Evaluation of the Introduction of a Combined Heat and Power System in a Commercial Building in Shanghai

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Abstract
This paper discusses the evaluation of a proposed combined heat and power (CHP) system for Jin Mao Tower (JM Tower), a commercial building in the centre of Shanghai. Because of the essential similarity in climate condition and latitude between Shanghai and Tokyo, electricity and heating consumption estimates are based on available Tokyo data. However this study does point out degree-days in order to guarantee the accuracy of energy consumption intensities of Shanghai. Two types of energy supply systems are considered: conventional and CHP. Environmental impact and economic efficiency are evaluated regarding the efficiency of both systems. Relative to the conventional system, CHP is capable of reducing the primary energy consumption by 23% and CO₂ emission by 36%. The total annual running cost savings - the sum of energy, maintenance, and labour costs - are 11.8 million RMB, with a payback period of 3.8 years.

Keywords: combined heat and power (CHP) system; energy saving; environmental impact; economic performance; Jin Mao tower; Shanghai

1. Introduction
Global environmental problems have made energy demand and consumption in China a significant concern. This is in contrast to the past, when maintaining the rapid rate of economic growth in a sustainable way was the motivating concern. An interest in developing high-efficiency energy generation technologies has been motivated by the depletion of fossil energy resources and the pollution of the environment. Combined heat and power (CHP) is one such technology. By utilizing both electricity and heat generated from a single fuel source, fuel consumption and, in turn, energy costs and environmental impact, are reduced. Furthermore, CHP systems can provide a reliable, high-quality supply of electricity. These benefits promise the increasing popularity of CHP.

This paper considers a CHP system suitable to commercial buildings such as the JM Tower in Shanghai. Electricity and heating loads are determined for the building, and a comparative analysis of a conventional system and CHP system is performed.

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2. Research Object
Shanghai, in eastern China, is the country's largest economic centre, trade harbour and industrial city. JM Tower, constructed in 1999, is located in Pudong, the centre of Shanghai's new economic development zone. It is the tallest hotel ever built; the tallest building in China; the second tallest in Asia; and third tallest in the world. The combined office building and hotel stands 420.5 m tall, with 154,110 m$^2$ of office floor space and 85,406 m$^2$ of hotel floor space. Offices are located on the 3rd to 50th floors and the hotel's 555 spacious suites are located on the higher floors. Fig.1 shows the floor plan and building outline of JM Tower.

3. Methodology
3.1 Research Flow
The research flow is shown in Fig.2. First hourly heating, cooling, hot water and electricity consumption intensities for a building similar to JM Tower in Tokyo are obtained. The assumption of similarity between Tokyo and Shanghai climates is validated by a comparison of degree-days of the two cities. Cost and performance data for on-site electricity systems are estimated from available data, as are the prices and CO$_2$ intensities of natural gas and electricity. With the cost, performance, and emissions data, energy consumption, CO$_2$ emissions and site energy costs are obtained. Finally, the environmental impact of the conventional system and the CHP system are analyzed.

3.2 Cases
The conventional system schematic is shown in Fig.3. Electricity load is met by the electric utility grid. A natural gas-fired boiler provides hot water for absorption chilling (A-Chillers) to meet cooling loads and provides space heating and hot water via a heat exchanger (H-EX).

Fig.4 shows the CHP system schematic. Here, electricity loads are met by the natural gas-fired CHP system, which also provides heat to the A-Chillers to meet cooling loads, and to the H-EX to meet space and water heating loads.

3.3 Energy Intensity Data
Although there have been many location-specific studies on building energy consumption, to date, none have been done for Shanghai. Tokyo, however, has been the subject of studies such as Ojima's annual hourly energy unit and yearly energy consumption intensity from the Japan Co-generation System Centre.

Tokyo shares a similar latitude to Shanghai (Tokyo-35.40° and Shanghai-31.23°), solar radiation hours (both in the range of 1,800-2,000 h/a), average relative humidity (Tokyo-67% and Shanghai-79%). Load data for Tokyo has been adjusted to account for differences in heating degree-days (HHDS) and cooling...
degree-days (CCDS) between the two cities: Tokyo has 1,691 HHDS and 164 CCDS to Shanghai’s 1,405 HHDS and 210 CCDS. Based on these differences, Shanghai energy loads are estimated from Tokyo energy loads in the same manner as Shenzhen. Fig.5 shows the monthly average air temperatures for the two cities. Annual average temperature is approximately 17°. August is the hottest month, with an average temperature of 28°, January is the coldest month, with an average temperature about 6°. January, February, and March are the only three months with significant average temperature differences between the two cities. The cities have significant seasonal variation.

The technique of Ojima is used to determine energy loads per square meter for heating, cooling, hot water and electricity for different months for various types of building. For example, the January heating, hot water and electricity loads for an office are 33.66MJ/m², 1.26MJ/m², 40.14MJ/m² respectively, and 68.79MJ/m², 33.95MJ/m², 54MJ/m² for a hotel.

Table 1. specifies the parameters and constants used in the calculation. CO₂ emission intensities are calculated from the energy demand statistics of Shanghai. Annual maintenance costs are assumed to be 1% of initial costs. The electrical efficiency of on-site generation is assumed to be 33.25%, and that for a boiler 80%. Labour costs are assumed to be 3.4% of initial cost for a conventional system and 5.2% for a CHP system. The efficiency for generating electricity and heat recovery is assumed to be 30% and 45%, respectively. Table 2. shows Shanghai energy prices, which are mostly determined by the local government. The price of reverse power flow is assumed to be half the price of purchased power. The energy intensity of natural gas is assumed to be 3,8931KJ/m³ (9310Kcal/m³) in China.

3.4 Calculation Method of Equipment Capacity, Energy Saving, Environmental and Economical Performance

Costs of equipment, system operation, and fuel, utility electricity and natural gas consumption, primary energy consumption and CO₂ emissions for the two cases are calculated using the parameter values in Table 1. and fuel prices in Table 2.

![Fig.3. System Plan of Alternative Conventional System](image)

![Fig.4. System Plan of CHP](image)

In order to evaluate energy savings, CO₂ reduction, and energy costs for the above two cases, the following indexes are defined:

**Energy saving ratio:**

\[ \eta_{\text{save}} = \frac{Q_{\text{save}}}{Q_{\text{initial}}} \]

\[ = \frac{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}) \eta_{\text{initial}}^{\text{H}}}{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}})} \]

\[ = \frac{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}) \eta_{\text{initial}}^{\text{H}}}{Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}} \]

\[ \eta_{\text{save}} = \frac{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}) \eta_{\text{initial}}^{\text{H}}}{Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}} \]

\[ \eta_{\text{saving}} = \frac{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}) \eta_{\text{initial}}^{\text{H}}}{Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}} \]

\[ \eta_{\text{save}} = \frac{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}) \eta_{\text{initial}}^{\text{H}}}{Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}} \]

\[ \eta_{\text{saving}} = \frac{(Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}) \eta_{\text{initial}}^{\text{H}}}{Q_{\text{initial}}^{\text{H}} + Q_{\text{initial}}^{\text{C}}} \]

**CO₂ reduction ratio:**

\[ \eta_{\text{CO₂}} = \frac{EX_{\text{CO₂}} - EX_{\text{CO₂}}}{} \]

\[ = \frac{(\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}}) - (\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}})}{\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}}} \]

\[ \eta_{\text{CO₂}} = \frac{EX_{\text{CO₂}}}{EX_{\text{CO₂}}} \]

\[ = \frac{(\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}}) - (\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}})}{\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}}} \]

\[ \eta_{\text{CO₂}} = \frac{EX_{\text{CO₂}}}{EX_{\text{CO₂}}} \]

\[ = \frac{(\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}}) - (\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}})}{\varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{H}} + \varepsilon_{\text{CO₂}} \times G_{\text{CO₂}}^{\text{C}}} \]
Payback period:

\[
Y_{\text{payback}} = \frac{r_{\text{Cap}} - r_{\text{Gen}}}{r_{\text{Gen}}} \times \frac{C_{\text{Cap}}}{C_{\text{Gen}}}
\]  

(3)

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

The two described options are compared in terms of energy, economic and environmental factors.

4. Results and Discussions

4.1 Load Performance

Considering its representation in the summer and winter, January and August are regarded as an illustrative instance to show the annual efficiency of the CHP system. Figs. 6 and 7 show heating, cooling, hot water and electricity loads in summer (August) and in winter (January). Fig. 8 shows the sum of these loads over all hours (8,760 hours). From these profiles, the following characteristics are derived:

- The hourly heat load fluctuates more than the hourly electricity demand. The yearly peak energy occurs in the summer: 32695 MJ/h for electricity and 51784 MJ/h for space and water heating and cooling.
- The heat and electricity load peaks are not coincident.
- During the summer, heat loads peak at 15:00 while electric loads peak at 16:00. In the winter, heat loads peak at 8:00 and electric loads at 12:00.

The heat-power demand ratio is defined as the ratio of heat to electricity demanded in a home or office. Similarly, the heat-power supply ratio is defined as the ratio of useful thermal energy production to electrical energy production in a CHP system. Matching the heat-power demand and supply ratios can be challenging. The demand ratio fluctuates greatly; accurately estimating this ratio is necessary for proper CHP system selection. Fig. 9 shows the frequency distribution of heat-power demand ratio values. In this paper heat-power demand ratio has been considered by each hour demand of heat and electricity, and so the mean value is equal to 1.03, which is arrived at via the calculation of data for a period of 8,760 hours. When the heat-power demand ratio is more than 1, CHP is typically effective in saving energy. The heat-power demand ratio is between 0.36 and 1.66 more than 90% of the time.

4.2 Equipment Capacity

Table 4 shows the capacity of equipment for the two cases. The capacity (~51.8 x 106 KJ/h) of A-Chillers is the same for both systems. For the CHP system, a 9 MW gas engine with 50.9 x 106 KJ/h boiler are considered.

4.3 Primary Energy Consumption

CHP system energy savings relative to the conventional system are evaluated using expression

| Expression | Description                   | Unit               |
|------------|-------------------------------|--------------------|
| \( E_{\text{CO}_2} \) | CO2 emission for CHP system | kg CO2/h           |
| \( E_{\text{CO}_2} \) | CO2 emission for conventional system | kg CO2/h           |
| \( x \) | Unit of CO2 emission for cube meter natural gas; it equals to 2.36 kg | |
| \( e \) | Unit of CO2 emission for per kWh electricity; it equals to 0.68 kg | |
| \( G_{\text{CHP}} \) | Consumption amount of natural gas for the CHP System | MJ/h               |
| \( G_{\text{Conv}} \) | Consumption amount of natural gas for the conventional system | MJ/h               |
| \( P_{\text{Util}} \) | Utility electric power for the CHP system | kW/h               |
| \( P_{\text{ChP}} \) | Electric power for selling in the CHP system | kW/h               |
| \( C_{\text{ChP}} \) | Initial investment for the CHP system | kW/h               |
| \( C_{\text{Conv}} \) | Initial investment for the conventional system | kW/h               |
| \( C_{\text{ChP}} \) | Running investment for the CHP system | kW/h               |
| \( C_{\text{Conv}} \) | Running investment for the conventional system | kW/h               |

\[ \eta = \frac{P_{\text{Util}}}{P_{\text{Util}} + P_{\text{ChP}}} \]

Efficiency of the Utility, including generating electricity, transport and distribution

![Fig.6. Various Loads in the Summer Period (August)](image)

![Fig.7. Various Loads in the Winter Period (January)](image)

![Fig.8. Accumulation Curve of Heat and Power Demand](image)
Relative to the conventional system, the CHP system increases natural gas consumption by 88.9% (to ~150 TJ/a) and decreases primary energy consumption used to generate electricity by 69.7%, (to ~280 TJ). Thus, total primary energy consumption is reduced by ~135 TJ (~23%).

4.4 Environmental Evaluation

Environmental impact is an important factor: therefore CO₂ emissions are calculated and the results are shown in Fig.11. and Table 4. Carbon emissions are reduced by 4,600 tons/a, a 36% reduction.

4.5 Economic Evaluation

Economic results are also shown in Table 4. The initial cost of the CHP system (65,683,200 RMB) is 3.2 times that of the conventional system. However, the total annual energy cost - the sum of fuel, maintenance and labour costs - is 11,800,000 RMB less. The payback period, as determined by expression (3) is 3.8 years, i.e. initial investment costs are recovered in less than 4 years. This illustrates the potential for high profitability of CHP systems.

5. Conclusions

This paper discusses the evaluation of primary energy consumption, environmental and economic efficiency for conventional and CHP energy systems for commercial building in Shanghai. Energy demand estimates are based on energy consumption intensities in Tokyo. A CHP system can result in energy savings of ~135 TJ (23%), carbon reductions of 4,600 tons (36%) relative to the conventional system, and energy cost savings of ~11.8 million RMB with a payback period of 3.8 years. The CHP system is an attractive option for commercial buildings in Shanghai. CHP systems, however, are currently scarce in China, but expected to gain popularity (at least in the residential sector) in the coming decades.

Future studies may include the consideration of different energy intensities (the product of energy savings measures) and of alternative CHP systems.

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