Gas-fired Combined Cooling, Heating and Power (CCHP) in Beijing: A Techno-economic Analysis

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Abstract: The application of a gas-fired CCHP can effectively solve seasonal shortages of electricity and gas. To realize providing investment decision for gas-fired CCHP in Beijing, first, the paper analyses the status of gas-fired CCHP systems in Beijing; second, the technology structure and economic benefits of gas-fired CCHP systems are analysed; third, a technical economic evaluation framework of a gas-fired CCHP is built, which analyses the cascade utilization and energy saving effects of a heat and power energy system in a gas-fired CCHP system. Analysis of the gas-fired CCHP system economy and the factors that influence the economic performance is also performed, as well as a sensitivity analysis. In addition, the paper also analyses an energy efficiency sharing model of a cooling, heating and power system that considers the grid enterprises' economic efficiency. Finally, an empirical analysis of a trigeneration project control centre in the Beijing Gas Group is carried out. Research results show that gas-fired CCHP system is good to both customers and beneficial, fuel price and electricity price will influence revenue of Gas-fired CCHP system greatly, a reasonable energy efficiency sharing ratio will help to the recovery of investment in Gas-fired CCHP.

Key words: gas-fired combined cool and heat and power; techno-economic analysis; Beijing

1 Introduction

During the summer of 2010 in Beijing, 40% of the 16.66 million kilowatts of electricity produced was used for air-conditioning. Conversely, nearly 80% of the annual gas consumption was consumed in the heating season[1]. Gas and electricity have low energy efficiency, and both need dozens to tens of billions RMB to meet their own peak demand[2]. A gas-fired CCHP system is an effective solution to improve energy efficiency and is one of the important ways to build a city's usage of gas and energy[3,4]. This can effectively solve seasonal shortages of electricity and gas as well as reduce the demand for new generating capacity, investments in the transmission and distribution infrastructure, and related investments in gas due to final energy consumption[5]. In addition, gas-fired CCHP systems can also improve living environments and reduce the emission of pollutants.

Gas-fired CCHP systems (Combined Cooling Heat and Power, referred to as CCHP) are based on the energy cascade utilization concept, which uses gas as its primary energy source and produces electricity and usable heat (cold) energy simultaneously[6]. This system can be divided into three functional subsystems: the power system (generate electricity), heating system (heating, hot water, ventilation and etc.) and cooling system (cooling, dehumidification and etc.). In the long term, compared to a conventional energy supply system, a gas-fired CCHP system has a large potential for development, with energy efficiencies that can reach 80-90%[7]. However, currently the output of the distributed power grid is limited and gas prices are increasing[8]. Given this situation, can the advantages of the high energy efficiency of a distributed power system translate into a significant economic advantage? That is, can distributed power systems earn profits? What is the level of these profits? There are still many uncertainties. Therefore, this paper performs a technical and economic analysis of distributed energy investments in Beijing by studying factors that influence the economics of gas-fired CCHP programs and

performs a sensitivity analysis. Concurrently, given the on-grid problem that distributed power in China faces, this paper has also analyses the energy efficiency sharing model of a distributed cooling, heating and power supply system considering the economic efficiency of the grid enterprises. Finally, an empirical analysis of a trigeneration project control centre in Beijing Gas Group is carried out.

2 Statuses of gas-fired CCHP applications in Beijing

The operation model of distributed trigeneration project in Beijing learns from abroad operation model, set up many related distributed energy technology company[9]. They take advantage of professional technical company's high efficiency and low price in the operation of distributed trigeneration project, provide users train services including design, construction management, commission, operation and etc., sharing owner's technical risk, and ensure the successful implementation of the trigeneration project.

At present, there is over one thousand kilowatts trigeneration project that has been built or to be built in Beijing[10]. Also, project that using more than one billion RMB is being developed. Development of gas-fired CCHP system in Beijing is shown in Table 1.

Table 1

Development of gas-fired CCHP system in Beijing

According to existing research results[1,5], no matter from policies of government promulgated support CCHP development policies, or consumers' demands of CCHP, the commercial application of distributed energy system in Beijing constantly increase, and project configuration also differ according to actual needs about type, installed capacity, etc.. Aiming at existing distributed energy system, this section will introduce several kind of typical investments on distributed energy system specifically. We select these projects operating for their greater influence, Beijing Gas Group monitoring center project was the first CCHP project in Beijing, Beijing South Railway Station CCHP project caused widespread concern for its controversy about integration into network problem, and Beijing Olympics Energy Exhibition Center CCHP project was known because of the Olympic Games.

(1) Beijing Gas Group monitoring center gas-fired CCHP project

This project is invested by Beijing Gas Group Company, and Beijing Grace Knight Company is responsible

for command and management of the construction and system commission. Since debugging in 2003, the project generates energy-saving benefits for investment recovery as well as covering operation and maintenance costs. Since put into operation, the system provide all the cool, heat and power demand for Beijing gas dispatch center building during the cooling and heating seasons, the system fully realize the reliable, stable operation.

(2) Beijing South Railway Station **gas-fired CCHP** project

Beijing South Railway Station distributed energy project has two 1600kw internal combustion generators, and it adopt direct flue lithium bromide absorption heat recycling. The energy supply system project is invested by the Ministry of Railways, and the total investment is 73.71 million RMB which is a part of South Station investment. The trigeneration system's contactor is Beijing Grace Knight Distributed Energy Limited Company. The system uses the heat that generated by gas power directly for cooling or heating. By cascade utilization of energy, gas use efficiency can be raised from 50% to 90%, which meet 48.7% of the total electricity in South Station. Compared with the conventional energy supply system, South Station can save 6 million RMB of operating costs every year, reduce 2,000 tons of CO₂ emissions, and save 1,000 tons of standard coal. The project generates energy-saving benefits for investment recovery as well as covering operation and maintenance costs.

(3) Beijing Olympics Energy Exhibition Center **gas-fired CCHP** project

The investment of the project is 129.6 million RMB, which is mainly social investment. And Beijing Grace Knight Company is responsible for the command and management of construction and system debugging. Since operation in 2008, Energy Exhibition Center provide all the air-conditioning, heating, domestic hot water and part of power supply for 410,000 m² venue construction, including National Stadium, National Aquatics Center, the Information Building and etc.. It adopt advanced distributed CCHP system that the conventional energy and renewable energy are complementary, which belong to Area type distributed energy supply system. The project recovers the investment by providing green energy. And the estimated payback period is about 7.2 year.

Overall, the investment in distributed energy supply system in Beijing is mainly come from the user, and social investment in large-scale distributed energy projects increase gradually. Distributed energy systems mainly meet their owe electricity needs by combining to the grid and not getting in. Its operation and maintenance work is usually transmitted to the third party energy service companies. And the energy-saving benefits and economic benefits can recover investment and cover operation and maintenance costs. In addition, it should be referred that the third party energy service companies are less and small-scale, and their role only reflect in project construction, operation and maintenance, and cannot play important role in financing, construction in the early period and

promoting distributed energy.

3 Gas-fired CCHP'S technology structure and economic benefits analysis

Distributed energy is an important trend in the development of world's energy industry, and it is one of the important ways to achieve sustainable development[11]. Distributed energy covers aboard, including wind, solar, hydro, biomass, geothermal and other non-fossil energy. Small whole energy system, which is composed of gas turbine generators, waste heat boilers and other equipment, is the second generation distributed energy system or trigeneration energy supply system.

3.1 Technology structure of a gas-fired CCHP

“Trigeneration” of a heating, cooling and electric energy supply system is shown in [Figure 1](#).

Figure 1 “Trigeneration” of Heating, Cooling and Electricity Energy Supply System Concept

Gas-fired CCHP systems mainly adopt mature technologies, such as gas turbines, diesel power generators, as well as water heat recovery and refrigeration technologies. The small scale distributed system is built near the user (with a few kW to several MW), and it is configured to be flexible and easy to adjust according to the actual cooling, heating and electricity loads[12]. This can not only meet the users' energy need but also save the significant costs for the construction and operation of an urban heating pipe network. This also helps to shift peak loads, thereby reducing the emission of carbon and other harmful gases and produces good social benefits that are in line with the sustainable development strategy and the development of future energy technologies[13].

(1) Basic composition of a gas-fired CCHP

Gas-fired CCHP systems are composed of gas turbine equipment and waste heat utilization equipment. The core of the system is gas turbine equipment, which includes a gas turbine, internal combustion engine, and so on. Waste heat utilization equipment includes waste heat boilers, absorption chillers, heat exchanger devices, electric refrigerators, gas boilers, and so on.

By burning gas, gas turbines generate high temperature flue gases that are transmitted into the waste heat utilization equipment and can be used for heating in winter, cooling in summer and the production of domestic hot water. Short heating can also be supplied by the afterburn gas. According to the condition of the project,

trigeneration systems and the configuration equipment have various forms. For example, ice storage, heat storage, heat pumps, and so on can be used for raising the overall energy efficiency of the system.

(2) Categories of gas-fired CCHP systems

There are many categories of gas-fired CCHP systems. They can be categorized based on the type of the gas turbine or waste heat utilization equipment, the relationship between generator and municipal power and the system operation time.

According to the gas generator type, there are gas turbine CCHP, gas engine CCHP, micro gas turbine CCHP and fuel cell CCHP systems.

According to the waste heat utilization equipment type, there are traditional waste heat boiler + absorption chiller (including hot-water type and steam type), supplementary fired heat recovery boiler + absorption chiller, and heat absorption chiller systems[14].

Regarding the relation between the generator and municipal power, there are two modes of operation: generation connected to the Beijing power grid and generation isolated from the Beijing grid.

According to the system uptime, the categories are year-round and seasonal intermittent continuous. The former turbine does not shut down at all during the year and the latter runs in the heating and cooling seasons, but not in the transition seasons. Additionally, some systems' operation mode is intermittent daily, and generators shut down when the electric load is low at night.

3.2 Economic Benefits Analysis of gas-Fired CCHP

Due to its high energy efficiency and better energy saving effects, large-scale commercial application of the trigeneration energy supply system would effectively promote generation efficiency, raise generation levels and save energy. For the complementary processes, trigeneration energy supply systems involve two economic agents[15,16]: grid enterprises and directly involved users. The implementation of a trigeneration system will directly/indirectly affect the economic benefits of the two agents. Therefore, from these two aspects, the following paper will explain the economic benefits of a trigeneration system qualitatively.

(1) Economic benefit analysis of a trigeneration energy supply system from the power grid enterprises' viewpoint.

The trigeneration energy supply system is effective and flexible; its large-scale application affects the power grid enterprises, mainly in the following ways[17].

(i) Construction times for distributed energy systems are short and can meet the users' demand for energy. This helps reduce investment risks and operation costs, slow the expansion of investment in electricity transmission and distributed systems or upgrades the replacement investment, and reduces the construction costs of grid power enterprises as well as the system losses.

(ii) Users generate power for private use, which directly affects the sales revenue of the power company. The companies that invest in constructing trigeneration supply systems are large power companies that have significant influence over sales revenues. The major reason for the difficulty is that it is hard to combine the grid with CCHP.

(2) Analysis of the economic benefits of a trigeneration energy supply system from the power users' viewpoint

Users involved in the "Trigeneration" of heating, cooling and electricity supply systems are direct beneficiaries. The economic benefits are reflected in the following aspects:

(i) Energy cascade utilization is achieved, and energy efficiency is improved[18]. The conventional, centralized method of energy supply is too singular to meet various energy demands in real time, while the trigeneration distributed energy supply system is small-scale, and flexible. Through organic integration of different cycles, the system overcomes the restriction that cooling and heating cannot be transmitted over long distances and meet users' demands, thereby achieving integrated cascade utilization of energy.

(ii) Electricity reliability is ensuredp[19]. For the commercial and industrial users that cannot accept a power outage due to economic, health and safety concerns, the distributed energy system can provide the required, high quality power for them and ensure the reliability of electricity in the case of a continuous reduction in the power supply's reliability.

(iii) Energy costs are reduced. Gas-fired CCHP systems are often built near users or load centres, thereby avoiding transmission losses and improving the efficiency of the energy supply. The system can help users avoid the use of high-priced electricity in peak periods or sign low-priced and interruptible power contracts with energy companies, which reduces energy costs[20].

In addition, the fuels for trigeneration energy supply systems are mostly gas, light oil or renewable clean energy, and the emissions of SO₂, NO₂, CO₂, dust, and waste water will reduce significantly during the generation process. The voltage level of distributed power is low and the generated magnetic field is small; therefore, the electromagnetic pollution is much smaller than conventional centralized power[21]. This meets low-carbon

strategies and brings huge economic benefits for regional development directly or indirectly.

3.3 Existing problems and barriers of gas-fired CCHP

Existing problems and barriers of gas-fired CCHP can be divided into three categories, respectively is policy, technology, economy problems and barriers.

3.3.1 Policy problems and barriers

Gas-fired CCHP development faces two major problems and barriers, one is about integration into network, the other is lack of reasonable pricing mechanism.

Gas-fired CCHP system is suitable to be accessed to the power grid. However, the relevant authorities have not formulated feasible, practical operability of the project application, examination and approval, technical requirements of access network, acceptability criterion, buy and sale power and a series of other technical standards, rules and regulations and management measures for distributed natural gas[22]. To a certain extent, it affects the grid connection of distributed natural gas generation. Besides, gas-fired CCHP system involves heating (cooling) and power supply problem, which are franchised by different enterprises authorized by the government according to relevant laws. For example, *Electricity Law of the People's Republic of China* clearly stipulates that power production enterprises are required to have special power producing quality, while Gas-fired CCHP with the miniaturization, versatility and scattered characteristics is difficult to meet requirements of the regulation.

The second problem is that there is no clear gas-fired CCHP price formation mechanism. There is no useful reference benchmark electricity price, if take thermal power integration price as a reference, electricity price of gas-fired CCHP will be far higher than it[23]. These problems have directly affected the economic benefits of the projects and the investment enthusiasm of investors, and restricted the rapid development of distributed natural gas energy.

3.3.2 Technical problems and barriers

At present, China has not yet mastered the core manufacturing technology of micro gas turbine which is the key equipment of distributed natural gas generation projects. The production capacity stays only in the production with foreign cooperation. At the meantime, many key components are still relying on imports, and the price hold high[24]. Besides, the maintenance and overhaul of the units also need to employ foreign experts. So the operation cost is large. All of the above in a certain extent affect the competitiveness of the distributed natural gas generation.

At present, the United States, Europe and Japan have already put micro gas turbines into mass production. And the heating efficiency of micro gas turbines using for combined cooling, heating and power generation is up to 80%~90%[25]. The simple loop power supply efficiency of the 100 KV micro turbines manufactured by the independent property of micro gas turbines development projects revolved in the “863 project” is only 29%, which has significant gaps with highest world standard.

3.3.3 Economic problems and barriers

During gas-fired CCHP investment process, economy of the project should be paid more attention to. Judging from operation of gas-fired CCHP system, fuel, heating and electricity prices, the annual system utilization hours and other factors, the technical and economic data of a trigeneration system may change drastically in a dynamic environment which will affect gas-fired CCHP investment decisions and its development. These factors affecting the project economy will be detailedly analyzed in section 4.

4 Technical economic evaluation framework of gas-fired CCHP

How to improve energy efficiency as well as ensure economic benefits is an important issue in gas-fired CCHP investment. In the current market environment, a rational energy supply system design and effective operation management is key to profitability. Therefore, analysis of distributed energy development is particularly important. This section provides guidance for gas-fired CCHP systems through technical comparison, economic analysis and effects assessment, as well as a combined case analysing the best combination of economies and technology.

4.1 Technical analysis of a CCHP energy supply system

Trigeneration systems have a highly integrated energy utilization and good energy saving efficiency. The energy utilization efficiency of traditional thermal power generation is 30%-47%, while the trigeneration system can reach up to 85%[26]. Compared to traditional distributed circuits, trigeneration systems not only realize cascade utilization of energy but also greatly reduce transmission losses of power, heating and cooling. This section will make a technical analysis of CCHP energy supply system from the perspective of cascade utilization of energy and energy efficiency evaluation.

Table 1

Nomenclature

4.1.1 Cascade utilization of cooling, heating and power energy systems

Constructions in China mostly use fuel and industrial power. The main energy demands are HVAC, hot water supply, electricity, and cooking, with these sectors consuming 65%, 15%, 14%, and 6% of the required energy, respectively. Of this energy, 80% is low-grade energy, with a large energy loss and low utilization efficiency[27].

Gas is an ideal clean fuel and is important for civilian and industrial applications. The traditional direct combustion methods make high-grade energy used in low-grade applications, thus wasting a great deal of heating in the flue gas and resulting in low energy efficiencies and extensive energy waste. From a technical and economic viewpoint, “high-grade energy used in low grade applications” is unreasonable. Presently, as an efficient energy utilization method, gas-fired CCHP systems, which are a type of poly generation energy system based on energy cascade utilization concepts, fully combine distributed generation and thermal technology by integrating cooling, heating and power generation. According to the principle of “temperature counterparts, cascade utilization”, trigeneration systems can meet the energy requirements of the subsystems. High-grade heat ($>450\text{ }^{\circ}\text{C}$) is a priority for power system generation. Medium-grade heat (approximately $170 \sim 450\text{ }^{\circ}\text{C}$) is used for thermodynamic systems in the low and medium temperature region. Low-grade heat (generally below $170\text{ }^{\circ}\text{C}$) is used for thermodynamic systems in the low temperature region to provide absorption of low-temperature heat[28]. The system combines generation, cooling and heating, realizes cascade utilization of primary energy and improves energy utilization efficiency.

In trigeneration systems, 30%-40% of the gas energy is converted into electricity, a higher conversion efficiency than that of boiler steam turbine units in thermal power plants. As high temperature flue gas is exhausted, the high temperature and high pressure steam goes into steam turbines for generation, making the energy efficiency reach more than 60%. The remaining energy can also be used to produce cooling and hot water for different levels of energy users. With full usage of the energy cascade system, a total energy efficiency of over 80% can be realized[29]. Compared to traditional thermal power generation, gas-fired CCHP has a great advantage in energy efficiency, and greatly reducing users' energy costs.

4.1.2 Energy saving effects of a CCHP system

Trigeneration systems are composed of a number of relatively independent subsystems and provide users with various energy products. Compared to conventional generation systems, the trigeneration system is much more complex. Due to the various degrees of cascade utilization, the system has a great potential for energy saving. Optimization methods vary in specific applications, thus the energy saving potential varies as well.

There are currently two main energy analysis methods[30,31]: the first law of thermodynamics analysis and second law of thermodynamics analysis. The first law of thermodynamics analysis primarily uses the heat balance principle and thermal efficiency as the basis criteria. This method analyses and evaluates energy-using equipment and the efficiency of the utilization of the system energy, which reflects the quantity energy conserved, and such parameters as the thermal efficiency and consumption rate. The second law of thermodynamics analysis is mainly entropy analysis, the law that energy quality must change in the procession of energy transfer and energy conversion. This section mainly analyses energy saving effects of trigeneration systems from the first law of thermodynamic analysis and focuses on energy utilization coefficient and energy savings rate indicators.

(1) Energy utilization coefficient

The energy utilization coefficient (total energy efficiency) reflects the ratio of the output (income) and input (pay). This indicator regards the cooling, heating and power (outputs) that the CCHP provides as equivalent without considering the differences between cooling and heating. The energy utilization coefficient, η_1 is calculated as

$$\eta_1 = \frac{w + c + h}{f_{CCHP}} \quad (1)$$

Where w is the specific power in kW/kg, c is the cooling capacity in kJ/kg, h is heating capacity in kJ/kg, and f_{CCHP} is the low calorific value of fuel corresponding to a unit of working fluid in the trigeneration system in kJ/kg.

At present, the energy utilization coefficient is still an important evaluation criterion to evaluate trigeneration system performance. It inspects system performance from the first law of thermodynamics analysis view.

(2) Energy saving rate

The energy saving rate is also known as the primary energy saving rate. The primary energy saving rate of CCHP system refers to the relative saving rate of primary consumption for heating, cooling and generation compared to an independent system. Primary energy consumption refers to the consumed fuel energy for getting some sort of energy output.

The primary energy saving rate F_{en} of trigeneration energy system is:

$$F_{en} = \frac{\Delta f}{f_{re}} = \frac{f_{re} - f_{CCHP}}{f_{re}} \quad (2)$$

Where, f_{re} represents the subsystems' fuel consumption under the same output in kJ/kg. If the saving rate is positive, the system is energy-saving; if the rate is negative, it is not energy-saving.

For conventional generation and trigeneration systems, the primary energy savings rate reflects the thermal economy difference between CCHP and independent production systems. For the different operation modes in trigeneration systems, we can also calculate the primary energy saving rate to choose a more economical one.

Generally speaking, the proportion of primary energy converted into electricity is already an important indicator of the economic development level, energy utilization efficiency and environmental protection situation[32]. To improve the total energy utilization efficiency, we need to produce high-grade energy (convert other types of energy into electricity) and adopt a CCHP method to realize energy cascade utilization at the same time. Thus the system can provide users electricity as well as heating and cooling, thereby improving energy efficiency.

4.2 Economic analysis of a CCHP energy supply system

Trigeneration distributed energy system investments require a comprehensive analysis. From the enterprises' economic benefits, enterprises should gain the energy saving efficiency as well as the necessary investment revenue. This section will perform an analysis from the aspect of system operation costs, operation incomes and related financial indicators.

4.2.1 Cost analysis of a CCHP system

(1) Initial investment K_0

The main investments for CCHP systems are the gas turbine systems, absorption chillers and heat boilers. The price of a gas turbine generally includes the control system and gas/diesel dual fuel system. Electricity generated by gas turbines can be directly connected to a 380 V power supply system and the frequency and peak can be adjusted. Control systems can be matched to the gas turbine and automated.

The construction competition period for each distributed systems is one year, while the period for a large gas-steam cycle system is about three years, corresponding to the actual situation. During the investment budget

procession, in each system, the production, repayment, depreciation and amortization periods should be the same so that comparability among all of the systems is maintained.

(2) Operation cost C_{fm}

After a trigeneration system is put into operation, the costs are generally for operation and maintenance, fuel, and so on. When a project is completed, the first two costs are considered to be unchangeable factors, or fixed costs. In general, the construction investment of a gas turbine cycle system is low, with a high degree of automation and low-labour capacity. Thus, compared with conventional coal-fired power plants, this system has a smaller proportion of fixed costs, typically 35%-55%.

As seen from the system configuration, among the fuels consumed by the systems, gas accounts for the largest proportion. In addition to the fuel used for the gas turbine, flue gases of direct-fired machines and waste heat boiler combustion also requires a large amount of fuel, so the cost of burning gas is the largest, reaching up to 45%-65%. For simplicity, the calculation models only consider the amount of gas consumed by a device, but not the total consumption during the operation process; because fuel costs are the largest, the operation of a system will depend on the gas price to a large extent.

The operation costs of trigeneration systems mainly involve the annual fuel cost (C_{fu}) and operation and maintenance costs (C_{ma}).

$$C_{fm} = C_{fu} + C_{ma} \quad (3)$$

$$C_{fu} = \frac{3600 \times W \times H \times p_f}{\eta_e \times \delta_1} \quad (4)$$

Where W is the generation power in kW, H is the annual hours of operation of the equipment, p_f is the fuel price in RMB/m³, η_e is generation efficiency in % and δ_1 is the fuel calorific value in kJ/m³.

4.2.2 Analysis of system revenue

For CCHP energy supply systems, there are two types of economic revenues (R_{al} , RMB) after the system is put into operation: electricity revenues (R_e , RMB) and cooling and heating revenues (R_c and R_h , RMB).

$$R_{al} = R_e + R_c + R_h \quad (5)$$

First, the first revenue of a project investment is electricity revenue. Commercial and industrial electricity prices are complex in China. We use the average prices to calculate for convenience, and we can also use the weighted value of the local tariff price. In the calculation process, the device power generation efficiency should

be taken into account according to the average local condition, and other attenuation factors do not need to be considered.

$$R_e = W \times H \times p_e = G \times p_e \quad (6)$$

Where, G is the generation capacity in kWh and p_e is the electricity price in RMB/kWh.

The second revenue of a project investment is cooling and heating revenue. To compare each system easily, we can take the maximum cost of production cooling and heating in a system as a reference price. For example, the calorific value calculation method considers the thermal efficiency after the waste heat boiler combustion, which is on the basis of gas price. Simultaneously, we also need to pay water charges.

$$R_h = \frac{Q_h \times d \times 24 \times 3600 \times p_h}{10^6} \quad (7)$$

$$R_c = \frac{Q_c \times d \times 24 \times 3600 \times p_c}{10^6} \quad (8)$$

Where Q_h and Q_c are the heating and cooling supplies in kW, respectively; d is the annual supply day; and p_h and p_c are the price of heating and cooling in RMB/GJ, respectively.

4.2.3 Financial indicators of economic evaluations

Economic effects are the core of investment project evaluations. The variety of economic effect evaluation indicators reflects the different views of project economics. Combining the need of economic evaluation of a CCHP system, this section selects three main indicators: investment payback period, net present value and internal rate of return for economic analysis,

(1) Net present value NPV

NPV refers to the balance between the present value of total income and the initial investment.

$$NPV = \sum_{t=1}^n \frac{F_t}{(1+i_0)^t} - K_0 \quad (9)$$

Where, F_t is the cash flow in year t in RMB, i_0 is the discount rate in % and K_0 is the initial investment in RMB

(2) Payback period

(i) Static investment payback period T_f does not consider the time value.

$$T_j = \frac{K_0}{A_t} \quad (10)$$

$$A_t = R_{al} - C_{fm} \quad (11)$$

Where A_t is annual net income in RMB.

(ii) Dynamic investment payback period T_D considers the time value and is the time when cumulative NPV is equal to zero.

$$T_D = \lfloor T_D - 1 \rfloor + \frac{|NPV_{\lfloor T_D - 1 \rfloor}|}{A_{\lfloor T_D \rfloor}} \quad (12)$$

Where, $\lfloor T_D - 1 \rfloor$ is the last year in which cumulative NPV is negative(in the year T_D , cumulative net present value is greater than zero); $|NPV_{\lfloor T_D - 1 \rfloor}|$ is the absolute value of NPV until the year $\lfloor T_D - 1 \rfloor$; $A_{\lfloor T_D \rfloor}$ is net income in the year $\lfloor T_D \rfloor$.

(3) Internal rate of return IRR

Internal rate of return is the project's ROI and refers to the discount rate calculated when the annual net cash flow equals zero during the entire calculation period. The internal rate of return reflects the project's resilience to investment spending; the higher the value is, the better the economy of the project. When the internal rate of return is bigger than the benchmark rate of return, the project is acceptable. It is an important financial indicator for the evaluation of investment projects.

$$\sum_{t=0}^n A_t (1 + IRR)^{-t} = 0 \quad (13)$$

4.3 Factors affecting the project economy and sensitivity analysis

To improve the reliability of economic analysis and scientific decision-making during the technical and economic evaluation of the project, we need to further analyse the impact of the uncertainty factors on the project economic indicators on the basis of the certainty analysis, to predict the possible risks after the implementation of a project[33].

4.3.1 Factors affecting the project economy

During operation, due to the impact of fuel, heating and electricity prices, the annual system utilization hours and other factors, the technical and economic data of a trigeneration system may change drastically in a dynamic

environment.

This section selects fuel prices, heating prices, electricity prices and annual heating days as the variables and makes an analysis of the project economy.

(1) Fuel price effects

Fuel costs make up a large proportion in the DES/CCHP system's operation costs, up to 78%, with a minimum of only 44%. Therefore, fluctuations in the gas price will directly affect the annual operation costs of the system.

(2) Heating and electricity price effects

Raising the heating and electricity price will increase investment incomes and improve the operation economy of the system. The higher the generation efficiency, the bigger the proportion that the powers supply makes up in the annual incomes. Therefore, the effect of electricity price is more than heating price effects

(3) Annual heating day effects

The longer the heating period, the higher the heating load and system energy utilization efficiency. This is the advantage of DES/CCHP systems. If only the heating load is adequate, the system can gain a considerable heating income.

4.3.2 Sensitivity analysis

Sensitivity analysis determines the variation of the decision-making evaluation index by changing one or more uncertainties. This allows for the discovery of the degree of influence that the changes have in achieving the desired objectives. Then, judgments regarding the capacity of the plan when the outside environment has adverse changes can be made.

The steps of a sensitivity analysis are as follows:

(1) Choose uncertainties that are necessary to analyse and set the range of variation of these factors.

There are two principals for selecting factors: changes in the factors will strongly affect the economic indicators in the possible scope of changes; or second, the accuracy of the factors' data is unclear.

(2) Perform the certainty analysis. Sensitivity analysis is based on a certain economic analysis. Generally speaking, the indicator of the sensitivity analysis should be consistent with the indicator of the certainty analysis and not exceed the scope of the certainty analysis.

(3) Calculate the change in the economic indicators caused by the change in uncertainties, establish the

corresponding quantity relationship, and express the information with a graph or table.

(4) Determine the sensitivity factors and make judgments regarding the risk in the given situation.

There are two ways to determine the sensitivity factors. The first method is the relative evaluation method, which sets the value of the changing factors to begin with the value used in the certainty analysis and uses the same magnitude of change for each iteration. Then, with the same magnitude of change, the impacts on the economic indicators are compared, and the degree of sensitivity of the plan's economic effects with various factors is judged based on the level of the impacts. The second method is the absolute measurement method, which sets changing factors to be negative and selects the most unfavourable value. According to this method, calculations of the economic indicators are made to see if the project can be accepted in this situation.

4.4 The energy-saving effect analysis of CCHP considering the economic efficiency of grid enterprises

A distributed energy system is always built around load centres. This provides users with low-price electricity, reduces the quantity of electricity purchases from the grid enterprise to some degree and influences electricity sales directly[34]. On the other hand, the grid enterprises also reduce or even avoid the transformation investment into power transmission equipment due to the reduced electricity sales.

This section will mainly consider two situations: first, a situation with owners involved in the entire construction process, operation and maintenance; second, a situation is considered in which the owners are only involved in construction, but not in operation or maintenance. This section will also introduce the impact of a trigeneration system on grid enterprises from three aspects: electricity sales, energy savings efficiency, as well as transmission and distribution investments. Finally, by comparing the balance of reduced investments, energy savings efficiency and electricity sales revenue, the impact of a trigeneration system on the grid enterprises' economic benefits is analysed.

4.4.1 Owner involvement in the whole process of construction, operation and maintenance.

Owners involved in the whole process of construction, operation and maintenance affect the grid companies' economic benefits in three main aspects: reduction of revenue from electricity sales, reduction of network losses and avoidance of unnecessary investments in transmission and distribution. The details are as follows:

(1) Reduction of revenue from electricity sales

User-side distributed energy supply systems have a certain impact on the existing power system. They affect power systems' interests, leading to the reduction of electricity sales. Assuming the sale price does not change reductions in the grid companies' electricity sales and earnings in the distributed system come from the following two areas:

(i) Reduced terminal electricity sales ΔE_a

Reduced terminal electricity sales are the reduced electricity purchases from grid enterprises due to users' participation in distributed energy systems.

$$\Delta E_a = u \times T_E \quad (14)$$

Where, u is user participation rate and T_E is the electricity reduction owing to the distributed generation.

(ii) Reduced revenue B_{rd}

Reduced revenue is the annual reduced revenue of grid enterprises because of the reduced electricity sales.

$$B_{rd} = \Delta E_a \times (p_e - p_m) \quad (15)$$

Where, B_{rd} is the annual reduced electricity revenue of grid enterprises in RMB, ΔE_a is the power supply of the distributed system in MW, p_e is the sale price, and p_m is the purchase price in RMB.

(2) Avoidable investment in transmission and distribution and network losses

Distributed energy systems that are built near the load centre reduce the dependence of users on the power grid because they are meeting their own demand, thus indirectly reducing investments in transmission and distribution.

(i) Reduced terminal capacity ΔP_a in MW

Reduced terminal capacity is the power that users can reduce in the distributed energy supply system.

$$\Delta P_a = u \times T_p \quad (16)$$

Where, T_p is the capacity reductions due to the distributed generation.

(ii) Avoidable investments in transmission and distribution (C_s).and network losses (C_l).

$$C_s = p_{sc} \times \Delta P_a \quad (17)$$

$$C_l = p_l \times \Delta E'_a \times p_m \quad (18)$$

where p_{sc} is the supply cost of the unit load capacity of the supply side, including the substation and line construction, as well as maintenance and repair costs; p_l is loss reduction rate, Per kilowatt, the distributed system generation can replace $(1+p_l)$ kilowatts of purchased electricity from market; $\Delta E'_a$ is CCHP system's power

production.

(3) Sharing energy saving efficiency

In the beginning of the construction of a distributed energy supply system, as the construction side, grid enterprises sign sharing energy saving efficiency contract with users, determining the sharing energy savings efficiency ratio (θ_1). Then, the grid enterprises can share the annual energy savings benefits, ΔR :

$$\Delta R = \theta_1 \times (R_{it} - C_{it}) \quad (19)$$

Among them, R_{it} is the total revenue in RMB, C_{it} is the total spending in RMB.

(4) Economic benefits

Distributed energy impacts on the efficiency of grid enterprises mainly reflect through electricity income and transmission investments. During the process, grid enterprises will gain part of the financial compensation by sharing users' energy savings efficiency (ΔR) every year. By discounting the annual sharing energy savings efficiency and the reduced electricity sales and by comparing the initial investment in transmission and distribution, we can determine the impact of the distributed power supply system on the economic efficiency of the enterprises.

$$B_p = (\Delta R + C_t - B_{rd}) \left(\frac{(1+i)^t - 1}{i(1+i)^t} \right) \quad (20)$$

$$\Delta C = B_p + C_s - K_0 \quad (21)$$

Where, ΔC is the balance of discounted net income and reduced transmission and distribution investment. If $\Delta C < 0$, it is clear that distributed energy affects the economic benefits of grid companies; if $\Delta C > 0$, distributed energy increases economic efficiency of grid enterprises.

4.4.2 Owner involvement in investments

Owners only participate in investments in the distributed system, while a third party energy company is responsible for the operation and maintenance work. Owners and third party energy companies both participate in the sharing of energy savings efficiency. The impact of this case on the grid companies is similar to the prior case, the difference being that the operation and maintenance work is handed by the third party energy service companies, resulting in greatly reduced operation and maintenance costs because of the professional maintenance. This setup also increases energy savings efficiency, thereby further shortening the payback period.

5 Empirical studies in typical trigeneration projects

The "trigeneration" project—the Beijing Gas Group control centre building is used as an example[35]. The project aims to meet the electricity, heating in winter and cooling in summer demand of the Beijing Gas Group dispatch building. Here we completely show how to select final gas-fired CCHP investment plan in practical work in China. First, according to investment budget, actual energy use requirements, etc., several possible programs will be proposed, then final investment plan will be determined through techno-economic analysis among these proposed programs. This section selects three programs compiled by the Shanghai Power Equipment Research Institute to study the economic efficiency of distributed trigeneration and to analyse the impact of a distributed system on the economic efficiency of grid enterprises when they are involved in the investment in the system.

5.1 Economic analysis of the programs

(1) Installed programs

According to actual operations in the Beijing region, the basic indicators about design indicators, operation hours, tariff calculation, determined values of heating costs and natural gas storage component analysis of the project are listed in reference [35]. Some important data or value related to this case is shown in Table 3.

Table 3

Important Data Needed in the Case

Scenario 1, gas/steam combined cycle cogeneration program, namely: GT - waste heat boiler - steam lithium bromide absorption air conditioning solutions. First, the gas turbine generates electricity using gas and a heat recovery boiler converts the waste heat in the flue gas into steam. A heat exchanger uses the hot water for heating in winter and a steam lithium bromide absorption air conditioning system for cooling in the summer. The basic configuration of the gas turbine is shown in Table 4.

Table 4

Gas Consumption in Gas Turbine

Scenario 2, GT - heat / direct-fired lithium bromide absorption air conditioners combined cycle solution. This program also uses gas for generation of electricity in a gas turbine; the difference is that the heat from the flue gas

is directly converted using the heat/direct-fired lithium bromide absorption air conditioners, which converts hot water for heating in winter and cold water for cooling in summer. The basic configuration of the gas turbine is shown in [Table 4](#).

Scenario 3, the gas engine - Parallel heat / direct-fired lithium bromide absorption air conditioners combined cycle solution. First, gas is used for power generation; the waste heat is cooled in water by the flue gas from an internal combustion engine and liner and is directly used to shunt heat/direct-fired lithium bromide absorption air conditioners for recycling. Then, the waste heat is used for heating in winter and cooling in summer. The cooling water is used in the intercooler for the engine as the buildings' living water. The basic configuration of a gas engine is shown in [Table 5](#).

Table 5

Gas Consumption in Gas Engine

(2) Analysis of the financial indicators

(i) The payback period

According to basic data, the investment estimate of the energy supply system can be obtained as shown as in [Table 6](#). The investment cost-benefit analysis of the project is shown in [Table 7](#).

The payback periods of the three programs do not exceed five years and are all worthy of consideration. We can make this judgment according to the actual situation of the Beijing Gas Group as well as the development plan of the surrounding region. Because the device is placed in the basement of the Beijing Gas Group dispatch centre, space is limited. Therefore, it is recommended that scenarios 2 and 3 be used.

(ii) Internal rate of return

The best program was determined by comparing the internal rate of return of scenarios 2 and 3. These results are shown in [Tables 8 and 9](#). [Annual fuel costs data, operating costs data and revenue data in Tables 8 and 9 are all from Table 7](#). The first year is the construction and commissioning period.

Table 6

Investment Estimate of Each Project

Table 7

Comparative Analysis of Investment, Cost and Revenue of Each Project

Table 8

Scenario 2, 20 Years Wholly Internal Rate of Return

Table 9

Scenario 3, 20 Years Wholly Internal Rate of Return

By comparing the internal rate of return in scenarios 2 and 3, we can determine that they both have a good return on investment, with scenario 2 being slightly better than scenario 3.

(3) Sensitivity analysis

This section analyses scenario 2, assuming that the acceptable payback period is less than six years, and mainly examines the impact of two factors on the payback period: gas prices and electricity prices. The gas price has the biggest impact on the total expenditures. The generated revenue makes up the biggest proportion of the total revenue, and the power price has the biggest influence on revenue.

(i) The impact of changes in the gas price on the payback period is shown in [Table 10](#), and the sensitivity analysis is shown in [Figure 2](#).

(ii) The impact of changes in the sales price on payback period is shown in [Table 11](#), and the sensitivity analysis is shown in [Figure 2](#).

Table 10

The Impact of Gas Price Changes on the Payback Period

Table 11

The Impact Sales Price Changes on the Payback Period

Figure 2 The sensitivity analysis chart of the affecting factors

According to the analysis shown in Table 10, Table 11 and Figure 2, gas prices and electricity prices are the most sensitive factors in scenario 2. Before making a decision about whether to adopt the scenario, we should make a more accurate prediction and estimation regarding the possible changes in the range of gas and electricity prices. If it is possible that the gas price exceeds 13.5% of the original expected price or electricity price is less than 12.1% of the original expected price, there is a large investment risk, and it is difficult to recover all of the investment within an acceptable payback period.

5.2 Energy savings efficiency analysis of a gas-fired CCHP considering the economic efficiency of grid enterprises

Scenario 2 is the best scenario, assuming that the Beijing Electric Power Company is responsible for the project and there is an energy savings efficiency sharing construction plan signed with the owners. The calculation period for the project is twenty years. Then, its impact on the economic efficiency of Beijing Electric Power Company during the entire project life cycle is analysed, and the energy efficiency ratio is determined based on analysis. Basic data in this section are all from tables 7, 8 and 9.

(1) Reduced electricity sales revenue

In scenario 2, the annual generation capacity of the CCHP energy supply system is 2835620 kWh; the average selling price for the commercial and industrial sectors is 0.7525 RMB/kWh; the average purchase price is 0.6142, and the annual reduced electricity sales revenue for the grid enterprises is:

$$B_{rd} = \Delta E_a \times (p_e - p_m) = 2835620 \times (0.7525 - 0.6142) = 39.2166 \text{ ten thousand Yuan}$$

(2) Avoidable transmission and distribution investment and net loss

The capacity of a CCHP energy supply system in scenario 2 is 1177KW. For power construction, the average cost of a unit of installed capacity is 0.1 ten thousand Yuan/KW, and the avoidable transmission and distribution investment in grid corporation is:

$$C_s = p_s \times \Delta P_a = 1177 \times 0.1 = 117.7 \text{ ten thousand Yuan}$$

If the distributed generation loss reduction rate is 10%, the reducible net loss of the Beijing Power Supply Company per year is:

$$C_l = 10\% \times 2835620 \times 0.6142 = 17.4163 \text{ ten thousand Yuan}$$

(3) Annual sharing energy efficiency

This analysis assumes that the contract signed by the owners and Beijing Power Supply Company sets the sharing energy efficiency rate of CCHP system to θ . The total revenue in the distributed energy supply system is 3,802,666 Yuan, and the total expense is 1,812,842 Yuan. Then, the annual power-saving benefits to be shared are:

$$\Delta R = \theta \times (3802666 - 1812842) = 198.9824\theta$$

(4) Analysis of economic efficiency

Take avoidable transmission and distribution investment, discounted annual sharing total revenue (see Table 5) and grid loss as grid enterprises' benefit, take initial investment cost and discounted annually reduced electricity sales share as cost, impact of a distributed power supply system on the economic efficiency of grid enterprises can be shown as the following equation. Assuming the benchmark discount rate is 5%.

$$\Delta C = C_s + B_P - K_0 = 117.7 + (198.9824\theta + 17.4163)(P/A, 5\%, 20) - 889.5 - 39.2166(P/A, 5\%, 20)$$

$$(P/A, 5\%, 20) = 12.462$$

When $\Delta C = 0$, we can obtain an energy-sharing ratio $\theta = 0.4208$, which is the situation in that the Beijing Power Company obtains a balanced economic efficiency. To avoid affecting its economic efficiency, the Beijing Power Company's annual energy savings sharing ratio should not be less than 0.4208 during the specified operating period when the company signs the contract with owners. That is, the Beijing Power Company needs a proportional sharing energy efficiency during the entire life cycle of the equipment when the ratio is 0.4208. When the energy efficiency sharing ratio increases to 0.7, while $\Delta C = 0$, we can obtain $(P/A, 5\%, T_D)$ is 6.569. Using the table of present value of annuity, we know that $(P/A, 5\%, 8)$ is 6.463 while $(P/A, 5\%, 9)$ is 7.107, payback period T_D of Beijing Power Supply Company is 8.16 calculated by interpolation method in this scenarios.

6 Conclusions

The paper makes technical and economic evaluation of Gas-fired CCHP project. First, elaborate the basic principles and steps of investment project evaluation. Then select three trigeneration projects of Beijing Gas Group for empirical analysis. Finally summarize the following conclusions through the theoretical and empirical analysis.

(1) Gas-fired CCHP system is good to both customers and beneficial

Currently, distributed energy investment mode gradually transforms into maintenance and construction of third-party energy companies, and investors participate in sharing energy efficiency. It should be noted that investors should sign construction contract of distributed energy supply system and make clear of the rights and

obligations of the construction and operation process of the whole system, especially make clear of the energy efficiency ratio that investors can share when system operates.

(2) Revenue of Gas-fired CCHP system is influenced by fuel price and electricity price greatly.

During the operation process, operation costs of trigeneration energy supply system is mainly fuel costs and operation and maintenance costs, and the fuel costs have a larger uncertainty in the future market. We can see from the examples, changes in fuel price is bound to affect the payback period of the project, and changes in electricity price will also affect the payback period owing to the changes in revenue. In order to avoid possible acceptable risks or reduce the influence of risks in the future, we need make accurate predictions of fuel and electricity price before making investment decisions.

(3) A reasonable energy efficiency sharing ratio will help to the recovery of investment in Gas-fired CCHP

When a third-party, such as energy service companies, participates in construction process of distributed energy projects, the revenue mainly comes from the sharing energy efficiency of Gas-fired CCHP. Therefore, we should determine the energy efficiency sharing ratio according to the specific projects to ensure reasonable revenue.

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Figure 1

Figure 2

Table 1

Development of gas-fired CCHP system in Beijing

Project Location		Equipment	memo
1	Beijing Gas Group monitoring center	A 480kw and 725kw gas engine	Already in operation
		A BZ100 and BZ200 type direct fired machine	
2	Beijing South Railway Station	Two 1600kW gas engine	Already in operation
3	Beijing Olympics Energy Exhibition Center	13300kw gas turbine	Already in operation
4	Beijing Ciqu station building	A 80kw Bowman gas micro turbine	Already in operation
		A 200000 kcal direct-fired heat	
5	Beijing Gaobeidian sewage treatment biogas thermal power stations	Four 513kw 6GTLB type biogas engine	Already in operation
		Three 710kw JM316GS-B/L type biogas engine	
6	Software Square	A 1200kw solar gas turbine	Being built
		A 2.5 million kcal direct-fired heat	
7	International Mall	Two 4000kw solar Sagittarius 40 gas turbine	Being built
		Two 20t/h reburn HRSG	
8	Water Conservancy Hospital	115kw	Being built
9	Peixin business building	180kw	Being built
10	Tsinghua Wenjin	2400kw	Being built
11	Boland Heating Company	1200kw	Being built
12	Beijing Capital Airport Expansion (North) 13300kw	Two 1200kw gas turbine	Being built
13	Beijing University of Posts and Telecommunications	Two 2400kw gas turbine or three 1800kw internal combustion engine	Completed research

14	Beijing International Automotive Expo Center	Two 2850kw gas engine	Completed preliminary feasibility study
15	Beijing International Trade Center phase three project	Two 4000kw solar Sagittarius 40 gas turbine Two 20t/h reburn HRSG	Feasibility study
16	Zhongguancun Life medical chart	14500kw	Project development
17	Blankly Bear Casino	1500kw	Project development
18	Beijing World Trade Business Center	3500kw	Project development

Table 2**Nomenclature**

<i>Items</i>	Symbols and units	<i>Items</i>	Symbols and units
w	The specific power (kW/kg)	G	The generation capacity
c	The cooling capacity (kJ/kg)	K_0	The initial investment (RMB)
h	The heating capacity (kJ/kg)	T_J	The static investment payback period (year)
f_{CCHP}	The low calorific value of fuel corresponding to a unit of working fluid in the trigeneration system (kJ/kg)	T_D	The dynamic investment payback period (year)
F_{en}	The primary energy saving rate (%)	A_t	The annual net income in year t (RMB)
f_{re}	The subsystems' fuel consumption under the same output (kJ/kg)	$T_D - I_*$	The last year in which cumulative NPV is negative (year)
C_{fm}	The operation cost of trigeneration systems (RMB)	$ NPV_{T_D - I_*} $	The absolute value of NPV until the year $T_D - I_*$ (RMB)
C_{fu}	The annual fuel cost (RMB)	IRR	The internal rate of return (%)
C_{ma}	The operation and maintenance costs (RMB)	ΔE_a	The reduced terminal electricity sales (kWh)
W	The generation power (kW)	u	user participation (user)
p_f	The fuel price (RMB/m ³)	T_E	The electricity reduction owing to the distributed generation (kWh)
η_e	The generation efficiency (%)	B_{rd}	The annual reduced electricity revenue of grid enterprises (RMB)
δ_l	The fuel calorific value (kJ/m ³)	p_s	The price of electricity sold (RMB)
R_{al}	The economic revenues (RMB)	p_m	The price of electricity purchased (RMB)
R_c	The electricity revenues (RMB)	T_P	The capacity reductions due to the distributed generation (MW)
R_c	The cooling revenues (RMB)	C_s	Avoidable investments in transmission & distribution (RMB)
R_h	The heating revenues (RMB)	C_l	Avoidable investments in transmission network losses (RMB)
p_e	The electricity price (RMB/kWh)	p_{sc}	The supply cost of the unit load capacity of the supply side (RMB)
Q_h	The heating supplies (kW)	p_l	The loss reduction rate (%)
Q_c	The cooling supplies (kW)	$\Delta E_a'$	CCHP system's power production (MW)
d	The annual supply days (day)	θ_l	The sharing energy savings efficiency ratio (%)
p_h	The price of heating (RMB/GJ)	ΔR	The energy saving revenue (RMB)
p_c	The price of cooling (RMB/GJ)	R_{tl}	The total revenue (RMB)

NPV	The net present value	C_{it}	The total spending (RMB)
F_t	The cash flow in year t (RMB)	B_p	The discounted net income (RMB)
i_0	The discount rate (%)	ΔC	The balance of discounted net income and reduced transmission and distribution investment (RMB)

Table 3
Important data needed in the case

Project	Unit	Value
Sale price of electricity	Yuan/kWh	0.768
Heating price	Yuan/GJ	
Scenario 1	Yuan/GJ	103.64
Scenario 2	Yuan/GJ	95.12
Scenario 3	Yuan/GJ	103.64
Cooling price	Yuan/GJ	
Scenario 1	Yuan/GJ	82.40
Scenario 2	Yuan/GJ	82.40
Scenario 3	Yuan/GJ	70.75
Gas price	Yuan/m ³	1.4
Annual operating hours	hour	2510
Winter (heating)	hour	1050
Summer (cooling)	hour	880
Spring and fall (non-heating& cooling)	hour	580
User participation rate ¹	%	
Scenario 1	%	100
Scenario 2	%	100
Scenario 3	%	100

¹: The object of this case is a single commercial building, which means that all users in this building participate the DCCHP project. Therefore, user participation rate (w in equation 14 and 16) is 100% in all three scenarios.

Table 4
Gas Consumption in Gas Turbine

Project	Unit	Consumption
Capacity	kW	1177
Heat consumption of unit capacity ¹	kJ/kWh	14223
Total fuel consumption	GJ/h	16.74
Calorific value of gas	kJ	35169
Gas consumption	m ³ /h	476
Hours of operation	hours/year	2510
Annual gas consumption	m ³	1193615

¹: Heat consumption of unit capacity means the heat needed to maintain the out power of 1kW, the efficiency has been taken into account in this value.

Table 5
Gas Consumption in Gas Engine

Project	Unit	Consumption
Capacity	kW	975
Heat consumption of unit capacity ¹	kJ/kWh	10494
Total fuel consumption	GJ/h	10.23
Calorific value of gas	kJ	35169
Gas consumption	m ³ /h	291
Hours of operation	hours/year	2510
Annual gas consumption	m ³	730202

¹: Heat consumption of unit capacity means the heat needed to maintain the out power of 1kW, the efficiency has been taken into account in this value.

Table 6
Investment Estimate of Each Project

Project or fee name	Unit	Scenario 1	Scenario 2	Scenario 3
Prime mover price	Ten thousand RMB	539.5	539.5	273.9
Heat or auxiliary boilers	Ten thousand RMB	80		
Steam LiBr chiller	Ten thousand RMB	200		
Heat type - direct-fired lithium bromide air conditioning	Ten thousand RMB		250	265
Total cost of equipment	Ten thousand RMB	819.5	789.5	538.9
Installation fee	Ten thousand RMB	120	100	100

Table 7

Comparative Analysis of Investment, Cost and Revenue of Each Project

Project	Condition	Unit	Scenario 1	Scenario 2	Scenario 3
			Gas turbine - boiler - air conditioning	GT - Direct Fired	Engine - Direct Fired
Annual generation capacity	Winter	kWh	1228500	1228500	1018500
	Summer	kWh	938960	938960	853600
	Spring, autumn	kWh	668160	668160	562600
Total generating capacity ¹	All the year	kWh	2835620	2835620	2434700
Generation revenue ²	All the year	RMB	2178890	2178890	1870823
Annual heat supply ³	Winter	MWh	2345	2825	2345
	Summer	MWh	2214	2214	2214
Total heat supply	All the year	MWh	4559	5038	4559
Heat revenue ⁴	All the year	Yuan	874946	967046	874946
Cooling revenue	All the year	Yuan	656730	656730	563877
Prime mover fuel costs ⁵	Winter	Yuan	715582	715582	427648
	Summer	Yuan	575905	575905	358410
	Spring, autumn	Yuan	379574	379574	236225
Total fuel costs of prime mover	All the year	Yuan	1671061	1671061	1022283
Direct burning's fuel costs ⁶	Winter	Yuan			188926
	Summer	Yuan			197960
	Spring, autumn	Yuan			
Total direct burning's	All the year	Yuan			386885

fuel costs					
Total fuel costs	All the year	Yuan	1671061	1671061	1409168
Operation and maintenance costs per kWh			0.06	0.05	0.09
Operation and maintenance costs ⁷		Yuan	170137	141781	219123
Total expenditure	All the year	Yuan	1841198	1812842	1628291
Total revenue	All the year	Yuan	3710566	3802666	3309646
Save money	All the year	Yuan	1869368	1989824	1681355
Project investment	All the year	Ten thousand Yuan	939.5	889.5	638.9
Dynamic payback period (i=5%)		Year	5.93	5.18	4.32

¹: Theoretically, Generation capacity is the product of the installed capacity and operating hours. (1177kW*2510h=2954270kWh in scenario 1 and 2. 975kW*2510h=2447250kWh in scenario 3.) However, in actual production process, generation capacity is less than the theoretical value. The value used here is estimated according to the designed value and the actual operation value of the same kind of unit.

²: Generation revenue is the product of generation capacity and the price of electricity. (The electricity price is 0.768Yuan/kWh, which is given in Table 1.)

³: The value used here is obtained from the developers of this project. The value is estimated according to the designed heat-to-electric ratio and the actual operation value of the same kind of unit.

⁴: Heating and cooling revenue are the product of heating and cooling supply and the price of them. (The price of heating and cooling are given in Table 1.)

⁵: Fuel costs of prime mover is the product of gas consumption and the price of gas.

^{6,7}: Direct burning's fuel costs and O&M costs are taken from reference [36].

Table 8

Scenario 2, 20 Years Wholly Internal Rate of Return

	Year	Principal	Interest	fuel costs	Operating costs	Revenue	Balance
		5%					
1	2002	7,560,750		278,510	23,630	633,778	-7,229,113
2	2003	8,895,000	361,456	1,671,061	141,781	3,802,666	-1,334,250
3	2004	7,266,632	444,750	1,671,061	141,781	3,802,666	
4	2005	5,721,558	363,332	1,671,061	141,781	3,802,666	
5	2006	4,095,066	286,078	1,671,061	141,781	3,802,666	
6	2007	2,391,320	204,753	1,671,061	141,781	3,802,666	
7	2008	606,249	119,566	1,671,061	141,781	3,802,666	
8	2009		30,312	1,671,061	141,781	3,802,666	1,264,008
9	2010			1,671,061	141,781	3,802,666	1,989,824
10	2011			1,671,061	141,781	3,802,666	1,989,824
11	2012			1,671,061	141,781	3,802,666	1,989,824
12	2013			1,671,061	141,781	3,802,666	1,989,824
13	2014			1,671,061	141,781	3,802,666	1,989,824
14	2015			1,671,061	141,781	3,802,666	1,989,824
15	2016			1,671,061	141,781	3,802,666	1,989,824
16	2017			1,671,061	141,781	3,802,666	1,989,824
17	2018			1,671,061	141,781	3,802,666	1,989,824
18	2019			1,671,061	141,781	3,802,666	1,989,824
19	2020			1,671,061	141,781	3,802,666	1,989,824
20	2021			1,671,061	141,781	3,802,666	1,989,824
21	2022			1,671,061	141,781	3,802,666	1,989,824
		IRR					
		9.40%					

Table 9

Scenario 3, 20 Years Wholly Internal Rate of Return

Year		Principal	Interest	fuel costs	Operating costs	Revenue	Balance
		5%					
1	2002	5,430,650		278,510	36,512	551,608	-5,194,073
2	2003	6,389,000	259,704	1,671,061	219,123	3,309,646	-958,350
3	2004	5,229,632	319,450	1,671,061	219,123	3,309,646	
4	2005	4,129,231	261,462	1,671,061	219,123	3,309,646	
5	2006	2,971,233	206,462	1,671,061	219,123	3,309,646	
6	2007	2,391,320	148,562	1,671,061	219,123	3,309,646	
7	2008	487,334	87,912	1,671,061	219,123	3,309,646	
8	2009		24,367	1,671,061	219,123	3,309,646	844,216
9	2010			1,671,061	219,123	3,309,646	1,419,461
10	2011			1,671,061	219,123	3,309,646	1,419,461
11	2012			1,671,061	219,123	3,309,646	1,419,461
12	2013			1,671,061	219,123	3,309,646	1,419,461
13	2014			1,671,061	219,123	3,309,646	1,419,461
14	2015			1,671,061	219,123	3,309,646	1,419,461
15	2016			1,671,061	219,123	3,309,646	1,419,461
16	2017			1,671,061	219,123	3,309,646	1,419,461
17	2018			1,671,061	219,123	3,309,646	1,419,461
18	2019			1,671,061	219,123	3,309,646	1,419,461
19	2020			1,671,061	219,123	3,309,646	1,419,461
20	2021			1,671,061	219,123	3,309,646	1,419,461
21	2022			1,671,061	219,123	3,309,646	1,419,461
		IRR					

Table 10

The Impact of Gas Price Changes on the Payback Period

The magnitude of gas price changes	-20%	-15%	-10%	-5%	0	5%	10%	15%	20%
Scenario 2 dynamic investment recovery period	4.35	4.54	4.73	4.95	5.18	5.45	5.73	6.05	6.41

Table 11

The Impact Sales Price Changes on the Payback Period

The magnitude of power price changes	-20%	-15%	-10%	-5%	0	5%	10%	15%	20%
Scenario 2 dynamic investment recovery period	6.91	6.38	5.92	5.53	5.18	4.88	4.61	4.37	4.15