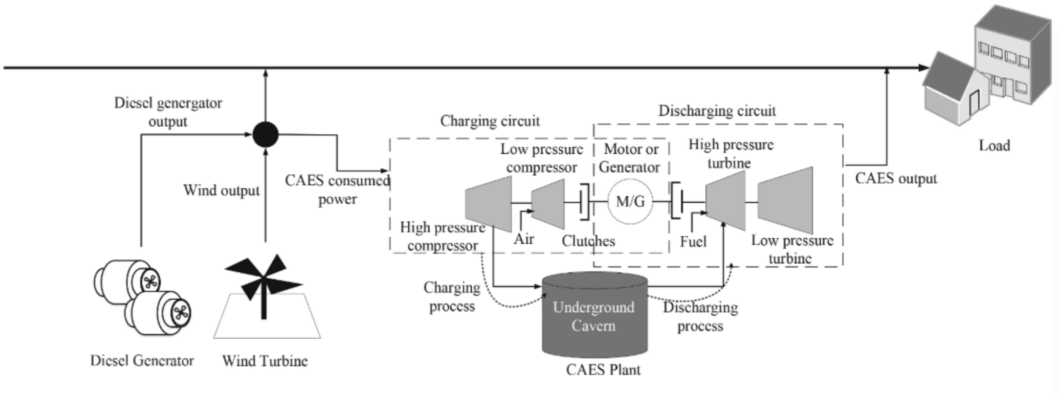

Fig.2-16 The typical configuration of MG [83].

Failure mode and effect analysis is a safety and reliability analysis tool that allows the identification of failures that could happen on a system and gives their effects and consequences. FMEA has many advantages, it is simple to use, time saving and highly effective. However, it has certainly some weaknesses. According to specialists, to obtain an effective result, FMEA needs the availability of all information and data. For new systems, a correct risk analysis cannot be performed. The use of 3 factors cannot describe and judge correctly failures in all activities. Mzougui et al. [84] proposed a modification to the conventional FMEA. Proposed the use of the TRIZ Anticipatory Failure Determination (AFD) to identify all possible failures of the system. The Analytic Hierarchy Process (AHP) is used to calculate the weight of each factor.

Li et al. [85] proposed a two-stage Failure Mode and Effect Analysis (FMEA) technique as a basis for implementing the failure analysis of offshore wind turbines. At the first stage, critical failure causes and failure modes of each component of offshore wind turbines are identified. In the next stage, critical components and systems of offshore wind turbines are ascertained by a cost-and-risk-based index that considers both risk priority and failure costs of components. The objective is to overcome some weak- nesses of the traditional FMEAs including: (i) Risk-based FMEA ignores practical information extracted in the operation stage of offshore wind turbines such as failure cost and, (ii) Cost-based FMEA addresses mainly failures of components and systems and cannot deepen to failure modes and failure causes of offshore wind turbines. A methodology towards conducting uncertainty analysis of FMEA results is developed to provide a new insight into a good understanding of FMEAs and their results. The developed uncertainty analysis methodology reveals that the proposed two-stage FMEA technique is adequate to reduce the uncertainty of FMEA results and is superior in failure analysis of offshore wind turbines. The application of the methodology can provide recommendations toward corrective actions and condition- based maintenance implementations.

Sinha et al. [86] introduced Failure Modes Effects and Criticality Analysis (FMECA) as an important failure analysis tool that has in the past successfully benefitted the airlines, marine, nuclear and spacecraft industries. FMECA is a structured failure analysis technique that can also evaluate the risk and priority number of a failure and hence assist in prioritising maintenance works. The work shows, how with a slight modification of the existing FMECA method, a very useful failure analysis method can be developed for offshore wind turbines including its operational uniqueness.

2.3 Sensitivity analysis

A sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions. In other words, sensitivity analyses study how various sources of uncertainty in a mathematical model contribute to the model's overall uncertainty. This technique is used within specific boundaries that depend on one or more input variables [87]. Sensitivity analysis is of great significance for CCHP system optimization because it can provide guidance for improving the performance of CCHP system [88].

Song et al. [89] analyzed of the factors that affect the performance of CCHP systems is adopted in terms of: (1) price of electricity and gas; (2) the ratio of thermal load to waste heat; and (3) load rate of gas turbine.

Zheng et al. [90] and Hajabdollahi et al. [91] analyzed the sensitivity of electricity price and gas price and explained the changes of important indexes at different prices.

In literature [92], the sensitivity analysis indicated that performance of the CCHP system improves with the increase of chiller COP, decrease of natural gas price and wind-photovoltaic equipment cost, but did not explain why these factors can affect the performance.

Wang et al. [93] deduced the energy consumption of BCHP system following the electrical load and presents the optimization problem of BCHP system that includes the decision variables, the objective function, the constraint conditions and the solution method. The influences of the initial parameters, which include the technical, economic and environmental parameters, the building loads and the optimization setting parameters, on the optimal decision variables and the performances of BCHP system are analyzed and compared. The contour curves of the performances of BCHP system in comparison to the conventional separation production (SP) system, and the sensitivity of the optimal decision variables to the initial parameters are obtained.

Guo et al. [94] analyzed he sensitivity of the optimum operation condition of the CCHP against the electricity and fuel price changes and share of the AC in supplying the cooling demand are studied to provide the system operators with the necessary tools needed to optimally handle price changes.

Wang et al. [95], a sensitivity analysis is presented in order to show how the optimal operation strategy would vary due to the changes of electricity price and gas price.

Ren et al. [37] according to the results of sensitivity analysis, the optimal system combination and corresponding economic and environmental performances are more or less sensitive to the scale of energy demand, energy prices (both electricity and city gas), as well as carbon tax rate.

Zhang et al. [96], sensitivity analysis was used to compare these factors. The results show that the current subsidy can reduce the economic gap between the CCHP system and the conventional system, but it still needs to be increased by 1.71 times to achieve market competitiveness of the CCHP system with 100% penetration under the current investment cost and energy prices. In addition, the introduction of a carbon tax could accelerate the promotion of the CCHP system. When the carbon tax reaches 25 $/ton, the CCHP system becomes the best choice of energy supply system.

2.4 Evaluation of the distributed energy system

Compared with the traditional energy supply system, distributed energy system is a kind of energy solution which includes all kinds of power generation, energy storage and energy management. It has the characteristics of diversification and dynamic [97]. The system contains multi-level energy and a lot of information flow. It can not only deal with power failure and interruption freely, but also improve the flexibility of energy units, thus bringing better economic benefits and stability. Distributed energy system is compatible with different kinds of energy input. In addition to natural gas turbine (or internal combustion engine) power generation system, it also includes solar energy, wind energy and other renewable energy sources, and provides a variety of energy supply, such as electricity, heat, cold, etc. It provides building power supply and cooling and heating load mainly through the mutual supplement and coordination of various energy sources.

Distributed energy system has a wide prospect, so it is very important to evaluate the system comprehensively, systematically and effectively in order to evaluate its benefits more accurately. The current definition of energy efficiency focuses more on technology. However, for the system with different energy input, conversion, output and storage, only considering a certain energy utilization efficiency or the energy efficiency of a certain conversion link cannot truly and comprehensively reflect the efficiency level of the whole system, and more comprehensive indicators are needed to investigate the energy efficiency level of the whole system as a whole. This paper evaluates the distributed energy system through the performance of economy, environment and reliability, in order to promote the development and construction of multi energy complementary distributed energy system.

DES evaluation is often based on the comparison with a reference system, with consideration of multiple performances [98]. Further, when the evaluation involves several DES options, the evaluation becomes complex owing to the following two reasons [99]. The first is that the subjective evaluation based on experts' knowledge and experience is involved, apart from the objective evaluation. The second is that how the subjective evaluation is obtained and how the two types of evaluation are combined have a significant effect on the ranking of DES alternatives [100]. Therefore, based on the comparison with the reference system, research on the performance evaluation of diverse DESs also have been conducted to assist the decision-maker or engineer to identify the optimal DES. Jing et al. [101] applied a multicriteria assessment model that combines the improved gray relational analysis approach and entropy information approach to evaluate the performances of SOFC-CCHP used in five public buildings in China. In the combination model, the improved gray relational analysis approach was applied to determine the integrated gray incidence degree, based on the criteria weights determined by the entropy information approach. The larger gray incidence degree is, the better the option is. Yang et al. [102] also applied a combined approach to evaluate the DES applied in a university. Differently, in this combined approach, both subjective and objective evaluation were considered and the weights in each evaluation were determined by rank correlation analysis and entropy information method, respectively.

Many criteria have been used to evaluate DES performance in energetic, environmental, economic and other aspects. One or two evaluation criteria are commonly selected to show the DES performance in a certain aspect. Because DES is entirely or partially fired by renewable energies and waste heat, there is a potential that primary energy is saved, and CO_2 emission and total cost are reduced by DES when compared with the reference system. Therefore, the primary energy saving ratio, CO_2 emission reduction ratio and annual total cost saving ratio are three of the most used criteria. Energy efficiency is usually proportional to environmental performance, but economic performance conflicts with them. Therefore, in the comprehensive performance analysis, economic, environmental, energy criteria, etc., are often integrated into one criterion by weights [103]. Reliability is also one of the most important advantages of the DES, which should be added into the evaluation. Trade-offs between different performances can be addressed by the comprehensive performance analysis. Among these evaluation performances, more attention is paid to economy, environment and reliability.

2.4.1 Economic performance

For any system, economic performance is an important part of whether it can be established and how to establish it reasonably. The economic evaluation of distributed energy system is usually reflected in investment cost and operation cost. For the part of investment cost, because the whole energy system is composed of a variety of equipment, it often needs a certain degree of investment support in the initial stage of construction, which is also an important standard to evaluate whether the whole distributed energy system meets the economic requirements. The investment cost consists of the total cost of each infrastructure. For the part of operation cost, in addition to the initial cost input, the energy system in the process of operation, for the needs of work and maintenance, will also produce a series of operating costs. The main factors include: the annual maintenance cost and annual operation cost of each infrastructure, the cost of fuel and energy consumption in a certain period of time, which can be followed according to different equipment.

Yan et al. [88] analyzed the economic benefit of a trigeneration energy supply system from the power grid enterprises' viewpoint and power users' viewpoint.

Memon et al. [104] deals with the economic analysis of a trigeneration system proposed for buildings. Firstly, a general feasibility analysis is presented for power and heating (P&H), power and cooling (P&C) and power, heating and cooling (PH&C) modes of operation using economic indices payback period (PBP) and net present value (NPV).

Yan et al. [105] used a novel approach – multidisciplinary design optimization (MDO) to examine the billions of options (e.g., technologies, sizes, climate zone, Etc.) and identified the Pareto front with the optimal environmental and economic impact. Fig.2-17 shows the DES configuration of combined cooling heat and power – renewable energy – energy storage systems (CCHP-RE-ESS) and CCEP.

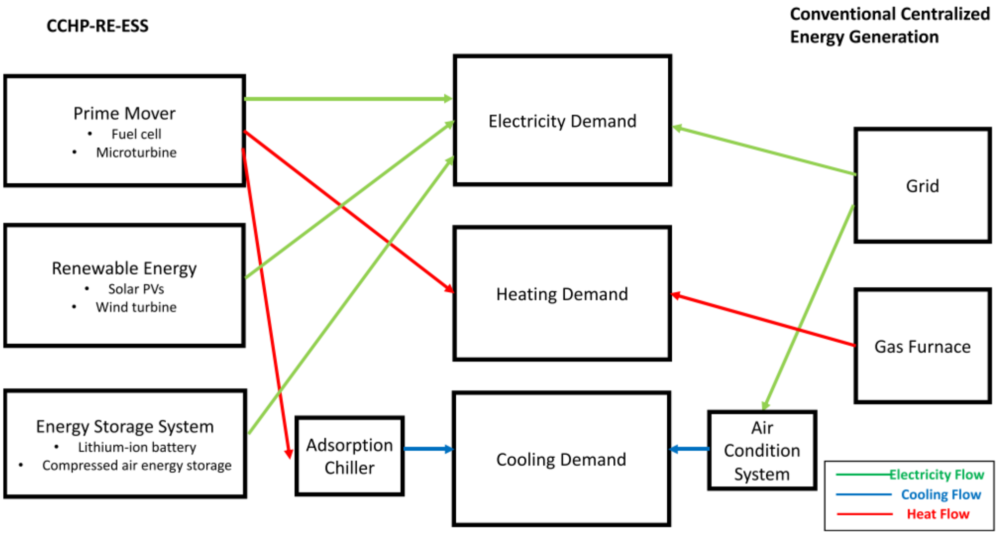

Fig.2-17 The DES configuration of combined cooling heat and power – renewable energy – energy storage systems (CCHP-RE-ESS) and CCEP [105]**.**

Zhang et al. [106] investigated energy, exergy and economic performances of proposed system. The total investment cost of system equipment is 908008$ and dynamic payback period can be reached at 3.032 year.

Ershadi et al. [107], an industrial combined cooling, heat and power (CCHP) generation system in a tile factory was simulated and optimized by the genetic algorithm approach taking into account electricity, heating and cooling loads. Modeling and optimization were performed based on thermodynamic, environmental and economic analyzes.

Soltani et al. [108] changes in the energy and economic parameters are analyzed versus the main effective parameters. The results show that the use of this CCHP system under a heat supplying strategy with the possibility of selling electricity to the network, leads to reductions of fuel consumption and system operating costs about 78.85% and 81.34% compared to the conventional systems, respectively. Also, the payback periods by considering the interest rate and without it are determined 4.075 and 2.701 years, respectively. Also, ac- cording to the results obtained and the study of the ratio of fuel to power, the best operating point of the system from technical and economic viewpoints is achieved at a fraction of 80% load and the overall efficiency of the system is evaluated about 89.59%.

Chang et al. [109] propose an improved distributed robust optimization approach with self-adaptive step-sizes based on the line search method and a polynomial filter, to minimize the overall costs of flexible resources including conventional generators, energy storage systems, renewable energy curtailments, deferrable loads and tie-line power exchanges, while considering various constraints, such as supply-demand power balance, line congestion constraints and power output limits. The results show that the proposed approach is effective and accurate compared to the traditional centralized gradient method.

Harder et al. [110] propose and develop a methodology for generic flexibility quantification. The result indicates the importance of realistically representing tariff structures for a proper flexibility quantification and cost estimation.

Kumamoto et al. [111] propose time-of-use (TOU) pricing that ensures every prosumer saves on energy costs. The results indicate that the proposed TOU pricing is economically efficient and enables the aggregator to procure flexibility from its prosumers while increasing its own profit and reducing the energy cost of its prosumers.

Niu et al. [112] proposed a mixed-integer and linear programming model for optimizing the dispatch of a distributed energy system with minimum operational costs. A detailed case study is conducted in which three types of flexibility measures are modeled, and their effects on end-users and power grid are discussed. The optimal results show that each flexibility measure can well response to the time-of-use price.

Bustos et al. [113] propose a robust framework based on a local and optimal microgrid combined with learning curves to assess the potential penetration of Distributed Energy Resources in households. Results show PV dominance with flat bundled volumetric tariffs and the increase of utility's bankruptcy risk if tariffs are not updated (47% revenue reduction).

Tao et al. [114] focus on the smart grid with integration of DE and storage devices and formulate the related real-time pricing (RTP) as a noncooperative game. With this approach, each user can schedule the optimal energy consumption, generation and/or storage strategies while preserving the privacies of the users and the provider. Numerical results illustrate that the RTP strategy can effectively reduce peak load, balance supply and demand and enhance the welfare of each user.

Ren et al. [115] proposed a Mixed Integer Nonlinear Programming (MINLP) model to deduce the optimal energy supply strategy of a DES. As a result, a systematic CBA framework is developed considering both multi-benefits and multi-stakeholders for a DES. According to the simulation results of a case study, the exploitation of various non-energy benefits is significant which may entirely reflect the social values of a DES. Also, the CBA from each stakeholder's viewpoint may increase their motivation to join the benefit-sharing union effectively. Furthermore, second benefit trade-off may be required to ensure the satisfied profit return for each stakeholder.

Eid et al. [116] presents an approach to determine the investment and short-term average costs of distributed energy resources to supply flexibility services in a local system, and compares those costs to the average costs in the Dutch markets for balancing and day-ahead flexibility. The analysis shows that local flexibility in many cases is much more expensive than centrally provided flexibility.

Wang et al. [117] carried out a thermodynamic and exergoeconomic analysis of CCHP system co-fired by biomass gasification gas and natural gas, and obtained that the energy and exergy efficiency can be increased by 9.5% and 13.7% respectively with mixing ratio from 0 to 1.0.

Kang et al. [118] aims to investigate the performance and benefits of the DES in Hong Kong. Based on the characteristic of energy demands, a DES, which integrates distributed generations and district cooling systems, is designed. Results denote that the DES can achieve a primary energy saving of 9.58%. Even the capital cost becomes higher, the DES is also economically beneficial due to the low operation cost.

Martinez et al. [119] presented a review of the available solutions of micro combined heat and power systems. First part focuses on existing energy conversion devices. If internal combustion engine technology seems to be the more mature and economically viable, several research and development works aim to develop other systems such as Stirling engine, organic Rankine cycle (ORC) and fuel cells. The second part deals with renewable energy fuelled micro combined heat and power systems with a focus on solar energy-based technologies. Fig.2-18 shows the basic architecture of ORC power plants.

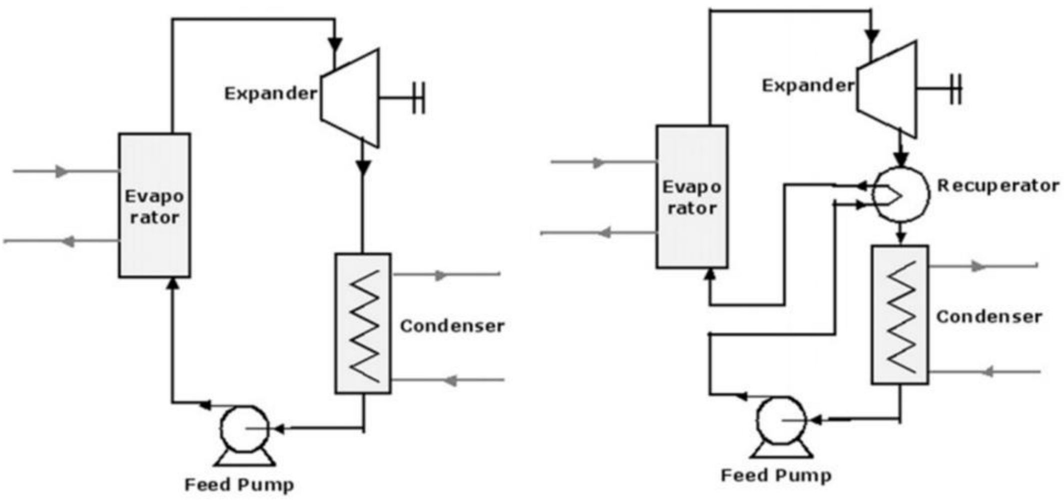

Fig.2-18 Basic architecture of ORC power plants. Simple (left), and with heat recuperator (right) [119]**.**

2.4.2 Environmental performance

The environmental assessment of distributed energy system is usually reflected in the annual emissions of carbon dioxide and nitrogen-containing harmful gases. For the part of annual emission of harmful gases of carbon dioxide, the amount of carbon dioxide emitted in the process of work includes the pollution emission caused by the use of gas and the carbon dioxide emission caused by electric energy conversion, etc., and a variety of equipment operation may cause gas consumption. Therefore, there are many aspects involved, so we must take a more rigorous attitude and consider various factors to calculate the carbon dioxide emissions within a certain range. For the part of annual emissions of nitrogen-containing harmful gases, in order to investigate the impact of energy system on the surrounding environment, it is mainly based on the emissions of various harmful substances. In the infrastructure required for system operation, gas-fired boilers, gas engines, gas-fired batteries and other equipment may emit harmful gases containing nitrogen and carbon dioxide, thus threatening the air quality of the surrounding environment.

Obara et al. [120] show that introduction of the proposed microgrid can significantly reduce the environmental and economic impact. This study clarified the environmental capability and economic efficiency of the microgrid for cold regions under management of electric power quality. The optimal output of an independent microgrids consisting of natural gas combined cycle and large-scale photovoltaic was examined to achieve the CO_2 emission reduction.

He et al. [121] carried out a low-carbon economic scheduling model to improve the wind power and reduce CO2 emissions.

Ren et al. [122] proposed a residential energy system consists of the PV/Fuel cell/Battery and optimized it with the minimizing annual running cost or annual CO2 emissions.

Ju et al. [92] construct a CCHP and renewable energy based hybrid energy system driven by distributed energy resources (DERs CCHP) and proposes a multi-objective optimization model for DERs CCHP system under four optimization of energy rate (ER), total operation cost (TOC), carbon dioxide emission reductions (CER) and joint optimization. The result indicates the performance of the DERs CCHP system will become better with the increase of chiller COP, decrease of NG price and wind-photovoltaic equipment cost.

Wu et al. [123] investigated the impact of energy consumption, carbon and energy market regulations, energy density, and transaction rate in the low carbon transition for distributed energy systems through an agent-based model. Simulation results show that a single system cannot achieve low carbon transition, while a one-way climate policy linked system can realize low carbon transition. And also show that the larger high and low energy capacity is, the system is less likely to achieve low carbon transition in the circumstance of the same transaction rate with the constant emission policy bias.

Zhang et al. [124] observed the new system based on the synthetic utilization of biomass partial gasification and ground source heat pump had a primary energy saving ratio (PESR) of 7.61%, annual total cost saving ratio (ATCSR) of 23.62%, carbon dioxide emission reduction ratio (CO2EER) of 66.52% and performance indicator (PI) of 32.58%, when compared with the separate system. Fig.2-19 shows the configuration of a simplified CHP system.

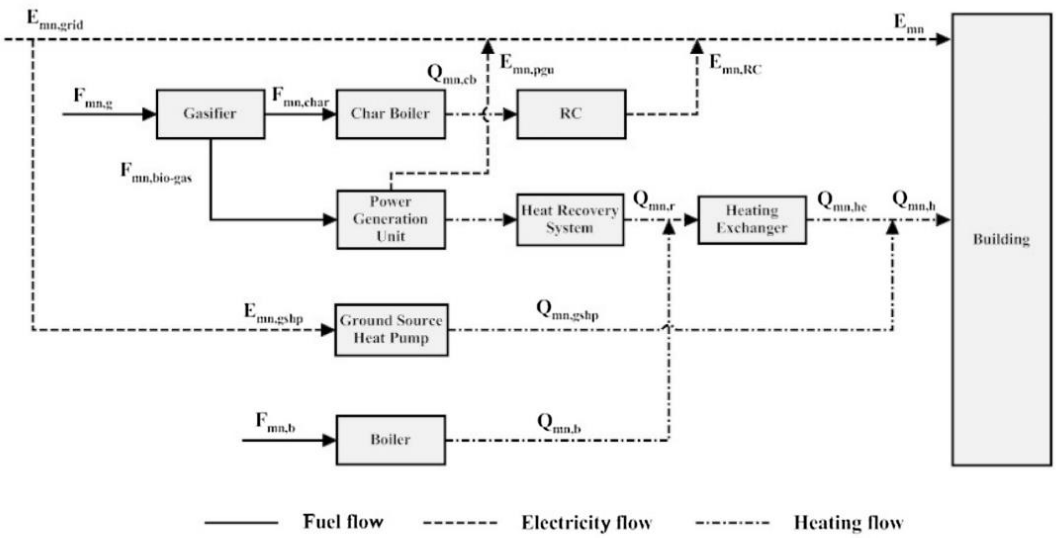

Fig.2-19 The configuration of a simplified CHP system [124].

Rong et al. [125] also found the CCHP- GSHP coupling system in the case study had a primary energy saving ratio of 26.10%, carbon dioxide emission reduction ratio of 35.02%, annual total cost saving ratio of 15.13%, comprehensive performance value of 25.42%, when compared with the separated generation system.

Wang et al. [126] used the integrated energy efficiency, primary energy saving ratio (PESR), CO2 emission reduction ratio (CO2ERR) plus social acceptability in the multicriteria decision-making method to evaluate the energy performance of Songshanhu high-tech industrial Park in Pearl River Delta in China, where three types of energy sources including fossil fuel, renew- able energy and low-grade energy are considered.

Wang et al. [127] analyzed the exergy efficiencies of the biomass-based DES and each component in each season and identified the component that caused the largest exergy destruction, based on which the proposed system can be improved. There is not yet a benchmark for exergy efficiency in legislations related to DES, different from energy efficiency.

Somma et al. [128] considered energy costs and exergy efficiency in the operation optimization of a hybrid DES. Results proved that exergy efficiency should be included in legislation to use energies with different grades more reasonably. For environment evaluation, CO_2 emitted during operation is usually calculated. Moreover, if only CO_2 is considered in greenhouse gas calculation, the environment evaluation based on greenhouse gas emission is similar to that based on CO_2 emission. Fig.2-20 shows the scheme of the DES for the operation optimization problem.

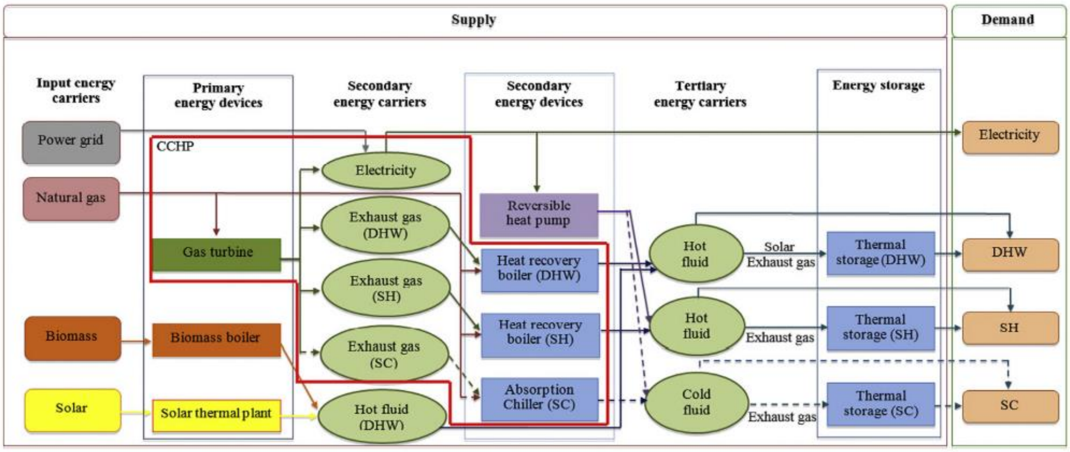

Fig.2-20 Scheme of the DES for the operation optimization problem [128]**.**

Wu et al. [129] employed a synthetic approach for the multicriteria evaluation of DES in hotels and hospitals located in 6 Japanese climate zones and 5 Chinese climate zones. The synthetic approach combines gray relational analysis and analytic hierarchy process. Different from the studies mentioned above, analytic hierarchy process approach in this study was employed to deduce the selected criteria's weights. Fig.2-21 shows the energy flows of the BCHP system and traditional system.

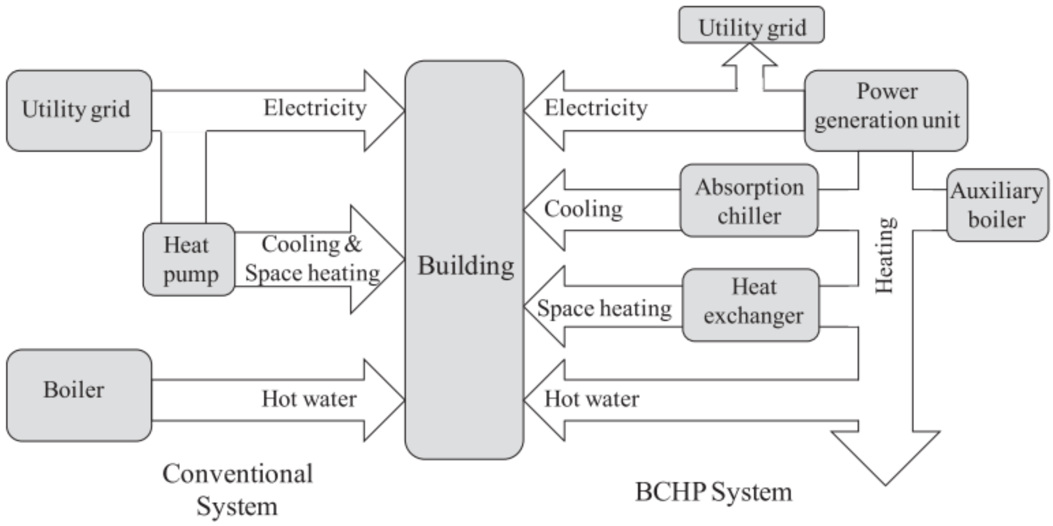

Fig.2-21 Energy flows of the BCHP system and traditional system [129].

Perera et al. [130] used an integrated method that combines fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach and level diagram approach. In the study, fuzzy TOPSIS was responsible for ranking the designed systems, while the level diagram approach was responsible for identifying the potential directions that could be used to improve criteria weight. In a nutshell, the methods used in the above researches firstly focuses on the relative importance of criteria in subjective and/or objective evaluations and then integrates the obtained relative values of all criteria of a DES option into a comprehensive value, based on which DES options are subsequently ranked to select the optimal DES. Fig.2-22 shows the graphical abstract.

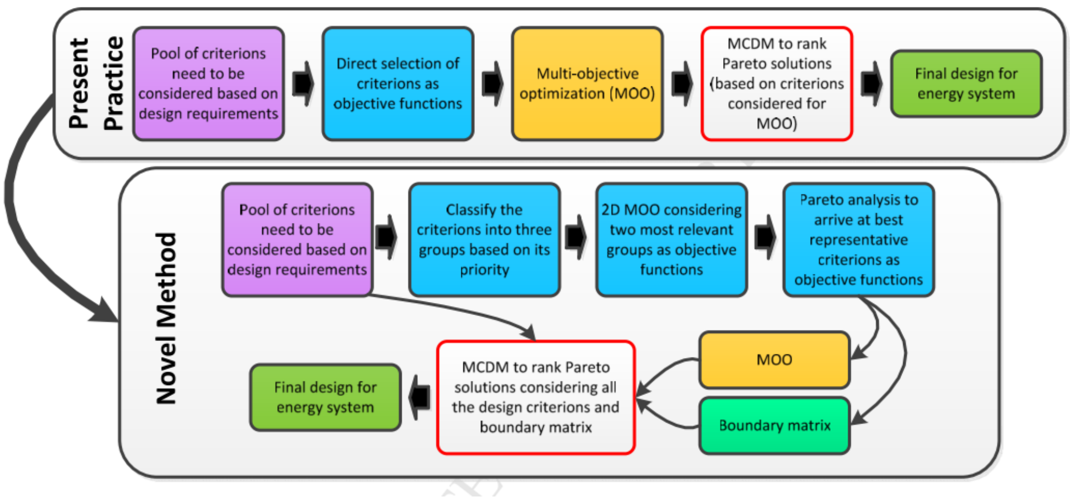

Fig.2-22 Graphical abstract [130].

Wang et al. [127], to evaluate the hybrid CCHP system utilizing biomass and solar energy, energy efficiency and exergy efficiency were adopted for thermodynamic performance evaluation, while carbon emission reduction ratio (CERR) was adopted for environmental performance evaluation. Under the design condition, energy efficiency, exergy efficiency and carbon emission reduction ratio were up to 57.9%, 16.1%, and 95.7%, respectively.

Nascimento et al. [98] proposed and applying a novel hybrid Levelized Cost of Storage (LCOS) analysis, the effects of adopting ESS in the Brazilian regulatory framework were evaluated. The proposed method is universal, and the Brazilian case study is presented to illustrate it. Results are compared with an alternative of PV-only systems in a flat tariff scheme and show that a sharp drop in ESS initial costs is required before PV systems plus storage become the best investment alternative for the end user. However, the PV + ESS alternative results in a positive impact for the whole grid, suggesting that policies towards cost reductions and incentives, such as a wider Time-of Use tariff spread, should be designed to stimulate the adoption of ESS associated with DG solar PV.

Wen et al. [99], the criteria are discussed from energetic, environmental, and economic aspects. Different supportive strategies are analyzed in several developed countries and developing countries. Finally, several potential challenges faced by DES development are presented, based on the above analysis of applications, evaluations, and strategies. This review hopes to offer some references for future research on DES.

Ameri et al. [131], the economic and environmental results obtained from the scenarios revealed saving in costs and reduction in CO2 emissions in the optimal cogeneration system compared with using boilers to produce heat and of buying electricity from the grid.

Previous research evaluated various DES from different points of view. Most of the papers use a single index economic performance to evaluate the DES. Some researchers also assessed the environmental performance to improve the advantage of the DES. There are few studies considering the grid stabilization performance when comparing various feasible combinations of DES technologies and their corresponding sizes. This research analyzed grid stabilization effect of the DES and used the multi-criteria evaluation to trade-off these different performances. The utilization of the DES as emergency power system to show the reliability improvement is also demonstrated in the research.

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Chapter 3

THEORIES AND METHODOLOGY OF THE STUDY

CHAPTER THREE: THEORIES AND METHODOLOGY OF THE STUDY

3.1 Introduction

Distributed energy resource (DER) system contains a variety of equipment that can meet the power, cooling and heating load at the same time. This increases the complexity of the energy supply mode of the distributed energy system. The same load demand can have multiple energy supply combinations and operating strategies. And energy-saving potential, it is necessary to determine the number and capacity of some alternative equipment, as well as system operation strategies, and target users' energy needs. An important factor that affects the best configuration and operating strategy selection of DES is an effective evaluation method. Different evaluations Generally, when designing distributed energy system, its evaluation only considers the economic benefits of system operation or primary energy utilization. However, only one evaluation index is not comprehensive enough to reasonably and accurately evaluate the advantages and disadvantages of distributed energy system. For example, from two different perspectives, energy cost and carbon emission are evaluation indicators and often conflict with each other. It is necessary to optimize these goals in an integrated manner. Multi-standard evaluation and analysis can be used to solve the trade-offs between different performances.

DER system is a complex system which can provide the electricity, heating, cooling at the same time, and composed of power generation system, cooling system, storage system, heating recovery system, heat boiler and so on. Among them, the power generation system is the core of the distributed energy system. Because of is should produce the electricity and the waste heat od power generation system can be recovery to meet the heating or cooling demand. Thus, it is very important that power generation system can have a good operation and maintenance for the distributed energy system.

Maintenance, health management and security are closely related. Inspection ana maintenance are necessary methods to keep the reliability of the distributed energy system. Reliability analysis is a process to make the quantitative reliability requirements into the product design through reliability prediction, allocation, analysis and improvement of a series of reliability engineering technology, so as to form the inherent reliability of the product. It is a kind of reliability engineering. The reliability analysis runs through the whole life cycle of products, and the methods of reliability analysis in different stages of products are different. The distributed energy system especially the gas engine and fuel cell has been development near 20 years, a lot of application program of distributed energy system is close to the design life of the distributed energy system. Considering the high cost of investment for a new power generation system, the maintenance and replacement a part of old equipment to prolong the service life for the whole system is the best way to improve the energy efficiency and reduce the cost.

In this chapter, the selection of configuration capacity in the DER system design stage and the analysis method of maintenance were introduced. The application and characteristics of analysis methods are discussed.

3.2 DER system model establishment

3.2.1 Power generation devices

1) Gas engine

The gas engines are theoretically simple, and have three main parts as seen in Fig.3-1. The compression is takes in air from outside of the engine and increases its pressure. The combustor is burning the fuel and produces high pressure and high velocity gas. The engine is extracting the energy from the gas coming from the combustor.

In Fig.3-1, air is sucked in from the left and input to the compressor which consists of many rows of fan blades. In some engines, the pressure of the air can increased by a factor of 30 [1]. The high-pressure air flows into this area, which is where the fuel is introduced. The fuel gets injected constantly into this part in order for the energy through the engine to be constant. The engine is connected to the compressor blades by a shaft, and they spin separately. The compressor connects to the engine which is connected to an output shaft, and because the engine spins separately, it can get up to tremendous speeds due to the hot gas flowing through it.

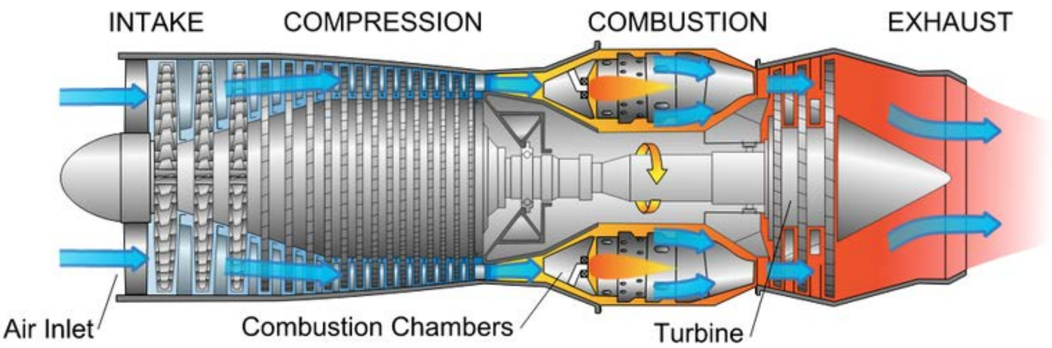

Fig.3-1 Schematic of natural gas engine [2]**.**

Gas engine (GE) is one of the prime movers commonly used in distributed energy system. The main advantages of gas engine lie in their high controllability, rapid start and stop, small size, low requirements on the operating environment, high reliability, and high energy efficiency; the optional capacity span is large, and corresponding configurations can be configured according to the park system capacity and load conditions. gas turbine. Its main working principle is the expansion of high-temperature gas produced by burning natural gas, which drives the impeller to rotate at a high speed, thereby driving the generator to generate electricity.

For the natural gas system, the gas engine consumes energy, which is a kind of load; for the power system, the gas engine outputs electric energy, which belongs to the energy supply side. The relationship between gas turbine power generation and gas consumption is as:

$$G_t^{GE} = \left[F(P_t^{GE}) + G_t^{q/s,GE}\right]/L_{HANG} \tag{3-1}$$

$$F(P_t^{GE}) = a_q + b_q P_t^{GE} + c_q (P_t^{GE})^2 \tag{3-2}$$

where G_t^{GE} is the gas consumption of gas engine at t-time, kW. P_t^{GE} is the power generation of gas engine at t-time, kW. $F(P_t^{GE})$ is the gas engine heat rate curve. $G_t^{q/s,GE}$ is the gas consumption of the gas engine starting and stopping at t-time, kW. a, b and c are the gas coefficient of the gas engine.

The power generation efficiency of a gas engine is related to the actual load situation. The available load rate represents the ratio of its actual power output to the rated power output. It off-loads characteristics are as shown in Fig.3-2:

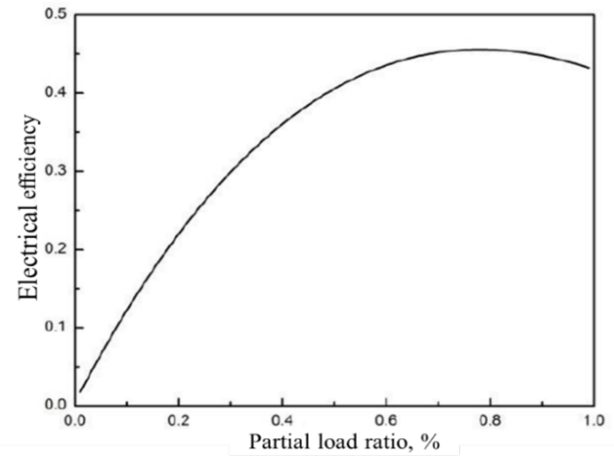

Fig.3-2 Schematic of natural gas engine [3]**.**

2) Fuel cell (FC)

Fuel cell is power generation system which convert chemical energy from a fuel into the electricity through a chemical reaction with oxygen or other oxidizing agents [4]. The power generation efficiency of fuel cell is about 40%, and when the system is adopted was heat recovery for the thermal supply, the total primary energy efficiency is approximately 80%. In [5], the maximum efficiency of 83% for energy trigeneration and heat recovery cycle can be achieved. Generally, the fuel cell uses the hydrogen and oxygen to generate electricity, it is seen as a clean source of energy, because only by-products such as water are produced in the process of producing electricity. However, it is difficult to consume a lot of energy in the process of making hydrogen. At present, many applications of hydrogen production technology are through electrolytic water or natural gas to produce hydrogen. New energy applications such as solar and wind energy can be used in the electrolytic hydrogen industry. Here exist various types of fuel cells, i.e., proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and the previously mentioned SOFC. The fuel cell is a complex system, fuel cell power plants contain a variety of functional units and many components. The main functional units include power section system (PSS), fuel processing system (FPS), air processing system (APS), thermal management system (TMS), water treatment system (WTS), nitrogen purge system (NPS), and cabinet ventilation system (CVS). Fig.3-3 is a system block diagram of fuel cell power plant.

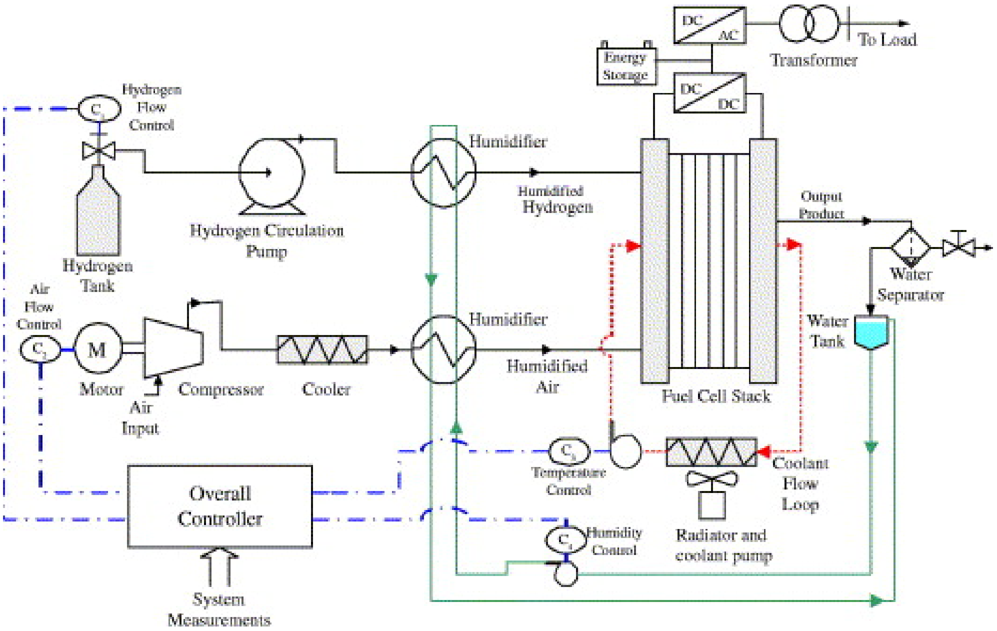

Fig.3-3 System block diagram of fuel cell power plant [6]**.**

3.2.1 Thermal generation devices

1) Absorption chiller (AC)

There are many different types of absorption chillers, but they all work on a similar principle. In a low-pressure system, an absorption fluid is evaporated, removing heat from the chilled water. A heat source such as steam, exhaust gas or hot water is used to regenerate the absorption solution. In this paper, we introduce the double effect exhaust gas driven absorption chiller, which can be operated under cooling mode or heating mode.

Its schematic diagram is displayed in Fig.3-4. A thorough explanation of single-, double- and triple-effect absorption chiller could be found in the literature. Fig.3-4 presents the illustration of these three configurations.

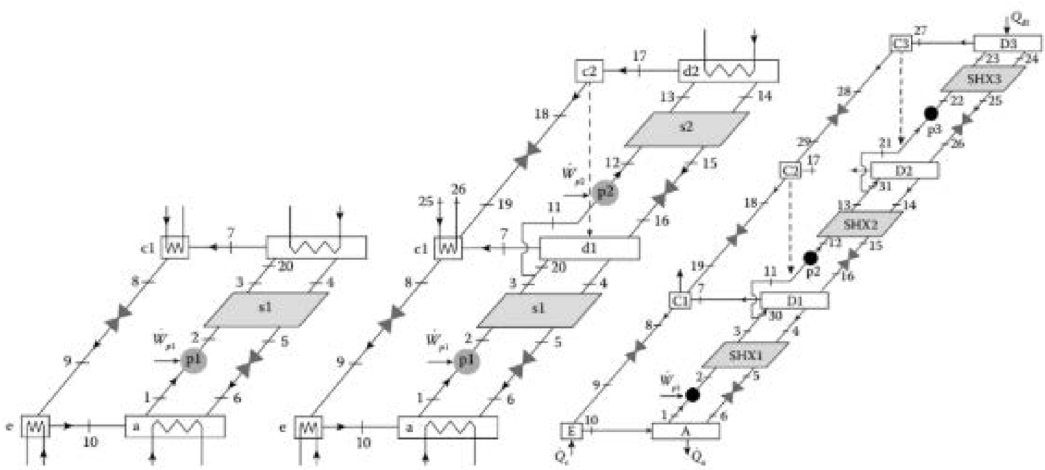

Fig.3-4 Schematic of single (left), double (middle) and triple-stage absorption chillers [7]**.**

(A) Single-effect absorption chiller

In this type of absorption chiller, we have just one disrober, one condenser, and one solution heat exchanger. The mass and energy balance equations on the evaporator and absorber will be as follows:

$$m_9 = m_{10} \tag{3-3}$$

$$Q_{eva} = m_{10}h_{10} - m_9h_9 \tag{3-4}$$

$$m_1 = m_{10} + m_6 \tag{3-5}$$

$$m_1x_1 = m_6x_6 \tag{3-6}$$

$$Q_{abs} = m_{10}h_{10} + m_6h_6 - m_1h_1 \tag{3-7}$$

or the disrober and the condenser, the mass and energy balance could be presented as:

$$m_3 = m_4 + m_7 \tag{3-8}$$

$$Q_{des} = m_4h_4 + m_7h_7 - m_3h_3 \tag{3-9}$$

$$m_3 = m_4 + m_7 \tag{3-10}$$

$$Q_{cond} = m_7(h_7 - h_8) \tag{3-11}$$

The heat transfer between the weak and strong solution could be written as:

$$m_4c_4(T_4 - T_5) = m_2c_2(T_3 - T_2) \tag{3-12}$$

(B) Double-effect absorption chiller

The type of double-effect machine which is considered here is parallel flow. In this type of absorption chiller, the machine has two condensers, two generators, two solution pumps and two solution heat exchangers. Heat is transferred into the cycle in both the high disrober and the evaporator. Heat is transferred out from the cycle in the absorber and low condenser. The mass and energy balance equations on the evaporator and absorber will be the same as equations of the single-effect machine. For the low disrober and high condenser, the mass and energy balance could be presented as:

$$m_3 = m_{20} + m_{11} \tag{3-13}$$

$$m_3 + m_{16} = m_4 + m_7 + m_{11} \tag{3-14}$$

$$X_{20}m_{20} + X_{16}m_{16} = X_4m_4 \tag{3-15}$$

$$Q_{des,low} = m_7h_7 + m_4h_4 - m_{16}h_{16} - m_{20}h_{20} \tag{3-16}$$

$$Q_{cond,high} = m_{17}(h_{17} - h_{18}) \tag{3-17}$$

For the low condenser, the mass and energy balance could be presented as:

$$m_8 = m_7 + m_{19} \tag{3-18}$$

$$Q_{cond,low} = m_{25}c_p(h_{26} - h_{25}) \tag{3-19}$$

$$Q_{cond,low} = m_7h_7 + m_{19}h_{19} - m_8h_8 \tag{3-20}$$

For the high disrober, the mass and energy balance could be presented as:

$$m_{13} = m_{14} + m_{17} \tag{3-21}$$

$$X_{13}m_{13} = X_{14}m_{14} \tag{3-22}$$

$$Q_{cond,low} = m_{17}h_{17} + m_{14}h_{14} - m_{13}h_{13} \tag{3-23}$$

The heat transfer between the weak and strong solution could be written as:

$$m_4c_4(T_4 - T_5) = m_2c_2(T_3 - T_2) \tag{3-24}$$

$$m_{14}c_{14}(T_{14} - T_{15}) = m_{12}c_{12}(T_{13} - T_{12}) \tag{3-25}$$

(C) Triple-effect absorption chiller

In comparison with the double-effect machine, it could be stated that the triple-effect concept requires an additional disrober and solution heat exchanger at the highest temperature level. Triple-effect absorption chiller includes three condenser, three disrobers, three solution pumps and three solution heat exchangers (These three components are called low, medium and high component according to pressure levels). Heat is transferred into the cycle in both the high disrober and the evaporator. Heat is transferred out from the cycle in the absorber and low condenser. The mass and energy balance equations on the evaporator and absorber will be the same as equations of the single-effect machine. For the low disrober and medium condenser, the mass and energy balance could be presented as:

$$m_3 = m_{30} + m_{11} \tag{3-26}$$

$$m_{30} + m_{16} = m_4 + m_7 \tag{3-27}$$

$$X_{30}m_{30} + X_{16}m_{16} = X_4m_4 \tag{3-28}$$

$$Q_{des,low} = m_7h_7 + m_4h_4 - m_{16}h_{16} - m_{30}h_{30} \tag{3-29}$$

$$Q_{cond,med} = m_{17}h_{17} + m_{29}h_{29} - m_{18}h_{18} \tag{3-30}$$

For the medium disrober and high condenser, the mass and energy balance could be presented as:

$$m_{26} + m_{31} = m_{14} + m_{17} \tag{3-31}$$

$$m_{31} + m_{21} = m_{13} \tag{3-32}$$

$$X_{31}m_{31} + X_{26}m_{26} = X_{14}m_{14} \tag{3-33}$$

$$Q_{cond,med} = m_{17}h_{17} + m_{14}h_{14} - m_{26}h_{26} - m_{31}h_{31} \tag{3-34}$$

$$Q_{des,high} = m_{27}h_{27} - m_{28}h_{28} \tag{3-35}$$

For the low condenser, the mass and energy balance could be presented as:

$$m_8 = m_7 + m_{19} \tag{3-36}$$

$$Q_{cond,low} = m_7h_7 - m_{19}h_{19} - m_{28}h_{28} \tag{3-37}$$

For the high disrober, the mass and energy balance could be presented as:

$$m_{23} = m_{24} + m_{19} \tag{3-38}$$

$$X_{23}m_{23} = X_{24}m_{24} \tag{3-39}$$

$$Q_{cond,high} = m_{27}h_{27} - m_{24}h_{24} - m_{23}h_{23} \tag{3-40}$$

The heat transfer between the weak and strong solution could be written as:

$$m_4c_4(T_4 - T_5) = m_2c_2(T_3 - T_2) \tag{3-41}$$

$$m_{14}c_{14}(T_{14} - T_{15}) = m_{12}c_{12}(T_{13} - T_{12}) \tag{3-42}$$

$$m_{24}c_{24}(T_{24} - T_{25}) = m_{22}c_{22}(T_{23} - T_{22}) \tag{3-43}$$

The coefficient of performance (COP) of the absorption chiller is calculated as following:

$$COP = \frac{Q_{0,1}}{Q_{HG,2}} \tag{3-44}$$

where, A is solution circulation rate. c_p is specific heat capacity of water at constant pressure, kJ/(kg·K). UF is unit transfer heat, kW/℃. Y is the steam generation ratio of high temperature generator, %. h is enthalpy, kJ/kg. q_m is mass flow, kg/s. q_V is volume flow, m^3/s. t is temperature, ℃. w is mass fraction of solution, %. ρ is the density of water, kg/m^3.

In the actual operation process, the absorption chiller usually operates under partial load. The partial load rate of the absorption chiller can be defined as:

$$PL_a = \frac{Q_0}{Q_0^N} \times 100\% \tag{3-45}$$

The COP of the absorption chiller will change with the partial load rate, as Fig.3-5 shows. It can be estimated as [8]:

$$COP_a^t = d_1 \cdot (PL_a^t)^2 + d_2 \cdot PL_a^t + d_3 \tag{3-46}$$

Equation (3-46) includes the quadratic fitting formulas, which can be estimated by the parameters of the actual devices.

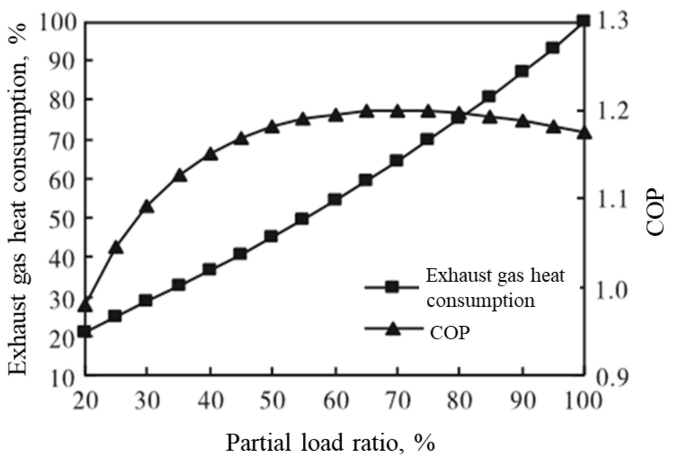

Fig.3-5 Exhaust gas heat consumption ratio and COP changes with the different partial load ratio [9]**.**

2) Electric chiller (EC)

Electric chiller is the most widely used refrigeration equipment in various facilities currently. It is a machine that transfers heat from a cooling object with a lower temperature to the environment to obtain cooling. Fig.3-6 shows the schematic diagram of electric chiller [10].

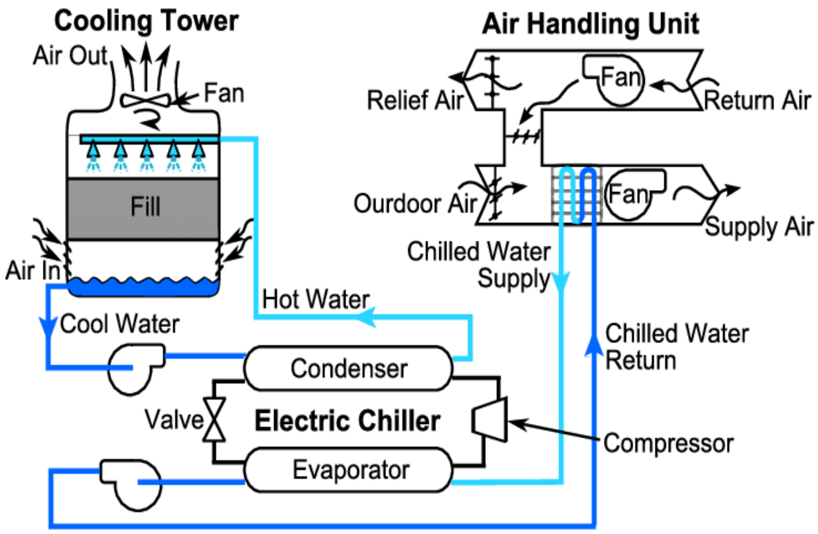

Fig.3-6 Schematic of a typical electric chiller [11]**.**

A chiller works on the principle of vapor compression or vapor absorption. Chillers provide a continuous flow of coolant to the cold side of a process water system at a desired temperature of about 50°F (10°C). The coolant is then pumped through the process, extracting heat out of one area of a facility (e.g., machinery, process equipment, etc.) as it flows back to the return side of the process water system. A chiller uses a vapor compression mechanical refrigeration system that connects to the process water system through a device called an evaporator. Refrigerant circulates through an evaporator, compressor, condenser and expansion device of a chiller. A thermodynamic process occurs in each of above components of a chiller. The evaporator functions as a heat exchanger such that heat captured by the process coolant flow transfers to the refrigerant. As the heat-transfer takes place, the refrigerant evaporates, changing from a low-pressure liquid into vapor, while the temperature of the process coolant reduces. The refrigerant then flows to a compressor, which performs multiple functions. First, it removes refrigerant from the evaporator and ensures that the pressure in the evaporator remains low enough to absorb heat at the correct rate. Second, it raises the pressure in outgoing refrigerant vapor to ensure that its temperature remains high enough to release heat when it reaches the condenser. The refrigerant returns to a liquid state at the condenser. The latent heat given up as the refrigerant changes from vapor to liquid is carried away from the environment by a cooling medium (air or water).

The cooling produced by electric chiller is calculated as following:

$$Q_{load} = m_{chw} \times C_{p,chw} \times (t_{chw,in} - t_{chw,set}) \tag{3-47}$$

$$Q_{met} = MIN(Ca, Q_{load}) \tag{3-48}$$

$$P = Ca \times FFRL \times COP_{nom} \tag{3-49}$$

$$COP = Q_{met}/P \tag{3-50}$$

where Ca is the capacity of the electric chiller, kW. m_{chw} is the freezing water flow, kg/s. $C_{p,chw}$ is the ratio of frozen water to heat. $t_{chw,in}$ is the freezing water intake temperature, ℃. $t_{chw,set}$ is the freezing water intake temperature setting value, ℃. $FFRL$ is the ratio of the actual power consumption of the electric refrigerator to the power consumption of the unit when the unit is operating at full load. COP_{nom} is the nominal energy efficiency ratio of electric chiller.

The electricity consumed by the electric chiller is calculated as following:

$$E_{ec} = \frac{Q_{ec}}{COP_{ec}} \tag{3-51}$$

where COP_{ec} is the COP of the electric chiller.

3) Heat exchanger (HE)

Heat exchangers are systems that use a fluid to absorb heat from a hotter outside source without the fluid and hot source mixing together. Therefore, the fluid that entered hot, leaves cold and the initially cold fluid leaves hot. For example, water can be heated while inside a metal pipe within a furnace or boiler. There could ways to heat water (and cool a heat source)—like throwing water onto a fire. Although the water is now hot and fire is now cooler, they are not useful anymore since the fire is put out and the water is lost as vapor. Avoiding this mess is the essence of a heat exchanger; the fluid never has to come in direct contact with the heat source. Heat exchangers with larger surface areas are more desirable, as they allow for more thermal contact and can therefore exchange heat faster. The schematic of the heat exchanger as shown in Fig.3-7.

Power plants use heat exchangers to collect heat from hot waste gases to get power. Refrigerators use heat exchangers to dump the heat from inside the fridge to the room that it's sitting in. Vehicles use heat exchangers to dump waste heat to the atmosphere so they don't overheat.[2] For instance, a car radiator is a type of heat exchanger. Coolant that takes heat from the engine flows through the radiator which has metal fins that open into the air. As the car drives along, air blowing through the front grille cools this coolant and the waste heat can flow into the passenger compartment, providing heat to the car.

Efficiencies of power plants can be increased with heat exchangers because the exhaust gases still have some useful energy in the form of heat. This heat is absorbed by heat exchangers in the smoke stack and brought somewhere where it can contribute usefully, such as to pre-heat the fuel going into the boiler, or to heat a nearby office [12].

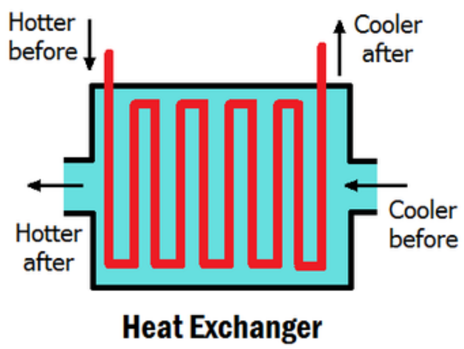

Fig.3-7 Schematic of heat exchanger [13].

The heat production of heat exchanger is calculated as following:

$$Q_{he} = \frac{Q_d}{\eta_{he}} \tag{3-52}$$

where Q_d is the heat demand of the user. η_{he} is the efficiency of the heat exchanger.

4) Gas boiler

Gas-fired Boiler (GB) is usually equipped as backup heat source of the cogeneration system, which can efficiently convert the chemical energy of natural gas into heat energy. If the heat energy of the cogeneration system is lower than the heating load demand, it can be supplemented by the gas boiler. The schematic of gas boiler is shown in Fig.3-8.

Fig.3-8 Schematic of gas boiler [14]**.**

The model of the gas boiler is as follows:

$$Q_{load} = m_{fluid,in} \times (h_{steam,out} - h_{cond,in}) \tag{3-53}$$

$$Q_{max} = m_{rated} \times (h_{steam,out} - h_{cond,out}) \tag{3-54}$$

$$Q_{boiler} = MIN(Q_{load}, Q_{max}) \tag{3-55}$$

$$Q_{fuel} = Q_{boiler}/\eta_{boiler} \tag{3-56}$$

$$F_b = \frac{Q_b}{\eta_b} \tag{3-57}$$

where $m_{fluid,in}$ is the boiler inlet fluid flow, kg/s. $h_{steam,out}$ is the steam enthalpy of boiler outlet, kJ/kg. $h_{cond,in}$ is the enthalpy of boiler inlet water, kJ/kg. $h_{cond,out}$ is the boiler outlet water enthalpy, kJ/kg. m_{rated} is the rated boiler evaporation, kg/s. η_{boiler} is the efficiency of boiler.

3.2.2 System model

1) Energy flow

As a typical kind of DESs, the performance of the combined cooling, heating and power system (CCHP) is usually determined by the matching degree between the energy demand side and the supply side. When generating electricity from coal, natural gas or nuclear power only a fraction of the actual energy content released during combustion is converted into electricity. The remainder of the energy is lost as waste heat. In a CCHP power plant, this waste heat is recovered for other applications such as space heating or other industrial processes that require heat. Hence, CCHP is an efficient process to recover energy that would have otherwise been lost [15]. Due to this increase in efficiency, cogeneration has many environmental benefits and can be a key factor in reducing climate change [16].

Cogeneration plants offer large cost savings, providing additional competitiveness for industrial and commercial uses by offering affordable heat for domestic users.[1] They provide clear environmental benefits due to their enhanced conversion of energy and use of waste heat. However, there are many roadblocks in building such plants [17]. One factor is the relatively high capital cost associated with such plants, making it unappealing to potential developers. Cogeneration plants are a threat to such companies, and there have been known to be many legal wranglings in the development of these plants [18]. In addition, distributed generation sources of electricity can create shock hazards for the power company by electrifying a portion of the electrical grid that would otherwise be off when the company needs to work on that portion of the grid.

Since fossil fuels are mainly used as the input source, CCHP cannot be considered an ultimately sustainable solution for the long term. However, it can help slow the rate of carbon emissions with substantial energy savings through higher efficiencies in situations where more sustainable options are not available or affordable [19].

The DER systems can be divided into three different units: power generation unit (PGU), exhaust thermal utilization unit (EHUU), and auxiliary unit (AU), as illustrated in Fig.3-9. In the co-generation part composed of the PGU and EHUU, the candidates of the PGU are the gas engine (GE), gas turbine (GT), and microturbine (MGT). In the EHUU, the exhausted thermal utilization technologies include the double and single-effect absorption chillers (AC-d and AC-s, respectively), the double and single-effect absorption heat pumps (AHP-d and AHP-s, respectively), and heat exchanger (HE). On the other hand, the AU is composed of the grid, electric chiller (EC), and supplementary boiler. And the combined cooling, heating and power (CCHP) system is shown in Fig.3-10.

Fuel is supplied to the PGU to generate electricity, and the exhaust gas or jacket water from the PGU is recovered by the heat recovery system (HRS). Accordingly, the AC is driven to provide cooling or the AHP and HE to provide heating. In some cases, the energy produced by the CCHP systems are insufficient to satisfy user demands. In this situation, the shortage in electricity (or cooling) and heating energy are compensated by the grid through an EC or a supplementary boiler, respectively.

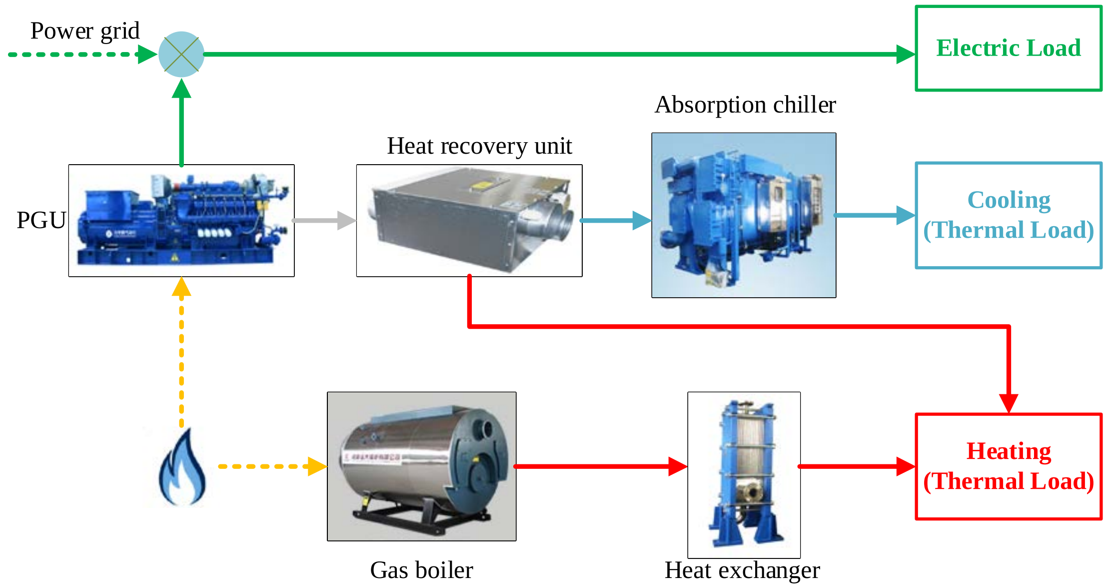

Fig.3-9 Schematic of the DER system.

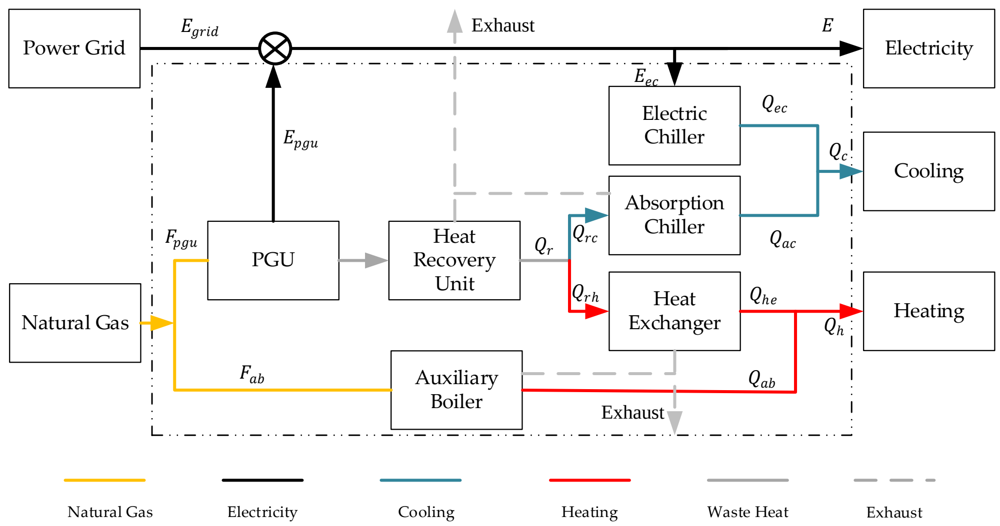

Fig.3-10 Schematic of the CCHP system.

The balance of the electricity energy of CCHP system is expressed as:

$$E_{grid} + E_{ge} = E + E_{ec} \tag{3-58}$$

where E_{grid} is the electricity purchased from the power grid, kWh. E_{ge} is the electricity generated by the gas engine, kWh. E is the electricity demand of the building (equipment, lights, etc.), kWh. E_{ec} is the electricity consumed by electric chiller.

The power generation and natural gas consumption of the gas engine are related to the power generation efficiency of the gas engine. The power generation efficiency of a gas engine is related to the actual load situation, and the available load rate represents the ratio of its actual power output to the rated power output, which is expressed as [5]:

$$PLR_{ge} = \frac{E+E_{ec}}{E_{ge,max}} \tag{3-59}$$

$$\eta_{ge} = a + bPLR_{ge} + cPLR_{ge}^2 \tag{3-60}$$

where PLR_{ge} is the part load ratio percentage of the gas engine. $E_{ge,max}$ is the maximum power output by gas engine when its runs at full load. η_{ge} is the power generation efficiency of the gas engine.

Then, the fuel energy consumption of the gas engine, F_{ge}, can be calculated as:

$$F_{ge} = \frac{E_{ge}}{\eta_{ge}} \tag{3-61}$$

The waste heat generation of the gas engine, Q_r, kWh, can be calculated as:

$$Q_r = F_{ge} \times (1 - \eta_{ge}) \times \eta_r \tag{3-62}$$

where η_r is the efficiency of heat recovery unit.

The waste heat from the gas engine is used to provide cooling and heating demand, is calculated as:

$$Q_{ac} = Q_r \times COP_{ac} \tag{3-63}$$

$$Q_{he} = Q_r \times \eta_{he} \tag{3-64}$$

where Q_{ac} and Q_{he} are the cooling load produced by absorption chiller and heating load produced by heat exchanger, respectively. COP_{ac} is the coefficient of performance (COP) of the absorption chiller. η_{he} is the efficiency of the heat exchanger.

The balance of the cooling load and heating load is expressed as:

$$Q_{ac} + Q_{ec} = Q_c \tag{3-65}$$

$$Q_{rh} + Q_{ab} = Q_h \tag{3-66}$$

where Q_{ec} is the cooling load produced by electric chiller, kWh. Q_c and Q_h are the cooling and heating demand of the building, kWh, respectively. Q_{rh} is the heat supplied to heat exchanger, kWh. Q_{ab} is the supplementary heat from the auxiliary boiler.

The cooling demand generated by electric chiller, Q_{ec} and electricity consumption of the electric chiller, E_{ec} are expressed as:

$$E_{ec} = \frac{Q_c}{COP_{ec}} \tag{3-67}$$

where COP_{ec} is the coefficient of performance of the electric chiller.

The fuel energy consumption of the auxiliary boiler, F_{ab}, kWh, is calculated as:

$$F_{ab} = \frac{Q_{ab}}{\eta_{ab}} \tag{3-68}$$

where η_{ab} is the efficiency of auxiliary boiler.

2) Operation strategies

There are two basic operation strategies of the CCHP system: following the electric load (FEL) and following the thermal load (FTL). According to the definition of the above two strategies (Fig. 3-9) [20], the system operating under the FEL or FTL strategy will not generate excess electricity or thermal energy.

For FEL strategy displayed in Fig.3-11 a), electricity demand should be satisfied preferentially by the CCHP system. Therefore, the system will not generate surplus electricity. When the electricity demand cannot reach the starting condition (E_{min}) of the ICE, the electricity, heating, and cooling load of demand side will be supplied by the utility grid, the gas-fired boiler, and the electric chiller, as in the area (1) in Fig.3-11 a). In the area (2), the CCHP system operates following the electric load. When the load is at point A, the ICE will operate at A’. The excess heat cannot be used by absorption chiller, which is dissipated or stored in a thermal tank. When the load is at point B, the ICE will operate at B’. The insufficient heat will be compensated by the back-up gas boiler. The ICE operates at full load when the electricity load is high and the surplus heat (C) or insufficient heat (D) can be stored in the storage tank or imported from the boiler.

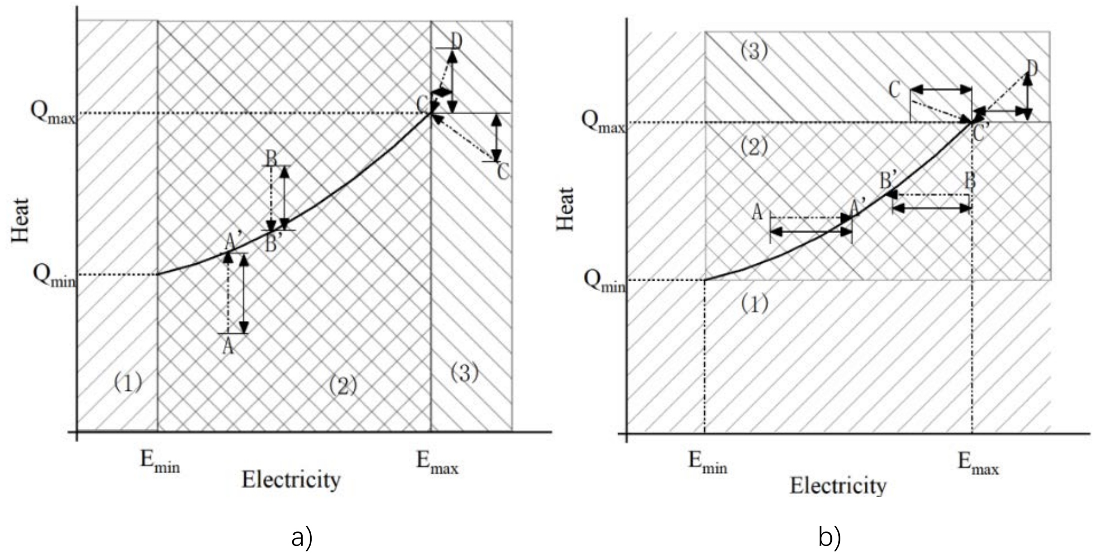

Fig.3-11 Two basic operation strategies of the CCHP system: a) following the electric load (FEL); b) following the thermal load (FTL) [20].

For FTL strategy displayed in Fig.3-11 b), heating demand should be satisfied preferentially by the CCHP system. Therefore, the system will not generate surplus heating or cooling load. When the electricity or heating demand cannot reach the starting condition (E_{min}) of the ICE, the electricity, heating, and cooling load of demand side will be supplied by the utility grid, the gas-fired boiler, and the electric chiller, as in the area (1) in Fig.3-11 b). In the area (2), the CCHP system operates following the heating load. When the load is at point A, the ICE will operate at A’. The excess electricity can be sold to the power grid. When the load is at point B, the ICE will operate at B’. The insufficient electricity will be supplied by the power grid. The ICE operates at full load when the thermal demand is high and the surplus electricity (C) or insufficient electricity (D) can be sold to or imported from the utility grid.

3.3 Evaluation criteria

3.3.1 Economic performance

The economic evaluation method is divided into static evaluation analysis and dynamic evaluation analysis. Static evaluation analysis method is generally used for the evaluation and analysis of the initial period of the system. Dynamic evaluation analysis method is to convert the inflow and outflow of current funds in different periods into the value of funds at the same time, such as the annualized total cost. The annualized total cost (ATC) includes the annualized investment cost (AIC), the annualized maintenance cost (AMC), and the annualized operation cost (AOC) of each equipment in the system, expressed as Equation (3-71). Among them, the annualized investment cost and annualized maintenance cost refer to that the total equipment investment cost and maintenance cost are evenly amortized throughout the lifetime of the system, calculated as Equation (3-69) and (3-70).

The payback period is the time required for a project to recover its initial investment cost, dynamic payback period mainly considers the time value, which can be calculated when the cumulative net present value (NPV) is zero. The NPV is the difference between the present value of cash inflows and the present value of cash outflows during a period, which mainly presents the balance between the present value of total income and initial investment. It can be expressed as (3-74) and (3-75).

$$AIC = R \times \sum_{k=1}^{k}(N_k \times I_k) \tag{3-69}$$

$$AMC = \sum_{k=1}^{k}(N_k \times M_k) \tag{3-70}$$

$$AOC = \sum_{t=1}^{8760}\left(E_{grid} \times C_e + F^{CCHP} \times C_f\right) \tag{3-71}$$

$$ATC = AIC + AMC + AOC \tag{3-72}$$

$$CSR = (1 - \frac{ATC^{CCHP}}{ATC^{SP}}) \times 100 \tag{3-73}$$

$$DPP = \lfloor DPP - 1 \rfloor + \frac{\left|NPV_{\lfloor DPP-1 \rfloor}\right|}{ATP_{\lfloor DPP \rfloor}} \tag{3-74}$$

$$NPV = \sum_{y=1}^{n} \frac{ATP_y}{(1+i)^y} - TIC \tag{3-75}$$

where N_k is the capacity of the kth equipment, kW. I_k is the investment cost of the kth equipment per unit capacity, \$/kW. M_k is the maintenance cost of kth equipment per unit capacity, \$/kW. F^{CCHP} is the natural gas consumption of the CCHP system. C_e and C_f are the energy price of electricity and natural gas, respectively, \$. $\lfloor DPP - 1 \rfloor$ is the last year when cumulative net present value the (NPV) is negative; $ATP_{\lfloor DPP \rfloor}$ is the cash flow in year $\lfloor DPP \rfloor$; $\left|NPV_{\lfloor DPP-1 \rfloor}\right|$ is the absolute value of NPV until the year $\lfloor DPP - 1 \rfloor$. i is the discount rate, %; ATP_y is the cash flow in year, y; TIC is the total investment cost.

3.3.2 Energy performance

The energy consumed by the gas-fired CCHP system includes primary energy and secondary energy. Primary energy includes heat provided by natural gas, coal gas, and liquefied petroleum gas. The secondary energy consumed by the CCHP system is the electrical energy consumed by pumps, fans and other equipment. Among them, the primary energy is the main energy consumed by the CCHP system. In order to calculate the energy consumption efficiency in a unified way, this paper chooses the primary energy utilization rate as the standard. Primary energy saving ratio (PESR) refers to the ratio of the primary energy consumption to the output energy. It represents the amount of primary energy consumed by the system under a given energy output demand.

Primary energy consumption (PEC) refers to the total amount of fuel to meet the electrical load and thermal load, kWh, calculated as:

$$PEC = F + \frac{E_{grid}}{\eta_{grid} \times \eta_{tr}} \tag{3-76}$$

where F is the total amount of fuel applied to meet electrical and thermal demand, kWh. η_{grid} is the power generation efficiency of power plant. η_{tr} is the transmission efficiency of power grid.

Primary energy saving ratio (PESR) is defined to assess the energy consumption of the CCHP system in comparison with the separate system, is defined as:

$$PESR = (1 - \frac{PEC^{CCHP}}{PEC^{SP}}) \times 100 \quad (3\text{-}77)$$

3.3.3 Environmental performance

At present, the world is vigorously advocating a low-carbon economy to achieve sustainable social development. The environmental performance evaluation of the system refers to the amount of pollutants emitted by the burning of fossil energy during the operation of the system. The pollutants produced by burning fossil energy will have a variety of effects on the environment, such as soil eutrophication, greenhouse effects, and ozone layer depletion. The system burns fossil energy to produce a lot of pollutants, mainly including CO_2, NO_X, CO and particulate matter (PM). Among them, the proportion of CO_2 is as high as 99.5%, while other pollutants account for a small proportion, which can be ignored. Therefore, this research takes Carbon Dioxide Emissions (CDE) as an environmental evaluation index. Their emission conversion factors in China and Japan are listed in Table 3-1 [20]–[22]**.** It can be calculated as:

$$CDE = E_{grid} \times \mu_e + F \times \mu_f \quad (3\text{-}78)$$

where μ_e and μ_f are the emission conversion factors for electricity and natural gas from the grid, respectively, kg/kWh.

The carbon dioxide emission reduction (CDER) is calculated as:

$$CDER = (1 - \frac{CDE^{CCHP}}{CDE^{SP}}) \times 100 \quad (3\text{-}79)$$

Table 3-1 Emission conversion factors of natural gas and electricity [20]–[22]**.**

Countries	Natural gas (t/m^3)	Electricity (g/kWh)
Japan	2.19	462

3.4 Analysis method and algorithm

3.4.1 Life cycle assessment (LCA)

LCA has two main objectives to quantify and evaluate the environmental performance of a product or a process from ‘‘cradle-to-grave’’, and to provide a basis for assessing potential improvements in the environmental performance of a product or system [24].

It first identifies and quantifies the consumption of energy and materials and environmental releases throughout the life cycle stages, then evaluates the environmental impacts of these consumptions and releases, and finally identifies and evaluates opportunities to reduce these impacts. Life cycle assessment focuses on studying the environmental impacts of systems in the areas of ecological health, human health, and resource consumption.

As industrialization grows more and more waste and pollutants enter the natural ecosystem, exceeding nature's own capacity to digest and absorb them, causing great impact on the environment and human health. At the same time, industrialization will consume more natural resources than it can recover, thus destroying the balance of the global ecosystem. Therefore, people are increasingly interested in a way to have a thorough, comprehensive and integrated understanding of the resource consumption and environmental impact of their activities, so that they can seek opportunities to take countermeasures to mitigate the impact of human beings on the environment.

Life Cycle Assessment (LCA) is an internationally accepted method to achieve the above purpose. It is a tool for evaluating the environmental factors associated with a product or service and its environmental impact throughout its life cycle. Starting from the definition of LCA, the technical framework and main contents of LCA are described, and then LCA is proposed as a powerful tool for environmental management, thus promoting the sustainable development of the whole social system. And the LCA procedure is shown in Fig.3-12.

There are four steps of life cycle assessment as follows:

1. Objective and scope definition

This phase is the first and the most critical part of the LCA study, which is the definition of the objectives and scope of the LCA study. The objective definition mainly describes the reason and application intention of conducting LCA, while the scope definition mainly describes the functional units of the product system under study, system boundaries, data allocation procedures, data requirements and raw data quality requirements. The objective and scope definitions directly determine the depth and breadth of the LCA study. Given the iterative nature of LCA, continuous adjustment and refinement of the scope of the study may be required.

2. Inventory analysis

Inventory analysis is the process of creating an inventory of the input and output data in the system under study. Inventory analysis mainly consists of data collection and calculation as a way to quantify the relevant inputs and outputs in the product system. The first step is to prepare the data collection by creating a lifecycle model based on the scope of the study as defined in the objective and scope definition phase. Then unit process data collection is performed, and calculations based on the data collection are aggregated to obtain the product life cycle inventory results.

3. Impact evaluation

The purpose of impact evaluation is to evaluate the environmental impact of the product life cycle based on the results of the inventory analysis phase. This process translates the inventory data into specific impact types and indicator parameters that make it easier to recognize the environmental impacts of the product life cycle. In addition, this phase provides the necessary information for the life cycle results interpretation phase.

4. Interpretation of results

The interpretation of results is based on the results of the inventory analysis and impact evaluation to identify significant issues in the product life cycle and assess the results, including completeness, sensitivity and consistency checks, leading to conclusions, limitations and recommendations.

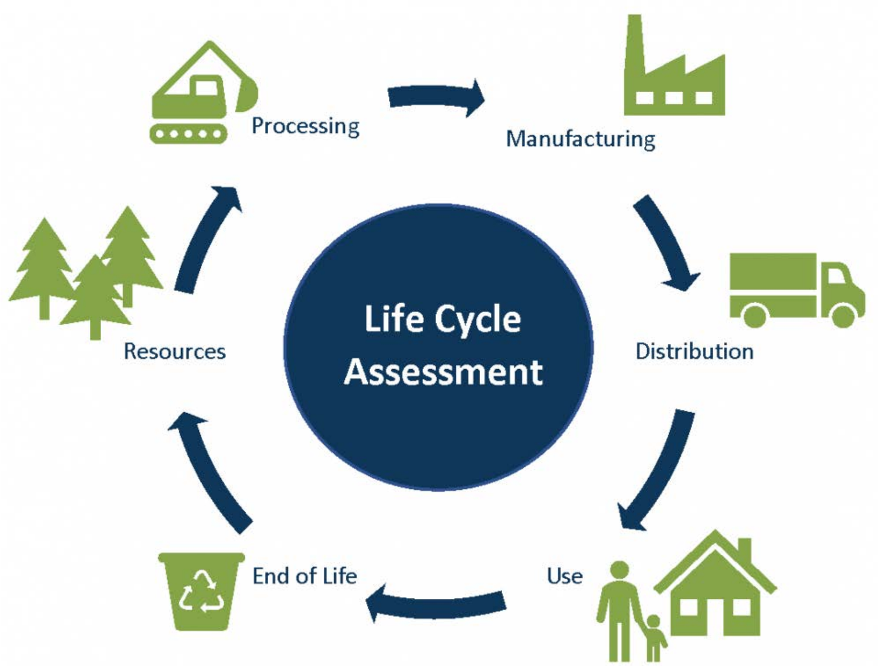

Fig.3-12 Life cycle assessment procedure [25]**.**

3.4.2 Failure mode and effect analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a systematic method for analyzing and ranking the risks associated with various products (or processes), failure modes (both existing and potential), prioritizing them for remedial action, acting on the highest ranked items, reevaluating those items and returning to the prioritization step in a continuous loop until marginal returns set in. Failure Mode and Effect Analysis is broadly used as a reliability tool to recognize likely failures before they happen with the aim of reducing their risks. Since Failure Mode and Effect Analysis method is based on finding, prioritizing and minimizing the failures, it has been broadly utilized in numerous types of industrial areas.

The failure mode and effect analysis are a design tool used to systematically analyze postulated component failures and identify the resultant effects on system operations. The analysis is sometimes characterized as consisting of two sub-analyses, the first being the failure mode and effect analysis, and the second, the criticality analysis. Successful development of an failure mode and effect analysis requires that the analyst include all significant failure modes for each contributing element or part in the system. Failure mode and effect analysis can be performed at the system, subsystem, assembly, subassembly or part level. The failure mode and effect analysis should be a living document during development of a hardware design. It should be schedule and completed concurrently with the design. If completed in a timely manner, the failure mode and effect analysis can help guide design decisions. The usefulness of the failure mode and effect analysis as a design tool and in the decision-making process is dependent on the effectiveness and timeliness with which design problems are identified. Timeliness is probably the most important consideration. In the extreme case, the failure mode and effect analysis would be of little value to the design decision process if the analysis is performed after the hardware is built. While the failure mode and effect analysis identify all part failure modes, its primary benefit is the early identification of all critical and catastrophic subsystem or system failure modes so they can be eliminated or minimized through design modification at the earliest point in the development effort; therefore, the FMECA should be performed at the system level as soon as preliminary design information is available and extended to the lower levels as the detail design progresses.

The analysis may be performed at the functional level until the design has matured sufficiently to identify specific hardware that will perform the functions; then the analysis should be extended to the hardware level. When performing the hardware level failure mode and effect analysis, interfacing hardware is considered to be operating within specification. In addition, each part failure postulated is considered to be the only failure in the system. In addition to the failure mode and effect analysis done on systems to evaluate the impact lower-level failures have on system operation, several other failure mode and effect analysis are done. Special attention is paid to interfaces between systems and in fact at all function interfaces. The purpose of these failure mode and effect analysis is to assure that irreversible physical and function damage is not propagated across the interface as a result of failures in one of the interface units. These analyses are done to the piece part level for the circuits that directly interface with the other units. The failure mode and effect analysis can be accomplished without a CA, but CA requires that the FMEA has previously identified system level critical failures. When both steps are done, the total process is called a FMEA.

A large number of FMEA methods are used to analyze the reliability analysis and maintenance priority of the system. Kang Jichuan, et al [4]. presented and evaluated a correlation FMEA method of the floating offshore wind turbine risk assessment. The reliable index vector method is employed to calculate correlation of failure modes, and to obtain the weakest failure basis of the FOWT system. Probability Network Evaluation Technique (PNET) was used to get the weakest failure modes set of the system based on those coefficients. The relative importance of risk factors O, S and D have been considered and evaluated in a linguistic manner rather than by precise numerical values, which makes the prioritization of failure modes more realistic and objective. For example, the historical data can be applied to determine the weights of risk factors, or a higher weight can be assigned to the factor that is more concerned about, which can make the results more aligned to the practical situation [26]. Sharma and Srivastava compared between the quantitative results of FMEA and reliability field data from real tube systems. These results are discussed to establish relationships which are useful for future water tube designs.

The ground rules of each FMEA include a set of project selected procedures; the assumptions on which the analysis is based; the hardware that has been included and excluded from the analysis and the rationale for the exclusions. The ground rules also describe the indenture level of the analysis, the basic hardware status, and the criteria for system and mission success. Every effort should be made to define all ground rules before the FMEA begins; however, the ground rules may be expanded and clarified as the analysis proceeds. A typical set of ground rules follows: 1). Only one failure mode exists at a time. 2). All inputs to the item being analyzed are present and at nominal values. 3). All consumables are present in sufficient quantities. 4). Nominal power is available.

Major benefits derived from a properly implemented FMEA effort are as follows: 1). It provides a documented method for selecting a design with a high probability of successful operation and safety. 2). A documented uniform method of assessing potential failure mechanisms, failure modes and their impact on system operation, resulting in a list of failure modes ranked according to the seriousness of their system impact and likelihood of occurrence. 3). Early identification of single failure points and system interface problems, which may be critical to mission success and safety. They also provide a method of verifying that switching between redundant elements is not jeopardized by postulated single failures. 4). An effective method for evaluating the effect of proposed changes to the design and operational procedures on mission success and safety. 5). A basis for in-flight troubleshooting procedures and for locating performance monitoring and fault-detection devices. 6). Criteria for early planning of tests.

Failure Mode and Effect Analysis procedure commences with reviewing design details, illustrating equipment block diagram and recognizing all potential failures, respectively. Following recognition, all possible causes and effects should be classified to the related failure modes. After this practice, priority of failures due to their disaster effects should be ranked by a Risk Priority Number (RPN), which is the multiplication of severity of failures (S), their portability of occurrence (O), and the possibility of detection (D).

$$RPN = S \times O \times D \tag{3-80}$$

Basically, by computing RPNs, engineers will be allowed to focus on high RPNs immediately rather than all failure modes due to the highest priority. Moreover, they can prevent the disaster to assess the improvements for priority items.

According to formula 1, severity refers to the immensity of the last effect of a system failure. Rate 10 is allocated to the failure will result in major damage. Occurrence refers to the probability of a failure to occur, which is described in a qualitative way. Detection refers to the likelihood of detecting a failure before it can occur.

Table 3-2 to 3-4 is the severity, occurrence and detection rating scale of FMEA. The scores from 1 to 10. For the table 3-2 severity rating scale, 1-2 refers to failure is of such minor nature that the operate will probably not detect the failure. 3-5 refers to failure will result in slight deterioration of part or system performance. 6-7 refers to failure will result in operator dissatisfaction and/or deterioration of part or system performance. 8-9 refers to failure will result in high degree of operator dissatisfaction and cause non-functionality of system. 10 refers to failure will result in major operator dissatisfaction or major damage. For the table 3-3 occurrence rating scale, 1 refers to an unlikely probability of occurrence: probability of occurrence<0.001. 2-3 refers to a remote probability of occurrence: 0.001<probability of occurrence<0.01. 4-6 refers to an occasional probability of occurrence: 0.10< probability of occurrence<0.10. 7-9 refers to an occasional probability of occurrence: 0.10< probability of occurrence<0.20. 10 refers to a high probability of occurrence: 0.20<probability of occurrence. For table 3-4 detection rating scale, 1-2 refers to very high probability that the defect will be detected. 3-4 refers to high probability that the defect will be detected. 5-7 refers to moderate probability that the defect will be detected. 8-9 refers to low probability that the defect will be detected. 10 refers to very low (or zero) probability that the defect will be detected.

We score the failure parts of gas engine and fuel cell based on these score sheets. Then go to the energy center to find the professional staff to confirm the score.

Table 3-2 Severity rating scale of FMEA.

Rank of severity	Description
1-2	Failure is of such minor nature that the operate will probably not detect the failure.
3-5	Failure will result in slight deterioration of part or system performance.
6-7	Failure will result in operator dissatisfaction and/or deterioration of part or system performance.
8-9	Failure will result in high degree of operator dissatisfaction and cause non-functionality of system.
10	Failure will result in major operator dissatisfaction or major damage.

Table 3-3 Occurrence rating scale of FMEA.

Rank of occurrence	Description
1	An unlikely probability of occurrence: probability of occurrence<0.001
2-3	A remote probability of occurrence: 0.001<probability of occurrence<0.01
4-6	An occasional probability of occurrence: 0.10< probability of occurrence<0.10
7-9	An occasional probability of occurrence: 0.10< probability of occurrence<0.20
10	A high probability of occurrence: 0.20<probability of occurrence

Table 3-4 Detection rating scale of FMEA.

Rank of detection	Description
1-2	Very high probability that the defect will be detected.
3-4	High probability that the defect will be detected.
5-7	Moderate probability that the defect will be detected.
8-9	Low probability that the defect will be detected.
10	Very low (or zero) probability that the defect will be detected.

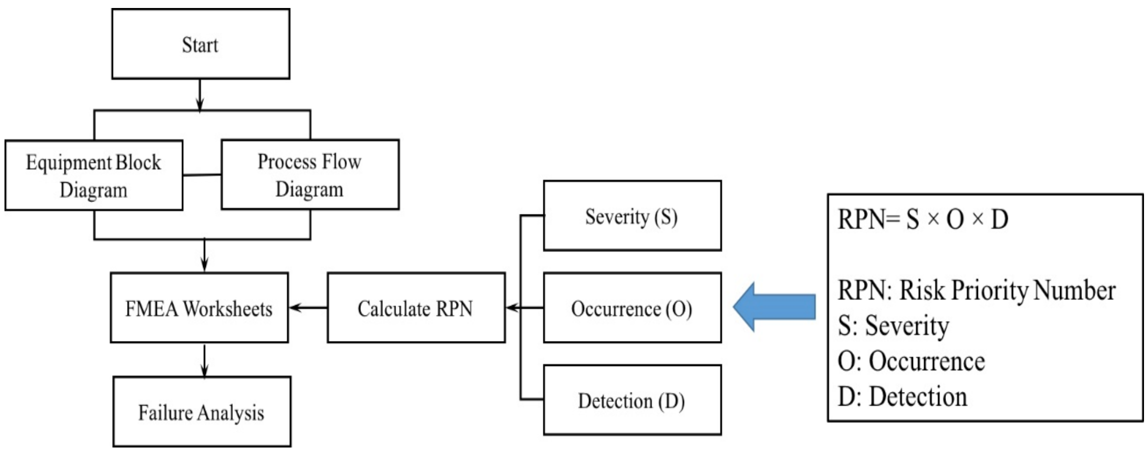

Fig.3-13 Analysis process flow of FMEA.

Suggested failure modes and effects analysis process applied to distributed energy system including the main steps are represented in Fig.3-13. First, I will make the equipment block diagram. Then calculate the Risk Priority Number (RPN), and get the FMEA worksheets. The higher the RPN the more significant the criticality. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

3.4.3 Genetic algorithm (GA)

A genetic algorithm is a search heuristic that is inspired by Charles Darwin's theory of natural evolution. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation [27].

Genetic algorithm (GA), inspired by evolutionary biology, is classified as a global search heuristic method. Heuristic strategies are often used for computationally intractable problems. To be solved exactly, these problems take enormous time on computation, as in this study. The ability of GA to optimize energy systems has been proved in researches. Javan et al. [28] used GA to compare three working fluids to find the best one for a tri-generation system to maximize the recovered low-grade heat. Wang et al. [21] used GA to determine the optimal configuration and operation strategy for the commercial application of the tri-generation system in the cold climate zone. Zhang et al. [29] proposed a multi-objective optimization method based on genetic algorithm was employed to determine the best design parameters for a micro-turbine CCHP System.

GA simulates the evolution process of an artificial population. Through selection, crossover and mutation mechanisms, a group of candidate individuals are retained in each iteration. The process is repeated. After several generations of evolution, the fitness of the population reaches the state of "approximate optimal".

Six phases are considered in a genetic algorithm [30].

1) Initial population

The process begins with a set of individuals which is called a Population. Each individual is a solution to the problem you want to solve. An individual is characterized by a set of parameters (variables) known as Genes. Genes are joined into a string to form a Chromosome (solution). In a genetic algorithm, the set of genes of an individual is represented using a string, in terms of an alphabet. Usually, binary values are used (string of 1s and 0s). We say that we encode the genes in a chromosome. The definition of population, chromosomes and genes as show in Fig.3-14.

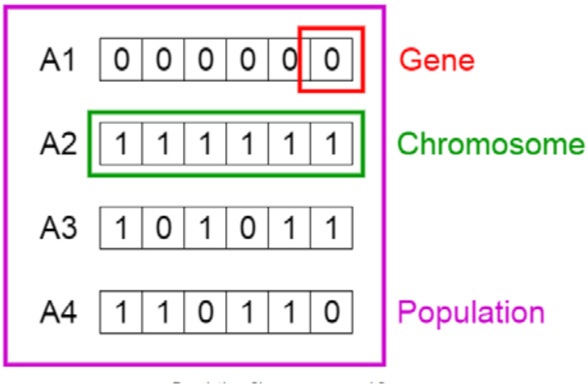

Fig.3-14 Definition of population, chromosomes and genes.

2) Fitness function

The fitness function determines how fit an individual is (the ability of an individual to compete with other individuals). It gives a fitness score to each individual. The probability that an individual will be selected for reproduction is based on its fitness score.

3) Selection

The idea of selection phase is to select the fittest individuals and let them pass their genes to the next generation. Two pairs of individuals (parents) are selected based on their fitness scores. Individuals with high fitness have more chance to be selected for reproduction.

4) Crossover

Crossover is the most significant phase in a genetic algorithm. For each pair of parents to be mated, a crossover point is chosen at random from within the genes. For example, consider the crossover point to be 3 as shown in Fig.3-15.

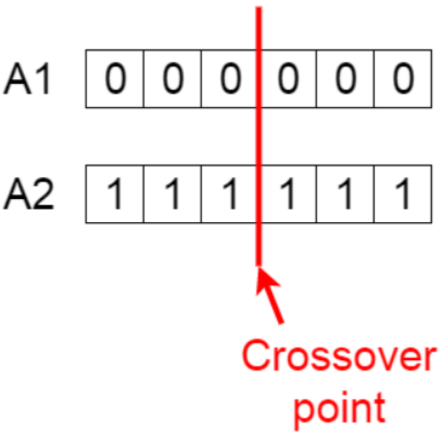

Fig.3-15 Crossover point.

Offspring are created by exchanging the genes of parents among themselves until the crossover point is reached and shown in Fig.3-16.

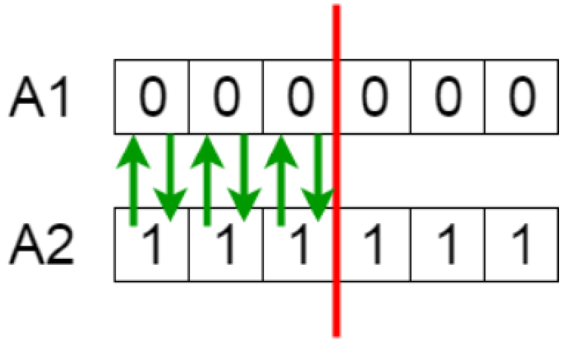

Fig.3-16 Exchanging genes among parents.

The new offspring are added to the population and as shown in Fig.3-17.

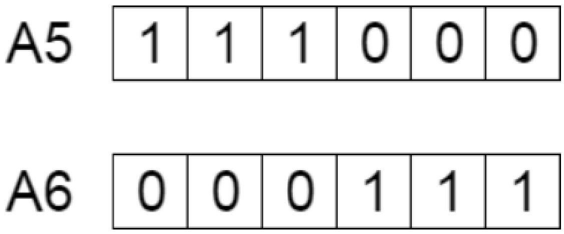

Fig.3-17 New offspring.

5) Mutation

In certain new offspring formed, some of their genes can be subjected to a mutation with a low random probability. This implies that some of the bits in the bit string can be flipped and as shown in Fig.3-18. Mutation occurs to maintain diversity within the population and prevent premature convergence.

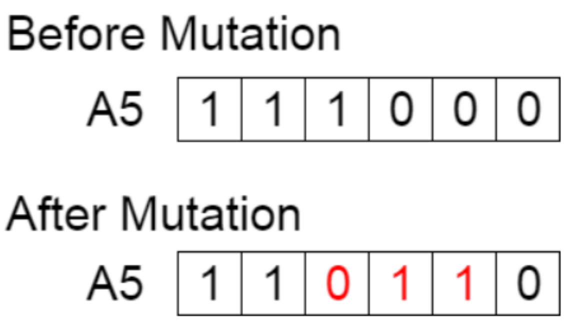

Fig.3-18 Mutation: before and after.

6) Termination

The algorithm terminates if the population has converged (does not produce offspring which are significantly different from the previous generation). Then it is said that the genetic algorithm has provided a set of solutions to our problem.

The algorithm simulation flowchart is demonstrated in Fig.3-19 [31].

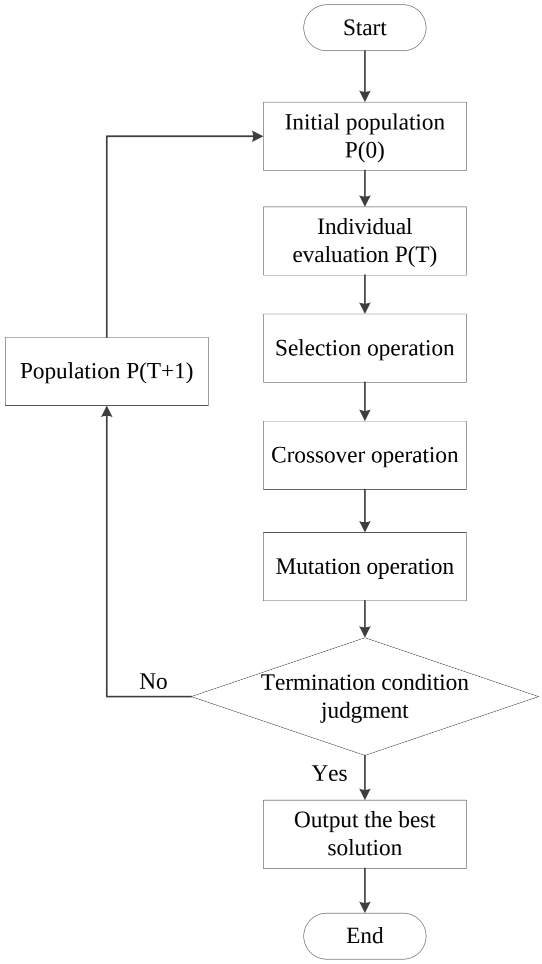

Fig.3-19 GA algorithm simulation flowchart.

3.5 Summary

In this chapter, firstly introduces the devices applied to the DER system, and the DER system model was established, then proposed the evaluation criteria of DER system. Finally introduces the optimization models and algorithms.

The equipment for DER system applications consists of two parts, the power generation unit and the thermal generation unit. The power generation unit consists of a combustion engine and a fuel cell. The thermal generation unit contains absorption chillers, electric chillers, heat exchangers, and gas boilers. The principles of each device are described in this chapter.

Evaluation metrics are used to analyze the performance of distributed energy systems, and three evaluation metrics are presented: economic, energy and environmental. A basic introduction is provided for the later comprehensive performance evaluation of the system.

The whole life cycle assessment is used to analyze the economic performance, energy consumption performance and carbon emission performance of existing systems. Failure Mode and Effect Analysis (FMEA) is a systematic method for analyzing and ranking the risks associated with various products (or processes), failure modes (both existing and potential), prioritizing them for remedial action, acting on the highest ranked items, reevaluating those items and returning to the prioritization step in a continuous loop until marginal returns set in.

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Chapter 4

INVESTIGATION ON REAL OPERATION DATA OF DISTRIBUTED ENERGY RESOURCE SYSTEM

CHAPTER FOUR: INVESTIGATION ON REAL OPERATION DATA OF DISTRIBUTED ENERGY RESOURCE SYSTEM

4.1 Introduction

Distributed energy (DER) system is used to meet electricity demand, heating demand, cooling demand, and hot water demand. DER systems are medium and small-scale energy conversion and utilization systems that are directly oriented to customers, produce and supply energy locally according to their needs, and have multiple functions to meet multiple objectives.

For continuous and stable production, it is necessary to rely on the normal operation of machinery and equipment to maintain. Only by constantly strengthening the management of equipment, including the correct use of equipment, equipment maintenance management, can we ensure the normal operation of equipment. Otherwise, if the management of the equipment is neglected, it will certainly lead to the serious bad technical condition of the equipment, and also frequent failures, which will not ensure the timely completion of the production plan. Maintenance management is an orderly and systematic administrative, financial and technical framework approach for continuously assessing, planning, organizing, monitoring and evaluating maintenance and operation activities and their costs. The maintenance program also depends on maintenance experience; the purpose of the maintenance program is to ensure that the equipment operates as required by the system. Therefore, it is necessary to analyze the system maintenance strategy and the system operational status.

In this chapter, the operation status, maintenance management strategy and classification of energy supply side system of the DER system in Kitakyushu Science and Research Park (KSRP) are investigated and analyzed.

4.2 The DER System in KSRP

4.2.1 Introduction of KSRP

Kitakyushu Science and Research Park (KSRP) is located in the western part of Wakamatsu, Kitakyushu City, Fukuoka. Kitakyushu is an industrial city in Japan. KSRP is located in the western part of Wakamatsu ward and the northwestern part of Yahatanishi ward, with a total development area of approximately 335 hectares. Fig.4-1 shows the plan of the Kitakyushu Science and Technology Park (KSPR), which was opened in April 2001, with the aim of bringing together national, municipal and private universities focused on science and engineering on one campus, with the goal of "future technological development and the creation of new industries" and "becoming an academic research center in Asia. KSRP has a number of university and industrial academic collaboration facilities, and four universities; Kitakyushu City University School of Environmental Engineering, Kyushu Institute of Technology, and Waseda University Graduate School of Information, Production and Systems. The Eco-Campus is a campus of environmental symbiosis, water recycling, power generation and heating. The Park has a number of research institutes and companies. Besides, it has some buildings such as Collaboration Center, Semiconductor Center, Library, Technology Development and Communication Center and so on [1, 2].

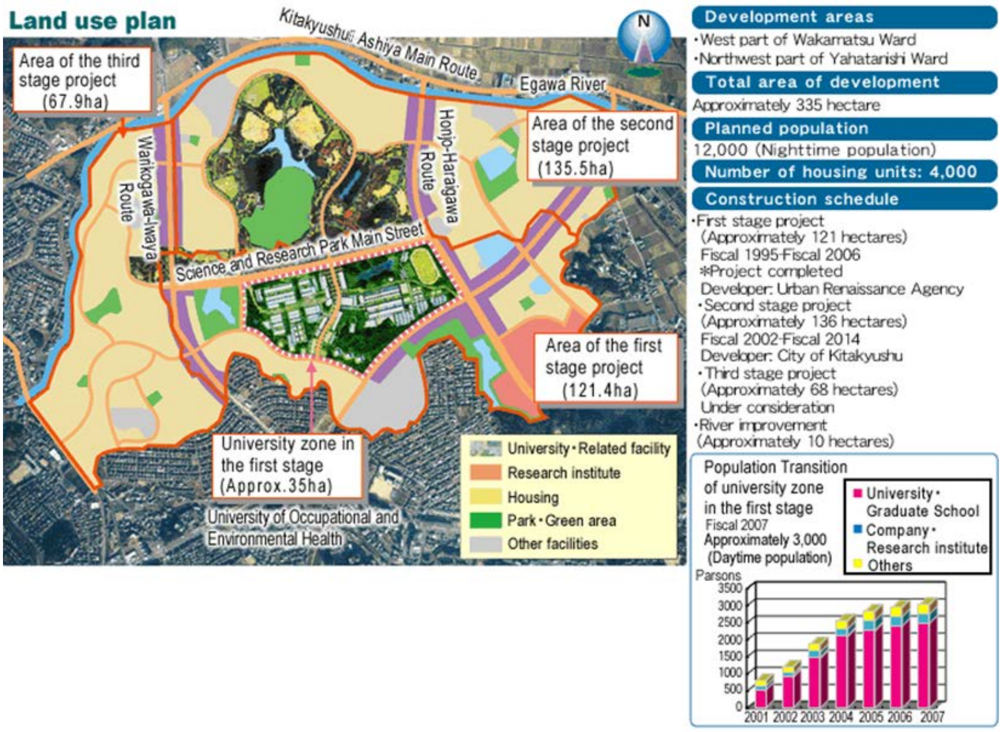


Fig.4-1 The land use plan of Kitakyushu Science and Research Park.

(Source: Kitakyushu Science and Research Park website [1] **and report 2012** [2] **)**

In Kitakyushu Science and Research Park, several of technologies and measures were used to reduce the energy consumptions, improve the energy efficiency and the water use efficiency because KSRP is composed of universities, research institutes and companies are located on science and engineering and focus on the future technology and sustainable development. Especially, in the faculty of environmental and engineering of the university of Kitakyushu campus, some technologies were used [3], such as the natural wind, natural light, green roofs and walls, underground heat storage system for air conditioning and heating, generation of electricity and heat, water recycling system and so on.

Conventional power systems are based on unidirectional power flow in which power generated by large centralized power stations is supplied in the order of transmission system, substation and customer. In this case, the voltage of the high voltage line decreases from the transmission end to the downstream side due to the line impedance, so the voltage drop of this high voltage line can be considered to determine the tap position of the pole transformer, and the transformer and the SVR load tap changer are used to manage the line voltage. To solve this problem, a method is used in which each distributed energy system performs reactive power control based on its own system information, etc. However, when distributed energy systems are introduced on a large scale, conflicting causes cause problems such as performing operations and bearing a large burden only for some distributed energy systems.

The major buildings and facilities in the KSRP are shown in Table 4-1. The main academic buildings include the Faculty Building, Kitakyushu City University, Special Experimental Area, Kitakyushu City University, Instrumentation Center, Kitakyushu City University, Graduate School of Information, Production and Systems, Waseda University, Research Center for Information, Production and Systems, and Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology. Office and research buildings include the Collaboration Center, Semiconductor Center, IT Promotion Center, Business Venture Support Center, and Technology Development and Communication Center. Public buildings include a media center (library), conference center, gymnasium, and restaurant. Some public facilities include parking spaces (several sections) and stadiums. University buildings are managed by the respective universities; the remaining buildings and facilities are managed by the FAIS. In addition, other facilities such as street lights and benches are managed by the FAIS.

Table 4-1 The main buildings and facilities in the KSRP.

No.	Building	Manager
1	The Teaching Building, the University of Kitakyushu	the University of Kitakyushu
2	Special Experiment Ward, the University of Kitakyushu	the University of Kitakyushu
3	Instrumentation Center, the University of Kitakyushu	the University of Kitakyushu
4	Graduate School of Information, Production and Systems, Waseda University	Waseda University
5	Information, Production and Systems Research Center, Waseda University	Waseda University
6	Graduate School of Life Science and System Engineering, Kyushu Institute of Technology	Kyushu Institute of Technology
7	Energy Center	FAIS
8	Collaboration Center	FAIS
9	Semiconductor Center	FAIS
10	IT Advancement Center	FAIS
11	Business Venture Support Center	FAIS
12	Technology Development and Exchange Center	FAIS
13	Media Center (Library)	FAIS
14	Conference Center	FAIS
15	Gymnasium	FAIS
16	Dining hall	FAIS
17	Parking Space (Several parts)	FAIS
18	Stadium	FAIS

***FAIS: Kitakyushu Foundation for the Advancement of Industry, Science and Technology

The Energy Center is the main part of building an environmentally pro-active campus supports the educational research activities in KSRP. The function of Energy Center is to supply the energy (electricity, heating, cooling and hot water), water; and to dispose of sewage water. Therefore, there are many and complex equipment are many of the facilities are located in Energy Center. For instance, power generation system, cooling and heating system, equipment monitoring system, middle water treatment system, water supply system, power exchange system, standby power equipment, maintenance centers, component stores and so on.

The Energy Center provides electricity, heating, cooling and hot water to a number of buildings and facilities within the KSRP. It provides energy to only a few buildings and facilities, not to all buildings and facilities in the KSRP. As shown in Fig.4-2, the blue line is the energy supply line for the Energy Center.

In order to build an eco-campus, various technologies and measures are used to reduce energy consumption and improve energy efficiency and water efficiency. In particular, the College of Environment and Engineering of Kitakyushu City University Campus uses technologies such as natural wind, natural light, green roofs, underground thermal storage air conditioning systems, electricity, thermal power generation, and water recycling systems. The distributed energy resource (DER) system in KSRP is the main technology to meet the energy demand and improve the environmental profit. The more details are introduced in next section.

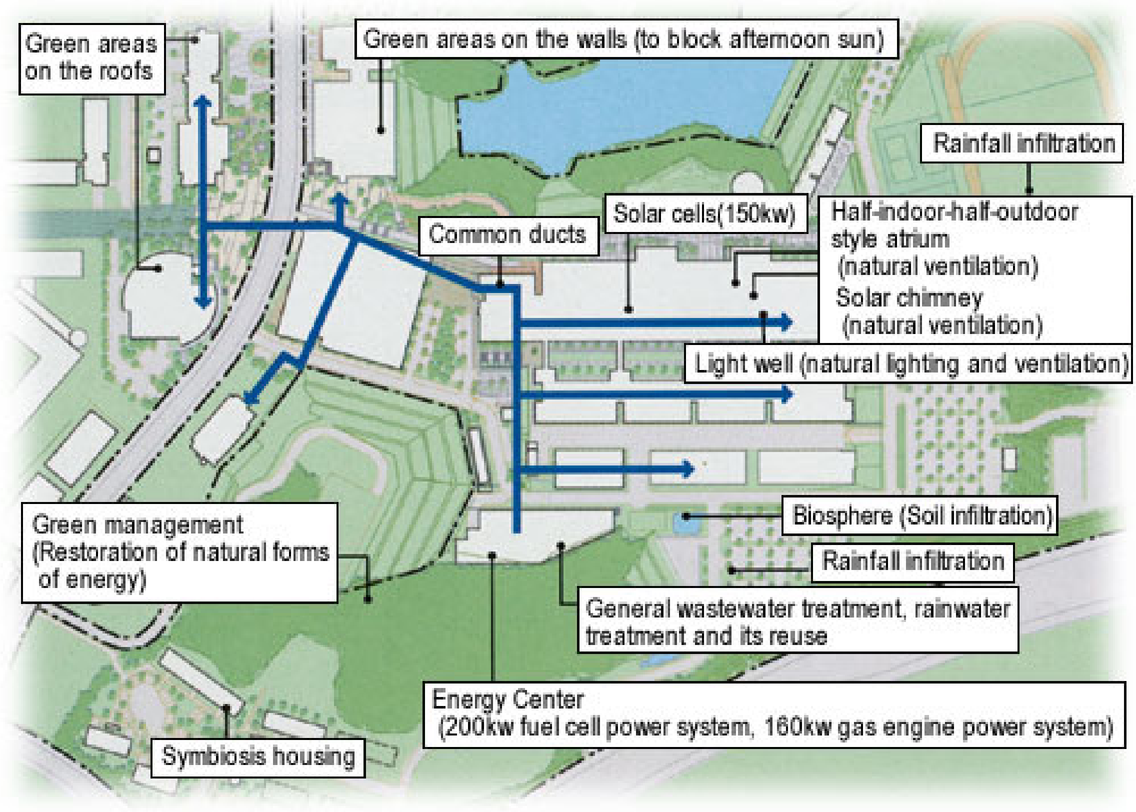


Fig.4-2 The eco-campus planning of KSRP.

(Source: Kitakyushu Science and Research Park website [1]**)**

4.2.2 Technologies of Distributed Energy System

DER system is used to meet the power demand, heating demand, cooling demand and hot water demand of KSRP. DER system is an energy system where energy production is close to the end use and usually rely on a large number of modular and small-scale technologies [3]. DER system has the highest energy use efficiency and low environmental load. In the KSRP DER system, electricity is provided by gas engines (160 kW capacity) and fuel cell (200 kW capacity; fuel cell was discontinued in 2011 and was in use today), photovoltaic, and the Kyushu grid utility. The waste heat from the gas boiler, gas engine and fuel cell meet the heat load. The waste from the gas engine and fuel cell meets the cooling load.

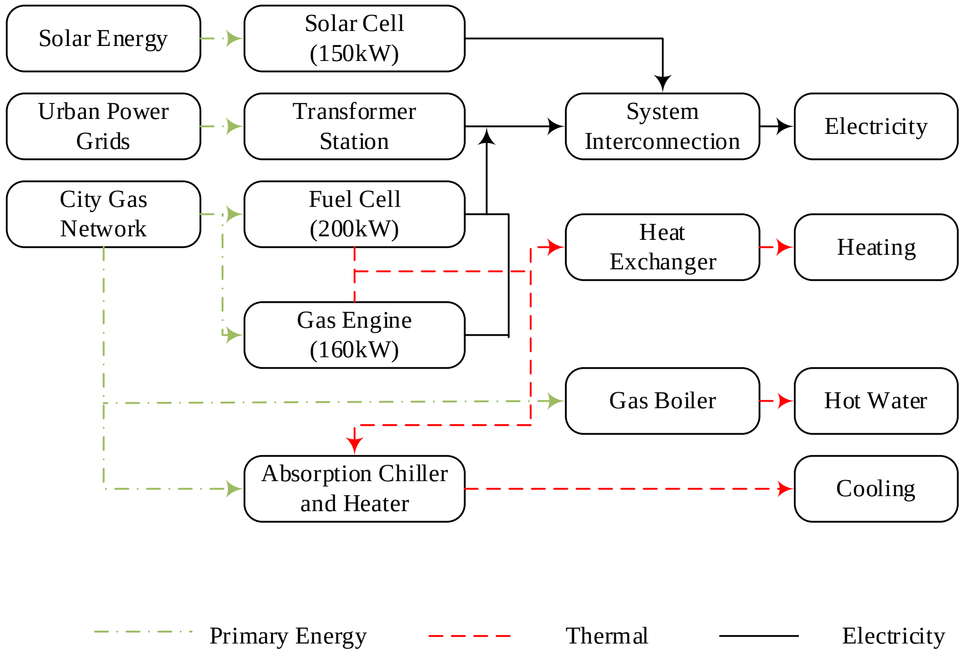


Fig.4-3 Schematic illustration of the distributed energy system in KSRP.

Fig.4-3 shows the schematic diagram of the DER system installed in the Kitakyushu Science and Research Park (KSRP). It is known that the energy load of a building or campus includes electrical load, space cooling load, space heating load and hot water load. The system at the KSRP includes photovoltaic, fuel cell, gas engine, gas absorption chiller, heat exchanger, and gas boiler. In addition to the main equipment, the system includes a large number of auxiliary equipment, such as various pumps (for cooling water, heating, cooling supply, circulation, etc.), cooling towers, ejectors, valves, piping, etc.

In this system, the city gas is used to supply the gas engine and the fuel cell to produce the electricity. In order to reduce the fossil energy consumption and carbon dioxide (CO_2) emissions, and improve energy efficiency; gas engine and fuel cell were used to produce the electricity as a small-case power generation system. The gas engine has 160 kW capacity; and the fuel cell has 200kW capacity. The capacity of the 150kW solar PV is used to meet some electricity demand in the system. When the electricity load is low or the electricity production is not enough, the electricity from grid utilities is used to meet the load. A part of waste heat was sent to the absorption chiller and heater to meet the cooling load; and a part of waste heat was sent to heat exchanger unit to meet the heating space load and hot-water load. And the gas boiler is used to meet the hot-water load in this system.

Table 4-2 provides a detail of the heat recovery efficiency and generator set efficiency of gas engine and fuel cell in distributed energy system when the equipment and system are running at full capacity.

Table 4-2 Details of system [4]**.**

Equipment system	Gas cogeneration system		Solar energy cell	
Type	Fuel cell	Gas engine	Polysilicon	Monocrystalline silicon
Capacity	200kW	160kW	129.6kW	23.4kW
Power Generation Efficiency (with 100% load)	40%	28.70%	13.30%	7.20%
Heat recovery efficiency	(90℃ Hot Water) 20% (50℃ Hot Water) 20%	47.7% (90℃ Hot Water)	None	
Gas cost	43.3Nm3/h	44.1Nm3/h	None	
Operation Mode	24 Hours/Day	Run for 8:00~22:00	All the year	
Waste Heat Utilization Equipment	Heat Exchanger, Absorption chiller and heater, Hot water tank		None	

The capacity of the fuel cell is 200 kW; the two circuits have a generation efficiency of 40% and a heat recovery efficiency of 20%, with a high temperature of 90°C for one circuit and 50°C for the other. The high-temperature hot water circuit preheats the hot water supply scheme. The system operates continuously for 24 hours throughout the year. The gas-fired unit has a capacity of 160kW, a generation efficiency of 28.7%, and a heat recovery efficiency of 47.7%.

The solar cell consists of a single crystal silicon solar cell sliced from a single crystal of high purity silicon and a polycrystalline silicon solar cell obtained by polycrystallizing metallic silicon with a mold in order to make the manufacturing cost lower. There are other types of amorphous silicon solar cells and hybrid type combined with crystal type. Kitakyushu Science and Research Park has installed

156 single crystal molds (250 cm × 75 cm) and 864 polycrystalline molds (132 cm × 89.5 cm) on the roof sloping table in the eaves of the North Building.

It is well known that generating units are the most important component of distributed energy systems, not only because they are related to power generation and waste heat recovery, but also because they are more complex than other units, usually including fuel supply, combustion system, generator, cooling water, lubrication parts and other subsystems. KSRP distributed energy systems have power generation units including photovoltaic, gas engines and fuel cells.

Fig.4-4 is a simplified process flow diagram for gas engine. The gas engine uses city gas to generate electricity and the wastewater is sent to the heat exchanger to supply high temperature water to the heat recovery unit (heat exchanger, absorption chiller cooling or heating or hot water heat exchanger), then the return water is sent to the condenser for cooling and the water is circulated to the gas engine.

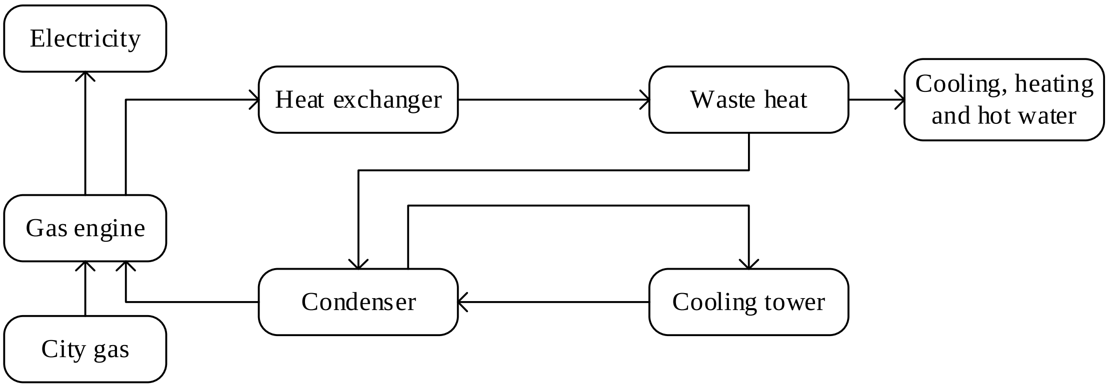


Fig.4-4 A simplified process flow diagram for gas engine.

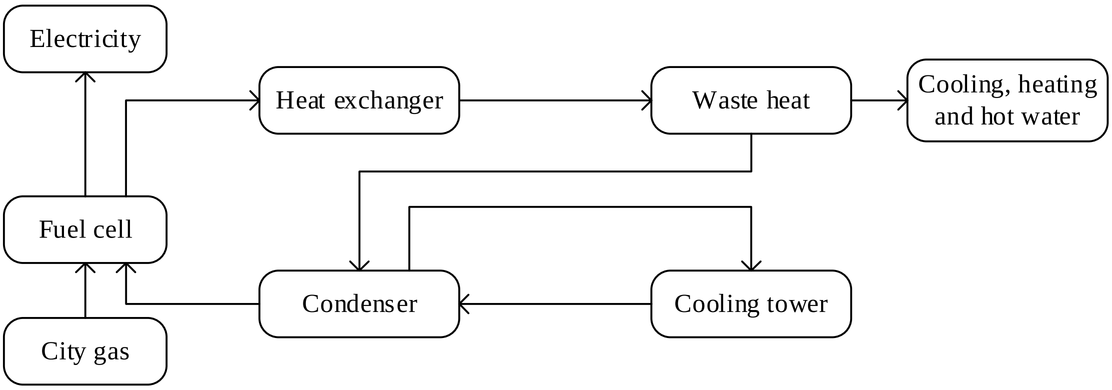


Fig.4-5 A simplified process flow diagram for fuel cell.

Fig.4-5 is a simplified process flow diagram for fuel cell. The fuel cell uses city gas to generate electricity by first converting the city gas to hydrogen in the fuel treatment system. The air is purified and converted in the air treatment system, and then the H2 and converted air are sent to the power section system to generate electricity. Waste heat will be delivered to a heat exchanger to power a high temperature water heat recovery unit. The returned low temperature water is circulated to the condenser. It will then be sent back to the fuel cell.

4.3 Operation status of DER system

4.3.1 Introduction

The distributed energy system in Kitakyushu Science and Research Park includes the fuel cell, gas engine and solar cell. Because of the lack of the solar energy cell data, in this research, the gas engine and fuel cell will be the main object.

The operation status of equipment is so important because it can be the most intuitive expression of equipment performance. It is a main point to determine whether the equipment is degradation and it is also the important point to determine whether the equipment need to be inspected, maintained or replaced. In the long term, the operation status could provide the most realistic experimental run data for the development and transformation of new equipment. The data of inspection and power generation can also play such a role. In general, they are the important and valuable data to investigate the equipment. The operation and management of equipment have developed to a higher efficiency, higher security and higher stability in recent years. The effectiveness of the equipment includes the length and time effectiveness of the power generation and operation of the equipment. Long time operation is the basis of evaluating equipment efficiency and stability. The distributed energy system in Kitakyushu Science and Research Park has been used for about 15 years, the long enough run time makes it a meaningful research objective.

The data of gas engine and fuel cell has been collected from the Environmental Energy Center of KSRP. The data shows that the gas engine has operated for 15 years, from July 2001 to February 2016, while the fuel cell operated for about 10 years from June 2001 to November 2011.

4.3.2 Operation status analysis of gas engine

1) Object situation of investigation

As a mature distributed energy system technology, the gas engine has the advantage that it is able to generate electricity and recycling the waste heat generated by the system at the same time, to ensure the highly efficient use of energy. The complex gas engine system includes the power generation unit, space cooling unit, space heating unit and auxiliars.

For the operation status of the gas engine, according to the operation data, it could be divided to two parts: Operation and Stoppage. Fig.4-6 shows the relationship between the operation and the stoppage.

The situation of stoppage will include schedule stoppage, inspection and failure stoppage. The schedule stoppage includes the interim period days, holiday and weekend stoppage. While the inspection stoppage is mainly include the 1000 hours inspection which held per 1000 hours, determination of smoke emission and Generator panel inspection. The failure stoppage is the failure which can stop the operation and the maintenance to repair it. Table 4-3 shows the situation of the stoppage. While the operation means the gas engine was operating and provide both the electricity and heat. Gas engine runs at 8:00 a.m and stopped at 10:00 p.m. The stoppage means the gas engine was not used to generate the power.

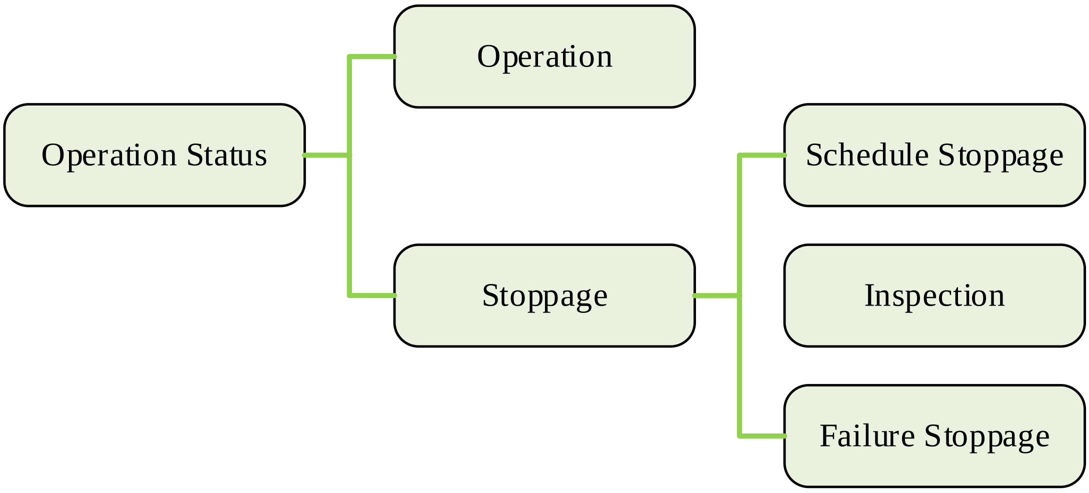


Fig.4-6 The relationship between operation and stoppage.

Table 4-3 The situation of stoppage.

Stoppage	Schedule Stoppage	Inspection	Failure Stoppage
	Period days	1000 hours Inspection	Failure
	Holidays	Determination of smoke emission	Maintenance
	Weekend	Generator panel inspection	

In order to investigation the basic operation and power generation situation, the inspection table of the gas engine has been chosen as the basic data basis. Table 4-4 presents that all the inspection content and object of the gas engine. For the power generation unit, power machine bearings and generator unit stator, charging device, ventilation fan and boiler control panel. For the cooling water system, it includes the cooling tower circulation pump and cooler cooling water pump. The inspection of the heat recovery system includes the cooler for heat exchanger, waste water pump, surplus heat for exchanger, expansion tank (for waste water), heat exchanger unit boiler. The auxiliaries include ventilation and air condition for the heat room. These inspection objects were checked by the inspection contents.

The contents of the gas engine inspection are also enumerated in the Table 4-4. For the power unit appearance part, it includes noise, odor, vibration, dirt and damaged. The inspection items of lubricating oil of power unit includes pressure and temperature of oil. The inspection items of cooling water power unit include temperature and water level. The inspection items of power machine bearings and generator unit stator include temperature of bearings. The inspection items of charging device include gas engine control panel and battery liquid level. The inspection items of ventilation fan include Electric currents. The inspection items of boiler control panel include lamps, toggle switch status, abnormal display and damper. The inspection items of cooling tower circulation pump include electric current, pressure, flow, noise, odor, vibration, dirt and damaged. The inspection items of cooler cooling water pump include electric current, pressure, flow, noise, odor, vibration, dirt and damaged. The inspection items of cooler for heat exchanger include cooling water temperature (cooler circulation and cooling tower circulation). The inspection items of waste water pump include electric current, pressure, flow, noise, odor, vibration, dirt and damaged. The inspection items of surplus heat for exchanger include cooling water temperature and discharge water temperature. The inspection items of expansion tank (waste water) include pressure. The inspection items of heat exchange unit boiler include waste hot water temperature. The inspection items of ventilation include ventilation inlet and outlet temperature and humidity. The inspection items of air condition for heat room include fan coil unit operating conditions, cold water source pressure, valve opening and closing conditions, noise, vibration, dirt, damage, leakage and so on. These inspection contents were recorded every time when the gas engine was operating. They could tell us the status and situation of the gas engine when it was operating.

Table 4-4 The inspection table of gas engine.

System	Inspection Objects	Contents
Power generation unit	Power unit body appearance	Noise, odor, vibration, dirt, damaged
	Lubricating oil of power unit	Pressure, temperature of oil
	Cooling water power unit	Temperature, water level
	Power machine bearings and generator unit stator	Temperature
	Charging device	Gas engine control panel, battery liquid level
	Ventilation fan	Electric currents
	Boiler control panel	Lamps, toggle switch status,

		abnormal display, damper
Cooling water unit	Cooling tower circulation pump	Electric current, pressure, flow, noise, odor, vibration, dirt, damaged
	Cooler cooling water pump	Electric current, pressure, flow, noise, odor, vibration, dirt, damaged
Heat recovery unit	Cooler for heat exchanger	Cooling water temperature (cooler circulation, cooling tower circulation)
	Waste water pump	Electric current, pressure, flow, noise, odor, vibration, dirt, damaged
	Surplus heat for exchanger	Cooling water temperature and discharge water temperature
	Expansion tank (waste water)	Pressure
	Heat exchange unit boiler	Waste hot water temperature
Auxiliaries	Ventilation	Ventilation inlet and outlet temperature and humidity
	Air condition for heat room	Fan coil unit operating conditions, cold water source pressure, valve opening and closing conditions, noise, vibration, dirt, damage, leakage

According to the inspection data of the gas engine, it began run from July 2001 to February 2016, for about 15 years. Table 4-5 shows the summary days of the gas engine. The data for one year is from April of the year to March of the next year. There are 365 days (366 days for leap years) in one year. The gas engine is operated from 8a.m to 10p.m, total of 14 hours for every day. Especially, the first year when the gas engine was set is from July 2001 to March 2002, 265 days in total, and the data of the last year is from April 2016 to February 2016, 335 days in total.

In the Table 4-5, all the classification was included. It can show us all the number of days in every classification during 15 years.

Table 4-5 Summary days of the gas engine.

Year	Days of the year	Operation days	Stoppage days	Schedule stoppage days	Inspection and maintenance	Failures
2001	265*1	201	64	46	13	30
2002	365	273	92	70	18	7
2003	366	299	67	55	12	17
2004	365	315	50	31	18	19
2005	365	278	87	66	8	14
2006	365	241	124	106	9	12
2007	366	240	126	117	6	11
2008	365	222	143	123	16	6
2009	365	236	129	123	10	7
2010	365	251	114	103	10	8
2011	366	238	128	92	12	28
2012	365	249	116	104	9	15
2013	365	238	127	113	14	3
2014	365	259	106	97	8	3
2015	335*2	221	114	105	6	5

The data of one year is from April of this year to March of the next year.

*1 the first year is from July, 2001.

*2 the last year is end of February, 2016.

The basic operation status of the gas engine during 15 years can be presented in Fig.4-7. The sum number of every year is 365 days (366 days for leap years). The first year and the last year is less than the other years because the first year began in July and the last year is end of February. Their data is not enough to investigate. Remove the special two years, in the began few years, the operation days is higher than after years, because of it did not have the interim period before 2006. The most operation days was occurred in 2004, the number of operation days are 315. The lower operation days was occurred in 2008, the number operation days are 222. The number of operation days were in the range of 220 to 260 from 2006 to 2014.

All the classification of stoppage status of gas engine during 15 years are presented in Fig.4-8. This figure consists of small figures: A is for schedule stoppage; B is for inspection and C is for failure stoppage. In the Fig.4-8A, it shows us that the most of the schedule stoppage days were in the range of 31 to 123 days. The lowest number of schedule stoppage days is occurred in 2004, only has 31 days.

It was caused by the operation on Sunday according to the inspection data. All the Sunday in June, July, Augest and September, the gas engine has operated because of the high temperture in the summer. From Fig. 4-8B, we can find the inspection and maintenance status during 15 years. It presented that the longer inspection and maintenance days were occurred in 2002, 2004, 2008 and 2013. That is because it did the overhaul in 2002 and 2008, respectively. In 2004, the inspection of 16000 hours has done for 7 days because the 16000 hours inspection is the Type E inspection, which has the largest scale. In 2013, the inspection of 48000 hours did 10 days, it was very longer than others, so it has long stoppage in 2013.

From the Fig.4-8C, it shows that the failures were happened in actual every year. The most failure days were in 2001 and 2011. That is because the minor failure was occurred in2001, it was not repaired more than 10 days; because it is a minor failure,so it also be able to operate. It had a long toppage time because of the failure in 2011. Beside that , there are 2 years which has faliues more than 15days, it was in 2003 and 2004.

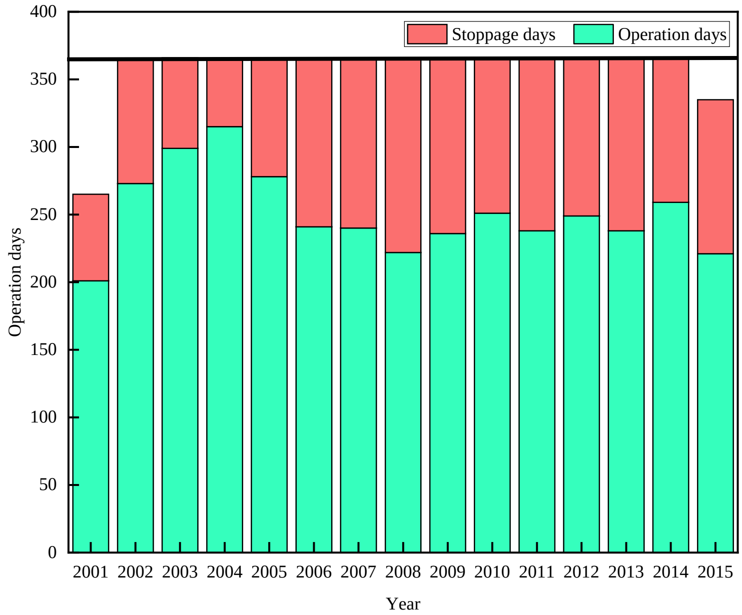


Fig.4-7 Operation status of gas engine during 15 years.

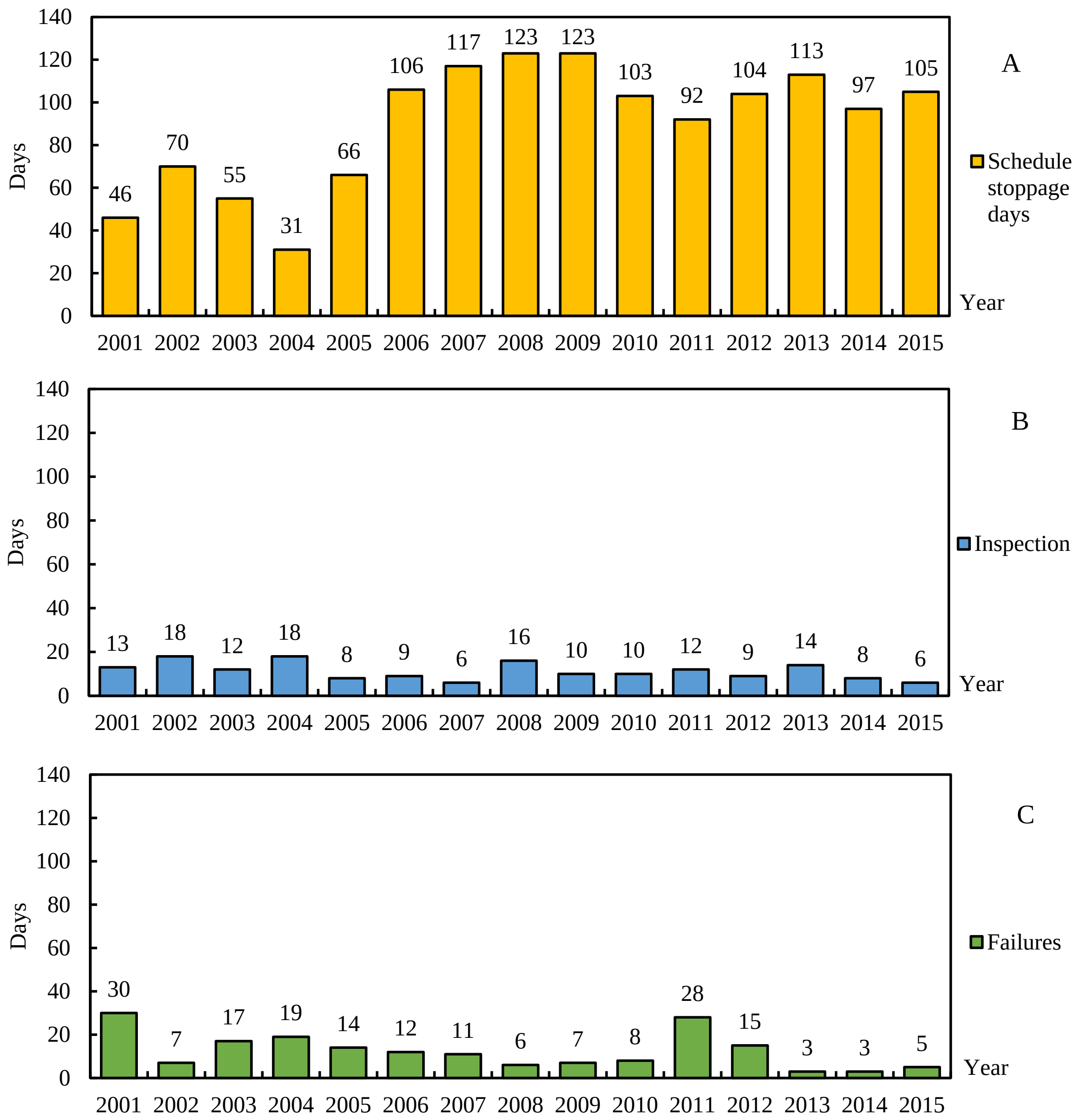


Fig.4-8 All classification of total stoppage of gas engine.

The power generation of the gas engine includes electricity generation and heat generation. The data which will be used was listed in Table 4-6. The electricity generation production and city gas cost are used to calculate and analyze the electricity generation and its efficiency of gas engine. The temperature of the forward hot water, temperature of the return hot water and the instantaneous flow rate of the hot water are used to calculate and analyze the heat recovery and its efficiency. Through comparing the power generation of the gas engine, the operation status could be presented more clearly.

Table 4-6 Data list of power generation investigation

No	Data	Investigation
50502	The electricity generation production	Electricity generation
50505	City gas cost	
50816	Temperature of the forward hot water	Heat recovery
50817	Temperature of the return hot water	
50818	The instantaneous flow rate of the hot water	

2) Electricity generation and efficiency

The Fig.4-9 shows the electricity power generation and city gas cost of the gas engine in Kitakyushu Science and Research Park situation during 15 years. From Fig.4-9, it has told us the year which has the most electricity power generation is 2004, 780644 kWh in total, at the same time, the year cost the most gas is also 2004, it has 235286 m^3 of city gas (13A). The situation of the power generation and city gas cost of the gas engine are generally similar. It means cost more city gas, the more electricity power will be created. The total electricity power generation of the gas engine for the 15 years is 8824397 kWh, while the cost of the city gas is 2691890 m^3 during the 15 years.

Power generation efficiency of gas engine was calculated by the city gas consumption and the power generation production data, the data was collected from the Environmental Energy Center in Kitakyushu Science and Research Park. And the power generation data was recorded every hour from July 2001 to February 2016.

The power generation efficiency calculation of gas engine is shown as the following:

$$\eta_g = \frac{E_g \times 0.86}{V_g \times 11 \times 0.1} \times 100\% \qquad (4\text{-}1)$$

where η_g is the power generation efficiency of gas engine. E_g is the power generation of gas engine (electricity/kWh). V_g is the city gas consumption of gas engine (unit/m³).

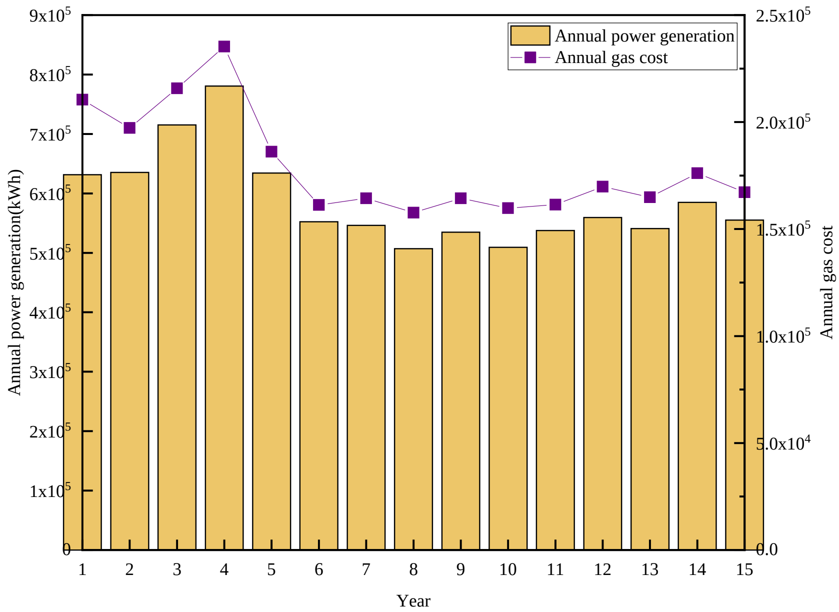


Fig.4-9 Electricity power generation and city gas cost of gas engine.

According to the formula 4-1, the efficiency of the electricity generation of the gas engine can be showed in Fig.4-10. It presented that the efficiency of electricity in every year during 15 years. Compared the electricity generation efficiency of 15 years, it is obvious that the efficiency of the first year, this is because the gas engine was still at the debugging phase, so that the efficiency of electricity generation is very unstable. In the next three years, its electricity generation efficiency tends to be stable, in the rang of 25.9%. There was a shock between 2008 to 2010 year, while the 2006 has the highest efficiency during the 15 years. It was caused that the gas engine was begun the interim period stoppage. The efficiency line was interrupted in this figure.

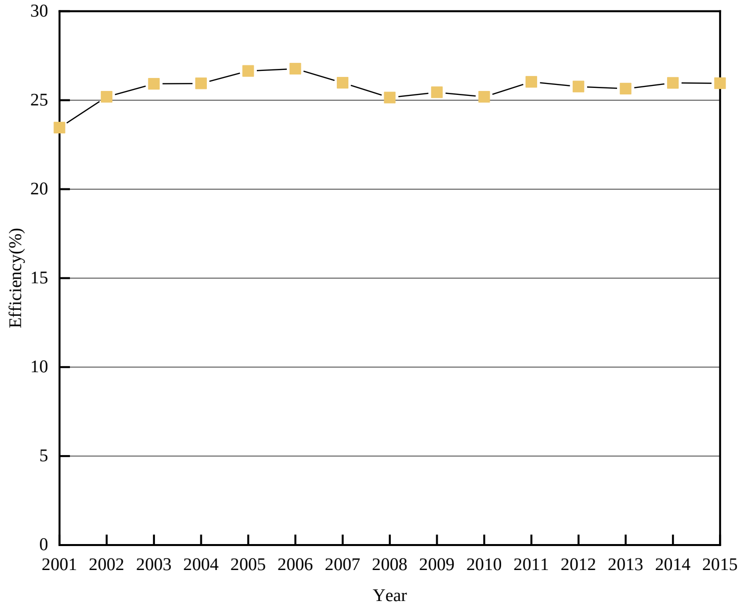


Fig.4-10 Efficiency of gas engine electricity generation.

3) Heat recovery and efficiency

Heat recovery of gas engine was calculated by the temperature of the forward hot water, temperature of the return hot water and the instantaneous flow rate of the hot water, these data were collected from the Environmental Energy Center in Kitakyushu Science and Research Park. And temperature of the forward hot water, temperature of the return hot water and the instantaneous flow rate of the hot water data were recorded every hour from July 2001 to February 2016.

The heat recovery calculation of gas engine is shown as the following:

$$Q_r = (T_f - T_r) \times V_f \tag{4-2}$$

where Q_r is the heat recovery of gas engine (heat/Mcal). T_f is the temperature of the forward hot water (temperature/°C). T_r is the temperature of the return hot water (temperature/°C). V_f is the instantaneous flow rate of the hot water (flow/m³/hour).

And the heat recovery efficiency of gas engine was calculated by the city gas cost and the heat recovery, the data was collected from the Environmental Energy Center in Kitakyushu Science and Research Park.

The power generation efficiency calculation of gas engine is shown as the following:

$$\eta_h = \frac{Q_r}{N_g \times 11} \times 100\% \tag{4-3}$$

where η_h is the heat recovery efficiency of gas engine. Q_r is the heat recovery of gas engine (heat/Mcal). N_g is the city gas consumption of gas engine (unit/ m^3).

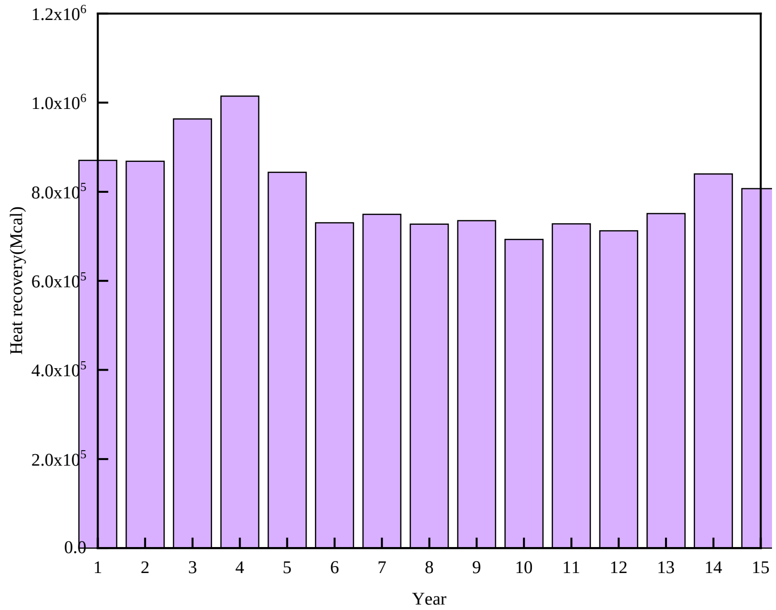


Fig.4-11 Heat recovery of the gas engine during 15 years.

The Fig.4-11 is the situation of heat recovery of the gas engine during 15 years. Because the heat recovery and electricity power generation was done at the same time, the shapes of heat recovery and electricity power generation are roughly the same in general. The most heat recovery is 2004, 1014852.89 Mcal in total, at the same time, the year cost the most gas is also 2004, it has cost 235286 m^3 of city gas (13A). The situation of the heat recovery and city gas cost of the gas engine are generally similar. It means cost more city gas, the more electricity power will be created, and more heat could be reused. At the same time, the waste heat was also increased. The total heat recovery of the gas engine for during 15 years is 12034602 Mcal, while the cost of the city gas is 2691890 m^3 during the 15 years.

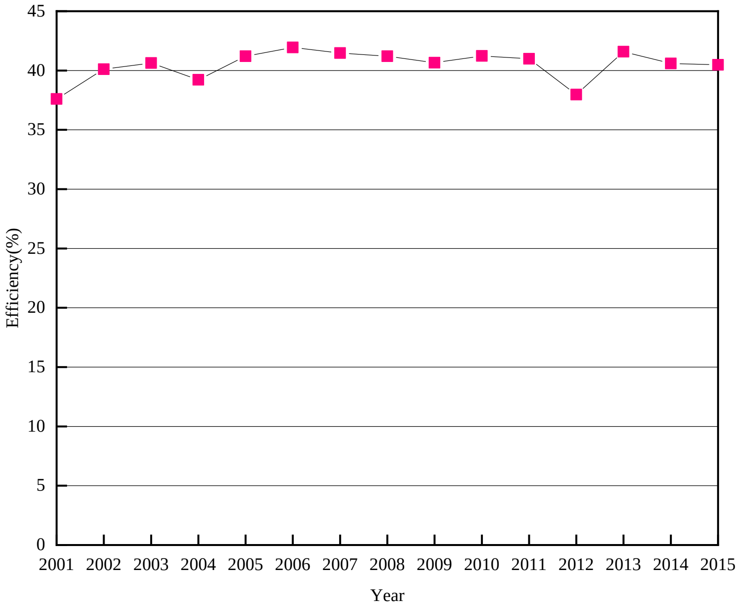


Fig.4-12 Heat recovery efficiency of the gas engine during 15 years.

The Fig.4-12 shows the heat recovery efficiency of the gas engine. It is noticed that in 2006, the efficiency is highest. It was caused that the gas engine was begun the interim period stoppage. The operation status and power generation of gas engine has been showed in this part.

4.3.3 Operation status analysis of fuel cell

1) Object situation of investigation

It is same to the gas engine, the fuel cell is also a complex system. It includes the power generation unit, space heating unit, space cooling unit and the city gas unit according to the inspection table of the fuel cell.

Table 3-5 shows the objects and contents of the fuel cell inspection. The inspection points include power supply unit of fuel cell, electric transformers edition, nitrogen gas supply system, waste water pump, waste water unit, hot water pump 1, hot water preheating heat exchanger, hot water pump 2, heat exchanger for space heating, hot water pump 2, heat exchanger for space heating, RH-1 waste water (operation for fuel cell), RH-2 waste water (operation for gas engine), gas measurement and gas detection alarm.

The inspection items of power supply unit include electric current, generating capacity and voltage. The inspection items of electric transformers edition include the temperature and the abnormal information of equipment. The inspection items of nitrogen gas supply system include a series pressure, B series pressure, intermediate pressure, outlet pressure, console input pressure, CRT data. The inspection items of waste water pump include electric current, pressure, noise, and odor, and vibration, dirt, damaged. The inspection items of waste water unit console output pressure, input temperature, output temperature. The inspection items of hot water pump 1 include electric current, pressure, noise, and odor, and vibration, dirt, damaged. The inspection items of hot water preheating heat exchanger include input temperature and pressure, output temperature and pressure. The hot water pump 2 and heat exchanger for space heating only used for space heating. The inspection items of hot water pump 2 include electric current, pressure, noise, and odor, and vibration, dirt, damaged. The inspection items of heat exchanger for space heating include the water flow, input temperature and output temperature. The RH-1 waste water unit and RH-2 waste water unit only used for space cooling. The RH-1 waste water unit is used when the fuel cell is operated. The RH-2 waste water unit is used when the gas engine is operated. The water flow was recorded for RH-1 and RH-2 waste water unit. The inspection items of gas measurement include gas pressure and gas flow. The inspection items of gas detection alarm include power indicator light, concentration, and abnormal status, alarm of equipment.

Table 4-7 The inspection objects and contents of fuel cell.

System	Inspection objects	Contents
Power generation unit	Power supply unit	Electric current, generating capacity, voltage
	Electric transformers edition	Temperature
	Nitrogen gas supply system	A series pressure, B series pressure, Intermediate pressure, Outlet pressure, Console input pressure, CRT data
	Waste water pump	Electric current, Pressure, Noise, odor, vibration, dirt, damaged
	Waste water unit	Console output pressure, input temperature, output temperature.
	Hot water pump 1	Electric current, Pressure, Noise, odor, vibration, dirt, damaged
	Hot water preheating heat exchanger	Input temperature and pressure, output temperature and pressure.
Space heating unit	Hot water pump 2.	Electric current, Pressure, Noise, odor, vibration, dirt, damaged
	Heat exchanger for space heating	Water flow, input and output temperature.

	(Hot water and waste water)	
Space cooling unit	RH-1 waste water (Operation for fuel cell)	Water flow rate
	RH-2 waste water (Operation for gas engine)	Water flow rate
City gas unit	Gas measurement	Pressure, gas flow,
	Gas detection alarm	Power indicator light, concentration, abnormal status and alarm of equipment.

Table 4-8 Operation and stoppage days of fuel cell.

Year	Days of the year	Operation days	Stoppage days
2001	304	263	41
2002	365	353	14
2003	366	357	9
2004	365	324	41
2005	365	349	63
2006	365	350	15
2007	366	326	40
2008	365	350	15
2009	365	348	17
2010	365	359	6
2011	241	175	66

Table 4-8 summaries all the date of operating conditions of fuel cell, all of statistical unit is the number of days when it operated, stoppage, inspection or malfunction. Table 4-8 shows the number of days in each situation of the fuel cell in each year. There are 10 years' record data from June 2001 to November 2011(the data of 2005 was lost), from April 1st of one year to March 31st of the next year. And the data of 2001 began in June because of it started operating in June 1st 2001, in total of 304 days; the data of 2011 finished in November because of the fuel cell stopped operation completely, in total of 241 days. The data indicates that in September 2002, the fuel cell was connecting with the cogeneration system which included space heating and space cooling, and from this year, space heating and space cooling had been operated. At the same time, the data of space heating and space cooling was begun to record.

According to the Table 4-8, the operation days of fuel cell are 3205 days, the stoppage days of fuel cell are 264 days. From the stoppage days, the inspection and repair days is the most, the number of it is 112 days. The data of July 2001, February 2004 and December 2007 was lost, so all these data were processed as the stoppage data.

Fig.4-13 is a line graph about the days when fuel cell was operating in each year. Remove two special years which are the beginning and ending, and calculate the average of the rest of these years. The number is 341. According to the Fig.4-13, it indicates that only three years the operation days are less than the average days. The three years have the most stoppage days. And each time the fuel cell stopped for long days, the next year would operate better

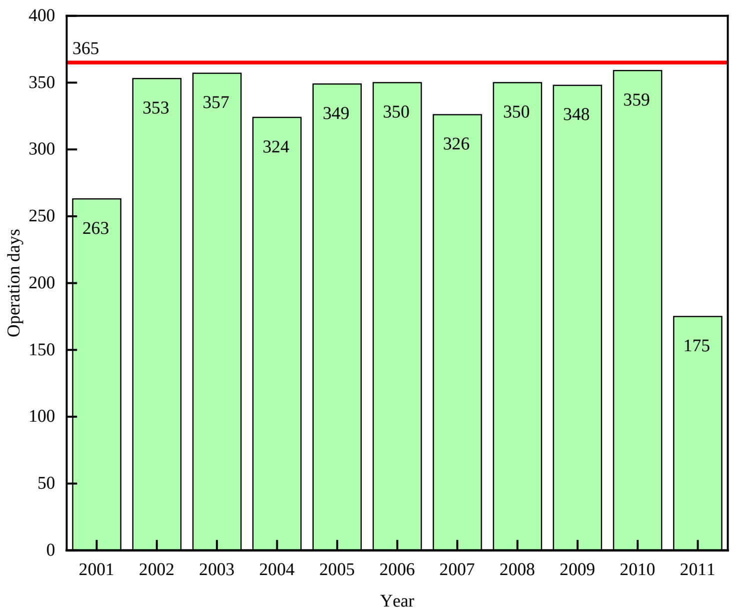


Fig.4-13 Operation days of the fuel cell during 11 years.

The operation status of fuel cell depended on the equipment whether could run on mormal condition, it means that it depends on the failures and reliability of equipment. In other words, the reliability and maintenance could be analyzed based on the power generation data. The power generation production and efficiency can be used to assess the status of the operation of fuel cell. the data which used in this paper is the power generation production data, the cumulative value of gas used and the temperature data of Environmental Energy Center of each hour in each day in the year 2001 to 2011. The data began to record in June 2001, there had only 7 months' data. And there had only 1 month data in 2011 because the fuel cell stopped in January 2011. So, the data of 2011 will not be used in this paper. In order to show the status of fuel cell operation clearly, the operation status was divided into four statuses. The status of the operation of fuel cell are schedule work days, inspection and repair, malfunction and others such as supporting student tour.

2) Electricity generation and efficiency

In this research, the data of power generation efficiency of fuel cell is also necessary, it can be described as follow:

$$\eta = \frac{E_f \times 0.86}{V_f \times 0.11} \times \frac{273+20}{273+T} \times 100\% \tag{4-4}$$

where η is the power generation efficiency of fuel cell (%). E_f is the power generation production of fuel cell (electricity/kWh). V_f is the city gas consumption of fuel cell (unit/m^3). T is the temperature of energy center (temperature /°C).

All of them are the data of each hour in each day of one year. With the data of power generation efficiency of fuel cell, the operation status of fuel cell will be more obvious. The operation status of fuel cell depends on the equipment whether could run on normal condition, it means that it depends on the failures and reliability of equipment. In other words, the reliability and maintenance could be analyzed based on the power generation data. The power generation production and efficiency can be used to assess the status of the operation of fuel cell.

The Fig.4-15 shows the electricity power generation and city gas cost of the fuel cell in Kitakyushu Science and Research Park situation during 11 years. From Fig.4-14, it has told us the year which has the most electricity power generation is 2006, 1697149 kWh in total, at the same time, the year cost the most gas is also 2006, it has cost 419003 m^3 of city gas (13A). The situation of the electricity power generation and city gas cost of the fuel cell are generally similar. It means cost more city gas, the more electricity power will be created. The total electricity power generation of the fuel cell for the 11 years is 15185001 kWh, while the cost of the city gas is 3694043 m^3 during the 11 years.

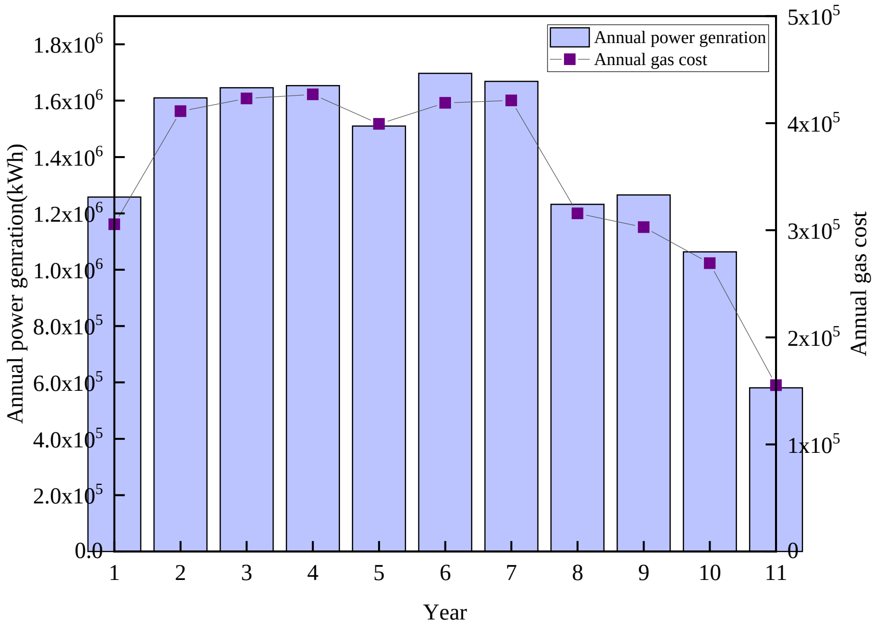


Fig.4-14 Electricity power generation and city gas cost of fuel cell.

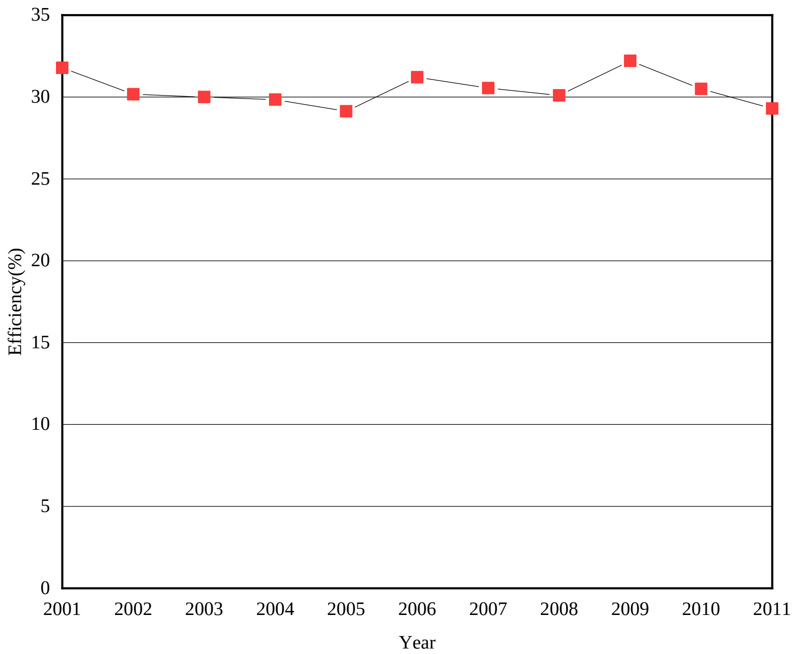


Fig.4-15 The average power generation efficiency of fuel cell.

According to the formula 4-4, the efficiency of the electricity generation of the fuel cell can showed in Fig.4-15. It presented that the efficiency of electricity in every year during 11 years. Compared the electricity generation efficiency of 11 years, it is obvious that the efficiency of the first year, this is because the gas engine was still at the debugging phase, so that the efficiency of electricity generation is very unstable.

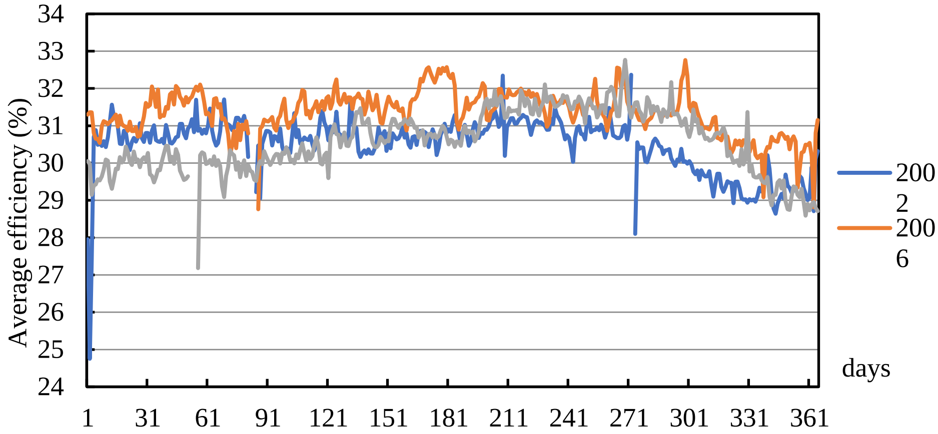


Fig.4-16 The average efficiency of three years.

In order to show the difference of operation status of fuel cell on the initial stage, intermediate stage and final stage, the year 2002, 2006, 2010 will be chose to compare. These three years have the same interval of time, and they are all belonging to the three stages of the fuel cell operation. Fig.4-16 is the comparison of these three years' average efficiency. At the time dealing with the average power generation efficiency, the impact of 0 power generation efficiency has been removed. It shows that the average power generation efficiency of 2006 is generally higher than 2002 and 2010. Because the fuel cell was operating all days in one year, the fluctuation of the average power generation efficiency of one year is not too obvious to see. It is noticeable that at the beginning of 2002, the average power generation efficiency is lowest, it is because the fuel cell was still in the debugging stage at that time, its power generation production was not enough stable. And the power generation efficiency of the year 2010 is almost lower than 2006, it is because the equipment of the fuel cell was aging and wear.

3) Heat recovery and efficiency

Heat recovery of fuel cell was calculated by the temperature of the forward hot water, temperature of the return hot water and instantaneous flow rate of the hot water, these data were collected from the Environmental Energy Center in Kitakyushu Science and Research Park. And the temperature of the forward hot water, temperature of the return hot water and instantaneous flow rate of the hot water data was recorded every hour from June 2001 to January 2010. Table 4-9 is the data list of the fuel cell.

The heat recovery efficiency of fuel cell was calculated by the city gas cost and the heat recovery, the data was collected from the Environmental Energy Center in Kitakyushu Science and Research

Park.

The power generation efficiency calculation of fuel cell is shown as the following:

$$\eta_H = \frac{V_i \times (t_f - t_r) \times 0.01}{V_f \times 0.11 + C \times 0.025} \times 100\% \tag{4-5}$$

where η_H is the heat recovery efficiency of fuel cell. t_f is the temperature of the forward hot water (temperature /°C). t_r is the temperature of the return hot water (temperature /°C). V_i is the instantaneous flow rate of the hot water (flow /m^3/hour). C is the cost of electricity (electricity/kWh). V_f is the city gas consumption of fuel cell (unit/m^3).

Table 4-9 Data list of the fuel cell.

No	Data	Investigation
50509	Commercial electric power consumption	Heat Recovery
50505	City gas consumption of fuel cell	
50838	Temperature of the forward hot water	
50839	Temperature of the return hot water	
50841	The instantaneous flow rate of the hot water	

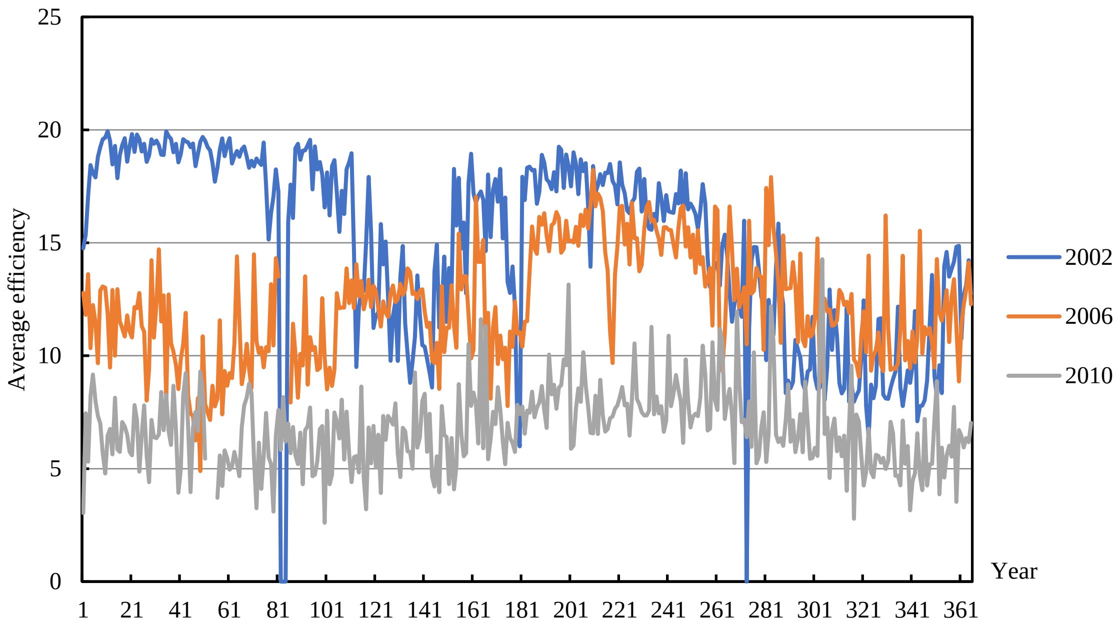


Fig.4-17 The average exhausts heat efficiency of three years.

In this paper, the exhaust heat efficiency also has been processed. The exhaust heat data of 2002, 2006, and 2010 are used in this paper. Fig.4-17 is the comparison of these three years' average exhaust heat efficiency. The impact of 0 exhaust heat efficiency has been removed. According to the Fig.4-17, it shows that the exhaust heat efficiency has an obvious decreasing trend in the three years. The efficiency of 2002 is about 15.0%, 2006 is 12.3% and 2010 is 6.78%. It means that the exhaust heat capacity becomes gradually weakened as the time goes by. It is noticeable that in the second half of 2002, the exhaust heat efficiency was lower than 2006. It is caused that the fuel cell was still in the debugging stage at that time, its operation, power production and exhaust heat was not stable enough. Compared to the exhaust heat efficiency of 2002, the efficiency of 2006 and 2010 are more stable. In another word, the fuel cell has kept in an inefficient operating condition stably in the second half of its life.

4.3.4 Comparison of operation status between gas engine and fuel cell

In this part, the operation status of gas engine and fuel cell is compared. Fig.4-18 shows the change of fuel cell, gas engine, solar cell and electricity purchase during 15 years. It is very obvious that the fuel cell is generating electricity more than the gas engine. However, the power generation of gas engine is stable every year, the power generation of fuel cell fluctuates greatly. The proportion of electricity purchased from the power grid is very large. Obviously, the power generation of fuel cell is much higher than that of gas engine and solar cell. Due to the fuel cell has been out of service in 2011, the power generation of fuel cell is zero after 2012.

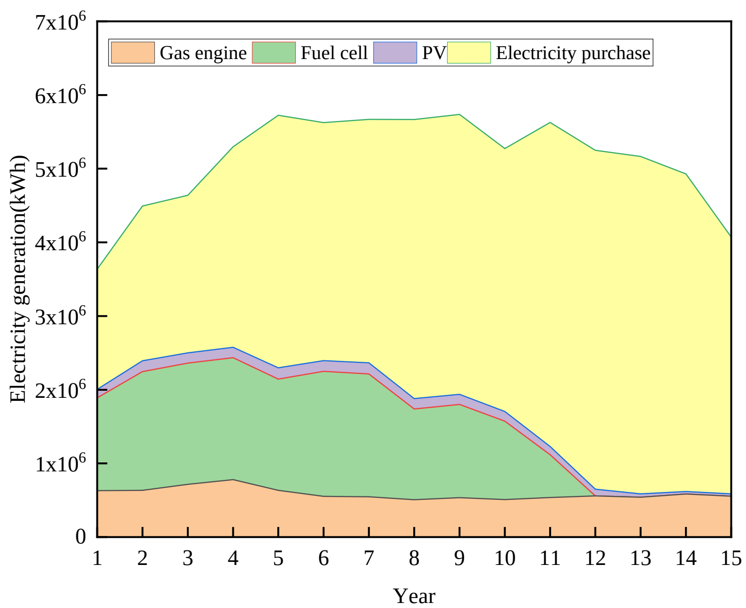


Fig.4-18 Changes of power generation and electricity purchase during 15 years.

Fig.4-19 shows the proportion of power generated by the fuel cell, gas engine, solar cell and electricity purchase from the grid. The power generation of solar cell and gas engine has been very stable during 15 years, but the power generation of fuel cell is declining year by year. The electricity purchased from the power grid is more than half of the electricity demand. This leads to the high operating cost of distributed energy system.

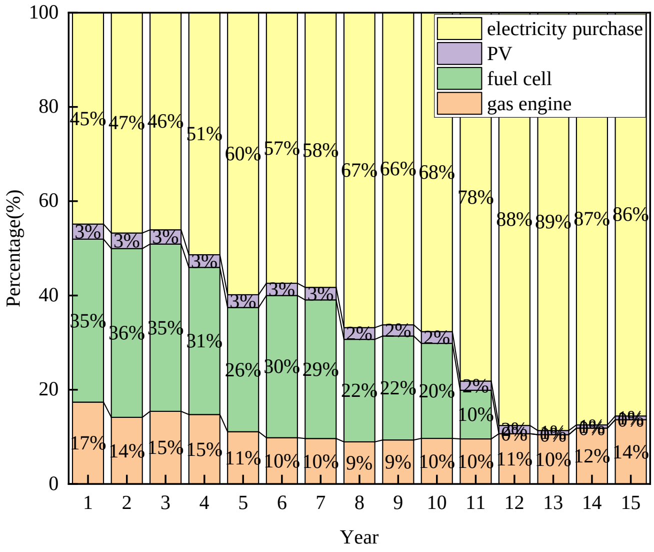


Fig.4-19 Percentage of electric power of 15 years.

Fig.4-21 shows the average exhausts heat efficiency of gas engine and fuel cell. Gas engine can remove more waste heat than the fuel cell.

This part introduces the operation status of gas engine and fuel cell. Through comparing the operation status of gas engine and fuel cell, we could find that the gas engine is better than the fuel cell. Although the electricity generation efficiency of fuel cell is more than the gas engine, but the gas engine power generation is relatively stable and the operation time is longer.

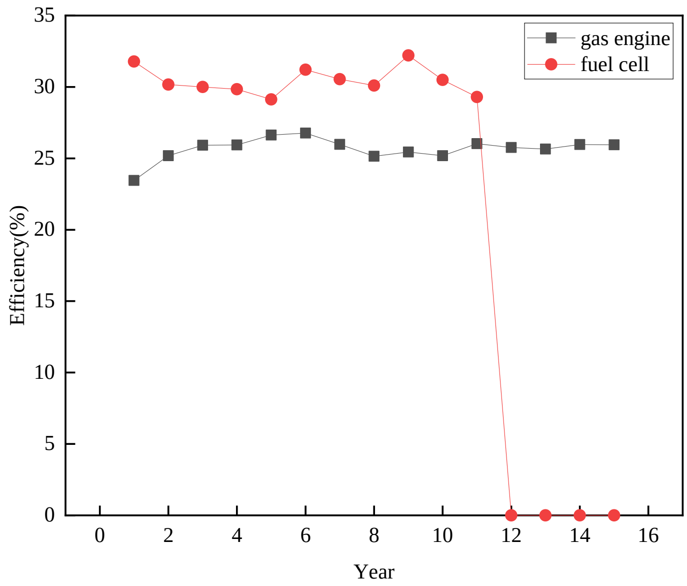


Fig.4-20 The average electricity generation efficiency of gas engine and fuel cell.

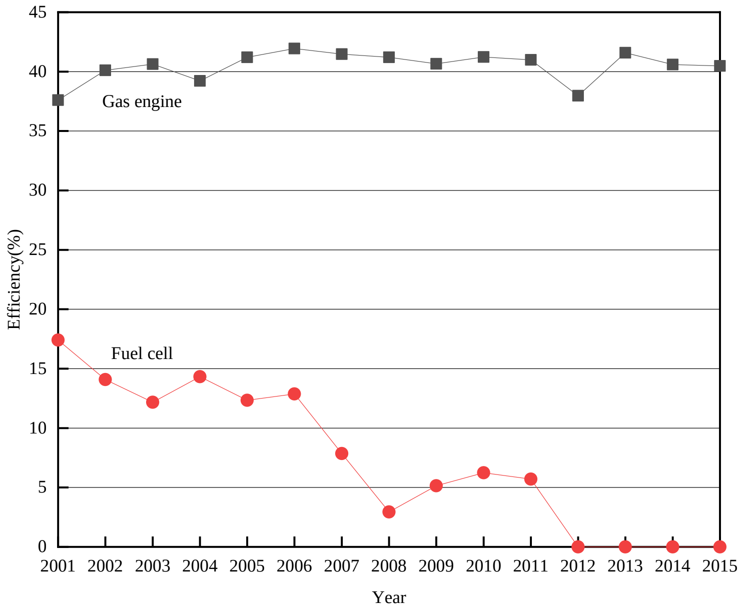


Fig.4-21 The average exhausts heat efficiency of gas engine and fuel cell.

4.4 Equipment maintenance status of DER system

4.4.1 Introduction

As previously mentioned, distributed energy system can satisfy user’s various needs (heat, cooling and electricity) while reducing the efficiency loss during energy transportation. The distributed energy system can provide the electricity, heating and cooling by use the different system and technologies. Through the heat recovery technologies can provide the cooling use the waste heat to improve the energy usage efficiency.

Maintenance, health management and security are closely related. Inspection and maintenance are necessary methods to keep the reliability of the system, Reliability analysis is a process to make the quantitative reliability requirements into the product design through reliability prediction, allocation, analysis and improvement of a series of reliability engineering technology, so as to form the inherent reliability of the product. It is a kind of reliability engineering. The reliability analysis runs through the whole life cycle of products, and the methods of reliability analysis in different stages of products are different. The distributed energy system especially the gas engine and fuel cell has been development near 20 years, a lot of application program of DER system is close to the design life of the distributed energy system. Considering the high cost of investment for a new power generation system, the maintenance and replacement a part of old equipment to prolong the service life for the whole system is the best way to improve the energy efficiency and reduce the cost.

In Kitakyushu Science and Research Park, the gas engine and fuel cell were used to produce the electricity and recover the wasted heat for nearly 15 years as the distributed energy system. And inspection and maintenance are carried out concurrently with the operation of the equipment. Because the inspection record data of the fuel cell is not enough and it has run for 11 years. The inspection of fuel cell will not be investigated in this chapter. While the inspection data of the gas engine will be mainly analyzed in this chapter, and the BN-FMEA method will be used to build the failure network, in order to get the theoretical basis of the reliability of the gas engine.

The power generation unit of the gas engine is the most important part of the gas engine. According to the Gas engine inspection and maintenance work report, the inspection could be divided into three major classifications: Gas engine part, Electric Generator Part, Auxiliary and Exhaust gas Part.

4.4.2 The equipment maintenance status of gas engine

In order to analyze the reliability of the gas engine, the data of gas engine were collected from the Manual of the gas engine, Gas engine inspection and maintenance work report, Construction completion certificate of gas engine, Construction plan statement of gas engine.

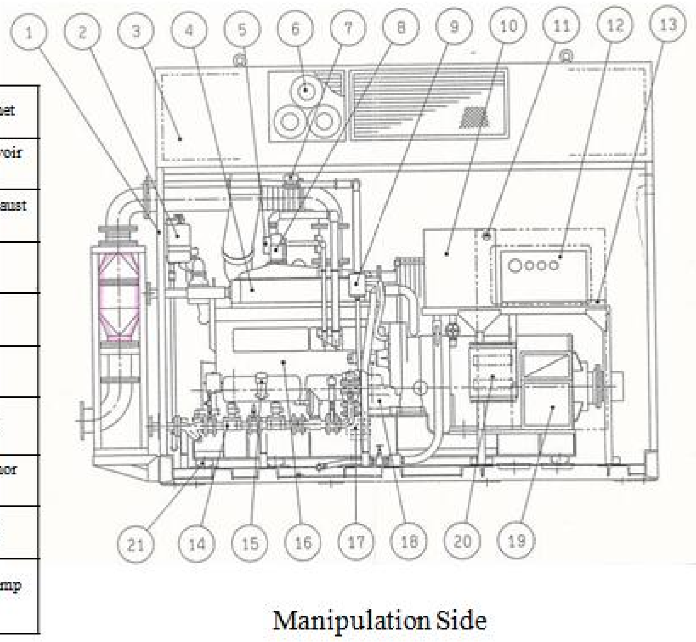
Table 4-10 shows the contents of the data which were used in this part. We can get the main information of the gas engine, the internal structure of gas engine and failure position description from the manual of the gas engine; the data of 1000 hours inspection record and failure reason review were recorded in gas engine inspection and maintenance work report (from the July 2001 to March 2015); from the construction completion certificate of gas engine and construction plan statement of gas engine, the data of failure's repair record, failure reason review, maintenance description and failure's reasons description can be gotten.

Here is the main information of the gas engine. The institution format is a 4 Cycle water-cooled gas engine. The institution name is 6LAALG-DT. The capacity of the gas engine is 206 kW. The gas engine combustion system uses the spark-ignition to power the engine. The city gas is used to support the fuel consumption, for this engine the best fuel is the No. 13A city gas fuel. The starting model of the gas engine is electrical start-up by starter motor. The cooling system for the gas engine, the clear water is used to cool the cylinder jacket part, lubricating oil and air cooler. In the piston part, the lubricating oil is used to cool this part. The turning part uses the turning bar. The institution total quality is 1950 kg. The suitable operating temperature is around 5~40℃, and the exhaust pressure of the gas engine is 4.9 kPa.

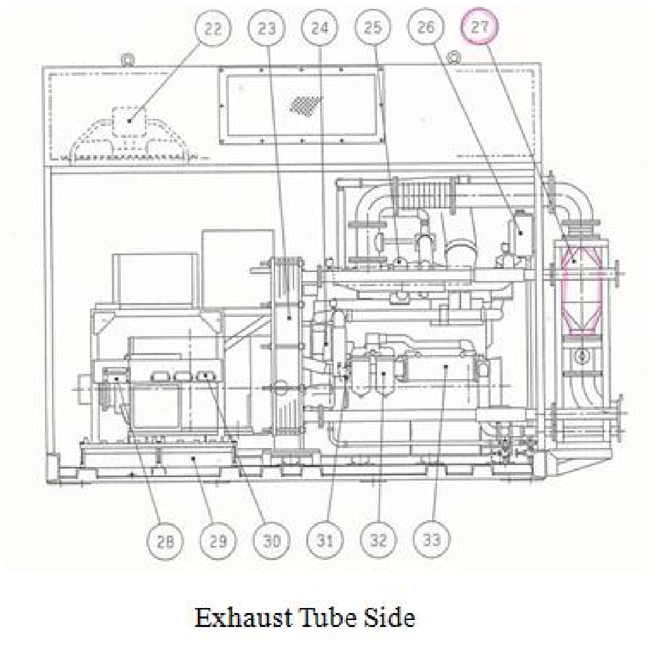
Table 4-10 Contents of the data of gas engine.

No.	Content	Details
1	Manual of the gas engine	Information of gas engine; Internal structure of Gas Engine; Failure position description.
2	Gas engine inspection and maintenance work report (from the July 2001 to March 2015)	Data of 1000 hours inspection record; Failure reason review.
3	Construction completion certificate of gas engine	Data of failure's repair record; Failure reason review, maintenance description.
4	Construction plan statement of gas engine	Operation instruction of gas engine; Maintenance and repairing methods; Failure's reasons description.

1	Soundproof bonnet
2	Jacket water reservoir tank
3	Air supply and exhaust duct
4	Air cooler
5	Gas mixer
6	Air filter
7	Gas detector
8	Electronic governor actuator
9	Mist separator
10	Lubricating oil sump tank



11	Lubricating oil sump tank refueling port
12	Instrument panel
13	DC voltage converter
14	Gas valve unit
15	Lubricating oil refueling port
16	Gas engine
17	Drain tank
18	Sel-motor
19	Three phase AC brushless generator
20	Engine terminal block
21	Rubber vibration isolator



22	ventilating fan
23	water-water heat exchanger
24	Jacket water pump
25	supercharger
26	Jacket water pressure tank
27	three-way catalyst
28	battery switch
29	battery
30	protective relay
31	Jacket water protective heater
32	lubricating oil filter
33	lubricating oil cooler

Fig.4-22 Internal structure of gas engine.

Fig.4-22 is the internal structure of the gas engine. For the manipulation side, it includes the soundproof bonnet, jacket water reservoir tank, air supply and exhaust duct, air cooler, gas mixer, air filter, gas detector, electronic governor actuator, mist separator, lubricating oil sump tank, lubricating oil sump tank refueling port, instrument panel, DC voltage converter, gas valve unit, lubricating oil refueling port, engine part, drain tank, sel-motor, three phase AC brushless generator, engine terminal block and rubber vibration isolator. For the exhaust tube side, there are ventilating fans, water-water heat exchanger, jacket water pump, supercharger, jacket water pressure tank, three-way catalyst, battery switch, battery, protective relay, jacket water protective heater, lubricating oil filter and lubricating oil cooler. These components are sorted by the Manual of the gas engine, it is a classification of the perspective of development design.

According to the Gas engine inspection and maintenance work report (from the July 2001 to March 2015), the gas engine could be divided into three major classifications according to the inspection contents: Gas engine part, Electric Generator Part, Auxiliary and Exhaust gas Part. And the three major classifications could be divided into 20 classifications as shown in Fig.4-23. The gas engine part includes, gas supply pipe unit, instruments, protection device, air-fuel ratio control device, power supply system, ignition device, cylinder head, speed control device, starting device, reciprocating part, rotary motion part, cooling water system, intake system, exhaust system, air overcharge and valve train. The auxiliary and exhaust gas parts include the exhaust gas steam boiler, auxiliary machine board and the exhaust gas hot water boiler. Last is the electric generator part, it mainly includes generator.

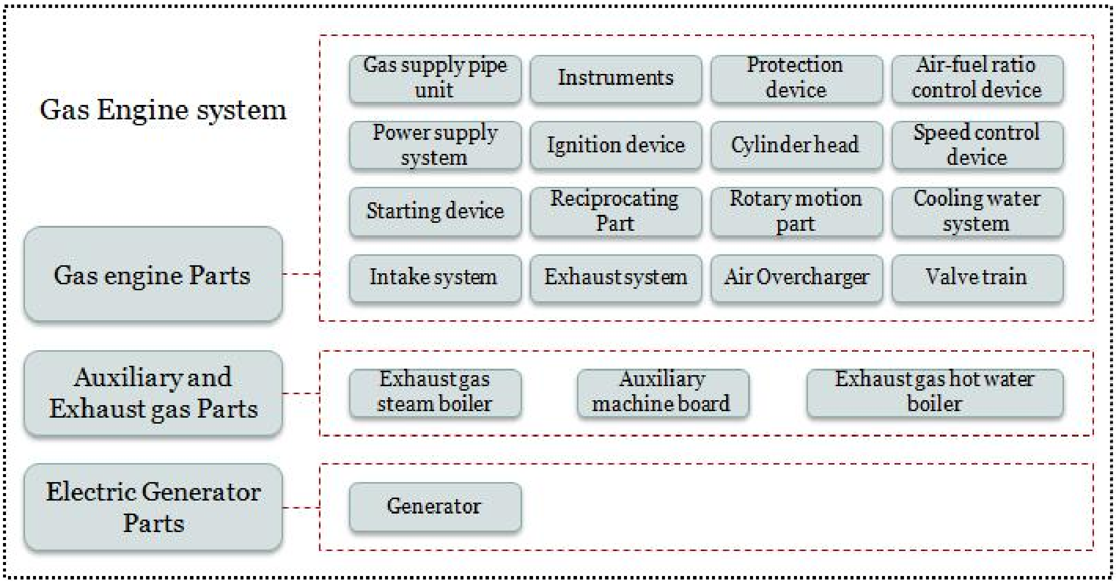


Fig.4-23 Classification according to inspection of gas engine.

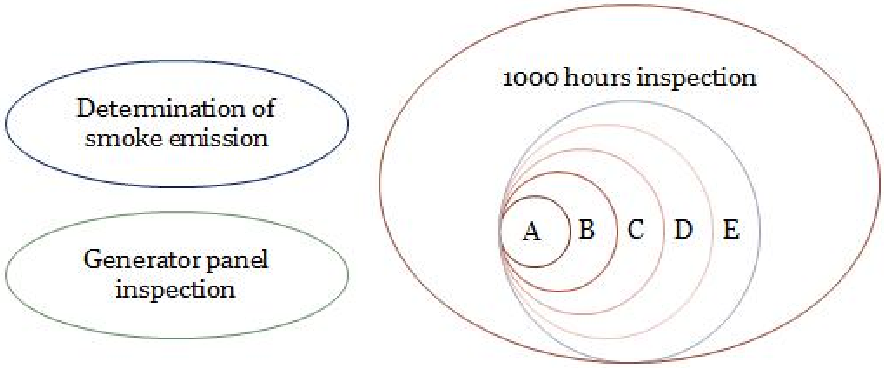


Fig.4-24 The relationship of each type inspection.

The types of inspection of gas engine are different according to the time of gas engine operation. It means that in different periods, different types of inspection are taken. There are three types of basic inspection: 1000 hours inspection, Determination of smoke emission and Generator panel inspection. Fig.4-24 shows the relationship of all the types of basic inspection.

For the 1000 hours inspection, it is the basic and common inspection of gas engine during its operation. As it is described by its name, the 1000 hours inspection would be held when the gas engine was operated per 1000 hours. The 1000 hours inspection means to do the inspection on all the safety devices, the environment of the component and the replacement of some component. Different types of inspection have to deal with different kinds of the components or parts of the gas engine. And the distinction among them is the operation hours. For the A type inspection, it will be held when the gas engine was operated per 1000 hours, and the contents include the inspection of all the safety devices, the environment of the component, the replacement of the lubricants, with the oil pan will also be replaced per 1000 hours. For the B type inspection, it will be held when the gas engine was operated per 2000 hours, but the contents include all the contents of A type inspection, and also include the internal inspection of various counters, distributor inspection and the exchange of ignition (according to the Gas engine inspection and maintenance work report 2002, the lubricants replacement of A type inspection was changed into the B type inspection.) For the C type inspection, it will be held when the gas engine was operated per 4000 hours, while the contents include all the contents of B type inspection, and also include the inspection of gas support unit, the inspection of plug cord, the inspection of mist tube, the cleaning of the intake filter and the inspection of the function of the protection device. The D type inspection will be held per 8000 hours, and hours, and the contents include all the contents of C type inspection, and also include the inspection of regulator and frame arrester, the inspection of exhaust gas heat exchanger, the distributor driving inspection, the magnet inspection, the cooling water pump inspection, management of cooling water and so on. The E type inspection is the largest scale inspection. It will be held per 16000 hours, and include all the contents of D type, also include the inspection, cleaning of heat exchanger decomposition, mixer and diaphragm exchange, the inspection and cleaning of cylinder liner and water cooler decomposition, lubricants pump, lubricants cooler inspection, crank inspection and measuring and so on.

According to the 5 types of the 1000 hours inspection, 16000 hours are one operation cycle of the gas engine. Table 4-11 is the inspection situation of one cycle of gas engine operation cycle. It means that there is only one time of the E type inspection during on operation cycle of the gas engine. According to the Gas engine inspection and maintenance work report from 2001 to 2014, the 1000 hours inspection had held for 53 times during 14y years.

Table 4-11 Inspection situation of one cycle of gas engine.

Inspection Type / Operation Time/hours	A Type	B Type	C Type	D Type	E Type
1000	○				
2000		○			
3000	○				
4000			○		
5000	○				
6000		○			
7000	○				
8000				○	
9000	○				
10000		○	○		
11000	○				
12000					
13000	○				
14000		○			
15000	○				
16000					○

The Determination of smoke emission inspection was held twice every year. It will mainly record the data of smoke temperature, the amount of water discharged of the flue smoke, composition of the smoke, sulfide and nitride concentrations of the smoke and exhaust flow rate of the smoke.

Generator panel inspection includes the circuit breaker wiring status, corrosion, deformation, fouling degree of the converter, condenser, casting machine. It will be held once every year by the operation of gas engine.

In this chapter, the 1000 hours inspection will be the main object of investigation, to analyze the reliability of gas engine.

In order to analyze the situation and reliability of the gas engine, this part will investigation the inspection data of the gas engine of the distributed energy system in Kitakyushu Science and Research Park. We have collected the data from the Gas engine inspection and maintenance work report during 2001 to 2015. Table 4-12 is the contents of each type 1000 hours inspection.

Fig.4-25 could show the times of each type 1000 hours inspection. From this figure we could find that though each year has different times of inspection, the A type inspection is the most, in total 28 times, while the E type is the least for only 4 times. It means that the operation of gas engine had spent three times of the operation cycle.

Table 4-12 Contents of 1000 hours inspection.

Type	Time Interval	Content	Remark
A Type	Per 1000 Hours	● Inspection of all the safety devices ● The environment of the component ● The replacement of lubricants	●Oil pan: Per 1000 Hours ●With Sub tank: Per 2000 Hours
B Type	Per 2000 Hours	●A type content ●Internal inspection of various counters ●Distributor inspection ●Exchange of ignition	Include A Type Inspection
C Type	Per 4000 Hours	●B Type content ●Inspection of gas support unit ●Inspection of Plug cord ●Inspection of mist tube ●Clean the intake filter ●Inspect the function of the protection device	Include A and B Type Inspection
D Type	Per 8000 Hours	●C Type content ●Inspection of Regulator and Frame arrester ●Inspection of Exhaust gas heat exchanger ●Distributor driving inspection ●Magnet inspection ●Cooling water pump inspection ●Management of cooling water ●And so on	Include A, B and C Type Inspection
E Type	Per 16000 Hours	●D Type content ●Heat exchanger decomposition, inspection, cleaning ●Mixer, diaphragm exchange ●Cylinder liner and water cooler decomposition, inspection, cleaning, lubricants pump, lubricants cooler inspection ●Crank inspection and measuring ●And so on	Include A, B, C and D Type Inspection

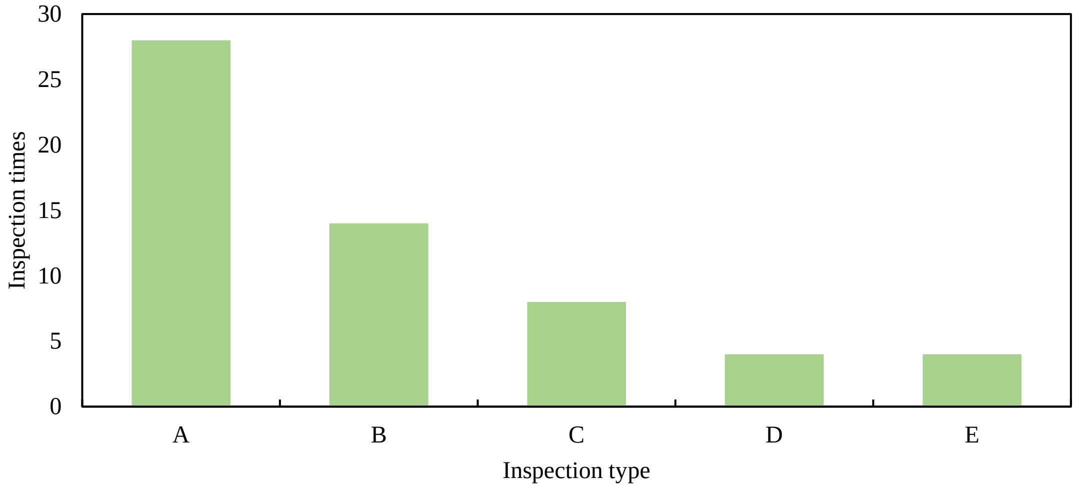


Fig.4-25 Total times of each type 1000 hours inspection.

Table 4-13 Total cumulative replacement times of each classification.

Classification	Gas supply pipe unit	Instruments	Protection device	Air-fuel ratio control device	Starting device
Total times	2	0	1	7	2
Classification	Power supply system	Ignition device	Cylinder head	Speed control device	Reciprocating Part
Total times	16	73	19	5	20
Classification	Rotary motion part	Cooling water system	Intake system	Exhaust system	Air Overcharge
Total times	106	36	12	2	8
Classification	Valve train	Exhaust gas steam boiler	Auxiliary machine board	Exhaust gas hot water boiler	Generator
Total times	0	0	0	0	4

Table 4-13 is the total cumulative replacement times of each classification. We can see that the replacement times higher than 10 is the power supply system, ignition device, cylinder head, reciprocating, rotary motion part, cooling water system and intake system. So we have to focus on these components.

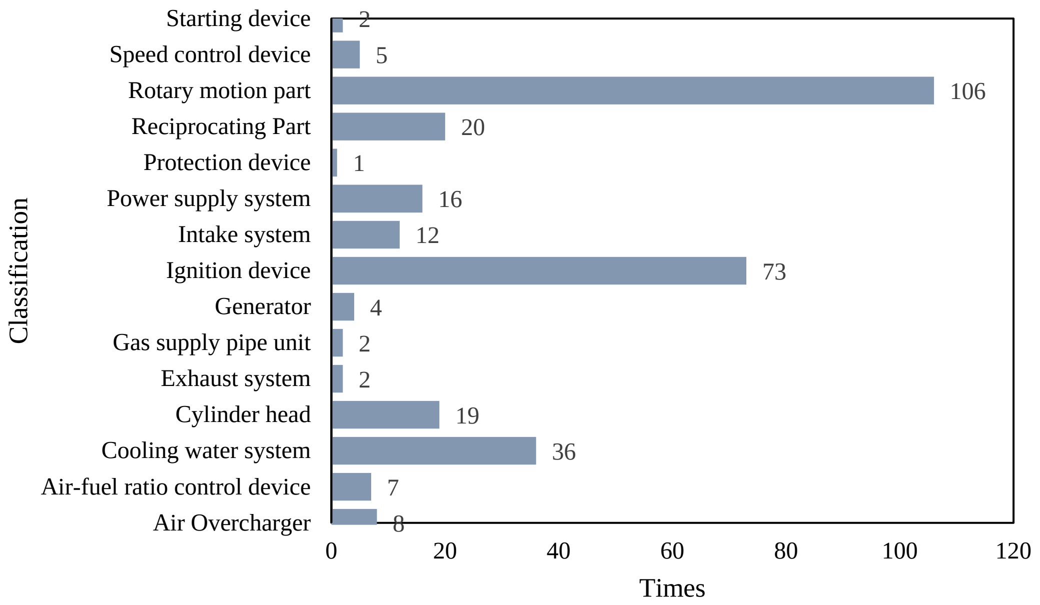
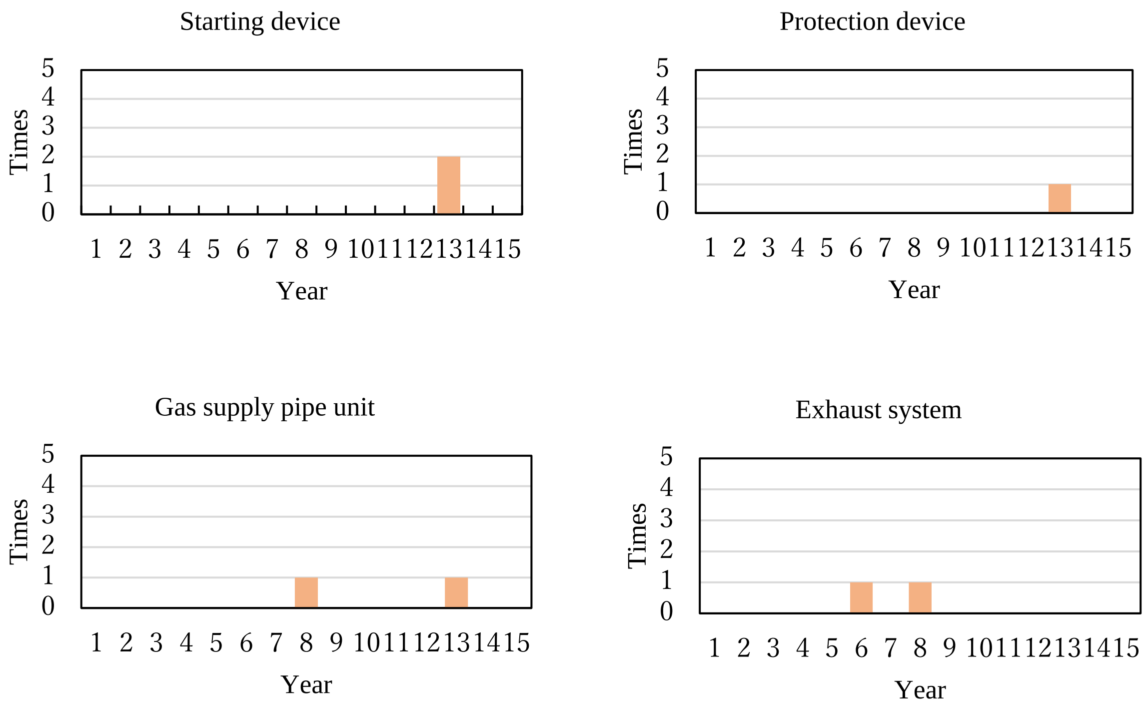
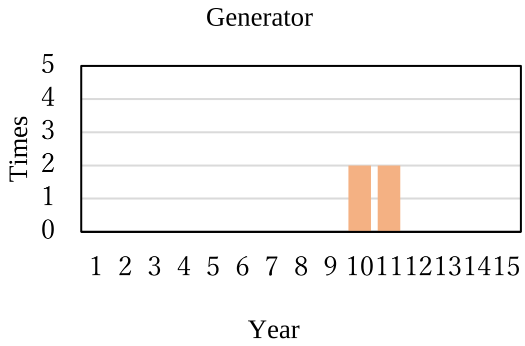
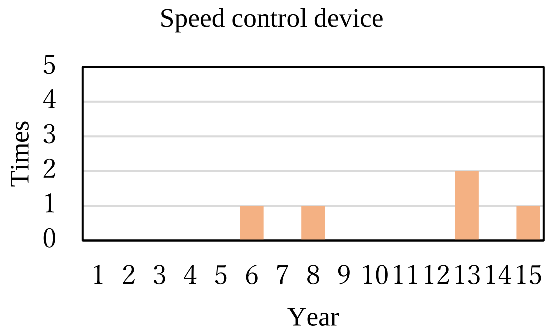
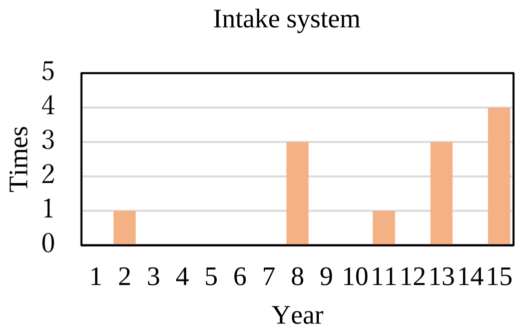


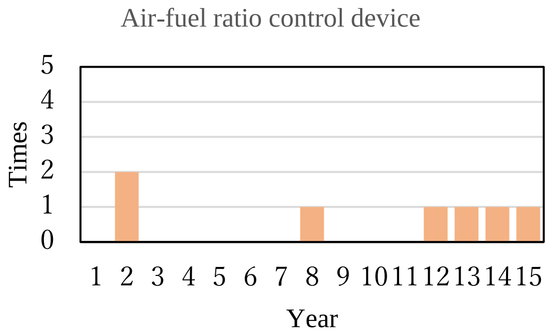
Fig.4-26 Total cumulative replacement times of each classification.

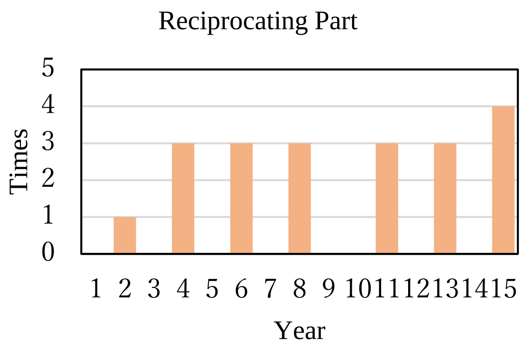


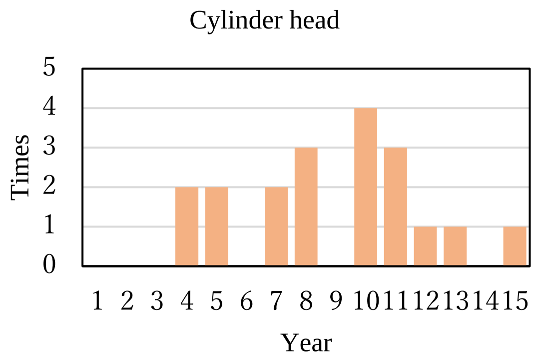

Generator
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

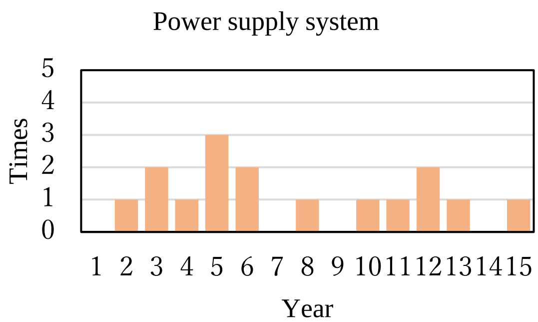

Speed control device
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

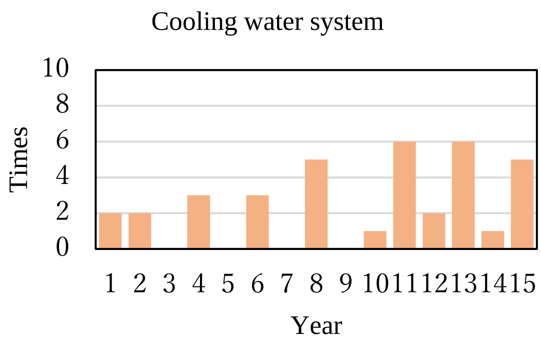

Intake system
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

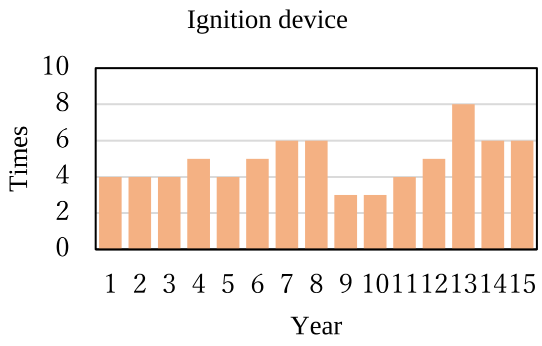

Air-fuel ratio control device
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


Reciprocating Part
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


Cylinder head
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


Power supply system
Times
Year
0 1 2 3 4 5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


Cooling water system
Times
Year
0 2 4 6 8 10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15



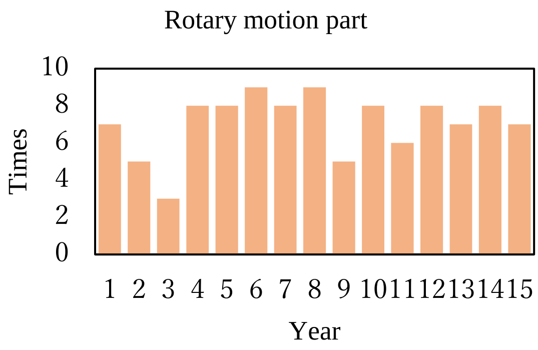


Fig.4-27 Replacement times of each component of gas engine during 15 years.

According to the Gas engine inspection and maintenance work report during 2001 to 2015, the total cumulative replacement times of each classification can be got. Table 4-13 and Fig.4-26 shows all of the 20 classifications replacement times during the 15 years. And because the times of different classification have a large disparity, this research will divide 20 classifications into two parts according to the frequency of replacement. First part includes starting device, protection device, gas supply unit, exhaust system, generator, speed control device, intake system and air-ratio control device. From Fig.4-27, it is obviously showed which have the least replacement times are the starting device and protection device, only had once replacement. For the exhaust system and generator, the two classifications were replaced twice in 15 years, and the intervals were very short, indicating that the first replacement did not achieve the desired results. Second part includes reciprocating part, cylinder head, power supply system, cooling water system, ignition device and rotary motion part. From Fig.3-10, we can see that these components have been changed frequently. The ignition device and rotary motion part are replaced every year. Therefore, the ignition device and the rotary motion part are the main causes of gas engine failure.

4.4.3 The equipment maintenance status of fuel cell

In order to analyze the reliability of the fuel cell, the data of fuel cell were collected from the Manual of the fuel cell, fuel cell inspection and maintenance work report, Construction completion certificate of fuel cell, Construction plan statement of fuel cell.

Table 4-14 shows the contents of the data which were used in this chapter. We can get the main information of the fuel cell, the internal structure of fuel cell and failure position description from the manual of the fuel cell; failure reason review were recorded in fuel cell inspection and maintenance work report (from the June 2001 to November 2011); from the construction completion certificate of fuel cell and construction plan statement of fuel cell, the data of failure's repair record, failure reason review, maintenance description and failure's reasons description can be gotten.

According to the fuel cell inspection and maintenance work report (from the June 2001 to November 2011), the fuel cell could be divided into two major classifications according to the inspection contents: Fuel cell part and Auxiliary part. And the two major classifications could be divided into 15 classifications. The fuel cell part includes, air processing system, exhaust cooling system, power plant controller, uninterrupted power supply, safety valve, battery cooling water system, reformer, rotating device, starting device, fuel processing system, steam system and water treatment system. The auxiliary part includes heat pump, flue damper and nitrogen cylinder.

Fig.4-29 is the replacement times of fuel cell during 10 years. We can see that the steam system and air processing system has been replaced most frequently.

Table 4-14 Contents of the data of fuel cell.

No.	Content	Details
1	Manual of the fuel cell	Information of fuel cell; Internal structure of fuel cell; Failure position description.
2	Fuel cell inspection and maintenance work report (from the July 2001 to March 2011)	Failure reason review.
3	Construction completion certificate of fuel cell	Data of failure's repair record; Failure reason review, maintenance description.
4	Construction plan statement of fuel cell	Operation instruction of fuel cell; Maintenance and repairing methods; Failure's reasons description.

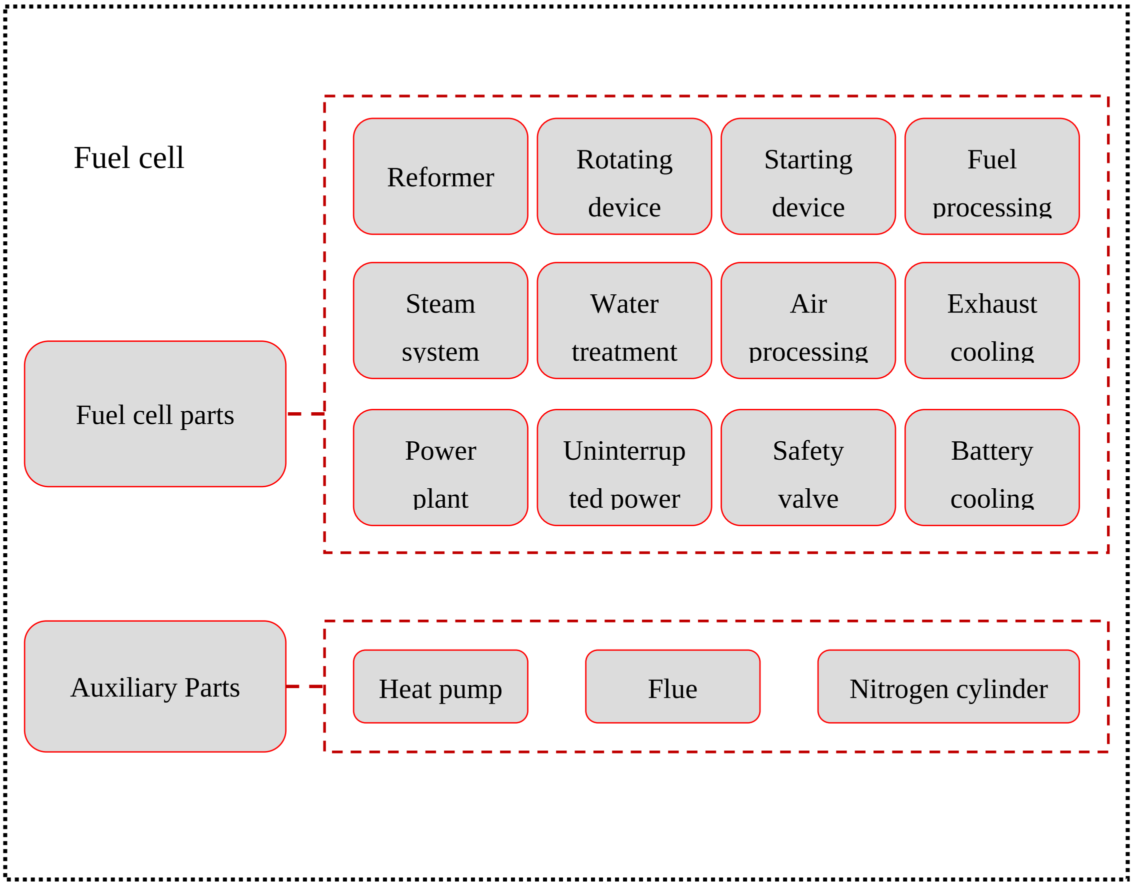


Fig.4-28 Classification according to inspection of fuel cell.

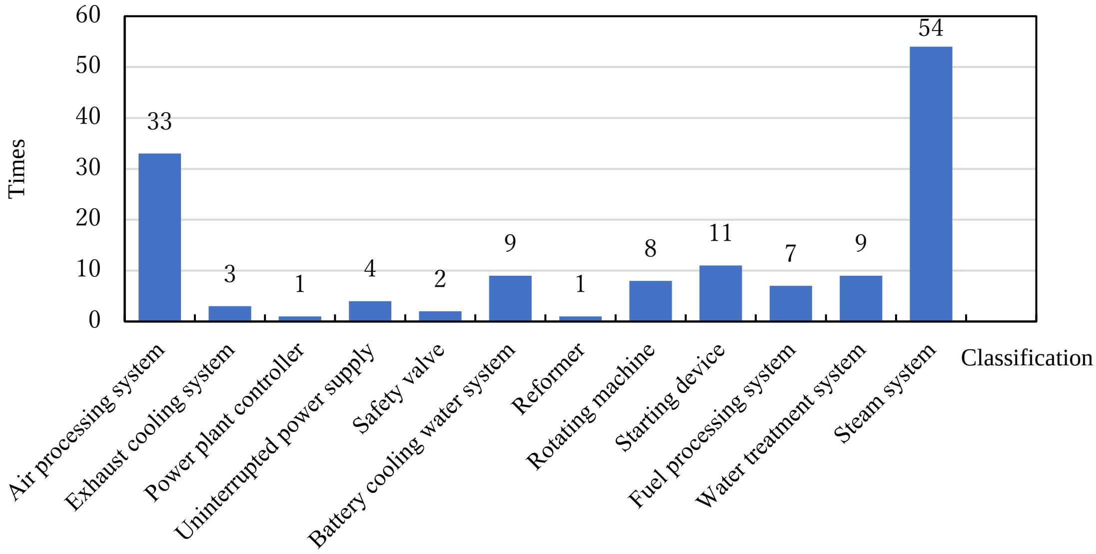


Fig.4-29 Replacement times of fuel cell during 11 years.

4.5 Summary

In this chapter, the operation and maintenance status situation of the power generation system of distributed energy were investigated. The data of gas engine is from June 2001 to February 2016, nearly 15 years; and the data for fuel cell is from June 2001 to January 2011, nearly 10 years. These data are collected, calculated and analyzed to investigate the operation status and power generation efficiency of the gas engine and fuel cell.

The operation status of gas engine was classified into operation, schedule stoppage, inspection and failure stoppage. Of which, inspection was classified into inspection per 1000 hours, casual inspection, maintenance, others. The failure was classified into power generation unit failure of gas engine, cooling water unit failure of gas engine, heat recovery unit failure of gas engine, heat recovery unit failure of gas engine and auxiliaries' failure of gas engine. The highest abnormal operation is operation with minor failure, it is nearly 42.62% of total abnormal operation, 52 days. All the results indicate that the inspection and maintenance of the gas engine are not very quickly, or the maintenance are not enough preparation. The highest abnormal stoppage is inspection and maintenance, it is nearly 60.52% of total abnormal stoppage, 141 days. the inspection and maintenance is the main reason which leads to the gas engine stoppage.

The maintenance status of gas engine is divided into two part. First part includes starting device, protection device, gas supply unit, exhaust system, generator, speed control device, intake system and air-ratio control device. Second part includes reciprocating part, cylinder head, power supply system, cooling water system, ignition device and rotary motion part.

The operation status of fuel cell was classified into operation, annual inpsetion stoppage, casual inspection stoppage, maintenance stoppage, failure stoppage, casual inspection with operation, and maintenance with operation, and failure with operation. The failure has occurred in 2009 was more than other years. The failure has occurred 8 days in 2011, after that the fuel cell was stopped. The annual is the main stoppage reason in the stoppage status. And most of maintenance was finished in the annual inspection time.

The maintenance status of fuel cell includes air processing system, exhaust cooling system, power plant controller, uninterrupted power supply, safety valve, battery cooling water system, reformer, rotating machine, starting device, fuel processing system, water treatment system and steam system.

Reference

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Chapter 5

LIFE CYCLE ASSESSMENRT ANALYSIS OF DISTRIBUTED ENERGY RESOURCE SYSTEM

CHAPTER FIVE: LIFE CYCLE ASSESSMENT ANALYSIS OF DISTRIBUTED ENERGY RESOURCE SYSTEM

5.1 Introduction

Energy demands in building mainly consist of electricity for lighting and appliance, space heating and cooling, and domestic hot water. Currently, energy consumption in building accounts for averagely 35% of the total energy use in the world [1]. With the rapid growth of global population and economic development, energy issues have become a growing concern for mankind, and the finite nature of traditional energy resources and their negative impact on the environment have prompted mankind to explore renewable, environmentally friendly and low-carbon new energy types. Distributed energy resource (DER) has the advantages of high energy utilization efficiency, low transmission losses, clean and low carbon.

Although distributed energy resource has many advantages, they suffer from the most serious problem: high investment. Distributed energy resource such as gas engines and fuel cells are expensive, while the investment in testing and breakdown maintenance costs are higher than those of conventional energy systems. The price of the energy used in distributed energy systems also affects the investment in distributed energy systems

However, how to achieve the best coupling between the devices in the system, and also how environmental, economic and social benefits of distributed energy systems from the whole life cycle perspective are really to be studied in depth. Analyzing renewable energy from the whole life cycle perspective of planning, design, production, operation, use, maintenance, and recycling and re-disposal can further our understanding of the environmental and energy saving benefits of the whole life cycle process of renewable energy.

Life cycle assessment (LCA) is a well-known method for assessing the environmental impacts of distributed energy resource. Briefly, LCA is a standardized tool that can determine and compute the potential environmental impacts caused by the emission of substances into the air, water, and soil and resources used throughout the life cycle of a product or process, from raw material extraction to waste management [2].

The Kitakyushu Science and Research Park has imported the gas engine and fuel cell as the distributed energy system for 15 years, it has been stopped because of its design life. It is a suitable object to analyze the life cycle assessment.

Based on the analysis of the operational data of the distributed energy system in KSRP in Chapter 4, we further conducted a life cycle assessment of the distributed energy system. In this chapter, the life cycle assessment will be investigated by the data of operation, inspection, maintenance and budget book from 2001 to 2015. These data could be used to calculate the primary energy cost and expenditure of inspection.

5.2 Methodology

5.2.1 Energy flow of systems

Distributed energy resource system is relative to the traditional centralized energy supply system, which uses large-capacity equipment, centralized production, and delivers various kinds of energy to many users in a large area through special transmission facilities (large power grids, large heat networks, etc.); whereas distributed energy system is directly oriented to users, producing and supplying energy in the amount demanded by users, and has multiple functions. The distributed energy system, on the other hand, is a medium- and small-scale energy conversion and utilization system that can meet multiple objectives. Today's third-generation distributed energy systems have three main elements: first, decentralization, second, multi-energy, and third, integrated application of end-use energy-saving resources and renewable energy. In this paper, the life cycle economic and environmental impacts of DER and conventional energy resource (CER) system are evaluated through an inventory analysis of actual data from their operational phases, using distributed energy systems and conventional energy systems in KSRP as study cases.

The distributed energy system is used to meet the electricity demand, space heating demand, space cooling demand and hot water demand of KSRP. A distributed energy system refers to an energy system where energy is produced close to end use, typically relying on a number of modular and small-scale technologies [3]. The distributed energy system has the highest efficiency of energy utilization and low environmental load. In the distributed energy system of KSRP, the electricity is met by gas engine (the capacity is 160kW) and fuel cell (the capacity is 200 kW, and the fuel cell was stoppage in 2011 until now), PV and the electrical grid utilities of Kyushu. Gas boiler and waste heat from gas engine and fuel cell meet the heating load. And the waste from gas engine and fuel cell meets the cooling load.

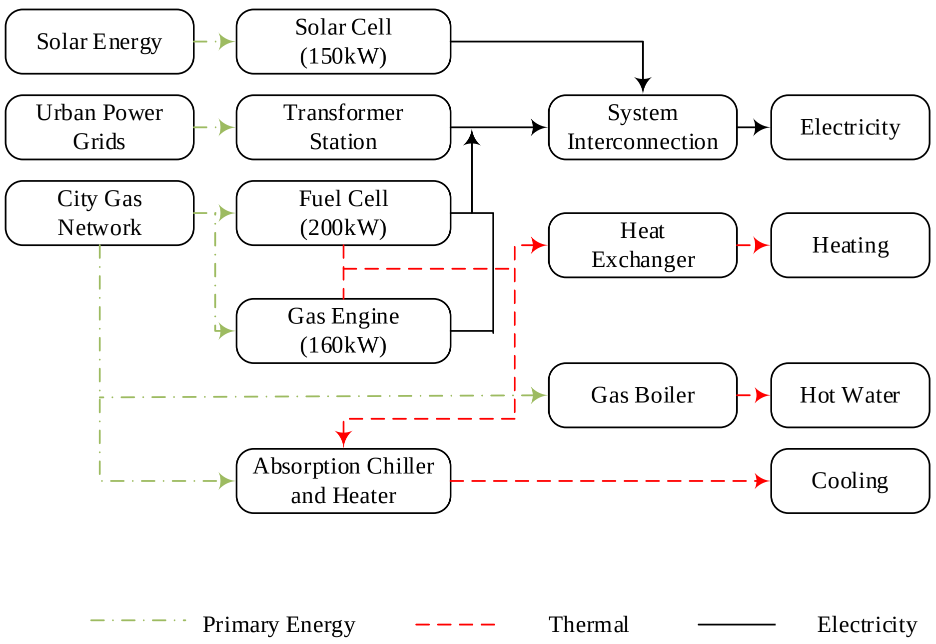

Fig.5-1 Schematic illustration of the DER.

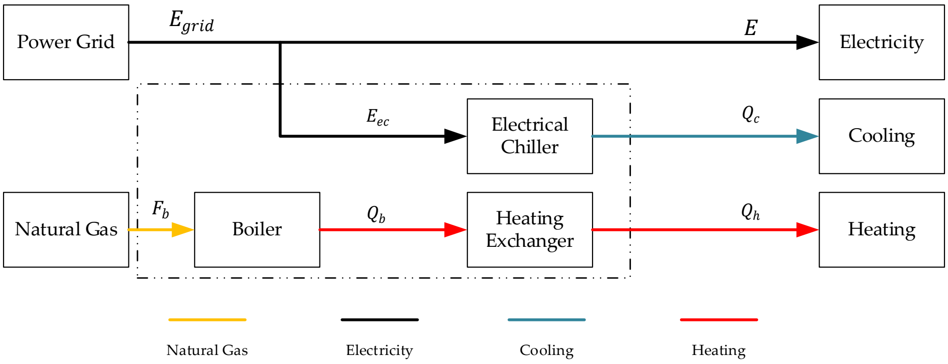

Fig.5-2 Schematic illustration of the CER.

Fig.5-1 is the schematic of the distributed energy resource system installed in the Environmental Energy Center of Kitakyushu Science and Research Park. As we known, the energy load of a building or campus include electricity load, space cooling load, space heating load and hot-water load. The system in Kitakyushu Science and Research Park includes the PV, fuel cell, gas engine, gas-fired absorption chiller, heat exchanger and gas boiler. In addition to the main equipment, the system also includes a large number of auxiliary equipment, such as various pumps (cooling water, heating supply, cooling supply, circulation, etc.), cooling towers, injectors, valves, pipes, etc.

In this system, the city gas is used to supply the gas engine and the fuel cell to produce the electricity. In order to reduce the fossil energy consumption and carbon dioxide (CO_2) emissions, and improve energy efficiency; gas engine and fuel cell were used to produce the electricity as a small-case power generation system. The gas engine has 160 kW capacity; and the fuel cell has 200kW capacity. The capacity of the 150kW solar PV is used to meet some electricity demand in the system. When the electricity load is low or the electricity production is not enough, the electricity from grid utilities is used to meet the load. A part of waste heat was sent to the absorption chiller and heater to meet the cooling load; and a part of waste heat was sent to heat exchanger unit to meet the heating space load and hot-water load. And the gas boiler is used to meet the hot-water load in this system.

Fig.5-1 is the schematic of the conventional energy resource system compared with the distributed energy resource system. The electricity demand of SP systems was supplied by the power grid, cooling demand was supplied by the electric chiller, and the heating demand was supplied by a gas boiler.

5.2.2 Built the LCA model

The energy flow of distributed energy resource systems and conventional energy resource systems were introduced, which was then, used to calculate whether the distributed energy resource system has more potential than conventional energy resource systems. We compared distributed energy resource systems with conventional energy resource systems in terms of three influencing factors: economic, energy consumption and environmental. The life cycle assessment procedure as shown in Fig.5-3. First, the operating costs of distributed energy resource systems and conventional energy resource systems were compared, followed by a comparison of carbon emissions.

The fuel energy consumption of the auxiliary boiler, F_{ab}, (kWh) was calculated using the following equation:

$$F_{ab} = \frac{Q_{ab}}{\eta_{ab}} \tag{5-1}$$

where Q_{ab} is the supplementary heat from the auxiliary boiler (kWh), and η_{ab} is the efficiency of the auxiliary boiler.

The total electricity purchased from the grid of SP systems, E^{SP}, (kWh) was calculated using the following equation:

$$E_{ec} = \frac{Q_c}{COP_{ec}} \tag{5-2}$$

$$E^{SP} = E + E_{ec} \tag{5-3}$$

The total fuel energy consumption of the SP systems, F^{SP}, (kWh) was calculated using the following equation:

$$F^{SP} = \frac{Q_h}{\eta_{he} \times \eta_b} \tag{5-4}$$

where η_b is the efficiency of the boiler.

In order to calculate the deficit or profit of the distributed energy resource system, we calculated the operating costs of distributed energy resource system and conventional energy resource system over 15 years. They can be expressed as follows:

$$C = \sum_{y=1}^{15} \sum_{t=1}^{8760} (E_{grid} \times C_e + F \times C_f) \tag{5-5}$$

where C is the operating costs ($); E_{grid} is the electricity purchased from the power grid (kWh); F is the total natural gas consumption (kWh); and C_e and C_f are the energy price of electricity and natural gas, respectively, ($/kWh).

Primary energy consumption (PEC) refers to the consumption of total fuels to meet the demand for electricity and thermal demands (kWh) and can be calculated using the following equation:

$$PEC = F_{total} + \frac{E_{grid}}{\eta_{grid} \times \eta_{tr}} \tag{5-6}$$

where F_{total} is the total amount of fuel applied to meet the electrical and thermal demands (kWh); η_{grid} is the power generation efficiency of power plants, and η_{tr} is the transmission efficiency of power grid.

Primary energy saving ratio (PESR) was defined to assess the energy consumption of CCHP systems in comparison with SP systems, using the following equation:

$$PESR = (1 - \frac{PEC^{CCHP}}{PEC^{SP}}) \times 100 \tag{5-7}$$

Then the carbon dioxide emission of distributed energy systems and conventional energy systems are expressed as follows:

$$CDE = E_{grid} \times \mu_e + F \times \mu_f \tag{5-8}$$

where CDE is the carbon dioxide emission; μ_e is the CO_2 emission conversion factor of electricity from the grid (kg CO_2/kWh); μ_f is the CO_2 emission conversion factor of natural gas from the grid (kg CO_2/m3).

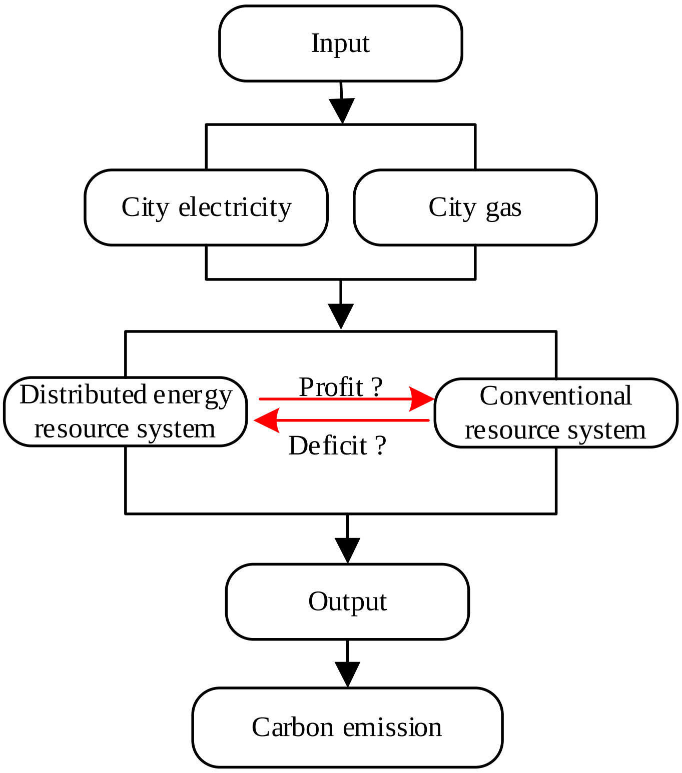

Fig.5-3 Life cycle assessment procedure.

5.3 Introduction of case study

5.3.1 Energy demands

In this study, we chose the eco-campus of the Kitakyushu Science and Research Park (KSRP) in Japan as an example [3]. KSRP is located in Kitakyushu, a world-renowned environmental symbiosis city, and is a scientific research core for environmentally friendly construction in Kitakyushu. The total area of KSRP is approximately 335 hectares. The eco-campus has been using distributed energy resource system since 2001 to provide electricity, cooling, and heating demand for the energy center, collaboration center, conference center, library, gym, teaching building and experiment building, technology development and exchange center. The buildings in the area are prefabricated buildings of 4-floor and below, and the fence structure has reached the standard of high-level energy-saving buildings. The area has received the A-class certification from CASBEE-block/region of Japan. The DER system can satisfy the larger electricity, cooling, and heating demand of the eco-campus, and effectively reduce the energy cost. The annual electricity, cooling, and heating demands were obtained through the energy center of the KSRP (Fig. 5-4).

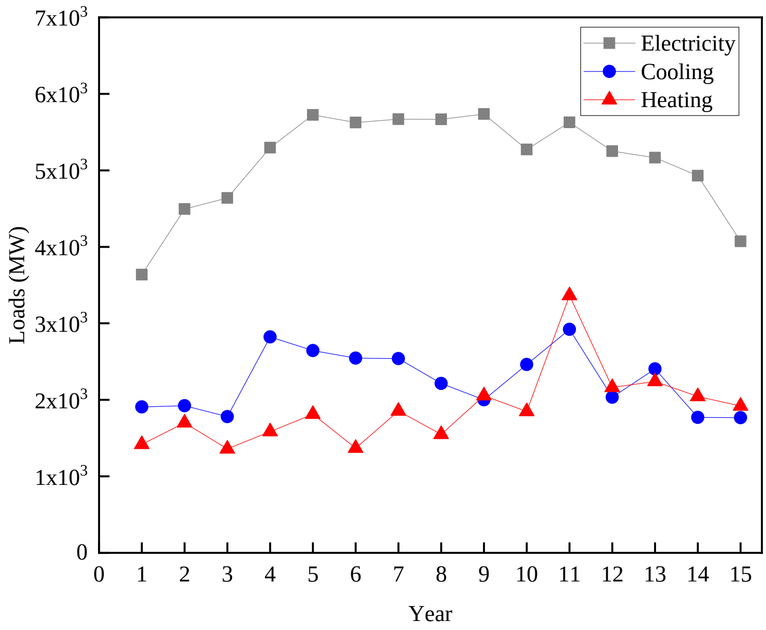

Fig.5-4 Annual electricity, cooling and heating demands.

5.3.2 Primary energy price

The economic evaluation of distributed energy systems focuses on the prices of primary energy sources such as city electricity and city gas. In Japan, the representative electric power companies are Tokyo Electric Power Company, Kansai Electric Power Company, Kyushu Electric Power Company and so on; for the city gas, they are Tokyo Gas Company, Osaka Gas Company, Western Gas Company and so on. Because there is not yet complete liberalization, there is no big difference on the price. In this chapter, the research will only introduce the price situation of city electricity and city gas which was used by gas engine of the distributed energy resource system in Kitakyushu Science and Research Park.

For the city electricity price, the basic charge is according to the cost of pick used time of different month. The summer pick used time is during July to September, and the winter pick used time is from January to June and September to December. Kyushu Electric Power Company which was used by Kitakyushu Science and Research Park has two main case of electricity price.

1. Commercial power A

Table 5-1 shows the price of commercial power A. It is a system has the high basic unit price of electricity, which is suitable to the customers for high voltage business used such as play facilities, shops, hospitals and so on.

2. Business holiday economy electricity

Table 5-2 shows the price of the business holiday economy electricity. In simple terms, this case has the high electricity use in holiday and weekend while the price on holiday and weekend is less than the working days. It is suitable to the industry which was busy in holiday and weekend than working days such as supermarket, wedding hall and so on.

Table 5-1 Commercial power A price

Different	Season different	Unit	Price/$
Basic		1kW	17.841
Electric charge	Summer	1kW	0.083
	Other seasons	1kW	0.076

Table 5-2 Business holiday economy electricity price

Different	Season different	Unit	Price/$
Basic		1kW	11.035
Electric charge	Summer holidays	1kW	0.084
	Summer working days	1kW	0.151
	Other holidays	1kW	0.076
	Other workings	1kW	0.138

For the city gas price, this research will mainly tell the case of the Western Gas Company:

Through the use of the power generation system and the total energy system, mainly by relatively small and medium-sized demand, this case aims at efficient use of our manufacturing and supply facilities while promoting load adjustment of customers, it aims to contribute to establishment of supply and demand of gas. Also, in contracting, it is necessary to decide the next contract amount. Table 5-3 shows the price of the total energy system case.

Table 5-3 Price of total energy system case

		Item	Unit	Price
Type 1	Basic price	Fixed amount	$/month	91.962
		Flow rate	$\$/m^3$*month	7.357
		Maximum demand period	$\$/m^3$*month	0.010
		Standard unit	$\$/m^3$*	0.368

		price		
Type 1	Basic price	Fixed amount	\$/month	275.887
		Flow rate	\$/m^3*month	7.357
		Maximum demand period	\$/m^3*month	0.010
		Standard unit price	\$/m^3*	0.412

In order to be closer to the model established by the LCA, the basic city electricity price will be set at 0.230 \$/kWh. The basic price of city gas will be set at 0.552 \$/m^3. This simple setting makes the LCA model clearer.

5.4 LCA analysis

5.4.2 The analysis on the economy of DER by LCA

1) Maintenance costs

Since the auxiliary equipment of the distributed energy resource system is the same as that of the conventional energy resource system, we only considered the maintenance cost of the power generation unit. And due to the lack of PV data, we ignore this part. Fig. 5-5 shows the life cycle maintenance cost of gas engine and fuel cell, and we can see that the maintenance cost of fuel cell is significantly higher than that of gas engine. And since the fuel cell only operated for 10 years, only the maintenance cost of the gas engine is incurred from year 11 to year 15.

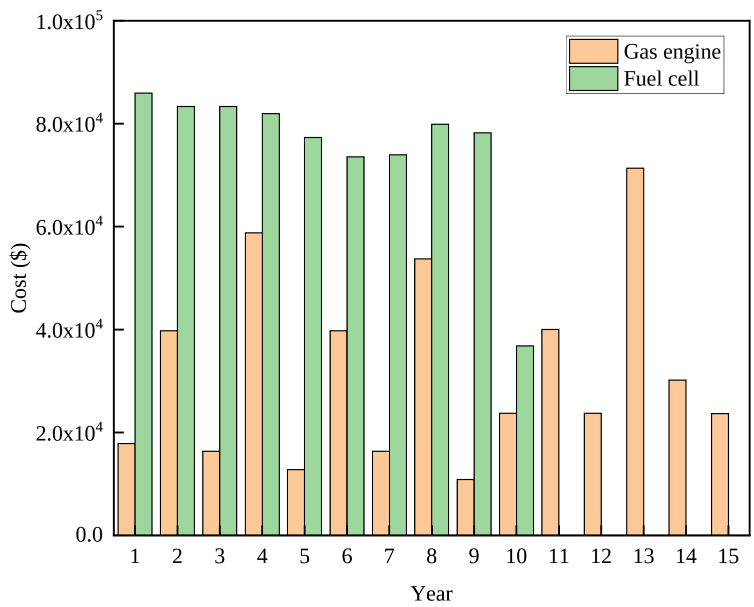

Fig.5-5 Maintenance costs of gas engine and fuel cell.

Figure 5-6 shows the total gas engine and fuel cell maintenance costs for 15 years. In this chapter, life cycle assessment will be investigated for 15 years from 2001 to 2015. Therefore, we can get the average annual expenditure of the gas engine with a price of 82216.48$.

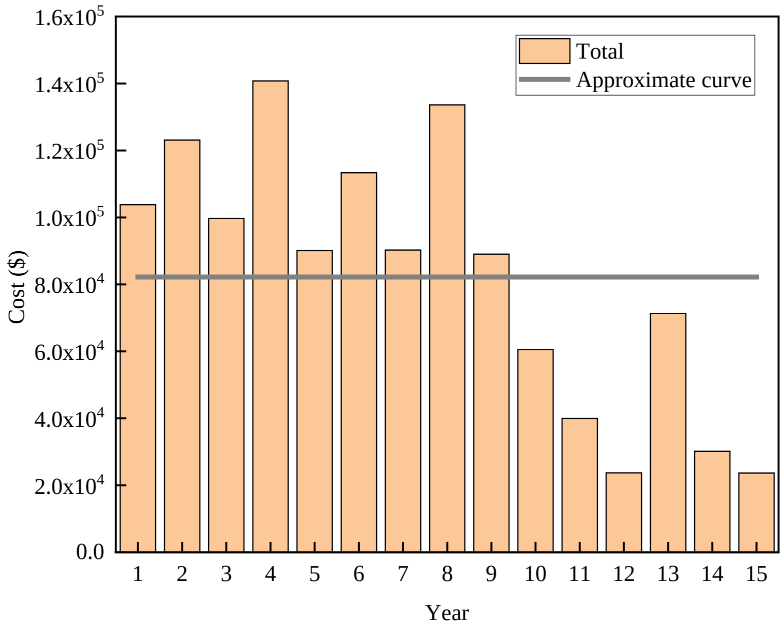

Fig. 5-6 The expenditure during 15 years.

2) Operating costs

Fig. 5-7 compared the annual total operating costs of the distributed energy resource system with conventional energy resource system. It can be seen that the total annual operating costs of distributed energy resource system is lower than that of conventional energy resource system in each year, and the total saving of operating cost is 13.66% in 15 years. It is indicated that the application of the distributed energy resource system has more economic potential, and it is worth to use the new type technology.

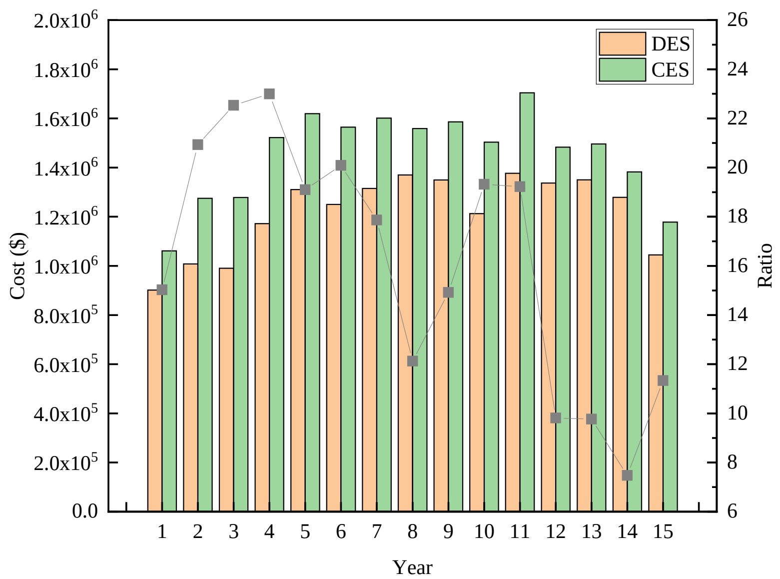

Fig. 5-7 Comparison of total costs between DES and CES during 15 years.

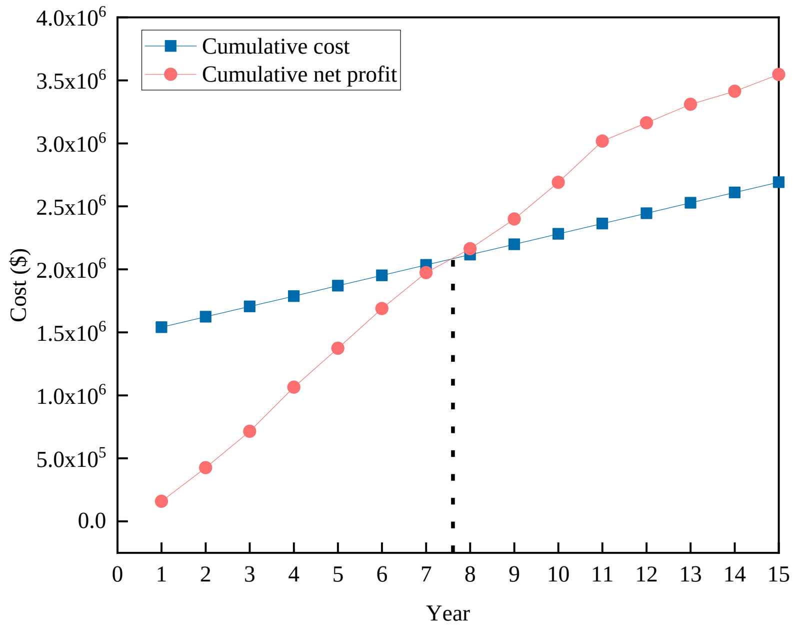

Fig. 5-8 The cumulative cost and cumulative net profit of the DES.

According to the information of the gas engine, the primary investment of the power generation unit in Kitakyushu Science and Research Park is 1541107.23 $. From Fig.5-6 we could get the annualized average expenditure of the gas engine, the price is 82216.48 $ every year.

Fig.5-8 shows the situation of the cumulative cost and the cumulative net profit during the nine years. From this figure we could see that, the gas engine had the net profit of 13276874 Yen in the first year. The cumulative is start at 1541107.23 $, and each year has 82216.48 $ increased. With the increasing of the net profit of the gas engine, it has recovered all the investment costs in 2007. It has been 7.6 years to recover the investment. After the 2008, the gas engine operation has been fully profitable.

5.4.1 The analysis on the energy consumption of DER system by LCA

Fig. 5-9 shows the electricity purchased and natural gas purchased for the distributed energy system over the 15-year period. The natural gas consumption includes fuel cell, gas engine, absorption chiller, and boiler, so the natural gas purchased are higher than the electricity purchased. Electricity purchased from the grid increase from year 11 onwards, when fuel cell was no longer used and only gas engine was used as power generator to provide electricity, heating and cooling demands. Fig. 5-10 shows the electricity purchased and natural gas purchased for the conventional energy system over the 15-year period.

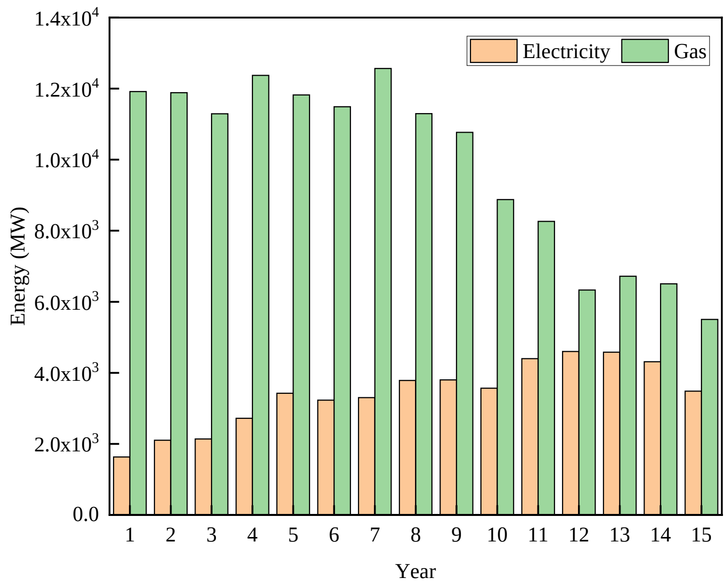

Fig.5-9 Electricity and gas purchased from grid of distributed energy system

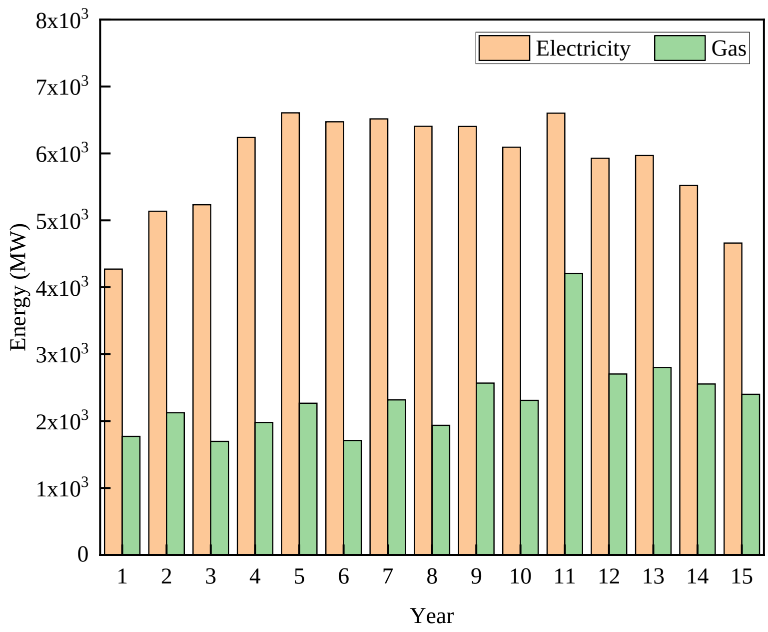

Fig.5-10 Electricity and gas purchased from grid of conventional energy system

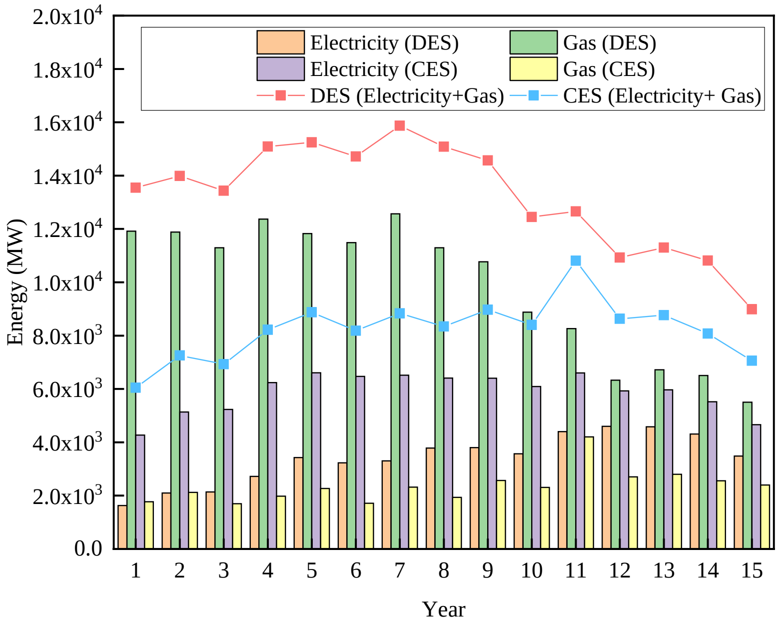

Fig.5-11 Comparison of annual energy consumption between DES and CES

Fig. 5-11 compared the energy consumption of the distributed energy system with that of the conventional energy system. It can be seen that the electricity consumption of the distributed energy system is lower than that of the conventional energy system, which is due to the fact that the distributed energy system has power generator to provide electricity to the users and the shortage is purchased from the power grid. However, the natural gas consumption of the distributed energy system is much larger than that of the conventional energy system, because the distributed energy system in this study gives priority to meet the electricity demand of the users (following the electric load), when less waste heat is used for cooling and heating, and the shortage needs to be supplied by natural gas to the absorption chiller and boiler for cooling and heating. Therefore, the total energy consumption of distributed energy systems is higher than that of conventional energy system. And Fig. 5-12 shows that the distributed energy system saved 12.25% of energy consumption.

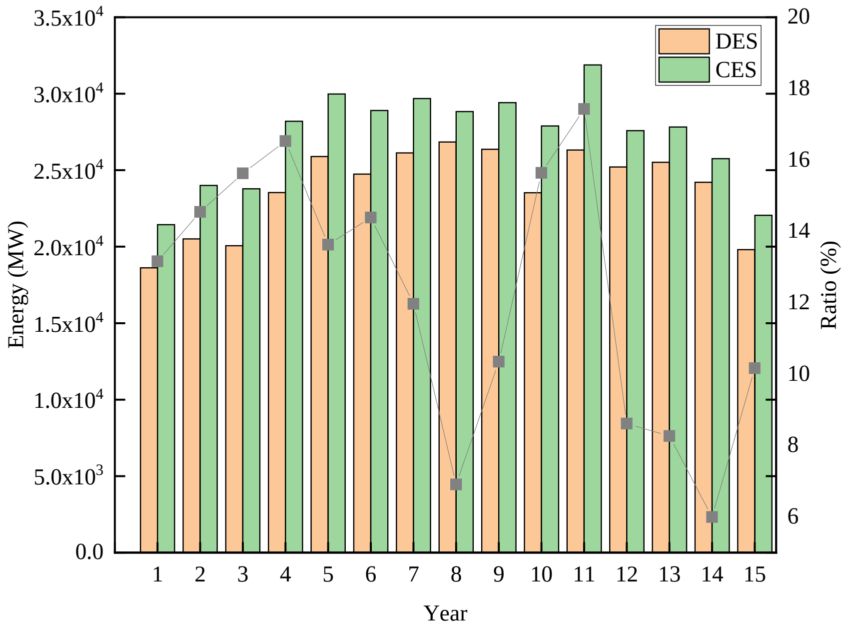

Fig.5-12 Comparison of annual energy consumption between DES and CES

5.4.2 The analysis on the environment of DER by LCA

Fig. 5-13 shows the carbon emissions of distributed energy systems and conventional energy systems. The carbon emissions of distributed energy system are higher than the conventional energy system due to the high natural gas consumption of distributed energy system and the carbon emission savings ratio is negative, resulting in a lack of environmental performance potential of distributed energy system.

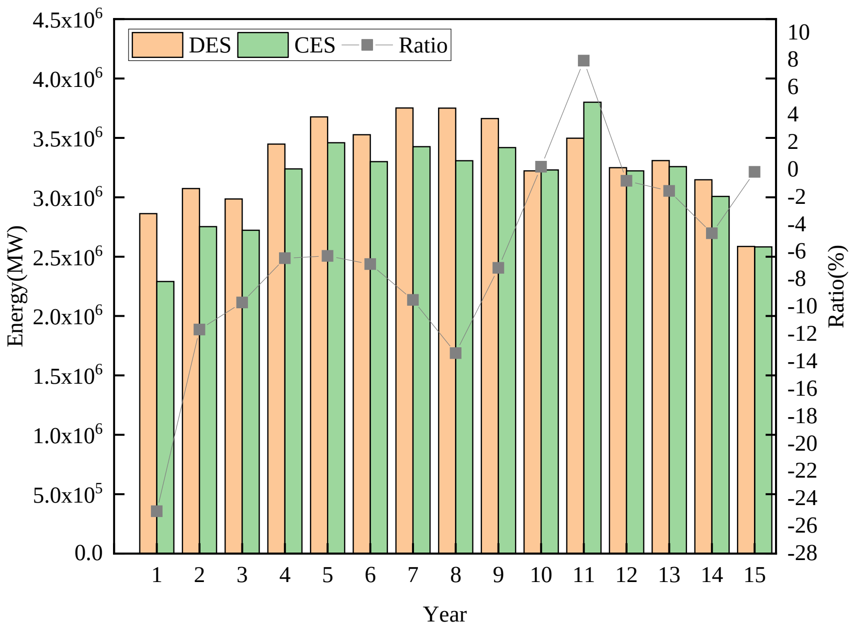

Fig.5-13 Comparison of CO_2 emissions between DES and CES

By comparing the energy consumption, economic performance and environmental performance of distributed energy systems and conventional energy systems, we can see that the distributed energy system is better in economic and energy consumption performance, and the environment performance is negative. This shows that the development of distributed energy system has more potential than conventional energy system. The development of distributed energy system should be strongly advocated.

5.5 Summary

In this chapter, the LCA model of the distributed energy system in Kitakyushu Science and Research Park had been presented. The data are from the Manual of distributed energy system, Construction completion certificate of distributed energy system, Construction plan state of distributed energy system and the distributed energy system inspection and maintenance work report.

According to the life cycle assessment of the distributed energy system in Kitakyushu Science and Research Park, we have established a life cycle model to compare with the conventional energy system through economic, energy consumption and environmental performance.

The results show that the cost saving ratio is 13.66%, the energy saving ratio is 12.25% and the carbon reduction ratio is -5.81%. Because the CO_2 emission coefficient of gas is 2.21 kg CO2/m3 and electricity is 0.463 kg CO2/kWh, the gas engine was only used for power generation; notably, more CO_2 was generated when the recovered heat was not used. Therefore, in this study, the CO_2 emission of distributed energy system was higher than that of conventional energy system.

By analyzing the life cycle assessment of distributed energy system, the development potential of distributed energy system is comprehensively analyzed in terms of economic performance, energy consumption performance and environmental performance, and a comprehensive performance evaluation method is proposed for future system optimization.

Appendix:

The list of all data in this chapter is as follows:

Table 5-4 Annual electricity, cooling and heating demands

Year	Unit	Electricity	Cooling	Heating total
1	kWh	3636468	1906857	3116352.58
2	kWh	4494355	1922884.4	2333602.66
3	kWh	4638583	1779994.8	1843763.5
4	kWh	5297039	2822756.8	2074160.2
5	kWh	5724987	2644599.6	2282969.706
6	kWh	5624473	2545913.6	1864705.506
7	kWh	5669256	2540288.8	2347529.724
8	kWh	5667371	2215243.8	2028429.82
9	kWh	5736653	1999781.8	2499059.67
10	kWh	5272404	2461135	2301899.624
11	kWh	5628324	2922434.4	3818088.226
12	kWh	5250353	2033611.2	2600647.598
13	kWh	5165544	2404964.8	2657291.438
14	kWh	4930083	1770514.2	2471845.356
15	kWh	4071890	1766544.8	2332237.946

Table 5-5 Maintenance cost of DES and CES

Year	Unit	DES	CES
1	$	17849.91723	85957.33
2	$	39764.57605	83336.4
3	$	16341.73257	83336.4
4	$	58800.80927	81947.77
5	$	12791.98087	77312.86
6	$	39764.57605	73569.98
7	$	16341.73257	73946.11
8	$	53742.87291	79894.24
9	$	10851.57256	78214.09
10	$	23726.31966	36828.21
11	$	40003.6785	0
12	$	23726.31966	0
13	$	71362.88394	0
14	$	30163.69321	0
15	$	23671.14217	0

Table 5-6 The expenditure during 15 years

Year	Unit	Total	Approximate curve
1	$	103807.2466	82216.47968
2	$	123100.9748	82216.47968
3	$	99678.13132	82216.47968
4	$	140748.5746	82216.47968
5	$	90104.83723	82216.47968
6	$	113334.5595	82216.47968
7	$	90287.84256	82216.47968
8	$	133637.1161	82216.47968
9	$	89065.66121	82216.47968
10	$	60554.53375	82216.47968
11	$	40003.6785	82216.47968
12	$	23726.31966	82216.47968
13	$	71362.88394	82216.47968
14	$	30163.69321	82216.47968
15	$	23671.14217	82216.47968

Table 5-7 Total energy costs of DES and CES during 15 years

Year	Unit	DES	CES	Ratio
1	$	947164.956	1060839.954	10.71556526
2	$	1053638.78	1274888.024	17.35440605
3	$	1033639.956	1278312.777	19.1402938
4	$	1219590.976	1522159.971	19.87760817
5	$	1355686.95	1619580.337	16.29393622
6	$	1294252.942	1564383.217	17.26752578
7	$	1363182.94	1600972.56	14.85282297
8	$	1413166.826	1558804.532	9.342910087
9	$	1390806.772	1586100.26	12.3128085
10	$	1246951.096	1503346.225	17.05496209
11	$	1408372.684	1704235.629	17.3604483
12	$	1361691.14	1482874.608	8.172199272
13	$	1375810.17	1496167.168	8.044355
14	$	1304046.47	1382445.625	5.671048
15	$	1065563.76	1177943.07	9.540300654

Table 5-8 The cumulative cost and cumulative net profit of the DES

Year	Unit	Cumulative net profit	Cumulative cost
1	$	113674.9975	1541107.228
2	$	334924.242	1623323.708
3	$	579597.0632	1705540.188
4	$	882166.0579	1787756.668
5	$	1146059.445	1869973.148
6	$	1416189.721	1952189.628
7	$	1653979.341	2034406.108
8	$	1799617.046	2116622.588
9	$	1994910.534	2198839.068
10	$	2251305.663	2281055.548
11	$	2547168.608	2363272.028
12	$	2668352.076	2445488.508
13	$	2788709.075	2527704.988
14	$	2867108.23	2609921.468
15	$	2979487.54	2692137.948

Table 5-9 Electricity and gas purchased from the grid of distributed energy system

Year	Unit	Electricity (DES)	Gas (DES)
1	MW	1630.995	11917.41888
2	MW	2100.466	11886.075
3	MW	2137.203	11293.40138
4	MW	2720.486	12372.48325
5	MW	3426.609	11824.31
6	MW	3229.322	11489.76838
7	MW	3303.911	12568.40438
8	MW	3786.64	11296.65888
9	MW	3799.601	10768.71963
10	MW	3568.64	8878.4145
11	MW	4399.244	8261.38675
12	MW	4599.184	6330.80875
13	MW	4579.185	6720.78375
14	MW	4312.357	6504.2575
15	MW	3484.488	5502.74

Table 5-10 Electricity and gas purchased from the grid of conventional energy system

Year	Unit	Electricity (CES)	Gas (CES)
1	MW	4272.087	3895.440725
2	MW	5135.316467	2917.003325
3	MW	5231.9146	2304.704375
4	MW	6237.957933	2592.70025
5	MW	6606.5202	2853.712133
6	MW	6473.110867	2330.881883
7	MW	6516.018933	2934.412155
8	MW	6405.7856	2535.537275
9	MW	6403.246933	3123.824588
10	MW	6092.782333	2877.37453
11	MW	6602.4688	4772.610283
12	MW	5928.2234	3250.809498
13	MW	5967.198933	3321.614298
14	MW	5520.2544	3089.806695
15	MW	4660.738267	2915.297433

Table 5-11 Comparison of energy consumption of DES and CES during 15 years

Year	Unit	DES	CES	Ratio
1	MW	18613.61574	21434.87866	13.16202
2	MW	20509.72734	24000.50758	14.54461
3	MW	20067.88077	23784.80096	15.62729
4	MW	23541.68354	28203.19835	16.52832
5	MW	25892.56186	29977.37581	13.62632
6	MW	24748.04069	28906.82153	14.38685
7	MW	26132.90854	29686.51473	11.97044
8	MW	26843.05043	28835.06697	6.908313
9	MW	26368.32373	29412.93156	10.35126
10	MW	23529.78742	27891.84113	15.63917
11	MW	26322.8792	31879.64057	17.43044
12	MW	25213.17287	27589.66457	8.613703
13	MW	25521.04018	27820.48694	8.2653
14	MW	24209.02754	25753.7083	5.997896
15	MW	19808.6193	22050.37814	10.16653

Table 5-12 Comparison of carbon emissions of DES and CES during 15 years

Year	Unit	DES	CES	Ratio
1	kg	2862150.342	2291299.606	-24.91384082
2	kg	3073973.818	2753052.202	-11.65693902
3	kg	2986198.352	2722537.776	-9.684367969
4	kg	3447040.057	3238209.882	-6.448938849
5	kg	3677057.975	3459504.229	-6.288581601
6	kg	3526567.135	3299595	-6.878787701
7	kg	3751804.687	3426440.197	-9.495700214
8	kg	3750463.609	3308083.796	-13.37269067
9	kg	3663124.893	3418527.891	-7.15503894
10	kg	3221984.004	3229352.96	0.228186786
11	kg	3497463.149	3800286.986	7.968446524
12	kg	3248709.179	3222732.886	-0.806033082
13	kg	3308397.222	3258106.991	-1.543541425
14	kg	3146574.017	3007434.888	-4.626505118
15	kg	2586202.376	2582198.855	-0.155043091

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Chapter 6

STUDY ON EQUIPMENT MAINTENAMCE OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM

CHAPTER SEVEN: STUDY ON EQUIPMENT MAINTENANC OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM

6.1 Introduction

As it mentions early, in current climate change, lack of fossil energy and energy security environmental, development the distributed energy system as a power generation system to meet the electricity, heating and cooling for an area or building is a best solution to all increasing the energy and improving usage efficiency. Therefore, more and more countries or regions use the distributed energy system to supply electricity demand, and use the waste heat from the power generation unit to meet the heating demand and cooling demand by the heat recovery and storage system.

Distributed energy system is a complex system which can provide the electricity, heating, cooling at the same time, and composed of power generation system, cooling system, storage system, heating recovery system, heat boiler and so on. Among them, the power generation system is the core of the distributed energy system. Because of is should produce the electricity and the waste heat od power generation system can be recovery to meet the heating or cooling demand. Thus, it is very important that power generation system can have a good operation and maintenance for the distributed energy system.

Reliability and maintenance, health management and security are closely related. Inspection and maintenance are necessary methods to keep the reliability of the distributed energy system. Reliability analysis is a process to make the quantitative reliability requirements into the product design through reliability prediction, allocation, analysis and improvement of a series of reliability engineering technology, so as to form the inherent reliability of the product. It is a kind of reliability engineering. The reliability analysis runs through the whole life cycle of products, and the methods of reliability analysis in different stages of products are different. The distributed energy system especially the gas engine and fuel cell has been development near 20 years, a lot of application program of distributed energy system is close to the design life of the distributed energy system. Considering the high cost of investment for a new power generation system, the maintenance and replacement a part of old equipment to prolong the service life for the whole system is the best way to improve the energy efficiency and reduce the cost.

In Kitakyushu Science and Research Park, the gas engine and fuel cell were used to produce the electricity and the recover the waste heat for nearly 15 years as the distributed energy system. And the inspection and maintenance are carried out concurrently with the operation of the equipment. The inspection data of the gas engine and fuel cell will be mainly analyzed in this chapter, and the Failure Modes and Effects Analysis (FMEA) method will be used to build the failure network, in order to get the theoretical basis of the reliability of the gas engine and fuel cell.

Gas engine of distributed energy system includes the power generation unit, fuel gas supply system, cooling water unit, heat recovery unit and auxiliaries. Fuel cell of distributed energy system includes power generation system, cooling system, heat recovery system and auxiliaries' system. Gas engine and fuel cell as a device to provide electricity production face vast risks which are responsible for failures. For instance, the drain tank leak, supercharger failure, power machine bearing temperature is too high and so on. To analyze the system reliability of gas engine and fuel cell, the necessary for a comprehensive study to consider common failures. These failures may occur in the device and even lead to the human consequences of the disaster.

In this chapter, the main content is the inspection and the maintenance investigation for the analysis gas engine and fuel cell.

6.2 Methodology

6.2.1 Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a systematic method for analyzing and ranking the risks associated with various products (or processes), failure modes (both existing and potential), prioritizing them for remedial action, acting on the highest ranked items, reevaluating those items and returning to the prioritization step in a continuous loop until marginal returns set in. Failure Mode and Effect Analysis is broadly used as a reliability tool to recognize likely failures before they happen with the aim of reducing their risks.

The Failure Modes and Effects Analysis (FMEA) method has been used to study the reliability of many different power generation systems. Hoseynabadi et al. [1] applies that method to a wind turbine (WT) system using a proprietary software reliability analysis tool. Comparison is made between the quantitative results of an FMEA and reliability field data from real wind turbine systems and their assemblies. These results are discussed to establish relationships which are useful for future wind turbine designs. Kang et al. [2] conducted risk assessment through a modified Failure Modes and Effects Analysis (FMEA) method, named correlation-FMEA, to study the connection between failure modes and its effect on the failure probability of the entire system.

The failure modes and effects analysis is a design tool used to systematically analyze postulated component failures and identify the resultant effects on system operations. The analysis is sometimes characterized as consisting of two sub-analyses, the first being the failure mode and effect analysis, and the second, the criticality analysis. Successful development of a failure mode and effect analysis requires that the analyst include all significant failure modes for each contributing element or part in the system. Failure mode and effect analysis can be performed at the system, subsystem, assembly, subassembly or part level. The failure mode and effect analysis should be a living document during development of a hardware design. It should be schedule and completed concurrently with the design. If completed in a timely manner, the failure mode and effect analysis can help guide design decisions. The usefulness of the failure mode and effect analysis as a design tool and in the decision-making process is dependent on the effectiveness and timeliness with which design problems are identified. Timeliness is probably the most important consideration. In the extreme case, the failure mode and effect analysis would be of little value to the design decision process if the analysis is performed after the hardware is built. While the failure mode and effect analysis identify all part failure modes, its primary benefit is the early identification of all critical and catastrophic subsystem or system failure modes so they can be eliminated or minimized through design modification at the earliest point in the development effort; therefore, the FMECA should be performed at the system level as soon as preliminary design information is available and extended to the lower levels as the detail design progresses.

The analysis may be performed at the functional level until the design has matured sufficiently to identify specific hardware that will perform the functions; then the analysis should be extended to the hardware level. When performing the hardware level failure mode and effect analysis, interfacing hardware is considered to be operating within specification. In addition, each part failure postulated is considered to be the only failure in the system. In addition to the failure mode and effect analysis done on systems to evaluate the impact lower-level failures have on system operation, several other failure mode and effect analysis are done. Special attention is paid to interfaces between systems and in fact at all function interfaces. The purpose of these failure mode and effect analysis is to assure that irreversible physical and function damage is not propagated across the interface as a result of failures in one of the interface units. These analyses are done to the piece part level for the circuits that directly interface with the other units. The failure mode and effect analysis can be accomplished without a CA, but CA requires that the FMEA has previously identified system level critical failures. When both steps are done, the total process is called a FMEA.

The ground rules of each FMEA include a set of project selected procedures; the assumptions on which the analysis is based; the hardware that has been included and excluded from the analysis and the rationale for the exclusions. The ground rules also describe the indenture level of the analysis, the basic hardware status, and the criteria for system and mission success. Every effort should be made to define all ground rules before the FMEA begins; however, the ground rules may be expanded and clarified as the analysis proceeds. A typical set of ground rules follows: 1). Only one failure mode exists at a time. 2). All inputs to the item being analyzed are present and at nominal values. 3). All consumables are present in sufficient quantities. 4). Nominal power is available.

Major benefits derived from a properly implemented FMEA effort are as follows: 1). It provides a documented method for selecting a design with a high probability of successful operation and safety. 2). A documented uniform method of assessing potential failure mechanisms, failure modes and their impact on system operation, resulting in a list of failure modes ranked according to the seriousness of their system impact and likelihood of occurrence. 3). Early identification of single failure points and system interface problems, which may be critical to mission success and safety. They also provide a method of verifying that switching between redundant elements is not jeopardized by postulated single failures. 4). An effective method for evaluating the effect of proposed changes to the design and operational procedures on mission success and safety. 5). A basis for in-flight troubleshooting procedures and for locating performance monitoring and fault-detection devices. 6). Criteria for early planning of tests.

Failure Modes and Effects Analysis procedure commences with reviewing design details, illustrating equipment block diagram and recognizing all potential failures, respectively. Following recognition, all possible causes and effects should be classified to the related failure modes. After this practice, priority of failures due to their disaster effects should be ranked by a Risk Priority Number (RPN), which is the multiplication of severity of failures (S), their portability of occurrence (O), and the possibility of detection (D).

$$RPN = S \times O \times D \tag{6-1}$$

Basically, by computing RPNs, engineers will be allowed to focus on high RPNs immediately rather than all failure modes due to the highest priority. Moreover, they can prevent the disaster to assess the improvements for priority items.

According to formula 6-1, severity refers to the immensity of the last effect of a system failure. Rate 10 is allocated to the failure will result in major damage. Occurrence refers to the probability of a failure to occur, which is described in a qualitative way. Detection refers to the likelihood of detecting a failure before it can occur.

The evaluation rank is based on a scale of 1–10, with the corresponding description from the Mauro Villarini et al. [3], and the investigation in KSRP. Table 6-1 to 6-3 is the severity, occurrence and detection rating scale of FMEA. The scores from 1 to 10. For the table 6-1 severity rating scale, 1-2 refers to failure is of such minor nature that the operate will probably not detect the failure. 3-5 refers to failure will result in slight deterioration of part or system performance. 6-7 refers to failure will result in operator dissatisfaction and/or deterioration of part or system performance. 8-9 refers to failure will result in high degree of operator dissatisfaction and cause non-functionality of system. 10 refers to failure will result in major operator dissatisfaction or major damage. For the table 6-2 occurrence rating scale, 1 refers to an unlikely probability of occurrence: probability of occurrence<0.001. 2-3 refers to a remote probability of occurrence: 0.001<probability of occurrence<0.01. 4-6 refers to an occasional probability of occurrence: 0.10< probability of occurrence<0.10. 7-9 refers to an occasional probability of occurrence: 0.10< probability of occurrence<0.20. 10 refers to a high probability of occurrence: 0.20<probability of occurrence. For table 6-3 detection rating scale, 1-2 refers to very high probability that the defect will be detected. 3-4 refers to high probability that the defect will be detected. 5-7 refers to moderate probability that the defect will be detected. 8-9 refers to low probability that the defect will be detected. 10 refers to very low (or zero) probability that the defect will be detected.

A team review will be applied for the maintenance strategy. The members for the team can include the engineers, operators, manufacturers, designers, managers and maintainers etc. Through professional maintenance knowledge, equipment knowledge, maintenance experience and management experience, put forward improvement strategy for equipment maintenance strategy and evaluate new RPN.

In this analysis, we invite some maintenance managers and workers to form a maintenance review team. Maintenance data and strategies for fuel cell sub-systems and gas engine sub-systems of DER system in KSRP are discussed in an interview. The members of the maintenance review team are shown in Table 6-3. The interview is divided into two stages. In the first stage, the causes and results of each failure mode and corresponding maintenance measures are given. In the second phase, S, O, and D of the maintenance plan are determined after the maintenance level is improved. The interview is divided into two stages. In the first stage, the causes and results of each failure mode and corresponding maintenance measures are given. In the second phase, S, O, and D of the maintenance plan are determined after the maintenance level is improved.

We score the failure parts of gas engine and fuel cell based on these score sheets. Then go to the energy center to find the professional staff to confirm the score. It is showed in table 4-5.

Table 6-1 Severity rating scale of FMEA.

Rank of severity	Description
1-2	Failure is of such minor nature that the operate will probably not detect the failure.
3-5	Failure will result in slight deterioration of part or system performance.
6-7	Failure will result in operator dissatisfaction and/or deterioration of part or system performance.
8-9	Failure will result in high degree of operator dissatisfaction and cause non-functionality of system.
10	Failure will result in major operator dissatisfaction or major damage.

Table 6-2 Occurrence rating scale of FMEA.

Rank of occurrence	Description
1	An unlikely probability of occurrence: probability of occurrence<0.001
2-3	A remote probability of occurrence: 0.001<probability of occurrence<0.01
4-6	An occasional probability of occurrence: 0.10< probability of occurrence<0.10
7-9	An occasional probability of occurrence: 0.10< probability of occurrence<0.20
10	A high probability of occurrence: 0.20<probability of occurrence

Table 6-3 Detection rating scale of FMEA.

Rank of detection	Description
1-2	Very high probability that the defect will be detected.

3-4	High probability that the defect will be detected.
5-7	Moderate probability that the defect will be detected.
8-9	Low probability that the defect will be detected.
10	Very low (or zero) probability that the defect will be detected.

Table 6-4 Effect of different RPN level.

Level	RPN	Effect
I	1～10	No effect.
II	10～100	Duty unfulfilled.
III	100～250	Failing an important mission.
IV	250～1000	Abandonment of duties.

Table 6-5 The members of the maintenance review team.

Qualification	Numbers	Experience
Asset manager	1	More than 5 years asset management in KSRP.
Technician	2	Good profile with more than 10 years of experience on system management and maintenance of DER system in KSRP.
Maintenance engineers	4	At least 5 years' experience in DER system management and maintenance.

6.2.2 Process flow of FMEA

Suggested failure modes and effects analysis process applied to distributed energy system including the main steps are represented in Fig.6-1. First, establish the equipment block diagram according to the power generation unit, components, sub-components and parts as shown in Fig.6-2. Then calculate the Risk Priority Number (RPN), and get the FMEA worksheets. The higher the

RPN the more significant the criticality. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

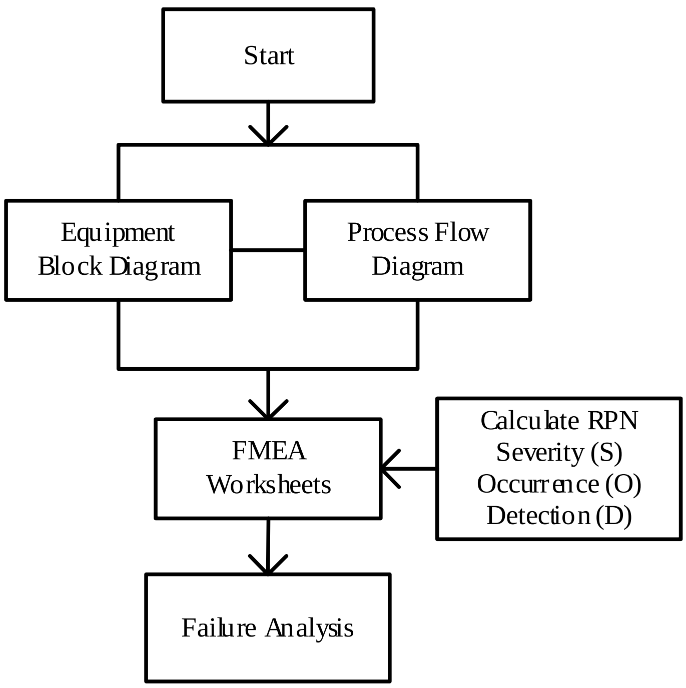

Fig.6-1 Analysis process flow of FMEA.

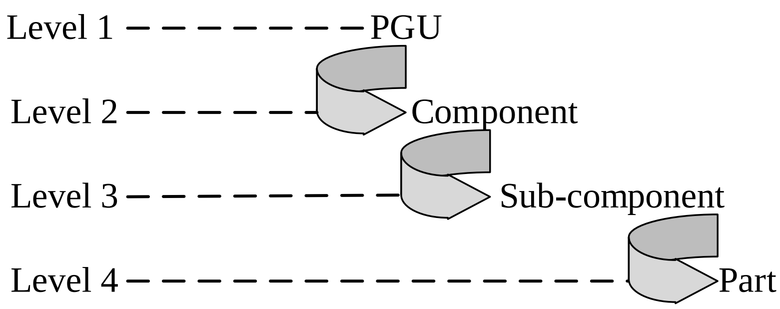

Fig.6-2 PGU construction hierarchy for FMEA.

6.3 Analysis of gas engine

6.3.1 Base data of gas engine

In order to analyze the failure modes and effects analysis of gas engine of distributed energy system in Kitakyushu Science and Research Park, this study was collected the failures data from the energy center of Kitakyushu Science and Research Park. The details of failures data source were shown in Table 6-6.

Table 6-6 Details of failures data source.

No.	Item	Details
1	Inspection table of gas engine (from the July 2001 to March 2015)	Data of failures; Preliminary estimate of the failure's reason; Failure position description.
2	Construction completion certificate of gas engine (from the July 2001 to March 2015)	Data of failure's repair record; Failure reason review; Maintenance description.
3	Gas engine yearly report (from the July 2001 to March 2015)	Report of inspection, maintenance and repair during one year.
4	Construction plan statement of gas engine	Operation instruction of gas engine; Maintenance and repairing methods; Failure's reasons description.

Total four kinds of data files used to collect and analyze the failures of gas engine. It includes Inspection table of gas engine, Construction completion certificate of gas engine, Gas engine yearly report, and Construction plan statement of gas engine. The analysis range is from the July 2001 to March 2015, total 15 year's data. Content of inspection table of gas engine includes the data information of failures, preliminary estimate of the failure's reason, and failure position description. Content of construction completion certificate of gas engine includes data of failure's repair record, failure reason review, maintenance description. Content of gas engine yearly report includes inspection, maintenance and repair information during one year. Content of construction plan statement of gas engine includes operation instruction of gas engine, maintenance and repairing methods, failure's reasons description.

6.3.2 Identifying effects and cause of gas engine

Gas engine of distributed energy system is a complex system, it includes the power generation unit, fuel gas supply system, cooling water unit, heat recovery unit, gas system and auxiliaries unit. Equipment block diagram is easily used to show how the different parts of the system as shown in

Fig.6-3.

Table 6-7 is the details of failure mode and failure cause. A total of 40 failure components. Each failure component has a corresponding failure mode and failure cause. The failure component of gas engine includes lubricating oil filter, ignition device, battery, gas regulator, cooling water pump, sell motor, actuator, shutoff valve, cooler water circulation pump, packing, intake valve / exhaust valve, supercharger, heat exchanger, mist pipe, crankshaft, gas line, gas source valve, piston, governor linkage, valve unit, cooling tower, pulsar, cylinder liner, piping, lubricating oil cooler.

The failure mode of gas engine includes be clogged up, wear, battery problem, outlet pressure shortage, electrode damage, viscosity defect, lack of cooling water, shutoff valve failure, pressure regulating valve defect, high temperature, water leak, cooling water pump capacity shortage, lack, sucking, exhaust valve head defect, capacity shortage, fuel supply pressure drop, obstruction, faulty fuel gas shutoff valve, lack of cooling water, gas leak, pressure gauge defect, deformation, piston ban, malfunction, voltage drop, manual valve failure, dust and fallen leaves mixed in the cooling tower, valve and valve seat failure, fuel supply shortage, water shortage.

The failure cause of gas engine includes clogging of lubricating oil sieve, ignition timing failure, no direct-current power supply, fuel gas has not arrived, bad ignition, selection defect of lubricating oil viscosity, mixture ratio of fuel gas and air is inappropriate, air is contained in cooling water piping, a defect of itself, failure of actuator, the signal from the magnetic pickup is weak or not at all, fuel shutoff valve closes due to malfunction, fuel gas has not arrived, lubricating oil pressure regulating valve defective, high cooling water temperature, junction part packing failure or bolt looseness, lack of cooling water, intake, exhaust valve head skimmer inappropriate, seat contact failure, intercooler cooling water temperature is high, heat dissipation system defect, fuel system failure, clogged mist pipe, burnout, unstable signal pressure, cooling water piping system resistance too large, air is in the fuel gas system, fuel gas has not arrived, clogging of intake filter, wear and sticking of piston ring, poor connection of governor linkage, fuel gas has not arrived, strainer clogging, ignition timing failure, intake, exhaust valve head skimmer inappropriate, seat contact failure, wear of cylinder liner, fuel system failure, lubricating oil temperature high.

Table 6-8 is the details of failure effects. It includes abrupt stop, output reduction, rotation does not rise; although the engine rotates according to the start command, the rotation does not rise; although the engine rotates according to the start command, the rotation does not rise, the engine starts but stops immediately; engine does not rotate by start command; the actuator of the governor does not operate at all; the engine starts but stops right away; the engine suddenly stops; the lubricating oil pressure becomes less than the specified value.

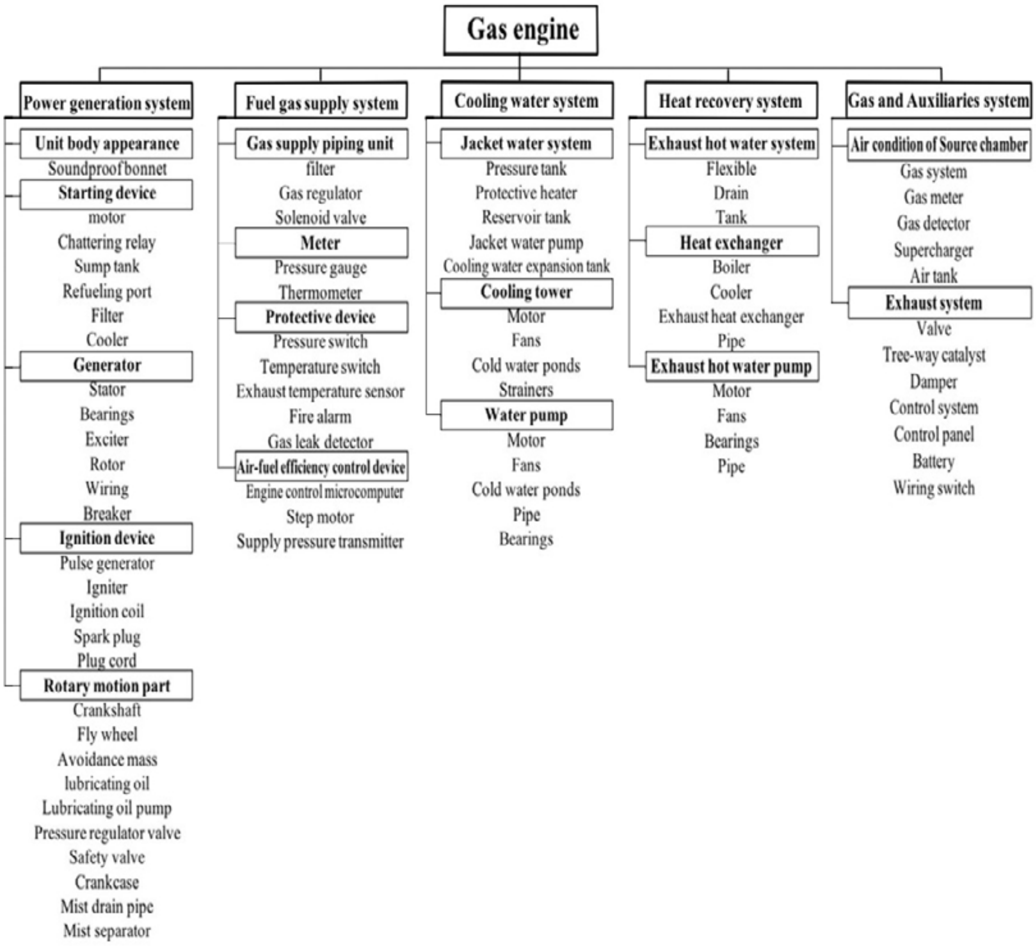

Fig.6-3 Equipment block diagram of gas engine system.

Table 6-7 Details of failure mode and failure cause.

Number	Component	Failure mode	Failure cause
1	Lubricating oil filter	Be clogged up	Clogging of lubricating oil sieve
2	Ignition device	Wear	Ignition timing failure
3	Battery	Battery problem	No direct-current power supply
4	Gas regulator	Outlet pressure shortage	Fuel gas has not arrived
5	Ignition device	Electrode damage	Bad ignition
6	Lubricant	Viscosity defect	Selection defect of lubricating oil viscosity
7	Gas regulator	Outlet pressure shortage	Mixture ratio of fuel gas and air is inappropriate
8	Cooling water pump	Lack of cooling water	Air is contained in cooling water piping
9	Sell motor	Failure	A defect of itself
10	Actuator	Failure	Failure of actuator
11	Battery	Battery failure	The signal from the magnetic pickup is weak or not at all
12	Shutoff valve	Shutoff valve failure	Fuel shutoff valve closes due to malfunction
13	Shutoff valve	Shutoff valve failure	Fuel gas has not arrived
14	Lubricant	Pressure regulating valve defect	Lubricating oil pressure regulating valve defective
15	Cooler water circulation pump	High temperature	High cooling water temperature
17	Packing	Water leak	Junction part packing failure or bolt looseness
18	Cooling water pump	Cooling water pump capacity shortage	Lack of cooling water
19	Lubricant	Lack	Lack
20	Intake valve / exhaust valve	Sucking, exhaust valve head defect	Intake, exhaust valve head skimmer inappropriate, seat contact failure
21	Supercharger	High temperature	Intercooler cooling water temperature is high

22	Heat exchanger	Capacity shortage	Heat dissipation system defect
23	Supercharger	Fuel supply pressure drop	Fuel system failure
24	Mist pipe	Obstruction	Clogged mist pipe
25	Shutoff valve	Faulty fuel gas shutoff valve	Burnout
26	Shutoff valve	Faulty fuel gas shutoff valve	Burnout
27	Crankshaft	Failure	Unstable signal pressure
28	Cooling water pump	Lack of cooling water	Cooling water piping system resistance too large
29	Gas line	Gas leak	Air is in the fuel gas system
30	Gas source valve	Pressure gauge defect	Fuel gas has not arrived
31	Supercharger	Deformation	Clogging of intake filter
32	Piston	Piston bad	Wear and sticking of piston ring
33	Governor linkage	Malfunction	Poor connection of governor linkage
34	Battery	Voltage drop	Lack
35	Valve unit	Manual valve failure	Fuel gas has not arrived
36	Cooling tower	Dust and fallen leaves mixed in the cooling tower	Strainer clogging
37	Pulsar	Failure	Ignition timing failure
38	Intake valve / exhaust valve	Valve and valve seat failure	Intake, exhaust valve head skimmer inappropriate, seat contact failure
39	Cylinder liner	Failure	Wear of cylinder liner
40	Piping	Fuel supply shortage	Fuel system failure
41	Lubricating oil cooler	Water shortage	Lubricating oil temperature high

Table 6-8 Details of failure effects.

Number	Component	Failure effects
1	Lubricating oil filter	The lubricating oil pressure becomes less than the specified value
2	Ignition device	Abrupt stop, output reduction, rotation does not rise
3	Battery	The actuator of the governor does not operate at all
4	Gas regulator	Although the engine rotates according to the start command, the rotation does not rise
5	Ignition device	Although the engine rotates according to the start command, the rotation does not rise
6	Lubricant	The lubricating oil pressure becomes less than the specified value
7	Gas regulator	Although the engine rotates according to the start command, the rotation does not rise
8	Cooling water pump	Overheat
9	Sell motor	Engine does not rotate by start command
10	Actuator	The actuator of the governor does not operate at all
11	Battery	The actuator of the governor does not operate at all
12	Shutoff valve	The engine starts but stops right away
13	Shutoff valve	Although the engine rotates according to the start command, the rotation does not rise
14	Lubricant	The lubricating oil pressure becomes less than the specified value
15	Cooler water circulation pump	Knocking
16	Packing	Lubricant leaks
17	Cooling water pump	Overheat
18	Lubricant	The lubricating oil pressure becomes less than the specified value
19	Intake valve / exhaust valve	Engine power reduction
20	Supercharger	Engine power reduction
21	Heat exchanger	Overheat
22	Supercharger	Engine power reduction
23	Mist pipe	Lubricant leaks

24	Shutoff valve	The engine suddenly stops
25	Shutoff valve	The engine suddenly stops
26	Crankshaft	Lubricant leaks
27	Cooling water pump	Overheat
28	Gas line	Although the engine rotates according to the start command, the rotation does not rise, the engine starts but stops immediately
29	Gas source valve	Although the engine rotates according to the start command, the rotation does not rise
30	Supercharger	Engine power reduction
31	Piston	Engine power reduction
32	Governor linkage	Idling malfunction
33	Battery	Engine does not rotate by start command
34	Valve unit	Although the engine rotates according to the start command, the rotation does not rise
35	Cooling tower	Overheat
36	Pulsar	Knocking
37	Intake valve / exhaust valve	Engine power reduction
38	Cylinder liner	Engine power reduction
39	Piping	Engine power reduction
40	Lubricating oil cooler	The lubricating oil pressure becomes less than the specified value

Table 6-9 Result of FMEA of gas engine.

Number	Component	Current maintenance strategy	S	O	D	RPN	New proposed maintenance strategy	S	O	D	New RPN
1	Lubricating oil filter	Element exchange	7	8	3	168	Increase the number of examinations	7	3	2	42
2	Ignition device	Replacement of spark plug	6	9	3	162	Increase the number of examinations	6	2	2	24
3	Battery	Battery charging or replacement	8	5	4	160	Exchange	8	3	4	96
4	Gas regulator	Adjust the regulator outlet to the specified pressure	7	4	5	140	Test piping size	7	4	3	84
5	Ignition device	Replacement of spark plug	6	7	3	126	Perform bolt retightening	6	4	3	72
6	Lubricant	Lubricating oil change	4	5	6	120	Increase the number of examinations	4	2	4	32
7	Gas regulator	Adjust the regulator outlet to the specified pressure	6	3	6	108	Timely cooling	6	3	3	54
8	Cooling water pump	Thorough air bleed	5	4	5	100	Increase the number of examinations	5	3	4	60
9	Sell motor	Exchange	7	2	7	98	Exchange regularly	7	2	7	98
10	Actuator	Actuator change	8	2	6	96	Increase the number of examinations	8	2	3	48
11	Battery	Pick up exchange	8	4	3	96	Increase the number of examinations	8	4	2	64
12	Shutoff valve	Modify wiring and sequence	8	4	3	96	Increase the number of	8	4	3	96

							examinations				
13	Shutoff valve	Correction of wiring, disassembly of gas shutoff valve or exchange	6	3	5	90	Increase the number of examinations	6	3	3	54
14	Lubricant	Exchange	6	2	7	84	Increase the number of examinations	6	2	4	48
15	Cooler water circulation pump	Reduce cooling water temperature	7	3	4	84	Exchange regularly	7	3	4	84
16	Packing	Perform bolt retightening, packing exchange	7	3	4	84	Increase the number of examinations	7	2	3	42
17	Cooling water pump	Appropriate cooling water pump capacity	4	4	5	80	Test piping size	4	4	5	80
18	Lubricant	Replenishment	3	5	5	75	Increase the number of examinations	3	3	3	27
19	Intake valve / exhaust valve	Adjust to specified value of intake valve head and exhaust valve head skimmer	5	3	5	75	cleaning	5	3	5	75
20	Supercharger	Decrease coolant inlet temperature of intercooler	3	4	6	72	Increase the number of examinations	3	4	4	48
21	Heat exchanger	Select capacity of heat exchanger	3	3	8	72	Timely cleaning	3	3	5	45
22	Supercharger	Increase supply pressure after consultation with gas company	4	3	6	72	Increase the number of examinations	4	3	4	48
23	Mist pipe	Change piping route	6	2	6	72	Exchange regularly	6	2	5	60

24	Shutoff valve	Cable, fuse replacement	8	3	3	72	Increase the number of examinations	8	3	2	48
25	Shutoff valve	Replace the coil	8	3	3	72	Regular cleaning	8	3	2	48
26	Crankshaft	Exchange of oil seal	7	2	5	70	Increase the number of examinations	7	2	4	56
27	Cooling water pump	Re-select coolant pump capacity, modify piping route, size	4	4	4	64	Increase the number of examinations	4	4	3	48
28	Gas line	Perform bleeding according to air removal	8	2	4	64	Increase the number of examinations	8	2	3	48
29	Gas source valve	Pass through the main source or gas	7	3	3	63	Increase the number of examinations	7	3	2	42
30	Supercharger	Intake air filter replacement; intake air filter reinforcement treatment	4	3	5	60	Confirm increase in inspiratory resistance and eliminate	4	3	3	36
31	Piston	Replace	3	3	6	54	Increase the number of examinations	3	3	4	36
32	Governor linkage	Linkage operation adjustment	4	4	3	48	Check and clearance	4	4	3	48
33	Battery	Replace the battery and recharge	6	4	2	48	Increase the number of examinations	6	4	2	48
34	Valve unit	Open manual valve	6	2	4	48	Exchange regularly	6	2	3	36
35	Cooling tower	Coolant water discontinuation	4	2	5	40	To confirm in advance	4	2	4	32
36	Pulsar	Rotate the pulsar body, adjust at the specified time	6	2	3	36	Exchange thermostat	6	2	3	36

37	Intake valve / exhaust valve	Valve and valve seat alignment	4	2	4	32	Turn off the switch	4	2	2	16
38	Cylinder liner	Replace	3	2	5	30	Downtime check	3	2	3	18
39	Piping	Increase piping size	3	2	5	30	Test piping size	3	2	3	18
40	Lubricating oil cooler	Keep cooling water temperature low, increase the amount of cooling water	3	2	5	30	Properly lower the lubricant to the machine temperature	3	2	3	18

6.3.3 Results

Table 6-9 is the results of FMEA of gas engine. We achieve optimized results by improving maintenance. In table 6-9, we introduce the current maintenance strategy and new proposed maintenance strategy. And score the severity, occurrence and detection of gas engine. The current maintenance strategy includes element exchange, replacement of spark plug, battery charging or replacement, adjust the regulator outlet to the specified pressure, replacement of spark plug, lubricating oil change, adjust the regulator outlet to the specified pressure, thorough air bleed, actuator change, pick up exchange, modify wiring and sequence, correction of wiring, disassembly of gas shutoff valve or exchange, reduce cooling water temperature, perform bolt retightening, packing exchange, appropriate cooling water pump capacity, adjust to specified value of intake valve head and exhaust valve head skimmer, decrease coolant inlet temperature of intercooler, select capacity of heat exchanger, increase supply pressure after consultation with gas company, change piping route, cable, fuse replacement, replace the coil, exchange of oil seal, re-select coolant pump capacity, modify piping route, size, perform bleeding according to air removal, pass through the main source or gas, intake air filter replacement; intake air filter reinforcement treatment, linkage operation adjustment, replace the battery and recharge, open manual valve, coolant water discontinuation, rotate the pulsar body, adjust at the specified time, valve and valve seat alignment, increase piping size, keep cooling water temperature low, increase the amount of cooling water.

The highest RPN is lubricating oil filter, and its severity is 7, occurrence is 8 detection is 3, the RPN is 168. Lubricating oil filter failure result in operator dissatisfaction and/or deterioration of part or system performance. The current maintenance strategy is exchange element, and new proposed maintenance strategy is increasing the number of examinations. So, the lubricating oil filter is optimized. And the new severity is 7, new occurrence is 3, new detection is 2, the new RPN is 42. The lowest RPN is cylinder liner, piping and lubricating oil cooler. Severity of cylinder liner is 3, occurrence is 2, detection is 5, the RPN is 30. Cylinder liner failure result in slight deterioration of part or system performance. The current maintenance strategy is replacing component, and the new proposed maintenance strategy is downtime check. So, the cylinder liner is optimized. Severity of piping is 3, occurrence is 2, detection is 5, the RPN is 30. Piping failure result in slight deterioration of part or system performance. The current maintenance strategy is increase piping size, and the new proposed maintenance strategy is test piping size. So, the piping is optimized. Severity of lubricating oil cooler is 3, occurrence is 2, detection is 5, the RPN is 30. Lubricating oil cooler failure result in slight deterioration of part or system performance. The current maintenance strategy is kept cooling water temperature low, increase the amount of cooling water, and the new proposed maintenance strategy is properly lower the lubricant to the machine temperature. So, the lubricating oil cooler is optimized.

According to previous literature description we set RPN higher than 90 as the key failure, it includes lubricating oil filter, ignition device, battery, gas regulator, ignition device, lubricant, gas regulator, cooling water pump, sell motor, actuator, battery, shutoff. Their impact on the equipment is failure will result in slight deterioration of part or system performance, failure will result in operator dissatisfaction and/or deterioration of part or system performance and failure will result in high degree of operator dissatisfaction and cause non-functionality of system.

Fig.6-4 is the components with RPN over 100. Here are 8 components with RPN over 100. It includes lubricating oil filter, ignition device, battery, gas regulator, ignition device, lubricant, gas regulator and cooling water pump.

Fig.6-5 is the severity index modification with corrective actions. Because all the components were maintained with original type, so the severity index before and after is the same. Fig.6-6 is the detection index modification with corrective actions. As most of the improvement measures increasing the number of inspections. Therefore, the index detection after corrective actions is lower than before. Fig.6-7 is the occurrence index modification with corrective actions. As the number of inspections is increased, the index of occurrence is reduced. Fig.6-8 is the risk priority number index modification with corrective actions. We can see that the optimization RPN is lower than the RPN before optimization. Only 7 RPN before and after is the same.

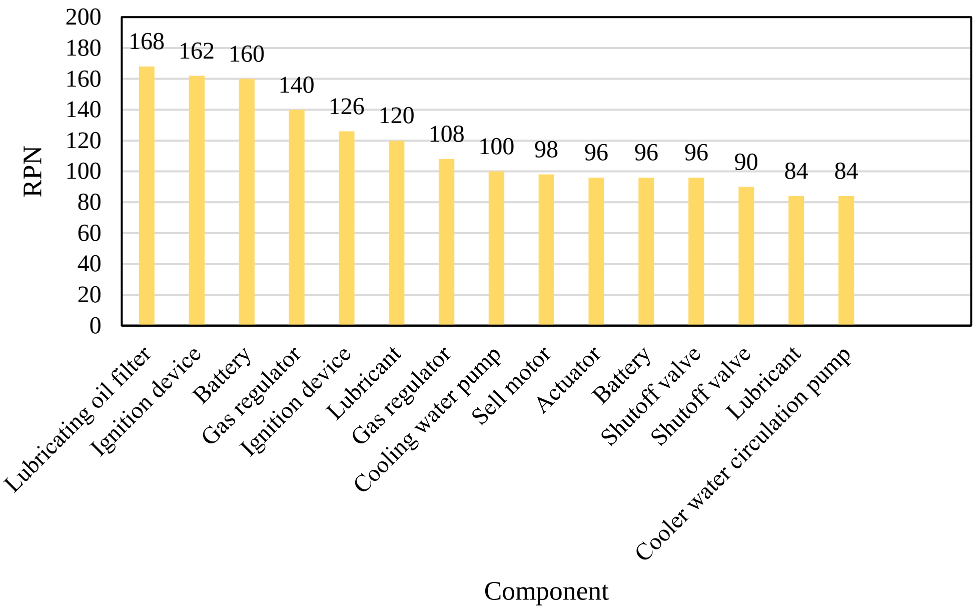

Fig.6-4 Components with RPN over 80.

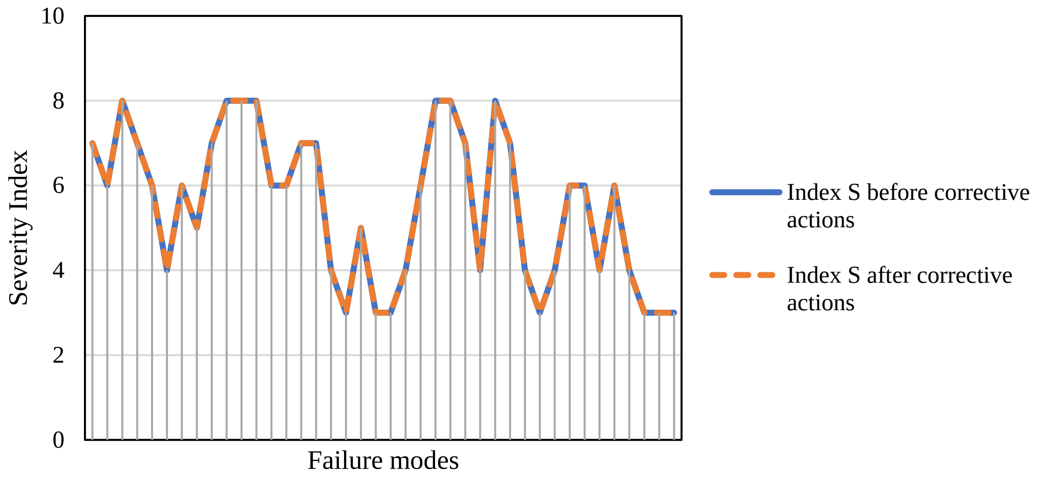

Fig.6-5 The severity index modification with corrective actions.

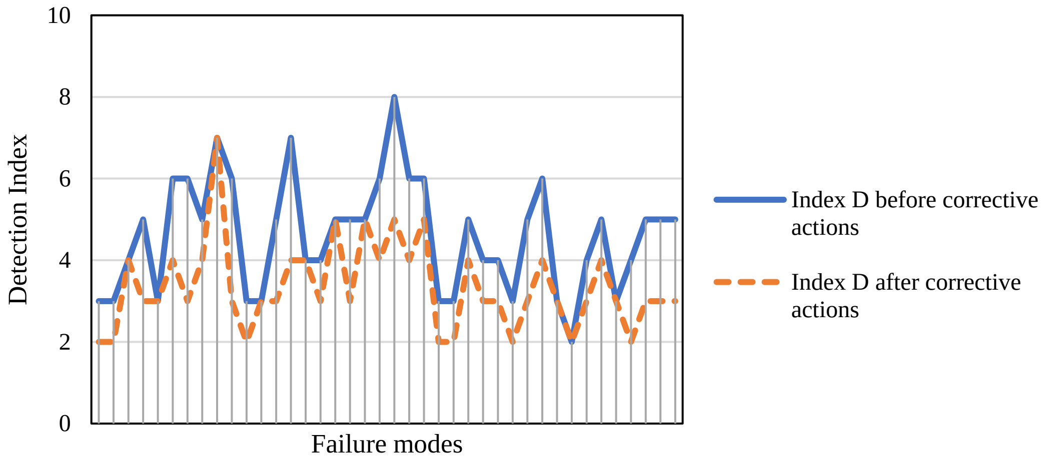

Fig.6-6 The detection index modification with corrective actions.

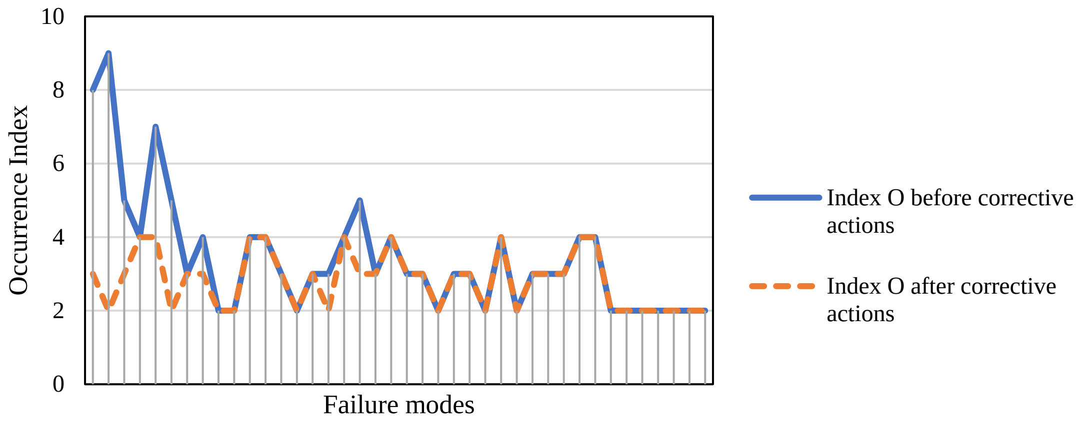

Fig.6-7 The occurrence index modification with corrective actions.

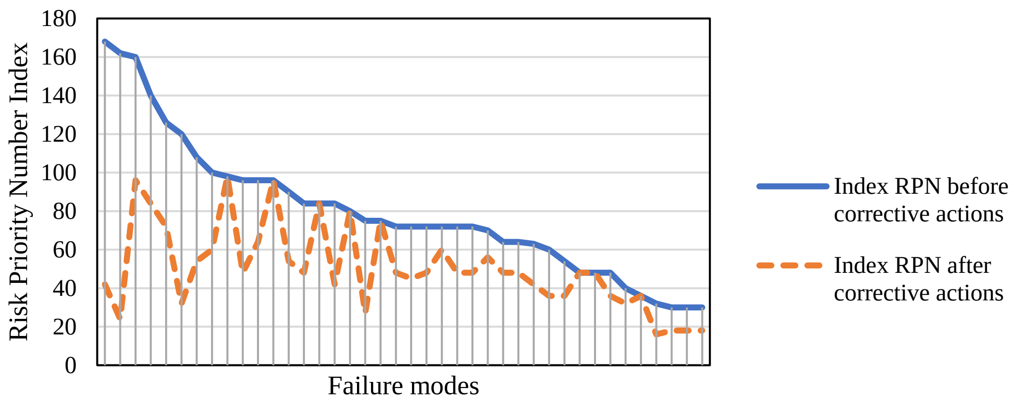

Fig.6-8 The risk priority number index modification with corrective actions.

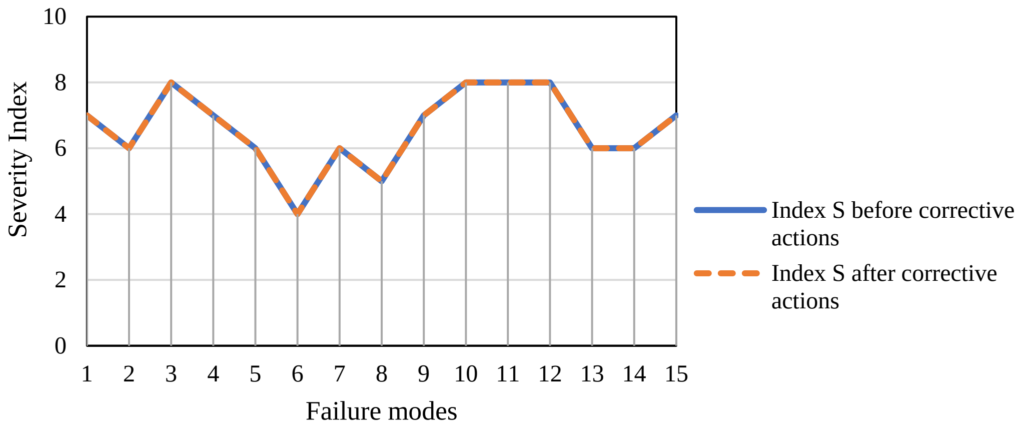

Fig.6-9 The severity index modification with corrective actions.

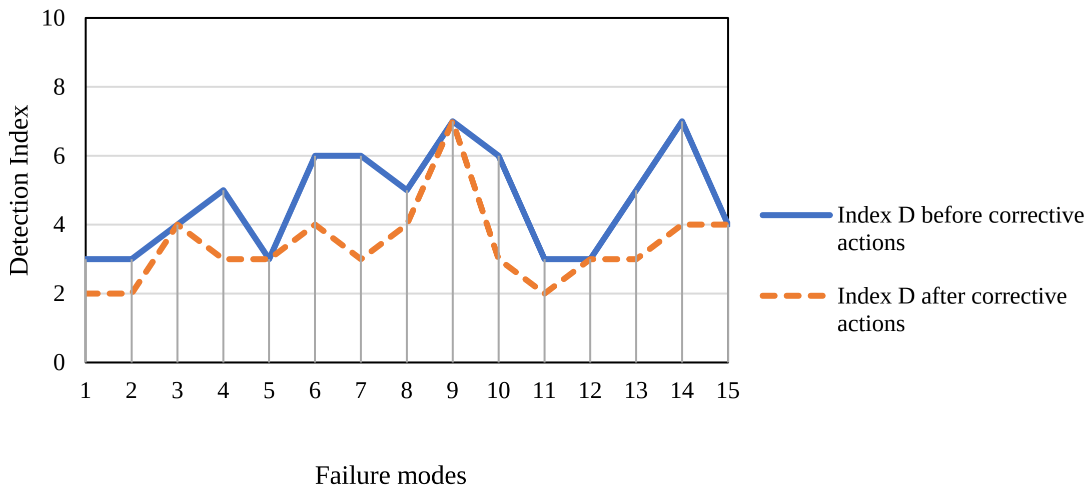

Fig.6-10 The detection index modification with corrective actions.

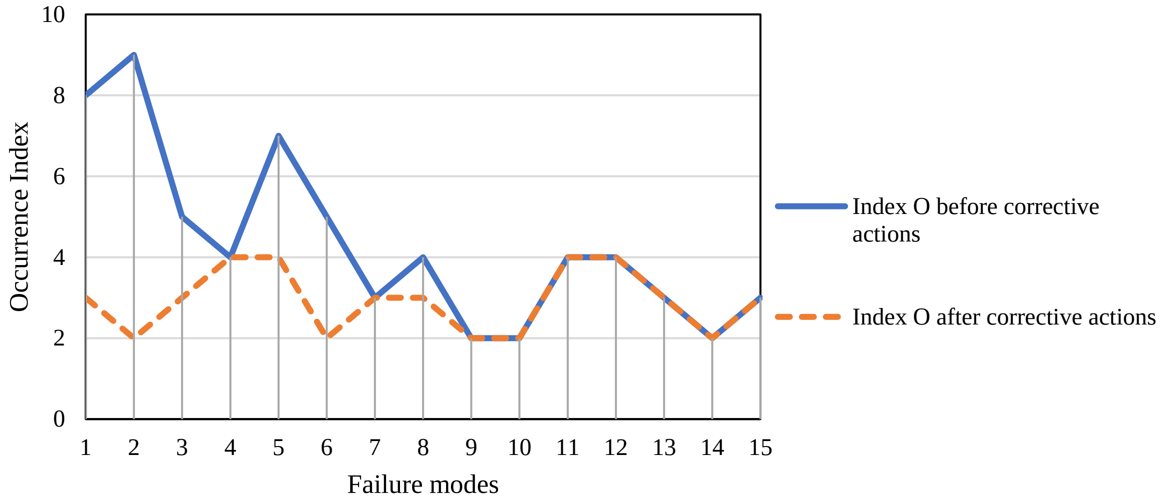

Fig.6-11 The occurrence index modification with corrective actions.

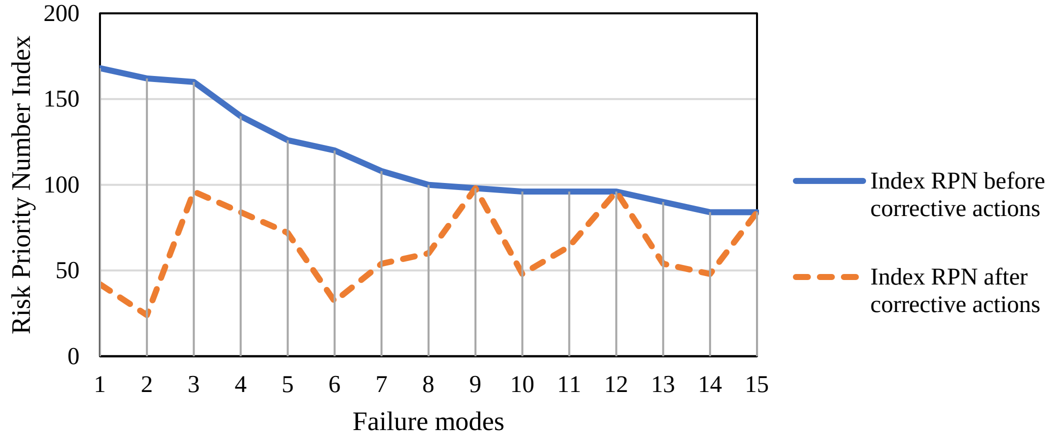

Fig.6-12 The risk priority number index modification with corrective actions.

Because the RPN higher than 90 is the key RPN. Therefore, the severity, detection, occurrence and risk priority number are show in Fig.6-9 to Fig.6-12. Fig.6-9 is the severity index modification with corrective actions. Because all the components were maintained with original type, so the severity index before and after is the same. Fig.6-10 is the detection index modification with corrective actions. As most of the improvement measures increasing the number of inspections. Therefore, the index detection after corrective actions is lower than before. Fig.6-11 is the occurrence index modification with corrective actions. As the number of inspections is increased, the index of occurrence is reduced. Fig.6-12 is the risk priority number index modification with corrective actions. We can see that the optimization RPN is lower than the RPN before optimization. Only 7 RPN before and after is the same.

6.4 Analysis of fuel cell

6.4.1 Base data of fuel cell

In order to analyze the failure rate of the fuel cell of distributed energy system in Kitakyushu Science and Research Park, this study was collected the failures data from the energy center of Kitakyushu Science and Research Park. The details of failures data source were shown in Table 6-10.

Table 6-10 Details of failures data source.

No.	Item	Details
1	Inspection table of gas engine (2001 to 2011)	Data of failures; Preliminary estimate of the failure's reason; Failure position description.
2	Construction completion certificate of gas engine (2001 to 2011)	Data of failure's repair record; Failure reason review; Maintenance description.
3	Gas engine yearly report (2001 to 2011)	Report of inspection, maintenance and repair during one year. Failure's position and repair details.
4	Construction plan statement of gas engine	Operation instruction of gas engine; Maintenance and repairing methods; Failure's reasons description.

Total four kinds of data files used to collect and analyze the failures of fuel cell. it includes Inspection table of gas engine, Construction completion certificate of gas engine, Gas engine yearly report, and Construction plan statement of gas engine. The analysis range is from 2001 to 2011, total ten year's data. Content of inspection table of gas engine includes the data information of failures, preliminary estimate of the failure's reason, and failure position description. Content of construction completion certificate of gas engine includes Data of failure's repair record, failure reason review, maintenance description. Content of Gas engine yearly report includes inspection, maintenance and repair information during one year. Content of Construction plan statement of gas engine includes Operation instruction of gas engine, maintenance and repairing methods, failure's reasons description.

6.4.2 Identifying effects and cause of fuel cell

Fuel cell of distributed energy system is a complex system, it includes the power generation unit, fuel gas supply system, cooling water unit, heat recovery unit, gas system, and Auxiliaries unit. Equipment block diagram is easily used to show how the different parts of the system as shown in Fig.6-13.

Table 6-11 is the details of failure mode and failure cause. A total of 18 failure components. Each failure component has a corresponding failure mode and failure cause. The failure component includes shutoff valve gasket, power conditioning system, filter401 gasket, generator, motorized valve electromagnetic brake, power distribution system, reformer, cooling tower fan800, hot water pump, fuel gas turbine meter, filter100, thermocouple, flame detector, terminal block, battery body, setting tank, filter150, ejector. The failure mode includes leakage, appearance and abnormality, failure, malfunction, do not work. The failure cause includes cracking or swelling, dirty, breakage or deformation, water leak, catalyst life time, pressure loss increase, wiring problem, abnormal sound and vibration, disconnection, high resistance value, sensor failure.

Table 6-12 is the details of failure effects. It includes fuel cell stopped, fuel ventilation chamber defect, low battery voltage, reduced power generation, reformer burner misfire, the ejector behaves abnormally, thermocouple high and vibration is large.

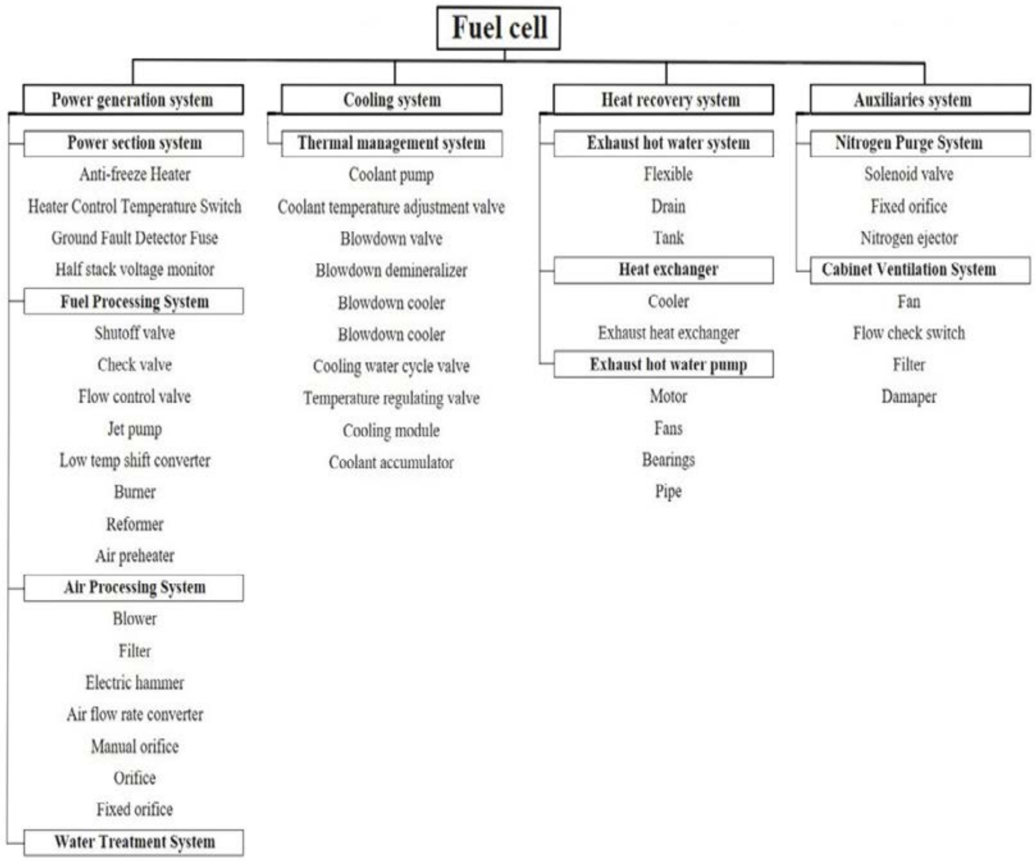

Fig.6-13 Equipment block diagram of fuel cell system.

Table 6-11 Details of failure mode and failure cause.

Number	Component	Failure mode	Failure cause
1	Shutoff valve gasket	leakage	Cracking or swelling
2	Power conditioning system	Appearance and abnormality	There is dirt
3	Filter401 gasket	Fault	Breakage or deformation
4	Motorized valve electromagnetic brake	Appearance and abnormality	There is dirt
5	Power distribution system	Appearance and abnormality	There is dirt
6	Reformer	Malfunction	Catalyst life time, pressure loss increase
7	Cooling tower fan800	Fault	Wiring problem
8	Hot water pump	Bad	Abnormal sound and vibration
9	Fuel gas turbine meter	Appearance and abnormality	There is dirt
10	Filter100	Fault	There is dirt
11	Thermocouple	Fault	Disconnection
12	Flame detector	Appearance and abnormality	There is dirt
13	Terminal block	Malfunction	High resistance value
14	Generator	Malfunction	Water leak
15	Battery body	Malfunction	Catalyst Life / Phosphorus Life
16	Settling tank	Fault	There is dirt
17	Filter150	Fault	There is dirt
18	Ejector	Do not work	Sensor problem

Table 6-12 Details of failure effects.

Number	Component	Failure effect
1	Shutoff valve gasket	Fuel cell stopped
2	Power conditioning system	Fuel cell stopped
3	Filter401 gasket	Fuel cell stopped
4	Motorized valve electromagnetic brake	Fuel cell stopped
5	Power distribution system	Fuel cell stopped
6	Reformer	Fuel cell stopped
7	Cooling tower fan800	Thermocouple high
8	Hot water pump	Vibration is large
9	Fuel gas turbine meter	Fuel cell stopped
10	Filter100	Thermocouple high
11	Thermocouple	Thermocouple high
12	Flame detector	Reformer burner misfire
13	Terminal block	Fuel ventilation chamber defect
14	Generator	Reduced power generation
15	Battery body	Low battery voltage
16	Settling tank	Decrease effect
17	Filter150	Thermocouple high
18	Ejector	The ejector behaves abnormally

Table 6-13 Results of FMEA of fuel cell.

Number	**Component**	**Current maintenance strategy**	**S**	**O**	**D**	**RPN**	**New proposed maintenance strategy**	**S**	**O**	**D**	**New RPN**
1	Shutoff valve gasket	Exchange	8	4	6	192	Exchange regularly	8	4	3	96
2	Power conditioning system	Exchange	8	5	4	160	Exchange regularly	8	3	3	72
3	Filter401 gasket	Exchange	7	3	6	126	Exchange regularly	7	3	4	84
4	Motorized valve electromagnetic brake	Brake exchange	8	4	3	96	Exchange regularly	8	3	3	72
5	Power distribution system	Exchange	6	3	5	90	Exchange regularly	6	3	4	72
6	Reformer	Exchange	6	3	5	90	Exchange regularly	6	3	4	72
7	Cooling tower fan800	Exchange	7	3	4	84	Exchange regularly	7	3	3	63

8	Hot water pump	Consult with us	7	3	4	84	Material change	5	3	4	60
9	Fuel gas turbine meter	Exchange	6	2	7	84	Exchange regularly	6	2	5	60
10	Filter100	Exchange	5	4	4	80	Exchange regularly	5	4	4	80
11	Thermocouple	Exchange	4	4	5	80	Exchange regularly	4	4	5	80
12	Flame detector	to clean	3	5	5	75	Regular cleaning	3	5	5	75
13	Terminal block	Exchange of FS 165	3	5	5	75	Exchange regularly	3	4	5	60
14	Generator	Leakage removal	5	3	5	75	Increase the number of examinations	5	3	5	75
15	Battery body	Cell change	8	3	3	72	Exchange regularly	8	3	3	72
16	Settling tank	to clean	6	2	6	72	Regular cleaning	6	2	5	60
17	Filter150	Exchange	3	4	5	60	Exchange regularly	3	4	5	60
18	Ejector	Exchange	3	5	3	45	Exchange regularly	3	4	3	36

6.4.3 Results

Table 6-13 is the results of FMEA of gas engine. We achieve optimized results by improving maintenance. The highest RPN is shutoff valve gasket, and its severity is 8, occurrence is 4, detection is 6, the RPN is 192. Shutoff valve gasket failure result in high degree of operator dissatisfaction and cause non-functionality of system. The current maintenance strategy is exchange component, and new proposed maintenance strategy is exchange regularly. The new severity is 8, new occurrence is 4, new detection is 3, new RPN is 96. Therefore, the lubricating oil filter is optimized. The lowest RPN is ejector. Severity of ejector is 3, occurrence is 5, detection is 3, the RPN is 45. Ejector failure result in slight deterioration of part or system performance. The current maintenance strategy is replacing component, and the new proposed maintenance strategy is exchange regularly. The new severity is 3, occurrence is 4, new detection is 3, new RPN is 36. Therefore, the cylinder liner is optimized.

According to previous literature description we set RPN higher than 90 as the key failure, it includes shutoff valve gasket, power conditioning system, filter401 gasket, motorized valve electromagnetic brake, power distribution system, reformer and cooling tower fan800. Their impact on the equipment is failure will result in operator dissatisfaction and/or deterioration of part or system performance, failure will result in high degree of operator dissatisfaction and cause non-functionality of system.

Fig.6-14 is the severity index modification with corrective actions. For one component was upgraded with a new type, so the index severity after corrective actions is a little bit different from index severity before corrective actions. Fig.6-15 is the detection index modification with corrective actions. As most of the improvement measures increasing the number of inspections. Therefore, the index detection after corrective actions is lower than before. Fig.6-16 is the occurrence index modification with corrective actions. As the number of inspections is increased, the index of occurrence is reduced. Fig.6-17 is the risk priority number index modification with corrective actions. We can see that the optimization RPN is lower than the RPN before optimization. Only 6 RPN before and after is the same.

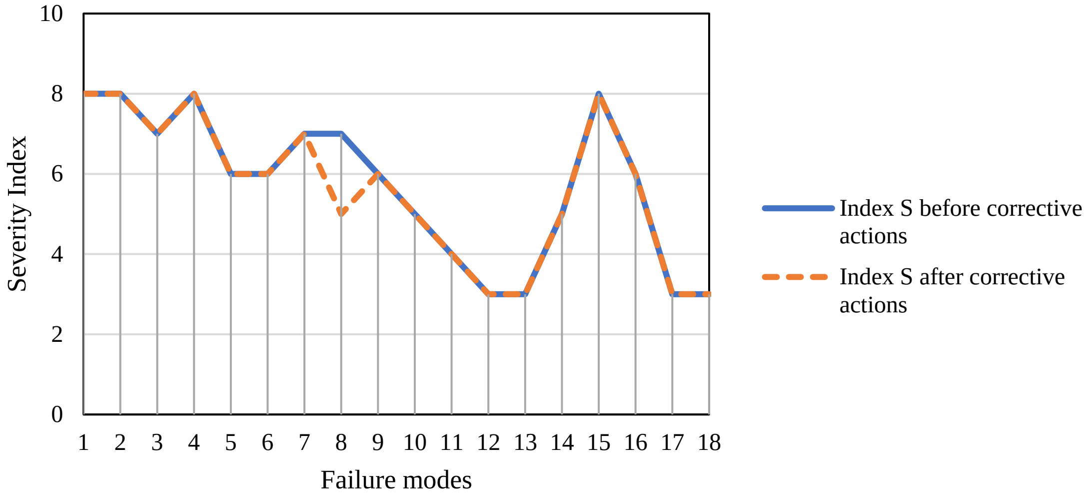

Fig.6-14 The severity index modification with corrective actions.

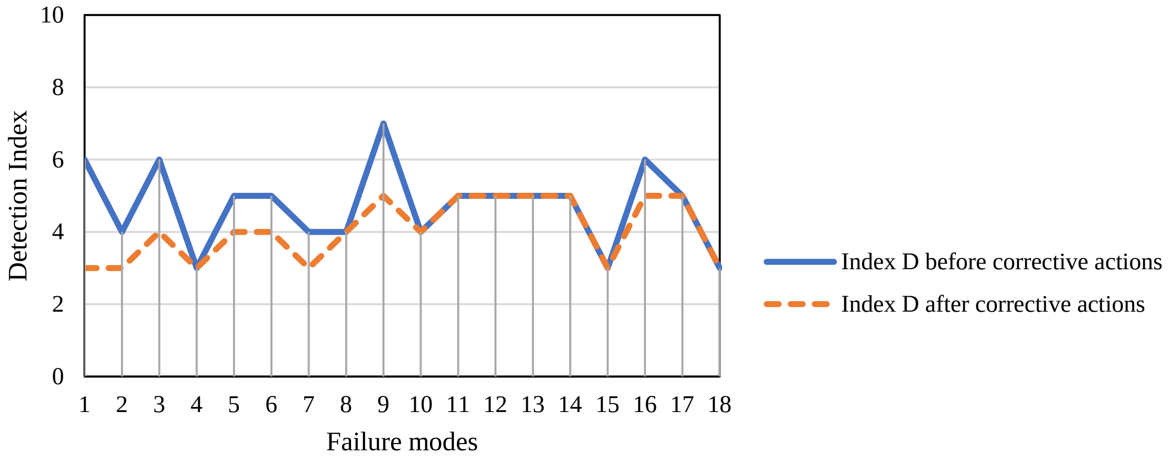

Fig.6-15 The detection index modification with corrective actions.

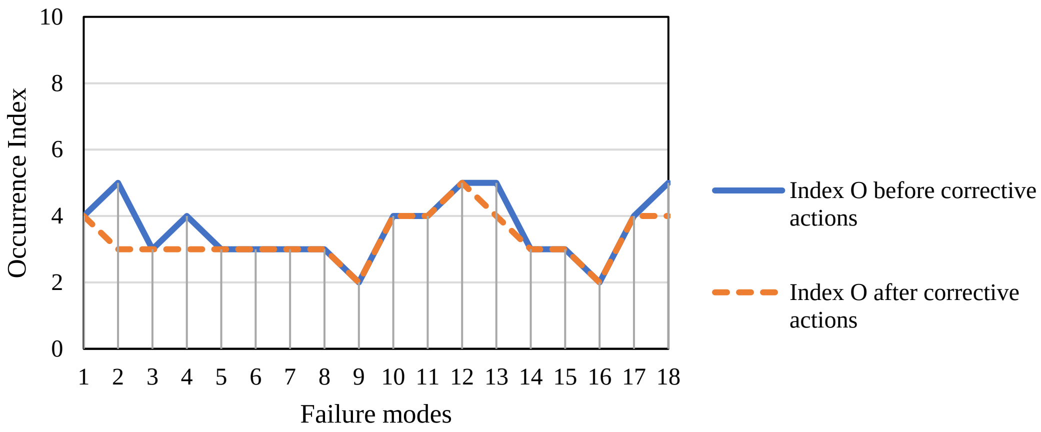

Fig.6-16 The occurrence index modification with corrective actions.

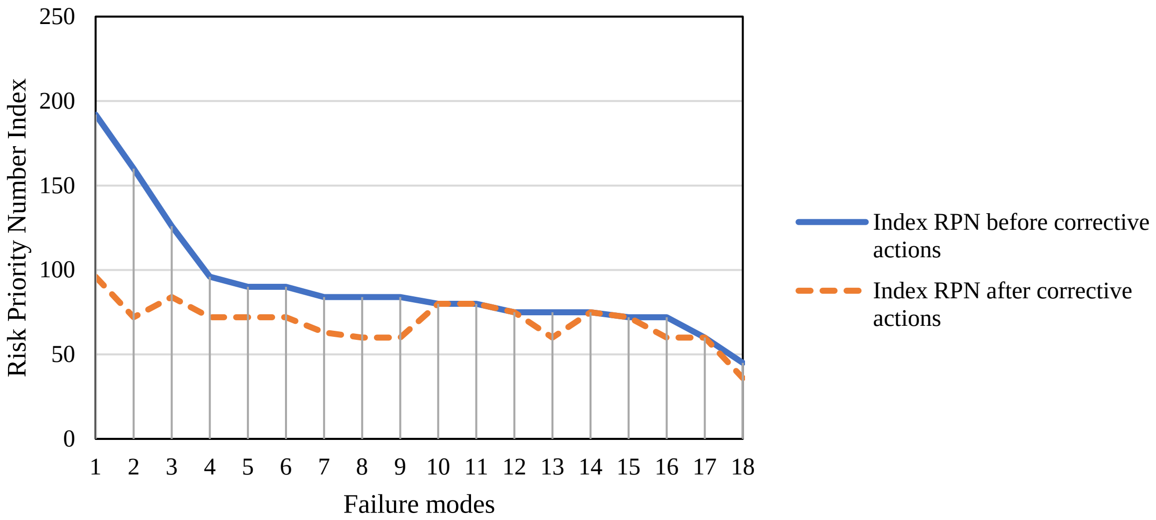

Fig.6-17 The risk priority number index modification with corrective actions.

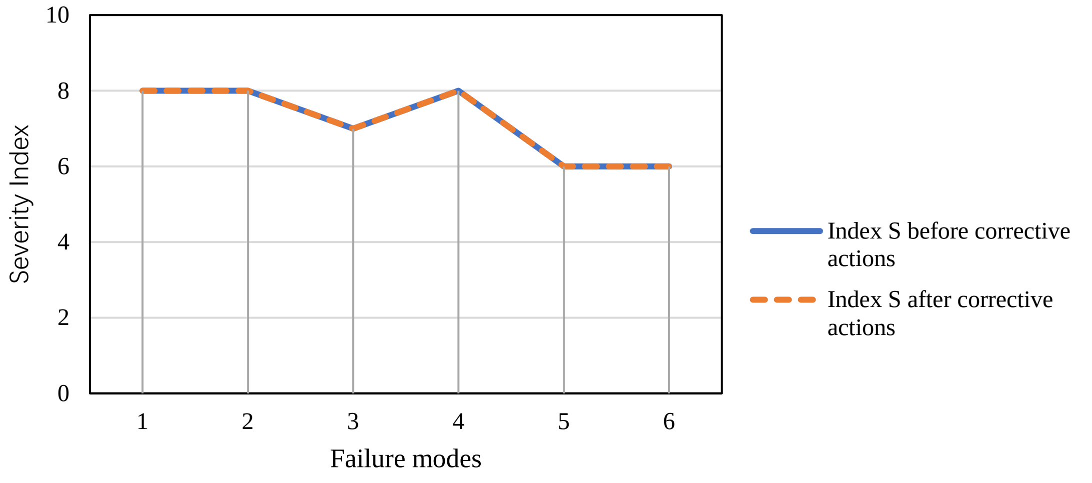

Fig.6-18 The severity index modification with corrective actions of RPN higher than 90.

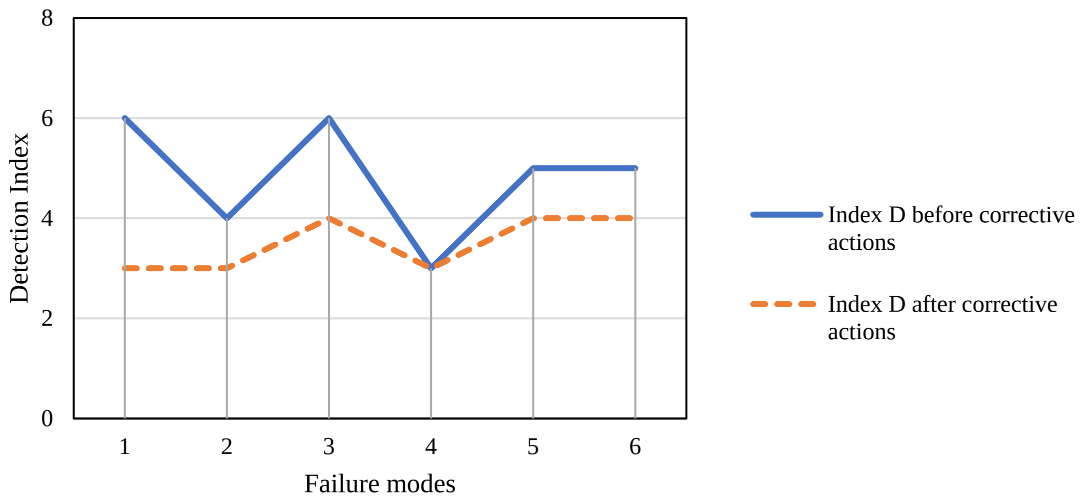

Fig.6-19 The detection index modification with corrective actions of RPN higher than 90.

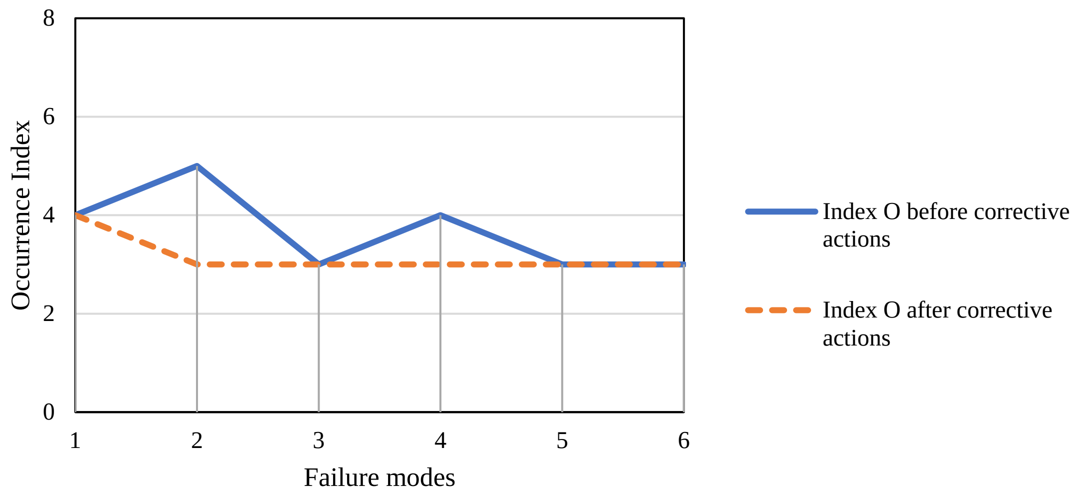

Fig.6-20 The occurrence index modification with corrective actions of RPN higher than 90.

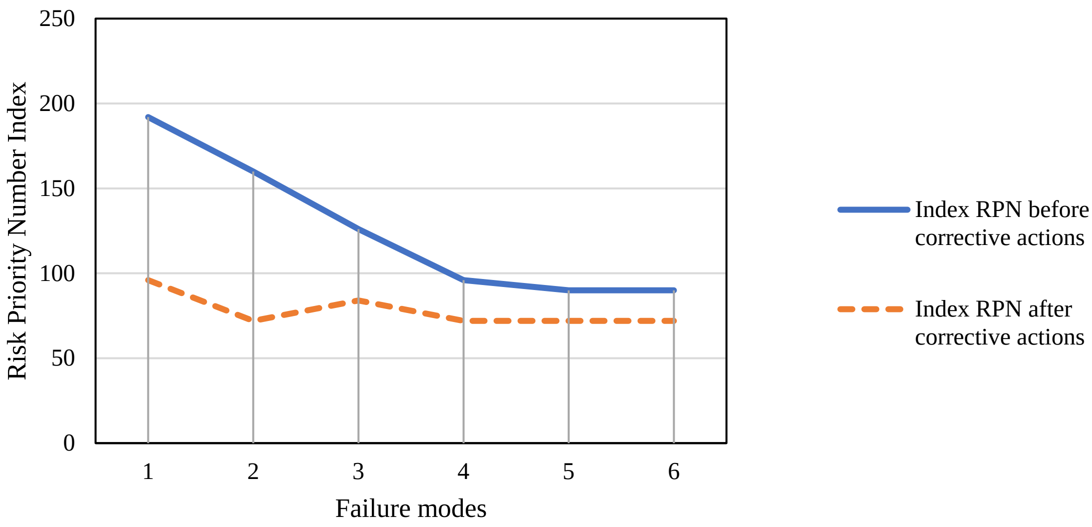

Fig.6-21 The risk priority number index modification with corrective actions of RPN higher than 90.

Fig.6-18 is the severity index modification with corrective actions. For one component was upgraded with a new type, so the index severity after corrective actions is a little bit different from index severity before corrective actions. Fig.6-19 is the detection index modification with corrective actions. As most of the improvement measures increasing the number of inspections. Therefore, the index detection after corrective actions is lower than before. Fig.6-20 is the occurrence index modification with corrective actions. As the number of inspections is increased, the index of occurrence is reduced. Fig.6-21 is the risk priority number index modification with corrective actions. We can see that the optimization RPN is lower than the RPN before optimization.

6.5 Summary

In this chapter, the failure mode and effects analysis of the distributed energy system in Kitakyushu Science and Research Park had been investigated. The data is from Manual of distributed energy system, Construction completion certificate of distributed energy system, Construction plan statement of distributed energy system and the distributed energy system inspection and maintenance work report during.

The failure mode and effects analysis told that the failure modes, failure cause and failure effects of the gas engine according to data. The failure effects mainly includes abrupt stop, output reduction, rotation does not rise; although the engine rotates according to the start command, the rotation does not rise; although the engine rotates according to the start command, the rotation does not rise, the engine starts but stops immediately; engine does not rotate by start command; the actuator of the governor does not operate at all; the engine starts but stops right away; the engine suddenly stops; the lubricating oil pressure becomes less than the specified value.

The failure mode and effects analysis told that the failure modes, failure cause and failure effects of the fuel cell according to data. The failure effects mainly include fuel cell stopped, fuel ventilation chamber defect, low battery voltage, reduced power generation, reformer burner misfire, the ejector behaves abnormally, thermocouple high and vibration is large.

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Chapter 7

COMPREHENSIVE PERFORMANCE ASSESSMENT AND OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM

CHAPTER SEVEN: COMPREHENSIVE PERFORMANCE ASSESSMENT AND OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM

7.1 Introduction

The distributed energy resource (DER) system is relative to the traditional centralized energy supply system. The traditional centralized energy supply system uses large capacity equipment, centralized production, and then transmits various kinds of energy to a large range of users through special transmission facilities (large power grid, large heat network, etc.); while the distributed energy system is directly oriented to users and produces on site according to the needs of users. It is a medium and small energy conversion and utilization system with multiple functions to meet multiple objectives. Owing to the continuous growth in the world's energy demand, the problems of energy consumption, greenhouse gas emission, and environmental pollution have become increasingly prominent [1]. Combined cooling, heating, and power (CCHP) system has been recognized as an efficient and economic method to realize the integration of power generation, cooling, and heating through the cascade utilization of energy; notably, the comprehensive energy utilization efficiency of the system can reach 85 % [2]. There are various types of equipment in CCHP systems, and there is a coupling relationship between the equipment [3]. The equipment installed capacity and operation strategy have a significant impact on the economic and environmental benefits and energy efficiency of the systems. The configuration of equipment is crucial in such cases. Unreasonable configuration of equipment types and excessive capacity can lead to the waste of investment and low utilization efficiency of systems, whereas undersized capacity cannot meet the demand of the building in the area load demand, which may lead to an increase (rather than decrease) in energy consumption. At present, the economic benefits of CCHP systems are greatly reduced due to the mismatch of installed capacity [4]. Therefore, to improve the performance of CCHP systems, the capacity and operation optimization of CCHP systems has become an important research direction.

Numerous studies have been conducted on the optimization of CCHP systems. Wang et al. [5] optimized the capacity of power generation unit (PGU) selected in the design period and the fixed ratio of electric cooling to cool demand used in operation period. Ren et al. [6] optimized the configuration and technology combination alternatives by minimizing the total energy cost. Furthermore, Ren et al. [7] optimized the hybrid CCHP systems for three buildings (hotel, office, and market) under different operation strategies. Kim et al. [8] selected the capacity of PGUs, value of thermal storage system, cooling/heating capacity ratio supplied by electrically driven systems, and maximum heat power from the storage system as the decision variables to optimized the CCHP system.

Notably, different optimization algorithms were applied to CCHP systems. Wang et al. [9] employed particle swarm optimization algorithm (PSOA) to optimize the capacity of PGUs and heat storage tank, on-off coefficient of PGU, and ratio of electric cooling to cooling load. Sanaye et al. [10] optimized the capacity of gas engine, backup boiler, energy storage tank, electrical and absorption chiller by combining an optimization algorithm with the maximum rectangle method. Kong et al. [11] adopted a non-linear-programming (NLP) cost-minimization optimization model to determine the operation strategies for the CCHP system. Bischi et al. [12] employed mixed integer nonlinear programming (MINLP) to determine an operating schedule. Cao et al. [13], [14] used owl search algorithm (OSA) to increase the efficiency of the CCHP system, in comparison with the separation production system. Ghersi et al. [14] adopted genetic algorithm (GA) to optimize the capacity of the CCHP system.

Conventional optimization is based on economy, and the most important parameter affecting economy is electricity price. Different electricity price mechanisms have different effects on the investment cost, operating cost, and energy saving of the CCHP system. Generally, to simplify calculations, most researchers used a fixed electricity price mechanism [15], [16]. Some researchers used time-of-use (TOU) electricity price to improve CCHP system utilization efficiency and reduce investment and operating costs [17]. However, only a few studies have been conducted on the STOU electricity price mechanism. Seasonal price refers to an electricity price mechanism that reflects the cost of power supply in different seasons. The main purpose is to suppress the excessively rapid growth of electricity load during peak seasons to reduce investment and operating costs. However, only a few studies have been conducted on the combination of peak-valley and seasonal electricity price mechanisms.

Sensitivity analysis determines the change of decision evaluation criteria by changing one or more uncertainties. Yan et al. [18] and Zheng et al. [19] analyzed the sensitivity of electricity price and natural gas price and explained the changes in important criteria at different prices. Zhang et al. [20] analyzed the performance of the CCHP system and deduced that it can be improved by changing the electricity price, natural gas price, investment subsidy, and carbon tax. Delgado et al. [21] analyzed the sensitivity of interest rate, heat export, and energy price escalation rates to address the behavior of the results due to changes in the economic context.

In addition to economic performance, the influencing factors of CCHP systems are also very important for energy saving and emission reduction [22]. Therefore, it is essential to evaluate the comprehensive performance assessment of CCHP systems. Tamjidi et al. [23] assessed the payback period and profitably index of a novel integrated CCHP system from energy and economic perspectives. Li et al. [24] presented a CCHP and ground source heat pump (GSHP) coupling system equipped with a heat exchanger and used life cycle cost saving rate and primary energy consumption saving ratio compared with separated generation system. Additionally, Wang et al. [25] used a comprehensive evaluation index to optimize the PGU capacity and the ratio of electric cooling to the cooling load.

The purpose of this study is to consider the comprehensive performance assessment of energy conservation and environmental protection and discuss the impact of different electricity price mechanisms on the development of CCHP system. In this study, the GA method was used to optimize the capacity of PGU and operation strategies for CCHP systems. Then, the economy, energy saving, and CO2 emission reduction of the CCHP system were analyzed. Finally, we conducted the sensitivity analysis of energy price and CO_2 emission reduction.

Table 7-1 The nomenclature in Chapter 7

Nomenclature	
AIC	annual investment cost ($/year)
AMC	annual maintenance cost ($/year)
AOC	annual operating cost ($/kWh)
ATC	annual total cost ($/year)
C	cost ($)
CCHP	combined cooling heating and power
CDE	carbon dioxide emission
CDER	carbon dioxide emission reduction
COP	coefficient of performance
CO_2	carbon dioxide
CPI	comprehensive performance index
CSR	cost-saving ratio
E	electricity demand (kWh)
F	fuel consumption (m^3)
FTL	following the thermal load
GA	genetic algorithm
I	investment cost ($)
KSRP	Kitakyushu Science and Research Park
M	maintenance cost ($)
N	capacity of the equipment (kWh)
PEC	primary energy consumption
PESR	primary energy consumption ratio
PGU	power generation unit
Q	heat (kWh)
SP	separated production
STOU	seasonal time-of-use
TOU	time-of-use
Greek letter	
η	efficiency
μ	CO_2 emission conversion factor
ω	weight vector
Subscript	
ab	auxiliary boiler
ac	absorption chiller
b	boiler
c	cooling
e	electricity
ec	electric chiller
f	fuel
$grid$	electricity grid

h	heating
he	heat exchanger
m	equipment number
pgu	power generation unit
r	recovery heat
rh	recovery heat supplied to heat exchanger
t	hours
$total$	total amount of fuel
tr	transmission of power grid

7.2 Methodology

7.2.1 Energy flow of CCHP and SP systems

Firstly, the model of CCHP systems and SP systems were established and the decision variables were proposed. Then a single objective comprehensive evaluation system was established for assessing cost saving, energy saving, and CO2 emission reduction. Finally, the GA was used to optimize the CCHP and SP systems.

The energy flow of CCHP systems and SP systems was introduced, which was then, used to calculate the power generation, energy consumption, and capacity of a power generation unit (PGU) and auxiliary equipment to obtain the optimal result of these systems.

The CCHP system used in our study was driven by PGU, as shown in Fig. 7-1. Natural gas was supplied to PGU to produce electricity. Considering the optimal economy for users, the power generated by PGU is supplied directly to users. If generated power cannot meet the electricity demand, the shortage of power can be purchased from the power grid. The exhaust heat from PGU was recovered by the heat recovery unit, and then the steam generated by the heat recovery unit is used as a heat source to heat the heat exchanger to meet the heat demand of users. When the recovered heat could not meet the heating demand, sufficient heat was provided by the auxiliary boiler. The cooling demand was provided by a heat recovery unit through an absorption chiller, and the insufficient cooling was supplied by the electric chiller.

As shown in Fig. 7-2, the electricity demand of SP systems was supplied by the power grid, cooling demand was supplied by the electric chiller, and the heating demand was supplied by a gas boiler.

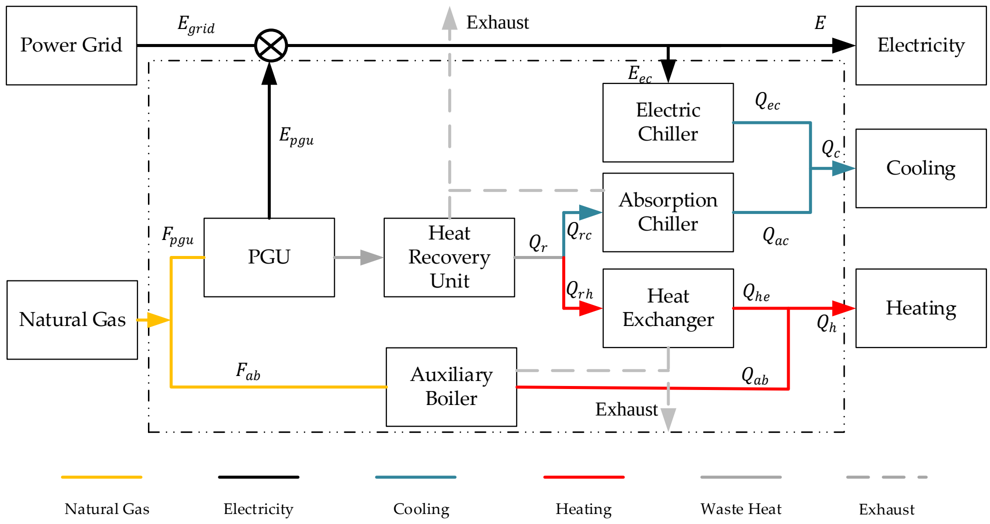
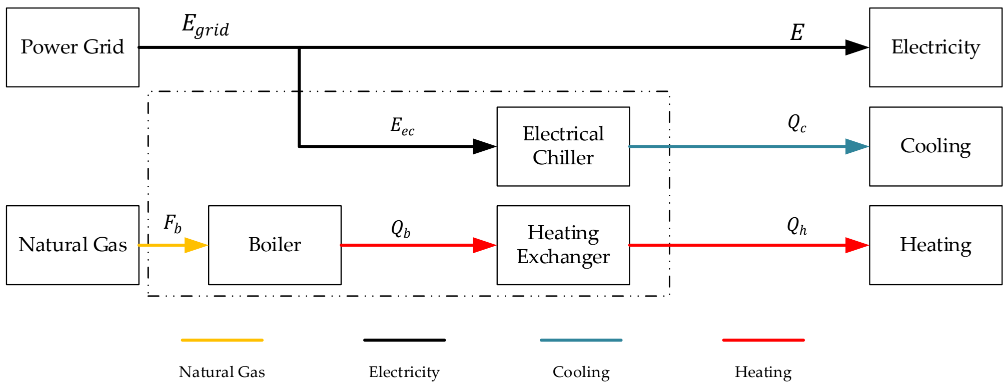


Fig. 7-1 Schematic of the CCHP system.



SP system

Fig. 7-2 Schematic of the SP system.

The balance of the electricity demand of CCHP systems is expressed as follows:

$$E_{grid} + E_{pgu} = E + E_{ec} \tag{7-1}$$

where E_{grid} is the electricity purchased from the power grid (kWh), (due to it is not easy to dispose of excess electricity in remote regions or in regions where the excess electricity is not allowed to be sold to the power grid; therefore, we do not consider selling the excess electricity to the power grid.); E_{pgu} is the electricity generated by the PGU (kWh); E is the electricity demand of the building (equipment, lights, etc.) (kWh), and E_{ec} is the electricity consumed by the electric chiller.

The fuel energy consumption of the PGU, F_{pgu}, (kWh), was estimated using the following equation:

$$F_{pgu} = \frac{E_{pgu}}{\eta_{pgu}} \tag{7-2}$$

where E_{pgu} is the electricity generated by the PGU (kWh); η_{pgu} is the power generation efficiency of PGU.

The waste heat generation of PGU, Q_r, (kWh), was estimated using the following equation:

$$Q_r = F_{pgu} \times (1 - \eta_{pgu}) \times \eta_r \tag{7-3}$$

where F_{pgu} is the fuel energy consumption of the PGU (kWh); η_{pgu} is the power generation efficiency of PGU; η_r is the efficiency of the heat recovery unit.

The waste heat from the PGU was used to cover the cooling and heating demand and can be expressed as follows:

$$Q_{ac} = Q_r \times COP_{ac} \tag{7-4}$$

$$Q_{he} = Q_r \times \eta_{he} \tag{7-5}$$

where Q_{ac} and Q_{he} are the cooling load produced by the absorption chiller and the heating load produced by the heat exchanger, respectively (kWh); COP_{ac} is the coefficient of performance (COP) of the absorption chiller; Q_r is the waste heat generation of PGU (kWh), and η_{he} is the efficiency of the heat exchanger.

$$Q_{ac} + Q_{ec} = Q_c \tag{7-6}$$

$$Q_{rh} + Q_{ab} = Q_h \tag{7-7}$$

where Q_{ac} is the cooling load produced by the absorption chiller (kWh); Q_{ec} is the cooling load produced by the electric chiller (kWh). Q_c and Q_h are the cooling and heating demands of the building, respectively (kWh); Q_{rh} is the heat supplied to the heat exchanger (kWh), and Q_{ab} is the supplementary heat from the auxiliary boiler (kWh).

The cooling demand generated by the electric chiller, Q_{ec}, and electricity consumption of the electric chiller, E_{ec}, can be expressed as:

$$Q_{ec} = x \cdot Q_c \tag{7-8}$$

$$E_{ec} = \frac{Q_{ec}}{COP_{ec}} \tag{7-9}$$

Where Q_{ec} is the cooling load produced by the electric chiller (kWh); x is the ratio of cooling load provided by electricity to the total cooling load of the building; Q_c is the cooling demand of the building (kWh), and COP_{ec} is the COP of the electric chiller.

The fuel energy consumption of the auxiliary boiler, F_{ab}, (kWh) was calculated using the following equation:

$$F_{ab} = \frac{Q_{ab}}{\eta_{ab}} \tag{7-10}$$

where Q_{ab} is the supplementary heat from the auxiliary boiler (kWh), and η_{ab} is the efficiency of the auxiliary boiler.

The total fuel energy consumption of the CCHP systems, F^{CCHP}, (kWh) was calculated using the following equation:

$$F^{CCHP} = F_{pgu} + F_{ab} \tag{7-11}$$

The total electricity purchased from the grid of SP systems, E^{SP}, (kWh) was calculated using the following equation:

$$E_{ec} = \frac{Q_c}{COP_{ec}} \tag{7-12}$$

$$E^{SP} = E + E_{ec} \tag{7-13}$$

The total fuel energy consumption of the SP systems, F^{SP}, (kWh) was calculated using the following equation:

$$F^{SP} = \frac{Q_h}{\eta_{he} \times \eta_b} \tag{7-14}$$

where η_b is the efficiency of the boiler.

7.2.2 Decision variables

1) Power generation unit (PGU) capacity

PGU capacity has a significant effect on the economic, energy-saving, and environmental performance of CCHP systems. When the capacity of the PGU is established, the capacity of heat recovery unit is determined using the maximum recovery heat of PGU. The absorption chiller uses the recovery heat of PGU to meet cooling demands, and therefore, the capacity of the system changes according to PGU. The capacity of other equipment was calculated using the cooling and heating loads.

2) Ratio of cooling load provided by electricity to total cooling load

The total cooling load of the building was provided by the absorption chiller and the electric chiller. When the recovery heat generated by the PGU was sufficient to meet the cooling demand, the electric chiller stopped operating. Otherwise, the electric chiller needed to be operated to supplement the insufficient cooling demand. Considering the change of cooling demand at each moment, the optimized ratio of cooling load provided by the electricity to total cooling load ratio was not a fixed value, owing to the innumerable changes in the cooling demand. Therefore, it was necessary to optimize the ratio of cooling load provided by the electricity to total cooling load ratio.

7.2.3 Evaluation index

1) Annual total cost reduction

The annual investment cost (AIC) is the total investment cost of all equipment of CCHP systems, \$/year, and can be expressed as:

$$AIC = R \times \sum_{m=1}^{m} (N_m \times I_m) \tag{7-15}$$

$$R = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{7-16}$$

$$R = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{7-16}$$

where N_m is the capacity of the mth equipment (kW); I_m is the investment cost of the mth equipment per unit capacity ($/kW/year); R is the coefficient of investment recovery; i is the annual interest rate; n is the number of years of service life of the equipment.

The annual maintenance cost (AMC) was calculated using the following equation:

$$AMC = \sum_{m=1}^{m} (N_m \times M_m) \tag{7-17}$$

where M_m is the maintenance cost of the mth equipment per unit capacity ($/kW/year).

The annual operating cost (AOC) is the total cost of the gas consumption and electricity purchase in a year, $, and was calculated using the following equation (due to the labour cost accounts for a small proportion of the total operating cost, it can be neglected):

$$AOC = \sum_{t=1}^{8760} (E_{grid} \times C_e + F \times C_f) \tag{7-18}$$

where F is the total natural gas consumption (kWh); and C_e and C_f are the energy price of electricity and natural gas, respectively, $/kWh.

The annual total cost (ATC) is the sum of the above three costs and can be calculated using the following equation:

$$ATC = AIC + AMC + AOC \tag{7-19}$$

The cost-saving ratio (CSR) is the annual total cost-saving ratio of the CCHP systems compared with SP systems:

$$CSR = (1 - \frac{ATC^{CCHP}}{ATC^{SP}}) \times 100 \tag{7-20}$$

2) Primary energy consumption

Primary energy consumption (PEC) refers to the consumption of total fuels to meet the demand for electricity and thermal demands (kWh) and can be calculated using the following equation:

$$PEC = F_{total} + \frac{E_{grid}}{\eta_{grid} \times \eta_{tr}} \tag{7-21}$$

where F_{total} is the total amount of fuel applied to meet the electrical and thermal demands (kWh); η_{grid} is the power generation efficiency of power plants, and η_{tr} is the transmission efficiency of power grid.

Primary energy saving ratio (PESR) was defined to assess the energy consumption of CCHP systems in comparison with SP systems, using the following equation:

$$PESR = (1 - \frac{PEC^{CCHP}}{PEC^{SP}}) \times 100 \tag{7-22}$$

3) Carbon dioxide emission reduction

The impact of CCHP systems on the environment mainly comes from carbon dioxide emission (CDE); it can be determined using the emission conversion factors as follows:

$$CDE = E_{grid} \times \mu_e + F \times \mu_f \tag{7-23}$$

where μ_e is the CO2 emission conversion factor of electricity from the grid (kg CO2/kWh); μ_f is the CO2 emission conversion factor of natural gas from the grid (kg CO2/m3).

Furthermore, the carbon dioxide emission reduction (CDER) was calculated using the following equation:

$$CDER = (1 - \frac{CDE^{CCHP}}{CDE^{SP}}) \times 100 \tag{7-24}$$

4) Payback period

The static investment payback period refers to the time required to recover the entire investment amount without considering the value of time. The static payback period (PB) of the system was calculated using the following equation:

$$PB = \frac{AIC_{CCHP} + AMC_{CCHP} + AOC_{CCHP}}{AOC_{SP} - AOC_{CCHP}} \tag{7-25}$$

where AIC_{CCHP}, AMC_{CCHP}, AOC_{CCHP} are the investment, maintenance, and operating costs of CCHP systems, respectively, and AOC_{SP} is the operating cost of the SP systems.

5) Objective function

The weight coefficient method was used to weight sum each evaluation index for obtaining the final optimization results in this study. The comprehensive performance index (CPI) was considered as the objective function of the model and the maximum value; it was defined using the following equation:

$$\begin{cases} Max\ CPI = \omega_1 CSR + \omega_2 PESR + \omega_3 CDER \\ \omega_1 + \omega_2 + \omega_3 = 1 \\ 0 \leq \omega_1, \omega_2, \omega_3 \leq 1 \end{cases} \tag{7-26}$$

where $\omega 1$, $\omega 2$, and $\omega 3$ is the weight coefficient of three indexes (CSR, PESR, and CDER, respectively). Notably, the optimal performance of CCHP systems is hardly achieved using the varying results of optimal cost saving, energy saving, and CO2 emission reduction due to the different weight distribution. Wang et al. [25] analyzed ten different cases of weight distribution and proposed that a better optimal result can be obtained when the weights are equaled. Therefore, ω_1, ω_2, ω_3 were selected as 1/3.

7.2.4 Optimization

GA was designed and proposed according to the evolution law of organisms in nature. It is a method to search for the optimal solution by simulating the natural evolution process. GA can be used for global optimization because it can extend the search space to the whole problem [26].

Notably, the optimization procedure of the CCHP systems is shown in Fig. 7-3. It can be summarized as follows:

1. The initial population was created randomly.

2. Each individual of the population was coded into a binary number.

3. Due to the objective value being greater than 0, the opposite number of objective values was used as the input of fitness function. Then, the fitness of each individual was evaluated. If the objective function was optimal, the optimal individual was output. Otherwise, we proceeded on to the next step.

4. The individuals with high fitness values were selected, because the higher the fitness value, the more likely an individual is to be chosen for crossover.

5. Then, new individuals were created through reproduction, crossover, and mutation.

6. A new population with new individuals was created. When the max comprehensive performance index (CPI) was satisfied, the optimization was concluded. If not, the optimization process was restarted from Step 3.

In this study, the GA method was implemented using MATLAB software. The GA function of MATLAB was used to solve the objective function. It should be pointed out that a negative sign must be added to revise the default minimum value of the result in MATLAB to the maximum value, because a maximum value is required as the result of the simulation.

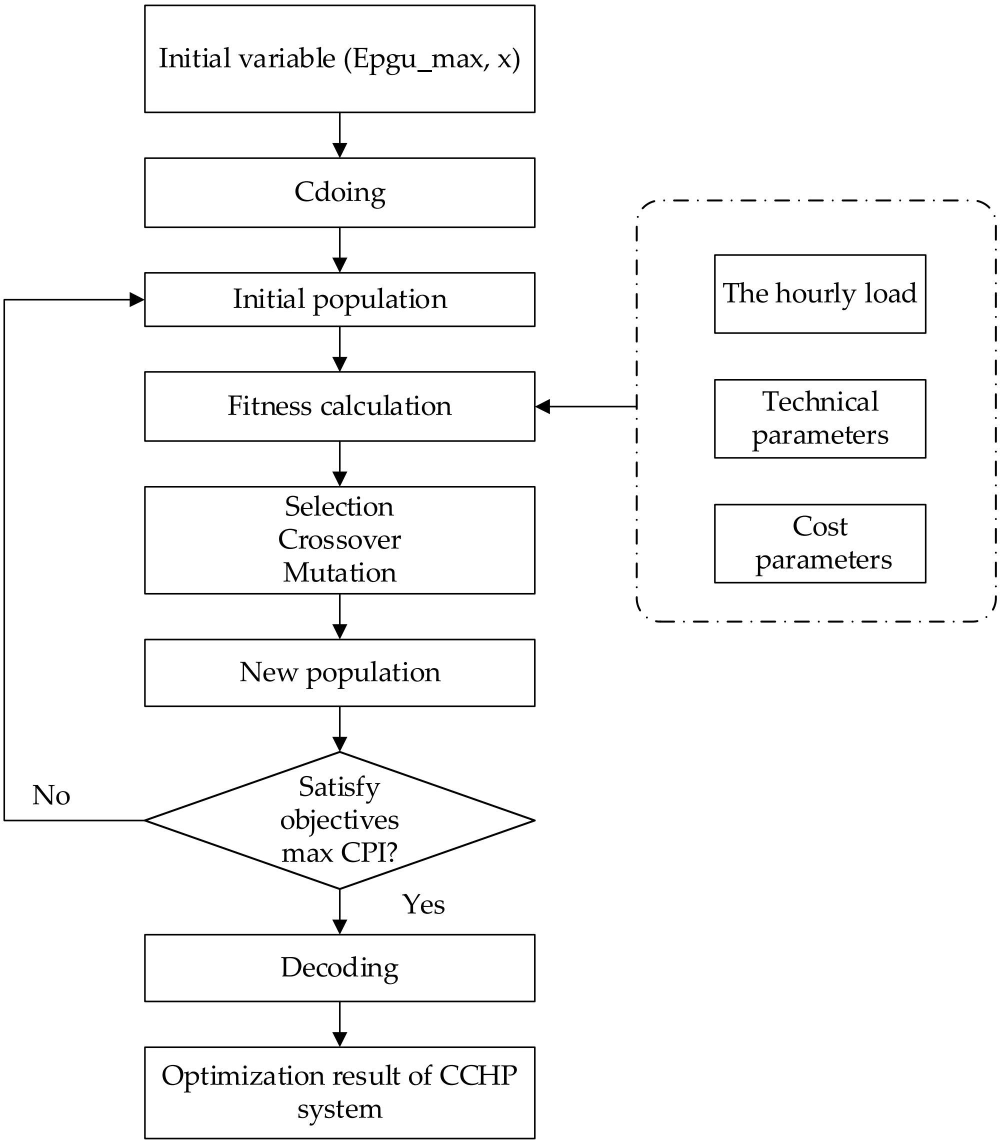


Fig. 7-3 Optimization procedure of the CCHP system.

7.2.5 Introduction of case studies

In this study, we compared different cases for energy saving analysis. The power generation efficiency of the gas engine and the coefficient of performance (COP) of the electric chiller affected the energy saving of the CCHP system. Three cases were considered for comparison with the basic case, and the measurements are shown in Table 7-2. In Case 1, the power generation efficiency and thermal efficiency of the gas engine remained unchanged, and the COP of the electric chiller increased to 4. In Case 2, the COP of the electric chiller remained unchanged, and the power generation efficiency of the gas engine is increased to 0.45; to ensure that the comprehensive energy utilization rate remained unchanged, the thermal efficiency of the gas engine was reduced to 0.327. In Case 3, the power generation efficiency of the gas engine increased to 0.45, thermal efficiency reduced to 0.327, and the COP of the electric chiller increased to 4.

Table 7-2. Comparison of different cases and basic case.

Parameters	Basic case	Case 1	Case 2	Case 3
COP of electric chiller	3	4	3	4
Gas engine power generation efficiency	0.3	0.3	0.45	0.45
Gas engine heat efficiency	0.477	0.477	0.327	0.327

7.3 Case study

7.3.1 Introduction of case and energy demands

In this study, we chose the eco-campus of the Kitakyushu Science and Research Park (KSRP) in Japan as an example [27]. KSRP is located in Kitakyushu, a world-renowned environmental symbiosis city, and is a scientific research core for environmentally friendly construction in Kitakyushu. The total area of KSRP is approximately 335 hectares. The eco-campus has been using CCHP system since 2001 to provide electricity, cooling, and heating demand for the energy center, collaboration center, conference center, library, gym, teaching building and experiment building, technology development and exchange center. The buildings in the area are prefabricated buildings of 4-floor and below, and the fence structure has reached the standard of high-level energy-saving buildings. The area has received the A-class certification from CASBEE-block/region of Japan. The CCHP system can satisfy the larger electricity, cooling, and heating demand of the eco-campus, and effectively reduce the energy cost. The hourly electricity, cooling, and heating demands were obtained through the energy center of the KSRP (Fig. 7-4).

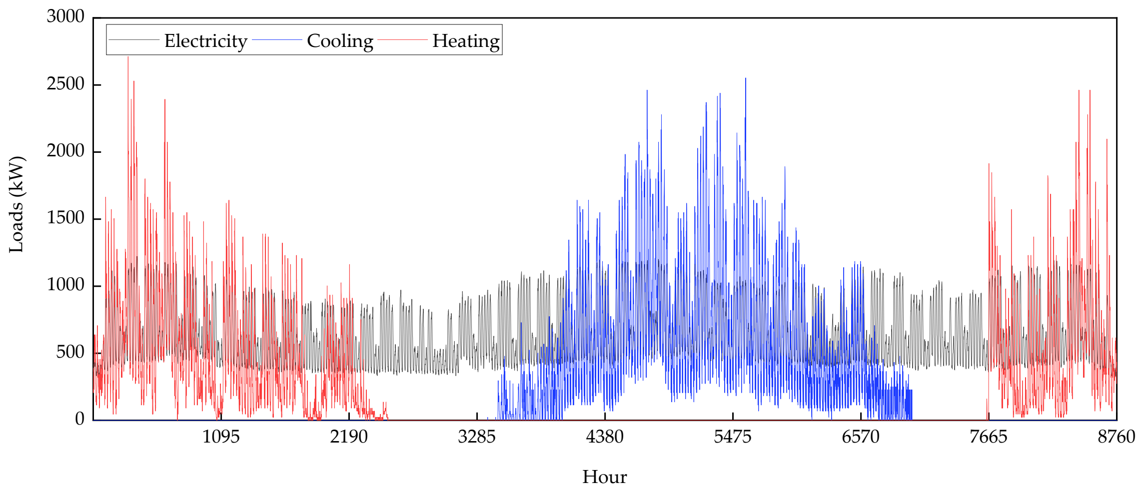


Fig. 7-4 Hourly electricity, cooling, and heating demands in one year.

Generally, there are two operation strategies of the CCHP system: following the electrical load and following the thermal load. When the system follows the electrical load, the excess heat will be generated. If there is no storage heat device, the excess heat will not be fully utilized and lead to the low utilization efficiency of energy. When the system follows the thermal load, it gives priority to meet the cooling and heating load of the building. If generated power cannot meet the electricity demand, the shortage of power can be purchased from the power grid, which makes full use of waste heat resources and makes the system more efficient of the energy utilization. The eco-campus energy demand is mainly electricity, heating and cooling. The demand for heating and cooling are significantly greater than the demand for electricity, and there is no heat storage device designed in the system. Therefore, in order to avoid more energy cost due to larger heating and cooling load and inefficient energy utilization, this study adopts following the thermal load (FTL).

7.3.2 Setting of parameters

According to the investigation and based on the information provided by the energy center of the eco-campus and related studies, the technical parameters and investment cost and maintenance cost of the main equipment of the system are shown in Table 7-3. To reduce the operation cost, we adopted the STOU electricity price mechanism. The prices of electricity and gas and GA parameters are shown in Table 7-4.

Table 7-3 Technical parameters and investment cost and maintenance cost of the system.

Variable	Symbol	Value
Gas engine power generation efficiency[1]	η_{pgu}	0.30
Gas engine heat efficiency[1]	η_{th}	0.477
Heat recovery unit efficiency[1]	η_r	0.80
Heat exchanger unit efficiency[1]	η_{he}	0.80
COP of absorption chiller[1]	COP_{ac}	0.70
COP of electric chiller[1]	COP_{ec}	3.00
Boiler efficiency[1]	η_b, η_{ab}	0.80
Power generation efficiency of power plant[2]	η_{grid}	0.35
Grid transmission efficiency[2]	η_{tr}	0.92
CO_2 conversion factor of electricity (kg CO_2/kWh)[3]	μ_e	0.463
CO_2 conversion factor of fuel (kg CO_2/m^3) [3]	μ_f	2.21
Equipment	**Investment Cost ($/kW[a])**	**Maintenance Cost ($/kW/year)**
Gas engine	750[1]	30.00[4]
Heat recover unit	130[1]	5.20[4]
Heat exchanger[5]	31	0.05
Absorption chiller[6]	154	1.24
Electric chiller[6]	108	1.05
Boiler[6]	31	0.07

[a] 1$=108.74Yen.

[1] The parameter values were provided by the energy center of the eco-campus.

[2] The parameter values and cost were determined according to Song. [28].

[3] The CO_2 emission conversion factors were determined according to the Kyushu Electric Power and Saibu Gas company in Japan [29].

[4] Maintenance cost was assumed as 4 % of the investment cost according to Ali. [30].

[5] Heat exchanger price was determined according to Wang [5].

[6] The costs were determined according to Song. [28].

Table 7-4 Prices of electricity and gas and GA parameter.

Time				Prices
Electricity	Summer	Peak time	13:00–16:00 h	0.248$/kWh
		Daytime	8:00–13:00,16:00–22:00 h	0.213$/kWh
	Other seasons	Daytime	8:00–22:00 h	0.203$/kWh
	All year	Night	22:00–8:00 h	0.120$/kWh
Natural gas	0.20$/m^3			
Parameter		**Value**		
Population size		80		
Generations		100		
Migration fraction		0.1		
Crossover fraction		0.8		
Search space of PGU capacity		[0,3000]		
Search ratio of cooling provided by electricity to total cooling load		[0,1]		

7.4 Results and discussion

7.4.1 Results of optimization

The equipment capacity of the CCHP system obtained after optimization is shown in Table 7-5. It can be seen that the cost-saving ratio was 25.02 %, primary energy saving ratio was 41.14 %, CO2 emission reduction ratio was -3.58 %, and CPI was 20.86 %. Because the CO_2 emission coefficient of gas is 2.21 kg CO2/m3 and electricity is 0.463 kg CO2/kWh, the gas engine was only used for power generation; notably, more CO_2 was generated when the recovered heat was not used. Therefore, in our study, the CO2 emission of CCHP system was higher than that of separated production (SP) system.

Table 7-5 Optimal configuration results and performance comparison between CCHP and SP systems.

Equipment	**Gas engine**	**Heat recovery unit**	**Absorption chiller**	**Electric chiller**	**Heat exchanger**	**Auxiliary boiler**
Capacity (kW)	1473	2342	1874	1881	1874	1186
		CCHP		**SP**		**Saving ratio (%)**
ATC		940866		1254799		25.02
PEC		15591460		26489058		41.14
CDE		3569203		3445791		-3.58
CPI		20.86				

Fig. 7-5 shows the hourly electricity generated from the gas engine and purchased from the grid. The yellow line in Fig. 7-5 indicates the electricity purchased from the grid, and the lower part indicates the excess electricity generated by the gas engine. Notably, the excess electricity was generated by the gas engine in winter or summer, when the cooling and heating demands were high (and the electricity price was high). Because the system following the thermal load, the system prioritized meeting the cooling and heating demands, which increased the gas engine power generation (higher than the electricity demand). During the transition seasons, there was no demand for cooling and heating, and the gas engine power generation only needed to meet the electricity demand; in this case, the required electricity was purchased from the grid.

Fig. 7-6 shows the hourly operation strategies of the absorption chiller and electric chiller. The electric chiller provided cooling mainly during the period of valley electricity prices and low cooling demands. The absorption chiller provided cooling during the day when electricity prices were high, and the electric chiller covered the unmet cooling demand during peak electricity prices.

Fig. 7-7 shows the hourly operation strategies of the cooling and heating equipment. The gray line in Fig. 7-6 represents the recovered heat generated by the gas engine. Due to the high demand for cooling and heating in winter and summer, the recovered heat could be fully utilized. However, during the transition season, there was no demand for cooling and heating, but large electricity demand; therefore, a gas engine was required to generate electricity to meet the electricity demand, and the recovered heat at this time was wasted.

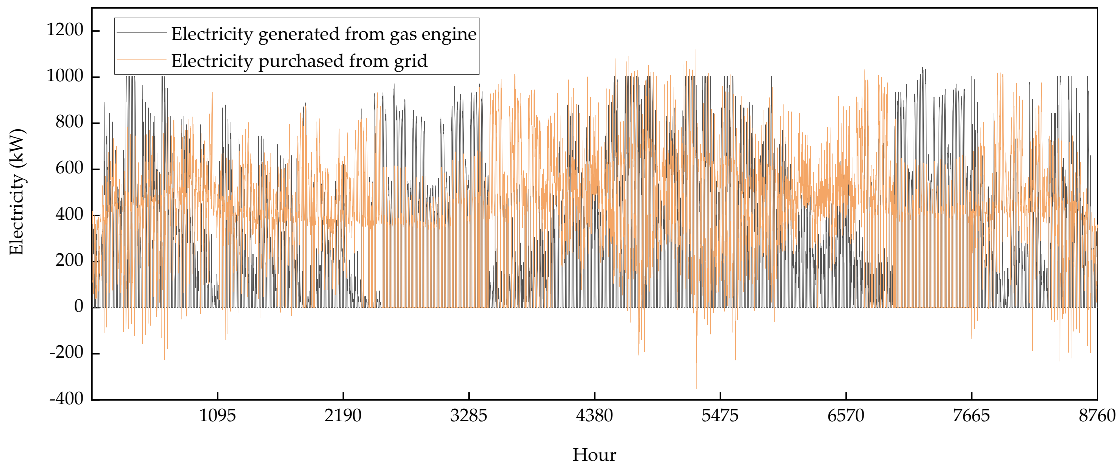


Fig. 7-5 Hourly electricity generated from gas engine and purchased from grid

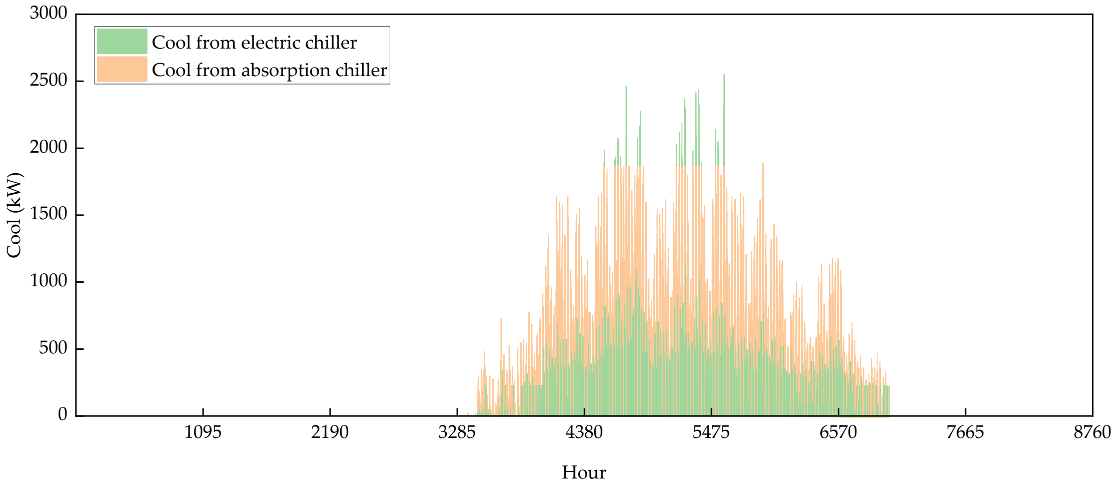


Fig. 7-6 Hourly operation strategies of absorption chiller and electric chiller

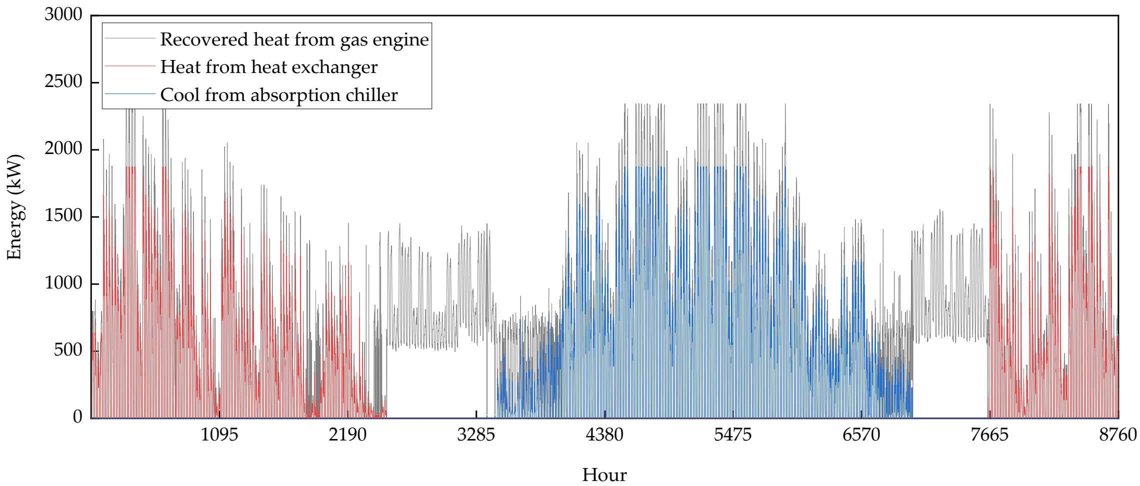
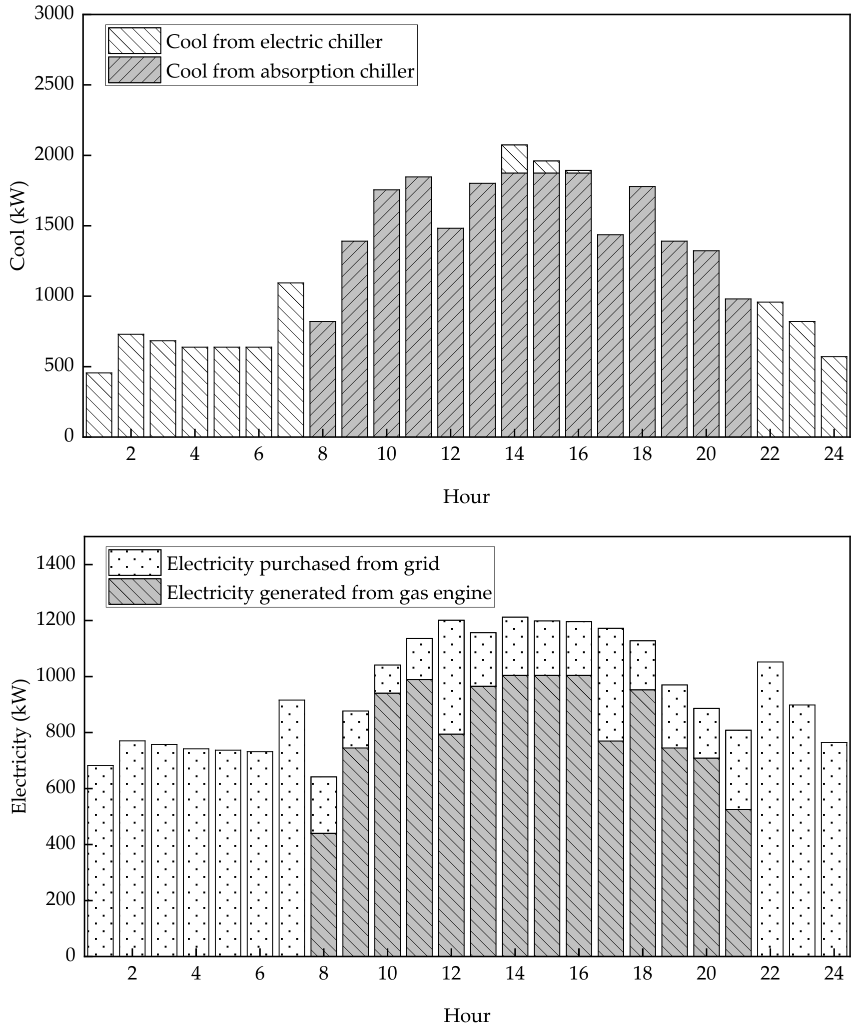


Fig. 7-7 Hourly operation strategies of cooling and heating equipment

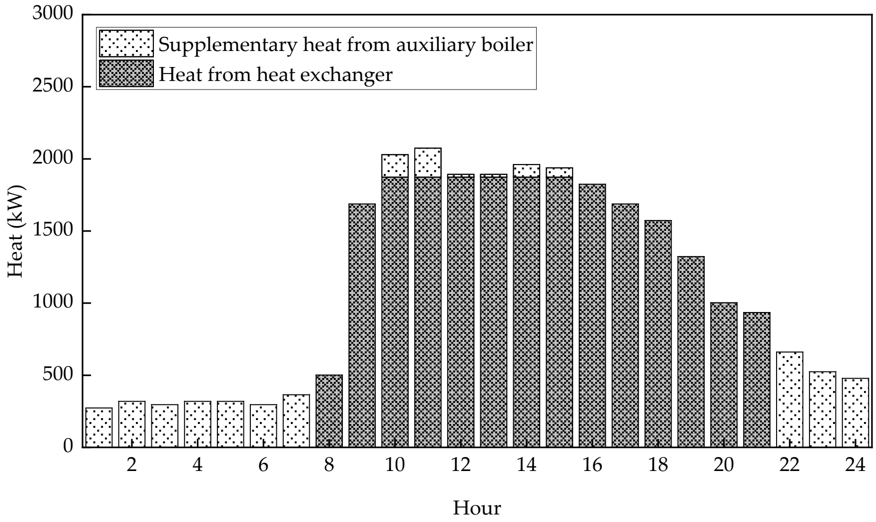
Fig. 7-8 (A) and (B) shows the optimal strategies of the typical days in summer and winter. It can be seen that the gas engine runs from 8:00 to 21:00 and stops from 22:00 to 7:00. During the valley electricity price period in summer, all the cooling demand is provided by the electric chiller. During the day that the cooling demand is provided by the absorption chiller, and the insufficient cooling demand during the peak electricity price period is supplemented by the electric chiller. During the valley price period in winter, all the heating demand is provided by the auxiliary boiler. The heating demand is provided by the heat exchanger during the day, and the insufficient heat is supplemented by the auxiliary boiler. Because the gas engine stops during the valley electricity price period, the electricity at this time is all purchased from the grid to meet the electricity demand. The electricity supply of the gas engine during the day is determined by the demand for cooling and heating, and the unmet electricity demand is fulfilled by the grid. Fig. 7-8 (C) and (D) shows the economic comparison between the CCHP system and the SP system for typical days in summer and winter. It can be seen that the CCHP system has more economic advantages than the separate production system no matter in summer or winter. However, the energy cost of the CCHP system is higher than the separate production system during the period when the CCHP system is stop running, due to the heating and cooling demand during the valley electricity price period is provided by auxiliary equipment, which results in higher energy costs. In summer, CCHP systems save 53.47% of energy costs compared to separate production systems, and 51.20% of energy costs in winter. Therefore, using CCHP systems under this operation strategy has more economic potential than the separate production system.

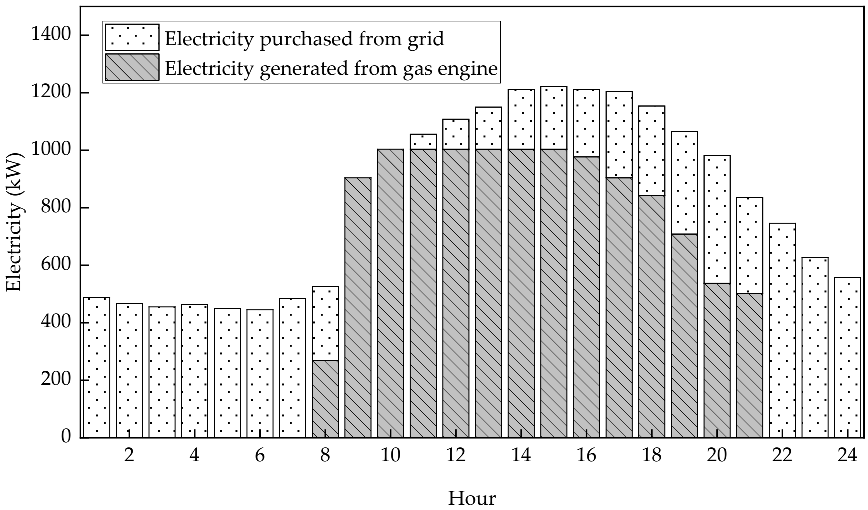
(A)



Operation strategies in summer

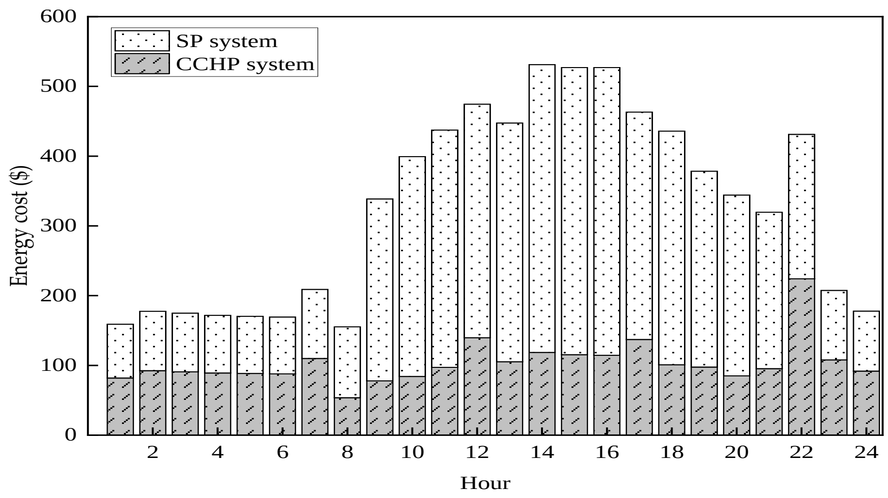
(B)





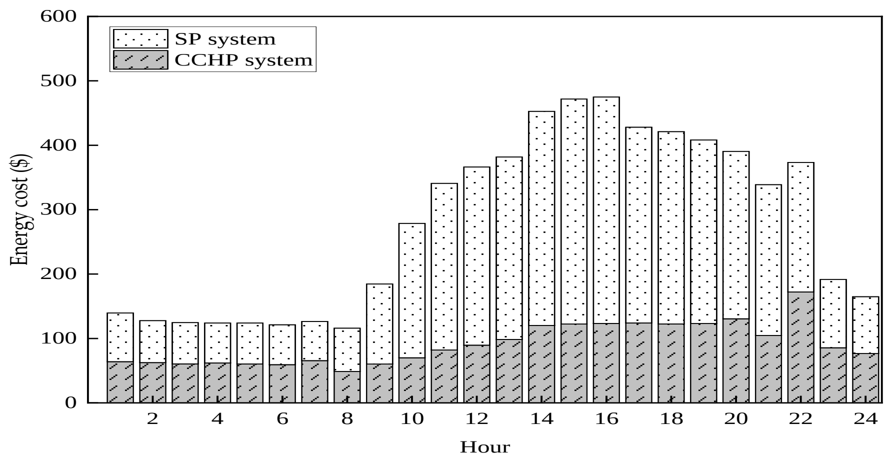
Operation strategies in winter

(C)



Economic comparison in summer

(D)



Economic comparison in winter

Fig. 7-8 Optimal strategies and economic comparison between the CCHP system and the SP system for typical days in summer and winter: (A) Operation strategies in summer, (B) Operation strategies in winter, (C) Economic comparison in summer, (D) Economic comparison in winter.

7.4.2 Comprehensive performance analysis

1) Cost saving analysis

In Japan, there are many electricity pricing mechanisms. In this section, we have compared the seasonal time-of-use (STOU) and time-of-use (TOU) prices (Fig. 7-9). We observed that the Primary energy saving ratio (PESR) and carbon dioxide emission reduction (CDER) were basically unaffected by the changes in the electricity price. The electric chiller needed to be operated to meet the largest cooling demand from 13:00 h to 16:00 h in summer, and peak electricity appeared in the period because of the STOU electricity mechanism. To save the operating cost during the peak period of electricity consumption, the gas engine was shut down during the valley price period, and all the cooling load was provided by the electric chiller. The gas engine was started during the day to meet the cooling demand as much as possible. In this way, the cooling load supplemented by the electric chiller was reduced, and the operation cost during the peak electricity price period in summer was saved in a large section. When the TOU price was adopted, the cost-saving ratio of the CCHP system was 24.31 %. When the STOU was considered, the cost-saving ratio of the CCHP system was 25.02 %. Thus, the TOU price has advantages for the economy of the CCHP system, but for the regions having large cooling demands in summer, it was more economic to adopt the STOU pricing mechanism.

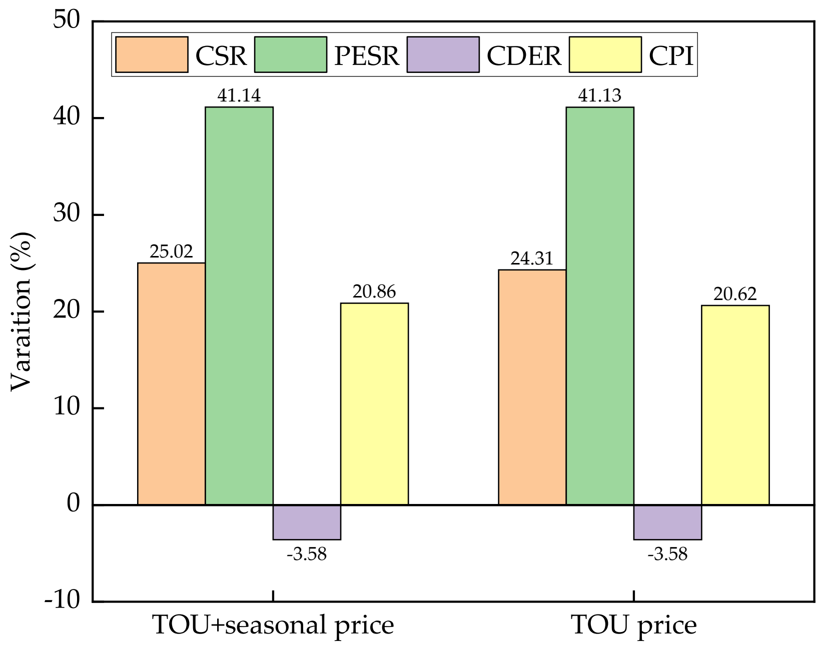


Fig. 7-9 Comparison between STOU and TOU electricity price.

2) Energy saving analysis

Fig. 7-10 shows the energy consumption of the CCHP system in different cases. All cases had better energy-saving performance than the basic case; Case 3 was the ideal case and could save energy by 61.49 %. Notably, the electricity purchase in Case 1 was significantly higher than that in Case 2, and the natural gas consumption of Case 2 was higher than that of Case 1, while the CDER remained the same. This is because Case 2 improved the power generation efficiency of the gas engine and increased the power generation of the gas engine, while the reduction of the thermal efficiency reduced the recovery heat generated by the gas engine and required more natural gas consumption to meet the heating demand in winter. Thus, improvement in the COP of the electric chiller and the power generation efficiency of the gas engine can save energy consumption.

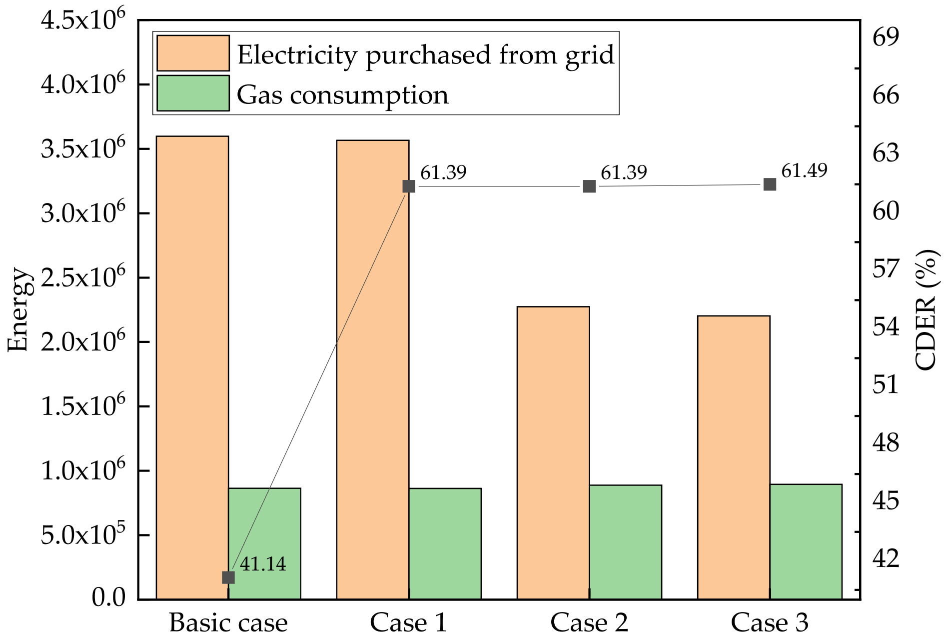


Fig. 7-10 Energy comparison of CCHP system in different cases.

3) CO_2 emission reduction analysis

The CO_2 emission reduction performance in this study was negative. However, in Japan, the CO_2 emission coefficient of electricity is different in each region. The reason for the different CO_2 emission coefficients of electricity is that the proportion of renewable energy and nuclear power, which do not emit carbon dioxide, is different. Table 7-6, shows the CO_2 emission coefficient of electricity in different regions, and the results are shown in Fig. 7-11. In our study, the CDER of Hokkaido, Tohoku, Kinki, and Chugoku were positive, while those of other regions were negative. This shows that the CCHP system is more suitable in regions where the CO_2 emission coefficient of electricity is greater than 0.5 and the CDER is positive. And we convert the CO_2 emission coefficient of electricity into the clean energy ratio, accounting for 40%.

Table 7-6 CO_2 emission coefficient of electricity in different regions.

Region	Hokkaido	Tohoku	Kanto	Chubu	Kinki	Chugoku	Shikoku	Kyushu
CO_2 emission coefficients (kg/kWh)[1]	0.601	0.521	0.441	0.426	0.530	0.585	0.382	0.463

[1] The CO2 emission conversion factors were determined according to the Hokkaido Electric Power, Northeastern Electric Power, Mito Electric Power, Aichi Electric Power, Wakayama Electric Power, Chugoku Electric Power, Shikoku Electric Power, and Kyushu Electric Power company in Japan.

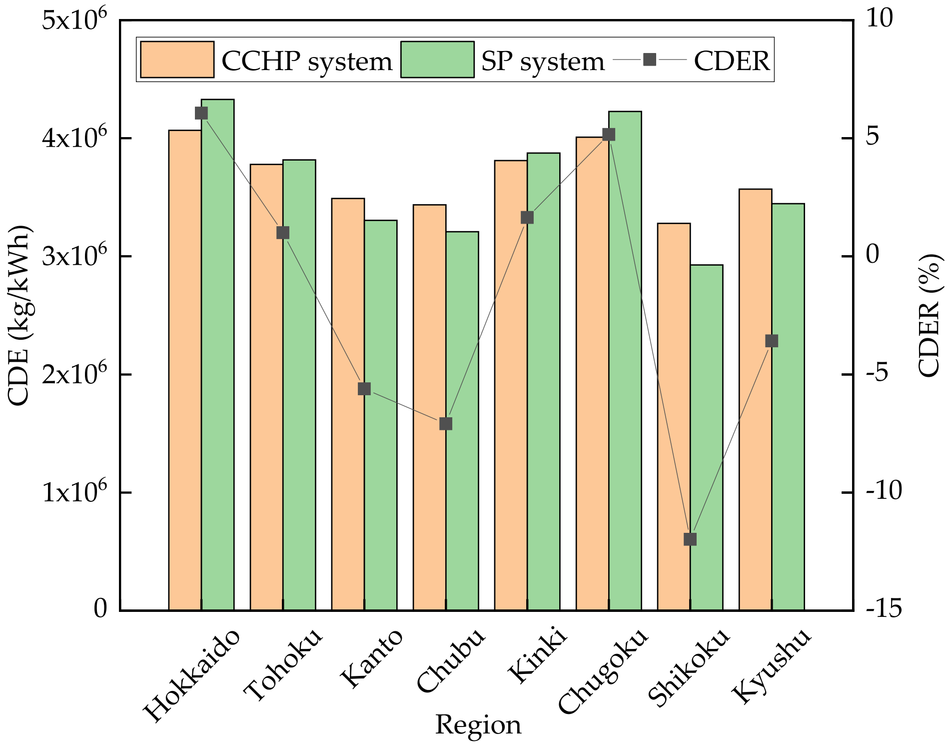


Fig. 7-11 Carbon dioxide emission and Carbon dioxide emission reduction in different regions of Japan.

7.4.3 Sensitivity analysis

1) Influence of energy price on the economic performance of CCHP system

The electricity price affects the operating cost of the CCHP system, and the operating costs account for a large proportion of the total system costs. Consider the electricity price in Table 7-3 as the basic price, and decrease or increase 0–50 % of that to analyze the impact of electricity price on the CCHP system's economic performance. Fig. 7-12 shows the change in the payback period and the total cost-saving ratio of the CCHP system, with different electricity prices, when the gas price remained unchanged. With the increase in electricity price, the payback period showed a downward trend, while the cost-saving ratio showed an upward trend. When the electricity price dropped by 50 %, the payback period of the CCHP system was 12.6 years, and the total cost-saving ratio (CSR) of that was 4.11 %. However, when the electricity price increased by 50 %, the payback period of the CCHP system was about 3.6 years, and the total CSR of that was 32.98 %. This indicates that a drop in the electricity price can decrease the economic performance of the CCHP system. This is because all electricity consumption of the SP system was purchased from the grid, while the CCHP system could generate electricity by the gas engine; the electricity deficit was fulfilled by the grid, which greatly reduced the amount of electricity purchased.

The natural gas price also affects the economic performance of the CCHO systems. The impact of gas price on the economic performance of the CCHP system is shown in Fig. 7-13. Contrary to the electricity price, the payback period of the CCHP system showed an increasing trend with increasing gas price, whereas the total CSR showed a downward trend. When the gas price dropped by 50 %, the payback period was 4.4 years, and the total CSR was 30.75 %. When the gas price increased by 50%, the payback period was 6.3 years, and the total CSR was 19.54 %. The natural gas consumption of the CCHP system was greater than that of the SP system because natural gas was required by the CCHP system for power generation and boiler operation. Therefore, the increase in gas price can lead to a decrease in the economic performance of the CCHP system.

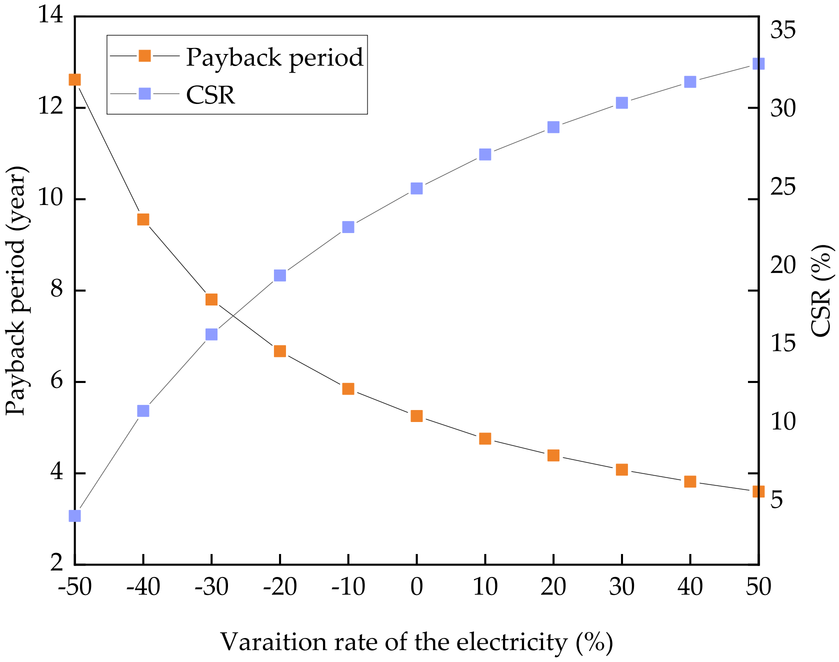


Fig. 7-12 Sensitivity analysis of electricity price

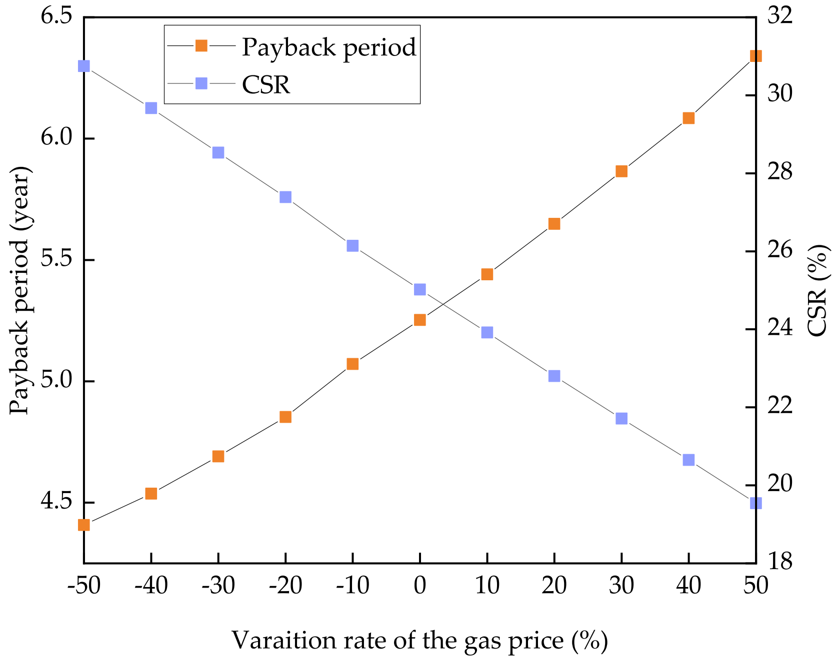


Fig. 7-13 Sensitivity analysis of gas price

2) Influence of CO_2 emission coefficients on the economic performance of CCHP system

The CO_2 emission coefficient of electricity affected the CO_2 saving potential of CCHP systems. The CO_2 emission coefficient in this study was calculated for the Kyushu region; the CDER was negative for the CCHP system, while the comprehensive performance index was positive. Fig. 7-14 shows the effect of CO_2 emission coefficient decreasing from 0 %to 90 %. Notably, the overall development direction of the power system in Japan is towards low-carbon development. When the CO_2 emission coefficient of electricity in the Kyushu region was reduced to 67 %, the impact of the economic and energy-saving index was offset, and the comprehensive performance index was below 0, which was not suitable for the CCHP system.

Through the sensitivity analysis of energy price and CO_2 emission coefficient of electricity, it can be concluded that when the parameters change greatly, the comprehensive performance of CCHP systems will be significantly affected.

In this part, firstly, the optimization results are analyzed. Then the development potential of CCHP system is analyzed from three factors: cost saving, energy saving and carbon saving. Finally, the sensitivity analysis of energy price and carbon emission coefficient provides suggestions for the promotion of cogeneration system.

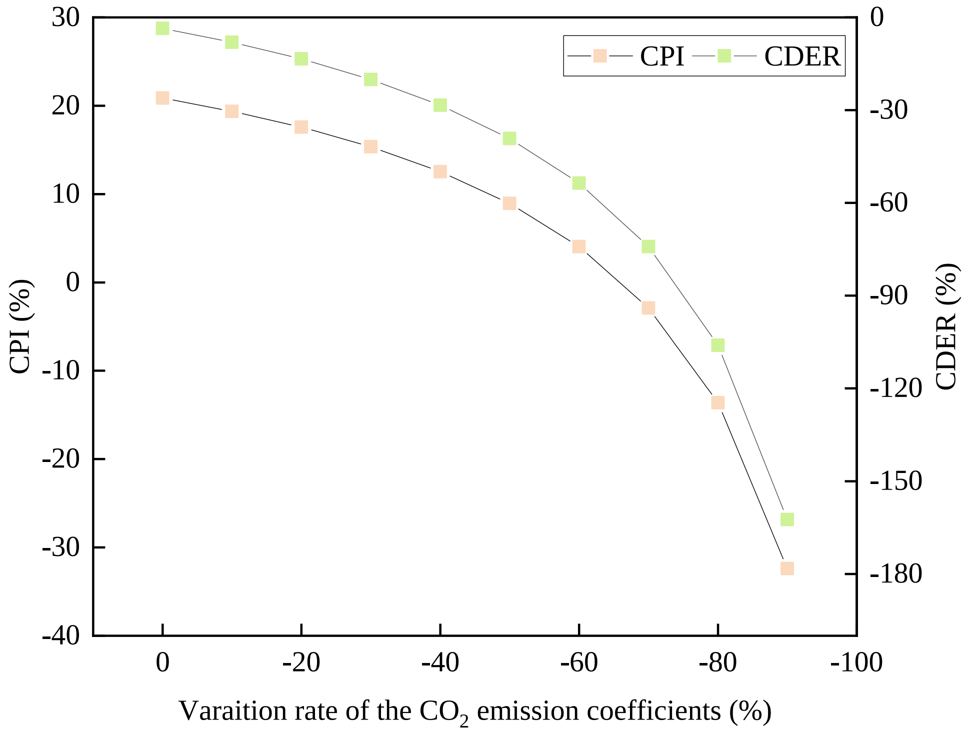


Fig. 7-14 Sensitivity analysis of CO_2 emission coefficient of electricity.

7.5 Summary

In this study, we optimized and evaluated the comprehensive performance of the CCHP system for an eco-campus in Japan. The genetic algorithm (GA) method was used to determine the capacity of each piece of equipment and the operation strategies of the CCHP system. A comprehensive performance index was proposed to evaluate the economy, energy-saving, and CO_2 emission reduction potential of the CCHP system. Then, sensitivity analysis was conducted for determining the impacts of electricity and natural gas prices and CO_2 emission on the performance of the CCHP system. The main conclusions of our study are as follows:

1. The economic performance of the CCHP system was better than that of the SP system and the total cost of the system could be reduced by 25.02 %. The electricity and natural gas prices were selected as the factors that affect the economic performance of the CCHP system. With the increase of electricity price, the economic performance of the CCHP system improved; however, in the case of natural gas price, the opposite effect occurred. With the increase of natural gas prices, the economic performance of the system decreased. When the electricity price changed, the change range of the system payback period was from 3.6 to 12.6, while in the case of when the natural gas price changed, the change range of the payback period was from 4.4 to 6.3. This shows that changes in the electricity price can affect the economic performance of the CCHP system more than changes in the natural gas price. By comparing the economy of seasonal TOU price and TOU price, we found that it is more economical to use seasonal TOU price in areas that have an excessive cooling demand in summer.
2. By comparing the COP of the electric chiller and the power generation efficiency of the gas engine, we found that the improvement of the COP of the electric chiller and the power generation efficiency of the gas engine can greatly save the energy consumption of the CCHP system. When the efficiencies of these two parameters were improved at the same time, energy-saving was optimal.
3. After optimization, the result of CDER was negative because there was a wide variation in the CO_2 emission coefficients of electricity and gas. However, the CO_2 emission coefficients of electricity in different regions were different. By comparing the CO_2 emission coefficients of electricity in different regions, we could conclude that the regions having a clean energy ratio higher than 40 % were more suitable for the promotion of the CCHP system.

Overall, this study optimized and evaluated the CCHP system of a specific building to promote its comprehensive performance. And the influence of different electricity price mechanisms on the development of the CCHP system was analyzed. Our results can provide a reference for eco-campus to establish a CCHP system to improve the comprehensive performance. The comprehensive performance assessment method used in this study put forward suggestions on the adaptability and development potential of CCHP systems in the future.

This study mainly improved the performance by optimized the installed capacity and operation strategies of the CCHP system. However, the failure during equipment operation also seriously affects the development of CCHP system. Therefore, a more detailed optimization analysis of CCHP system should be carried out in combination with equipment maintenance in the future work.

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Chapter 8

CONCLUSIONS

CHAPTER EIGHT: CONCLUSIONS

Due to the continuous growth in the world's energy demand, the problems of energy consumption, greenhouse gas emission, and environmental pollution have become increasingly prominent. At present, countries all around the world have implemented energy-saving and emission reduction measures to achieve carbon neutralization. The distributed energy resource (DER) system is a high-efficiency energy system that can promote energy-saving and decrease carbon emissions. However, the implementation of DER is still hindered, mainly due to improper maintenance management and unsuitable installed capacity. Maintenance management is a key element for the equipment or system to complete its function during the production cycle. Each component has a different operation and maintenance mode. Inadequate resources for maintenance management or poor maintenance strategies will lead to equipment or system failures and losses. The choice of installed capacity and operating strategy affects the economy, energy efficiency and environmental protection of DER. If the installed capacity is too large, it will lead to higher investment costs and energy consumption. If the equipment capacity is too small, it will lead to high system operation cost. Therefore, it is necessary to select the appropriate equipment capacity according to the energy demand of the user. Therefore, the focus of this research is on the equipment maintenance and system optimization of DER. In the maintenance optimization stage, a maintenance priority assessment method is used to allocate maintenance management resources based on the assessment results to help managers develop reasonable maintenance strategies and reduce maintenance costs. In the system design optimization stage, the capacity and operation strategy of the system is optimized for the energy demand of users to achieve the purpose of improving economic benefits and promoting energy saving and emission reduction.

The main works and results can be summarized as follows:

In chapter one, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY, the significance of DER system for future energy development was analyzed. Through the analysis of the advantages of DER system, it is shown that DER system has the ability to reduce energy crisis and environmental pollution and improve energy security. In addition, the current development status of DER system was analyzed, and the technologies and building categories that can be applied to DER system were introduced. Due to the advantages of energy saving and environmental protection, DER system has been strongly developed by the government. However, the high investment costs, inappropriate installed capacity, and unsuitable maintenance management have hindered the promotion of DER system.

In chapter tow, LITERATURE REVIEW OF THE DISTRIBUTED ENERGY RESOURCE SYSTEM, the main purpose is to sort out the current status of DER system research. First, the optimization of DER system design and maintenance is investigated. Since DER system is a complex system consisting of multiple devices capable of providing multiple energy sources, its configuration design and maintenance management determine the performance of the DER system and are the main research focus of DER system. Second, the performance of DER system evaluated in the existing literature is reviewed and analyzed. Different evaluation methods will have a significant impact on the configuration and operation strategies of DER system.

In chapter three, THEORIES AND METHODOLOGY OF THE STUDY, the methodological study and the mathematical model were presented. And the system models are established. Also, the economy benefit, energy consumption, carbon emission reduction and maintenance management of the equipment of DER are analyzed. In addition, the simulation models and algorithms used in the follow-up study are provided.

In chapter four, INVESTIGATION ON REAL OPERATION DATA OF DISTRIBUTED ENERGY RESOURCE SYSTEM, the operation and maintenance status situation of the power generation system of distributed energy were investigated. The data of gas engine is from June 2001 to February 2016, nearly 15 years; and the data for fuel cell is from June 2001 to January 2011, nearly 10 years. These data are collected, calculated and analyzed to investigate the operation status and power generation efficiency of the gas engine and fuel cell. The operation status of gas engine was classified into operation, schedule stoppage, inspection and failure stoppage. Of which, inspection was classified into inspection per 1000 hours, casual inspection, maintenance, others. The failure was classified into power generation unit failure of gas engine, cooling water unit failure of gas engine, heat recovery unit failure of gas engine, heat recovery unit failure of gas engine and auxiliaries' failure of gas engine. The highest abnormal operation is operation with minor failure, it is nearly 42.62% of total abnormal operation, 52 days. All the results indicate that the inspection and maintenance of the gas engine are not very quickly, or the maintenance are not enough preparation. The highest abnormal stoppage is inspection and maintenance, it is nearly 60.52% of total abnormal stoppage, 141 days. the inspection and maintenance is the main reason which leads to the gas engine stoppage. The maintenance status of gas engine is divided into two part. First part includes starting device, protection device, gas supply unit, exhaust system, generator, speed control device, intake system and air-ratio control device. Second part includes reciprocating part, cylinder head, power supply system, cooling water system, ignition device and rotary motion part. The operation status of fuel cell was classified into operation, annual inpsetion stoppage, casual inspection stoppage, maintenance stoppage, failure stoppage, casual inspection with operation, and maintenance with operation, and failure with operation. The failure has occurred in 2009 was more than other years. The failure has occurred 8 days in 2011, after that the fuel cell was stopped. The annual is the main stoppage reason in the stoppage status. And most of maintenance was finished in the annual inspection time. The maintenance status of fuel cell includes air processing system, exhaust cooling system, power plant controller, uninterrupted power supply, safety valve, battery cooling water system, reformer, rotating machine, starting device, fuel processing system, water treatment system and steam system.

In chapter five, LIFE CYCLE ASSESSMENT ANALYSIS OF DISTRIBUTED ENERGY RESOURCE SYSTEM, based on the analysis of the operation status of the DER system in chapter 4, this section proposed a life cycle assessment method to evaluated the DER system performance. The comprehensive benefits of DERs were analyzed in terms of economic benefit, energy consumption and environmental performance compared with conventional energy systems (CES), respectively. According to the life cycle assessment of the distributed energy system in Kitakyushu

Science and Research Park, we have established a life cycle model to compare with the conventional energy system through economic, energy consumption and environmental performance. The results show that the cost saving ratio is 13.66%, the energy saving ratio is 12.25% and the carbon reduction ratio is -5.81%. Because the CO_2 emission coefficient of gas is 2.21 kg CO2/m3 and electricity is 0.463 kg CO2/kWh, the gas engine was only used for power generation; notably, more CO_2 was generated when the recovered heat was not used. Therefore, in this study, the CO_2 emission of distributed energy system was higher than that of conventional energy system. By analyzing the life cycle assessment of distributed energy system, the development potential of distributed energy system is comprehensively analyzed in terms of economic performance, energy consumption performance and environmental performance, and a comprehensive performance evaluation method is proposed for future system optimization.

In chapter six, STUDY ON MAINTENANCE OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM, the maintenance strategy of the DES system in KSRP is analyzed and optimized. The main power generation units of the DER system in KSRP includes fuel cell and gas engine. Each generator has associated equipment, absorption chiller, heat exchanger, cooling tower, cooling pump, etc. The failure modes, failure causes, and failure effects of the components were investigated; and severity (S), occurrence (O), and detection (D) factors were evaluated. The maintenance strategy was optimized to improve maintenance and reduce the risk priority number (RPN). The results can be used as a reference for component maintenance optimization. The failure mode and effects analysis told that the failure modes, failure cause and failure effects of the gas engine according to data. The failure effects mainly includes abrupt stop, output reduction, rotation does not rise; although the engine rotates according to the start command, the rotation does not rise; although the engine rotates according to the start command, the rotation does not rise, the engine starts but stops immediately; engine does not rotate by start command; the actuator of the governor does not operate at all; the engine starts but stops right away; the engine suddenly stops; the lubricating oil pressure becomes less than the specified value. The failure mode and effects analysis told that the failure modes, failure cause and failure effects of the fuel cell according to data. The failure effects mainly include fuel cell stopped, fuel ventilation chamber defect, low battery voltage, reduced power generation, reformer burner misfire, the ejector behaves abnormally, thermocouple high and vibration is large.

In chapter seven, COMPREHENSIVE PERFORMANCE ASSESSMENT AND OPTIMIZATION OF DISTRIBUTED ENERGY RESOURCE SYSTEM, different configurations of equipment will affect the performance of DER. In this section, a comprehensive performance assessment based on the economy, energy and environmental performance was proposed to optimize the system to find the optimal capacity. And discussed the impact of different electricity price mechanisms on the development of DER. The comprehensive evaluation index (CPI) was established based on economy, energy and environment performance, and a configuration optimization model of the DER with the maximum CPI as the goal was established by genetic algorithm (GA). Then, the development potential of the DER was evaluated by analyzing the economic saving, energy saving and carbon reduction performances. The economic performance of the CCHP system was better than that of the SP system and the total cost of the system could be reduced by 25.02 %. The electricity and natural gas prices were selected as the factors that affect the economic performance of the CCHP system. With the increase of electricity price, the economic performance of the CCHP system improved; however, in the case of natural gas price, the opposite effect occurred. With the increase of natural gas prices, the economic performance of the system decreased. When the electricity price changed, the change range of the system payback period was from 3.6 to 12.6, while in the case of when the natural gas price changed, the change range of the payback period was from 4.4 to 6.3. This shows that changes in the electricity price can affect the economic performance of the CCHP system more than changes in the natural gas price. By comparing the economy of seasonal TOU price and TOU price, we found that it is more economical to use seasonal TOU price in areas that have an excessive cooling demand in summer. By comparing the COP of the electric chiller and the power generation efficiency of the gas engine, we found that the improvement of the COP of the electric chiller and the power generation efficiency of the gas engine can greatly save the energy consumption of the CCHP system. When the efficiencies of these two parameters were improved at the same time, energy-saving was optimal. After optimization, the result of CDER was negative because there was a wide variation in the CO_2 emission coefficients of electricity and gas. However, the CO_2 emission coefficients of electricity in different regions were different. By comparing the CO_2 emission coefficients of electricity in different regions, we could conclude that the regions having a clean energy ratio higher than 40 % were more suitable for the promotion of the CCHP system.