ABSTRACT

As one of the most developed and energy intensive cities in China, the Shanghai's municipal government tries to make Shanghai one of the leading cities of energy conservation in China. Expanding the use of combined heat and power (CHP) system is the one of the main ways to optimize Shanghai's energy structure and to protect its environment. This paper aims to analyze the feasibility of introducing CHP in the central business district, in Shanghai, to determine the energy savings, environmental impact and economic efficiency. Three types of energy supply systems are considered: electricity-only system, 2 CHP systems with electric tracking and thermal tracking. Relative to the conventional electricity-only system, the CHP systems are capable of reducing the primary energy consumption by approximately 24% and 4%, CO₂ emission by 38% and 11%, respectively. For CHP, although the initial costs are often substantially higher than a conventional system, it is expected to dramatically reduce the cost of running. The result shows if introducing CHP, it only takes approximately 5 years can return the initial investment, in each case. This implies that the introduction of CHP can achieve high profitability.
INTRODUCTION

Combined heat and power (CHP), also known as co-generation, is an efficient, environment-friendly system that generates electricity and useful thermal energy in a single, integrated system.

At present there are very few small-scale CHP systems in China. In order to fulfill the long-term goal of development, huge energy consumption will be needed (social and economic). With the progress of economic development, carbon dioxide emissions are expected to increase continually as well as other pollution because of undeveloped environmental regulation, and lack of less interest in related problems. However, if pollution limitations are appropriately considered, environmental improvement can be achieved.

This study examines the feasibility of introducing CHP in the central business district of Shanghai. Furthermore, in order to assess potential adoption, many benefits (energy cost decrease, energy efficiency increase and environmental quality improvement) are analyzed.

Shanghai is situated in the east of China. It is well known that Shanghai is the largest economic centre, harbour, and integrated industrial city with a great volume of international trade, and is one of the most developed cities in China. Xuhui District, as shown in Fig. 1, is situated southwest of the centre of Shanghai. It has a flourishing economy, with all the functions and amenities of a bustling commercial area, and a comfortable high-grade residential district.
RESEARCH CHART

Fig. 2 shows a schematic of the analysis. Firstly, hourly energy consumption intensity for heating, cooling, hot water and electricity of Tokyo is presumed to apply to the corresponding conditions of Shanghai. Secondly, based on floor area, three prototypes of energy demand can be calculated. Simultaneously, some relative factors can be applied, such as generator efficiency and unit prices for various equipments. Then, the initial cost and energy consumption can be calculated. If the price of gas and electricity and CO₂ emissions rate are the known data, the running cost and the quantity of CO₂ emission can be calculated. Thirdly, the performance of economic, CO₂ emission and primary energy consumption of different energy systems can be evaluated. Finally, a comparison study of various systems can be conducted by analyzing different cases.

To analyze the energy saving, CO₂ reduction and economics of the above systems, the following energy consumption intensity, energy system, the cost and unit price of gas and electricity must be defined.

CASE SETTING

Based on the above-mentioned hourly heat and electricity loads, three different options, a conventional system (case 1) and CHP of 2 cases (case 2 and 3) are compared. Unlike many CHP models and analyses that only consider thermal loads, this study also considered the case of tracking electricity.

The conventional system alternative is described in Fig. 3. In this case, electricity demand is only supplied by utility electricity company. Cooling is provided by use of absorption chillers (A-Chillers), heat exchangers (H-EX) provide for the heating and hot water demand.

CHP is illustrated in Fig. 4. Heat (including heating load and hot water) and cooling load, are provided for mainly by utilizing recovered heat which supplies the heat exchanger and absorption chillers.

Another option is combining CHP with a Gas-Boiler, is shown in Fig. 5. If the heat demand does not satisfy the quantity what is necessary, it must be augmented by the gas-boiler. That is to say, in case 2 is tracking electricity, case 3 track thermal.

Fig.3. System Plan of Case 1

Fig.4. System Plan of Case 2

Fig.5. System Plan of Case3
ASSESSMENT OF ENERGY CONSUMPTION INTENSITY

The main building types considered are in this paper office, commercial and residence, with floor areas of 1,865,832 m², 1,458,629 m² and 3,127,000 m², respectively. It referred to the paper which used mathematical model to gain these data ⁹).

Although there are many research efforts on energy consumption underway, there is no energy consumption intensity data for Shanghai yet. However, they are much the same latitude between Tokyo at (35.40°) and Shanghai (31.23°). Shanghai has a subtropical monsoon climate with four distinct seasons. Also both of two have obvious season changes, with temperature big differences between winter and summer. Fig.6 shows the differences of annual average air temperature and sunshine times between the two cities. Annual average temperature is about 17 degrees C in Shanghai, 16 degrees C in Tokyo; humidity is 75% and 61%; and sunshine times are 1823 and 1714 hours respectively. Therefore, it is possible to assess energy consumption intensity of Shanghai according to the Tokyo experience. The method of presuming corresponding data which uses the same method used to calculate the energy consumption intensity of Shenzhen ²).

There are many kinds of energy consumption intensity information in Japan, for instance, Ojima’s hourly, monthly energy consumption intensity ³) and yearly energy consumption intensity from a Japanese co-generation system ⁴).

From a paper by Ojima (Ojima, 1995) it is possible to assess the unit load per square meter for heating, cooling, hot water and electricity in different months for prototype buildings and that is what is adopted in this paper. For example, yearly energy consumption intensity of heating, cooling, hot water and electricity of the office is assumed 31 Mcal/m², 70 Mcal/m², 2.2 Mcal/m² and 156 kWh/m².

CALCULATION METHOD OF EQUIPMENT CAPACITY, ENERGY SAVING, ENVIRONMENTAL AND ECONOMICAL PERFORMANCE

In this paper, equipment cost and running and maintenance cost for each option are discussed. By the way, equipment unit price, CO₂ emission intensities and energy price are based on the hourly energy consumption during a year. The maximum value and equipment efficiency can be estimated. Therefore, it
Table 1. Parameter and Constants

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Emission Rate</td>
<td>262.16 g·C/kWh</td>
</tr>
<tr>
<td>Grid Power</td>
<td>15.29 g/MJ</td>
</tr>
</tbody>
</table>

Equipment Parameter

<table>
<thead>
<tr>
<th>Item</th>
<th>Initial Cost</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Engine</td>
<td>5000 RMB/kW</td>
<td>(Power Generation) 30%</td>
</tr>
<tr>
<td>Boiler</td>
<td>0.036 RMB/kJ/h</td>
<td>(Heat Recovery) 45%</td>
</tr>
<tr>
<td>Absorption Chiller</td>
<td>0.358 RMB/kJ/h</td>
<td>85%</td>
</tr>
</tbody>
</table>

Note 1: The maintenance cost was assumed to be 1% of initial cost.

Note 2: Terminal efficiency of utility electricity accounts for 33.25%.

Table 2. Energy Price

<table>
<thead>
<tr>
<th>Energy (RMB/kWh)</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak 8:00h-11:00h</td>
<td>0.9843</td>
</tr>
<tr>
<td>Shoulder 12:00h-17:00h</td>
<td>0.6243</td>
</tr>
<tr>
<td>Other Times 18:00h-23:00h</td>
<td>0.2863</td>
</tr>
</tbody>
</table>

Gas (RMB/Nm³) 1.6

is possible to assume rated capacity of various equipments (CHP, boiler and absorption chillers) for energy supply systems. Environmental impact is an important factor which cannot be neglected in any project. In the paper, CO₂ output for every option is calculated using the emission rate per cubic meter from Table 1⁵. Finally, the total natural gas and electricity consumptions are also calculated. According to the capacity and unit price of equipment and the prices of gas and electricity are shown from Table 1 to 2, initial cost and running cost can be found. CO₂ emission intensities are calculated from the energy demand statistics of Shanghai. CO₂ emission intensity is assumed to be 15.29 g·CO₂/MJ. For case 2, purchased quantity of gas consumed and the quantity of electricity sold have been calculated referring to the Table 1 in the same way. Maintenance cost is assumed to be 1% of initial cost. Labour cost is for the conventional system 3.4% of initial cost; 5.2% for CHP. Table 2 shows the derivation of running cost for each operating period which is calculated by multiplying of energy consumption and unit price ⁶. Energy prices in China are determined mostly by local government. Accordingly, policy goals are included to a great extent in price determination. The price for gas is based on the results of a literature search. We use the electricity prices applied to commercial buildings, dividing into on-peak, shoulder and off-peak to determine the unit electricity price.

In order to evaluate the energy savings, CO₂ reduction and economics of the above cases, the following indexes are defined:

Energy saving ratio:

\[
\eta_{\text{En}}^{\text{Off}} = \frac{Q_{\text{En}}^{\text{Con}} - Q_{\text{En}}^{\text{CHP}}}{Q_{\text{En}}^{\text{Con}}}
\]

\[
= \frac{(Q_{\text{En}}^{\text{Con}} + Q_{\text{En}}^{\text{CHP}} \cdot \eta_{\text{En}}^{\text{CHP}}) - (Q_{\text{En}}^{\text{CHP}} + Q_{\text{En}}^{\text{CHP}} \cdot \eta_{\text{En}}^{\text{CHP}})}{(Q_{\text{En}}^{\text{Con}} + Q_{\text{En}}^{\text{CHP}} \cdot \eta_{\text{En}}^{\text{CHP}})}
\]

\[
\eta_{\text{CO2}}^{\text{Off}} = \frac{EX_{\text{CO2}}^{\text{Con}} - EX_{\text{CO2}}^{\text{CHP}}}{EX_{\text{CO2}}^{\text{Con}}}
\]

\[
= \frac{(ex_{\text{CHP}}^{\text{Gas}} \cdot G_{\text{Con}}^{\text{Gas}} + ex_{\text{CHP}}^{\text{Gas}} \cdot P_{\text{Con}}^{\text{Gas}})}{ex_{\text{CHP}}^{\text{Gas}} \cdot G_{\text{Con}}^{\text{Gas}} + ex_{\text{CHP}}^{\text{Gas}} \cdot P_{\text{Con}}^{\text{Gas}}}
\]

\[
\eta_{\text{CO2}}^{\text{Off}} = \frac{EX_{\text{CO2}}^{\text{Con}} - EX_{\text{CO2}}^{\text{CHP}}}{EX_{\text{CO2}}^{\text{Con}}}
\]

\[
= \frac{(ex_{\text{CHP}}^{\text{Gas}} \cdot G_{\text{Con}}^{\text{Gas}} + ex_{\text{CHP}}^{\text{Gas}} \cdot P_{\text{Con}}^{\text{Gas}})}{ex_{\text{CHP}}^{\text{Gas}} \cdot G_{\text{Con}}^{\text{Gas}} + ex_{\text{CHP}}^{\text{Gas}} \cdot P_{\text{Con}}^{\text{Gas}}}
\]
Payback period:

\[ Y_{\text{payback}} = \frac{C_{\text{CHP}} - C_{\text{Con}}} {C_{\text{Con}}} \]

The symbols in expressions (1)-(3) are described as Table 3.

<table>
<thead>
<tr>
<th>Table 3. Marks in Expression (1) - (3) and Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{CO}_2} \text{CHP} )</td>
</tr>
<tr>
<td>( E_{\text{CO}_2} \text{Con} )</td>
</tr>
<tr>
<td>( E_{\text{CO}_2}^{\text{Gas}} )</td>
</tr>
<tr>
<td>( E_{\text{CO}_2}^{\text{Pow}} )</td>
</tr>
<tr>
<td>( G_{\text{CHP}} )</td>
</tr>
<tr>
<td>( G_{\text{Con}} )</td>
</tr>
<tr>
<td>( P_{\text{Utility}}^{\text{CHP}} )</td>
</tr>
<tr>
<td>( P_{\text{Utility}}^{\text{Con}} )</td>
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<tr>
<td>( P_{\text{Sell}}^{\text{CHP}} )</td>
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<tr>
<td>( C_{\text{CHP}}^{\text{Initial}} )</td>
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<tr>
<td>( C_{\text{Con}}^{\text{Initial}} )</td>
</tr>
<tr>
<td>( C_{\text{CHP}}^{\text{Running}} )</td>
</tr>
<tr>
<td>( C_{\text{Con}}^{\text{Running}} )</td>
</tr>
<tr>
<td>( \eta_{\text{Efficiency}} )</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Fig. 7 and 8 show hourly heat loads (heating, cooling, hot water and) and electricity load shapes from Jan. to Dec. Fig. 9 shows the peak load shift effect of CHP in both summer (July) and winter (February) period. From these profiles, the following characteristics are derived:

1. Heat peak loads are most significant in winter, with 253190 Gcal.
2. Electricity peak loads are 247860 Gcal in summer, followed by winter with the loads of 206941 Gcal.
3. The hourly heat load fluctuates more than the hourly power demand, with the yearly heat peak load of 248 Gcal/h; 149 Gcal/h (173847 kWh) for electricity. And the peaks generally occur at different times, 8 am in Feb. for heat; 14 pm in Jul. for electricity.

The heat-power ratio, on the demand side, is defined as the rate of the heat and power demands in a home or office. At the same time, on the supply site, it can also be defined as the rate of useful thermal energy production to that of electrical energy production in CHP. Matching the heat-power ratio demanded by an individual building (and/or local network) with that supplied from a small scale CHP is a formidable task. On the demand site, the heat and power demanded varies rapidly and sporadically over a large range. Grasping the characteristic of the heat to power ratio of the demand side is very important to selecting reasonable CHP configurations. Fig. 10 shows the load duration curve of heat and power demands. For the heat and electricity loads for all 8760 hours, an annual mean heat-power ratio of 1.12 is
found. According to the paper 6), when the heat to power ratio is more than 1, energy savings can be achieved.
Fig. 10. Load Duration Curve of Heat and Power Demand

Fig. 11. Relative Distribution of Heat-Power Ratio

Fig. 11 is the relative frequency of heat-power ratio and shows how it fluctuates with time. Most of them are concentrated from 0.2-1.8. The maximum and minimum relative frequency is 13.8 and 0. The mean value is 2.04 and the standard deviation (S.D.) is 0.94.

CHP can achieve higher energy utilization efficiency, as we know. Therefore, saving energy is the most interesting evaluation index for CHP. According to Expression 1, the energy saving ratio for CHP can be calculated and shown in Fig. 12 and Table 4. Compared with case 1, although it is increased 47.06% of gas consumption, about 2268.2TJ, primary energy consumption used to generate electricity is decreased to 73.13%, about 4348.7TJ for case 2. In summary, energy saving ratio reached 24.36% and primary energy consumption is reduced 2080TJ for this case. However in case 3, the total energy efficiency rate is 28.62%.

Environmental impact is an important factor that cannot be neglected in any research project and so CO₂ emissions are calculated. CHP shifts the carbon emissions reductions. The results are shown in Fig. 13 and Table 4. Due to the use of more natural gas and less utility electricity, the total amount of CO₂ emission can be reduced by 70617tc every year, the reduction ratio reached to 38.38% in case 2. On the other hand, there is no consumed electricity in case 3. In other words, there is no need for purchasing electricity from the electric utility, so this case can reach a higher efficiency (with 49.35%) than case 2.
CHP shifts the amounts and sources of annual energy costs. Fig. 14 shows the economics of the CHP installations. From the data, the initial cost for CHP (cases 2 and 3) is 3.4 and 3.2 times that of the conventional system (case 1). However, the total running bill, comprising energy, maintenance and labour
can be saved. For case 2, costs are reduced by 254,497,500 RMB compared with conventional system; followed by case 1 (184,891,200 RMB saving). According to Expression 3, the payback period can be calculated as 5.0 years and 3.3 years. That is to say, CHP only takes less than 6 years can return the initial investment in each case. This implies that the introduction of CHP can achieve high profitability.

Capacity of equipment for different systems is shown in Table 4. Owing to a consistent pattern of demand in cooling and the efficiency of absorption chillers, the following capacity is also consistent between the two systems (~968GJ/h). For case 2, the capacity of gas engine is 192MW; 174MW for case 3. In addition, case 1 having boiler with the capacity of 1039GJ/h approximately; by contrast, in case 3, it must be augmented another one (with ~35GJ/h) to supply heat shortfall, based on the above mentioned boiler.

CONCLUSIONS

This paper considers CHP suitable for Xuhui district in Shanghai. The main results can be summarized as follows:
1) Comparing with the electricity-only system (case 1), tracking heating, tracking electricity of the CHP system (case 2 and case 3) can reduce primary energy consumption by 24.36% and 28.62%. In addition, it is capable of reducing CO\textsubscript{2} emission by 38.38% and 49.35%, respectively.
2) The pay back years of tracking heating and tracking electricity of the CHP system are 5.0 and 3.3 years, respectively, when the piping cost is not considered. That is to say, if introducing CHP, it only takes less than or equal to 5 years can return the initial investment.

3) The CHP system, with tracking electricity is the best choice in Xuhui district in Shanghai.

4) On a whole, the CHP is an attractive option for the centre of Shanghai. Presently, the market in Shanghai for CHP plants is underdeveloped. However, with the development of technologies for CHP and the implementation of policies to encourage their installation, it is expected to have a large potential in over the coming decades [7-8].

This research discusses the introduction effect of the CHP system in the business district in Shanghai. However, little focus is put on the load, cost, tube, evaluation index and evaluation strategy, etc. In the following research, we plan to put forward with this research approach to evaluate more new heat supply districts and verify the exactness of this method.

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REFERENCES

3. Ojima lab, Consumption unit for electricity and heating, cooling and hot water, Waseda University (1995)
4. Http://www.shasej.org/
7. K.H. LaCommare, et.al, A Model of U.S. Commercial Distributed Generation Adoption, LBNL-57962, Jan 2006. (This and all LBNL reports listed are available at: http://eett.lbl.gov/emp/)