Examination of the Viability of Co-generation for a Small-scale Housing Development in Kitakyushu, Japan

Yingjun Ruan*1, Bill Batt2, Wei-Jun Gao3, Noriyasu Sagara4 and Yuji Ryu4

1 Ph.D Candidates, Faculty of Environment Engineering, The University of Kitakyushu, Japan
2 Professor, Cranfield University at Kitakyushu and Visiting Professor, Faculty of Environment Engineering, The University of Kitakyushu, Japan
3 Associate Professor, Faculty of Environment Engineering, The University of Kitakyushu, Japan
4 Professor, Faculty of Environment Engineering, The University of Kitakyushu, Japan

Abstract
A multidisciplinary team comprising researchers at Cranfield University at Kitakyushu, a local architectural and engineering practice and the Development Office for KSRP examined how urban form could enhance the opportunities for more sustainable development. Options for energy provision particularly was considered at the scale of the overall site development and for the individual dwellings, as apartments, terraced and detached housing. A holistic approach was taken for the development of a 1-hectare site in order to assess the potentials and opportunities for energy systems and environmental solutions at this scale.

Subsequently a team from Cranfield University at Kitakyushu and the Environmental Engineering Faculty at Kitakyushu University investigated options for cogeneration on this development site in the form of Combined Cooling Heat and Power (CCHP). The options ranged from a centralised system based within the apartment building that served all the dwellings on the site to individual 1 kW electric cogeneration systems that served individual dwellings. A computer software model was used to examine the energy efficiencies of these options from hourly through to annual timescales, based upon typical electricity, heating, cooling and hot water consumption profiles for Japanese dwellings. In Japan a hot bathtub is filled each evening throughout the year and is used by the whole family. This constitutes a base load for hot water consumption that could be served through thermal storage. At present high output capacity gas boilers are used to provide the hot water for this purpose. Consequently, the computer models considered modes and scales of thermal storage as one of the key parameters for the examination of the relative viability of the options considered.

The analysis was carried out using hourly weather data provided by a Test Reference Year weather data file for the local area.

Keywords: co-generation; HEATMAP; simulation; KSRP

1. Introduction
Co-generation, also known as CHP (Combined heat and power), is an efficient approach to generating electricity and thermal energy from a single fuel source. It recovers the waste heat from the electricity generating cycle, otherwise that would be discarded into the environment. The heat recovered is used to provide cooling or heating for the consumer. By recycling this waste heat, co-generation systems can achieve the primary energy efficiencies of 40% to 70%, a dramatic improvement over the average 35% efficiency of conventional fossil-fuelled power plants. Higher efficiencies reduce air emissions of carbon dioxide and sulphur dioxide. At the same time, co-generation can provide high-quality and reliable electricity supply.

In Japan, which depends on imports for most of its primary energy supply, co-generation has grown more important and is widely expected to expand in order to increase the primary energy efficiency of electricity production and reduce the environmental load. During the last 20 years, co-generation has been developed rapidly. In Japan, the number of co-generation systems increased from 67 in 1986 to 4515 in 2003, and the total generation capacity has increased from 200kW in 1986 to 6,504MW as of March 2003. According to a survey, co-generation systems have mainly been installed in the industrial and commercial sectors in Japan and power output of co-generation plant generally is more than 1MW [1]. However, the energy consumption for dwellings in Japan accounts for 26.4% of total primary energy. Based on this, small-scale CHP plants should have a potential market in Japan.

This paper examined the viability of small-scale co-generation by analysis of a case study in Kitakyushu,
Japan. A computer software model was used to examine the energy efficiencies of a number of options from hourly through to annual timescales, based upon typical electricity, heating, cooling and hot water consumption profiles for Japanese dwellings. Four options combining gas-boiler and gas-turbine are evaluated regarding energy efficiency, environmental load and economic efficiency.

2. Outline of the project, load assessments and system options

2.1 Outline of project

The site researched in this paper is located in Kitakyushu Science and Research Park (KSRP). A multidisciplinary team comprising researchers at Cranfield University at Kitakyushu, a local architectural and engineering practice and the Development Office for KSRP examined how urban form could enhance the opportunities for more sustainable development. Options for energy provision particularly was considered at the scale of the overall site development and for the individual dwellings, as apartments, terraced and detached housing. A holistic approach was taken for the development of a 1-hectare site in order to assess the potentials and opportunities for energy systems and environmental solutions at this scale.

Figure 1 is the plan of project and shows the system comprising 19 Detached Houses (DH), 16 Terrace Houses (TH) and 34 Apartments (APT), whose total floor areas respectively are 2626m², 1075.2m² and 2740m².

2.2 Load assessment

Kitakyushu is located in the south of Japan on the northern tip of Kyushu and faces the Sea of Japan. It is a city with a typical maritime climate. Annual average temperature is about 17°C: the hottest month occurs generally in August with monthly average temperature approximately 30°C and the coldest month is January with monthly average temperature about 7°C.

From a paper by Ojima it was possible to assess the unit load per square meter for heating, cooling, hot water and electricity for different months for various types of building. For example, heating load, hot water and...
electricity for a detached house are respectively 31.22MJ/m², 15.38MJ/m² and 20.06MJ/m² in January. According to the data available [2], the daily and hourly demand profiles for a detached house (DH), terraced house (TH) and apartment (APT) were assessed and are shown in Figure2–Figure5 for the different dwellings in summer period (August) and winter period (January). From these profiles, the following characteristics were derived:
✧ The hourly heat load fluctuates more than the hourly electricity demand.
✧ Hourly heat load fluctuates more in winter than in summer and yearly peak heat load occurs in winter.
✧ The heat and electricity load peaks generally occur at different times. Correspondingly, the ratio of heat to electricity load fluctuates with time.
✧ The peak period for heat and electricity load starts at about 18:00 hours and continues until 23:00.
Table 1 provides the data of loads for various dwellings in winter and summer. From the data, it can be concluded that:
✧ Peak loads for heat demand for various dwellings in winter is about 3 times that in summer.
✧ The electricity load for various dwellings in winter is approximately the same as in summer.
✧ Overall, the ratio of heat to electricity for various dwellings changes dramatically. The range of this ratio varies from 0.104~1.74 for apartments during summer to 0~4.68 for the detached and terraced houses in winter.

2.3 Case setting
Based on the above-mentioned hourly heat and electricity loads and their characteristics, different options combining co-generation, gas-boiler and thermal storage tank are compared.

The following hypotheses have been used in this research:

1) CHP system is operated by heat-oriented. That is to say, the simulation mode selected for the CHP model was to satisfy the requirements of the heat load. Therefore, the minimum CHP capacity can be calculated from the following expression:

\[
\text{Min CHP Capacity} = \frac{\text{Heat load peak} \times \text{Gas turbine conversion efficiency}}{\text{Exhaust heat recovery efficiency}}
\]  

Consequently, the CHP capacity required for each option can be assessed from the calculated peak heat load.

2) Performance of the generator under the partial load condition is same as one at full-out electricity generating capacity.

3) In case 1–case 3, each case will be operated according to the heat load curve. In case 4, the system runs for 24 hours continuously throughout the whole year.

4) Specifications for various equipments are shown in appendix 1.

In order to obtain a reasonable ratio of heat to electricity demand, a different match was selected for
heat load and electricity load in the apartment, terrace house and detached house categories.

Four different options combining co-generation, gas-boiler and hot water storage tank are researched in this paper. Their CHP capacities and running patterns are shown from Figure 6 to Figure 9.

- **Case1**: Apartment and terraced houses use one CHP system with 160kW capacity; Each Detached House use one 1kW CHP system (Shown in Figure 6).
- **Case2**: All dwellings, including apartment, terraced and detached houses, use the CHP system and two CHP units are specified. One 96kW unit runs throughout the whole year, while the other 174kW unit only runs in winter (Shown in Figure 7).
- **Case3**: Apartment uses one 160kW CHP, and surplus electricity is supplied to the detached and terraced houses. In addition, one high output capacity gas boiler is used to provide the heat load and cooling load for the detached and terraced houses (Shown in Figure 8).
- **Case4**: One 100kW CHP system and thermal storage tank are used to satisfy to electricity and heat loads for overall dwellings, including apartment, detached and terraced houses. (Shown in Figure 9).

3. Simulation

3.1 Approach of simulation

HEATMAP, district energy system analysis software for steam, hot water and chilled-water system, was used to simulate the systems presented in this paper. HEATMAP is an available Microsoft Windows®-based software tool developed by Washington State University.

It is an easy-to-use software program that was specifically developed to help plan, analyse, and operate district heating and cooling systems for example for cities, towns, universities and industrial parks. It provides comprehensive computerized simulations of district heating and cooling systems, allowing users to analyse the performance of existing networks as well as model proposed systems, expansions and upgrades.

As shown in Figure 10, HEATMAP includes mainly five modules - AutoCAD, Consumer, Production, Distribution and Economics. AutoCAD can create a drawing layer with road, buildings, utilities, etc. HEATMAP components such as consumer and production can be added to the above layer by the menu of HEATMAP. After completing all settings for consumer and production, we can have special simulations on flow analysis, energy consumption and life cycle cost by Production, Distribution and Economics.

3.2 Simulation of Case2

In this part, using method of HEATMAP will be introduced by simulation of Case2. Firstly, an AutoCAD drawing on the system was constructed in Figure 11. It comprised consumers such as apartment building, detached houses and terrace houses and the site on the CHP production plant. Then equipment items and their
capacities and characteristics were selected. These details were used as input to the HEATMAP software and simulations were undertaken.

By simulations of HEATMAP, all kinds of profiles such as Monthly Plant Loads, Aggregate Consumer Loads, Peak Day Profile and Energy Consumption can be obtained as shown in Figure 12–Figure 14. Monthly Plant Loads includes variety load profiles like Figure 12, from which the change of heating, cooling and electricity can be griped. Aggregate Consumer Loads illustrated aggregate amount for different load demand. Aggregate electricity load in Figure 13 displayed running condition of CHP. Form Energy Consumption like Figure 14, all kinds of energy consumption can be achieved.

Similarly, different cases have been simulated in this paper. By analysing on different profiles described as the above, these results for the operating parameters of CHP systems for various cases are provided in Table 2.

### 3.3 Result of analysis

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

#### 3.3.1 Energy Analysis

The energy efficiency of the CHP and on site gas boilers (GB) systems alone and overall energy efficiency of energy production for the site were identified for consideration:

- **CHP&GB system energy efficiency**: energy utilization efficiency within the site, where CHP system is used. Electricity demand supplied by the Utility is not included in the energy efficiency. It can be calculated by the following expression:

  \[
  \text{CHP&GB energy efficiency} = \frac{\text{CHP&GB useful energy}}{\text{CHP&GB energy consumption}}
  \]  

- **Overall energy utilisation efficiency**: in this case the efficiency of the Utility electricity generation for that portion of the electricity demand provided by the Utility is included. It is defined as follows:

  \[
  \text{Overall energy efficiency} = \frac{\text{Overall useful energy}}{\text{Overall energy consumption}}
  \]  

In expression (3), Overall energy consumption comprises CHP&GB energy consumption in expression (2) and electric generating energy consumption in utility electricity generating equipment, correspondingly.

#### 3.3.2 Emission

Financial cost is a key criterion in any investment decision. In Japan, the profitability is the most cited

### Table 2. Simulation Result Data

| CASE   | Dwellings   | Equipment | Total Heat Load (GJ) | Total Cooling Load (GJ) | Total Electricity Load (GJ) | CHP Supply Electricity (GJ) | CHP/GB Energy Efficiency (%) | Overall Energy Efficiency (%) |
|--------|-------------|-----------|----------------------|-------------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|
| CASE1  | APT+TH+DH  | GT:160kW;GB:300kW | 1327.32 | 35.43 | 1327.32 | 1327.32 | 1327.32 | 55.33 | 1292.42 |
|        |             | GT:1kW;GB:300kW | 2000.42 | 13.76 | 2000.42 | 2000.42 | 2000.42 | 64.36 | 2107.49 |
| CASE2  | APT+TH+DH  | GT:270kW;GB:600kW | 2001.16 | 114.39 | 2001.16 | 2001.16 | 2001.16 | 55.71 | 1683.24 |
|        |             | GT:160kW;GB:300kW | 1047.92 | 58.52 | 1047.92 | 1047.92 | 1047.92 | 65.60 | 2141.33 |
| CASE3  | APT+TH+DH  | GT:160kW;GB:300kW | 953.24 | 55.78 | 953.24 | 953.24 | 953.24 | 62.18 | 1574.28 |
|        |             | GB:300kW | 1047.92 | 58.52 | 1047.92 | 1047.92 | 1047.92 | 65.60 | 2141.33 |
| CASE4  | APT+TH+DH  | GT:100kW;GB:300kW | 2001.16 | 114.39 | 2001.16 | 2001.16 | 2001.16 | 62.18 | 1574.28 |

### Table 3. Cost and Emission

| CONTENTS          | CASE1 | CASE2 | CASE3 | CASE4 |
|-------------------|-------|-------|-------|-------|
| Equipment Cost (Ten Thousand Yen) | 5820.21 | 7550.13 | 4350.11 | 5156.25 |
| Gas cost           | 362.95 | 473.15 | 178.11 | 424.74 |
| Water cost         | 1.64  | 3.85  | 0.68  | 4.35  |
| Steam cost         | 1.09  | 2.57  | 0.46  | 2.90  |
| Maintenance cost   | 21.89 | 51.31 | 9.13  | 57.98 |
| Electricity cost   | 1198.09 | 1187.67 | 1013.48 | 1008.19 |
| Boiler system cost | 290.71 | 728.69 | 35.97 | 41.92 |
| Total Running Cost | 1585.67 | 1718.53 | 1492.58 | 1505.16 |
| NOx                | 329.32 | 324.02 | 337.72 | 314.79 |
| SOx                | 212.16 | 188.27 | 195.91 | 189.07 |
| CO2                | 531621.55 | 563961.25 | 567160.25 | 535595.05 |

**Table 3. Cost and Emission**

**Table 2. Simulation Result Data**

**Table 3. Cost and Emission**

---

**JAABE vol.4 no.1 May. 2005 Yingjun Ruan**
reason for the adopting of CHP \[^{1}\]. In this paper, *Equipment Cost* and *Running and maintenance cost* for various options are discussed.

According to investigation, in Japan, initial equipment cost for CHP is 250,000 Yen/kW; 11,429 Yen/kW for Gas-Boiler; 120,000 Yen/RT for Centrifugal-chillers; 25,000 Yen/RT for Cooling Tower; 1506 Yen/litre for the thermal storage tank. Running and maintenance cost used the calculating method from \[^{1}\]~\[^{3}\].

*Equipment Cost* and *Running and maintenance cost* for various options are shown in Table 3.

From the data, it was concluded that Case 3 has the smallest equipment cost with Case 4 having the next smallest. Case 3 and Case 4 have similar running and maintenance costs. Case 2 has the highest equipment cost and running and maintenance cost. Compared with Case 2, Case 4 equipment costs were 42.5% lower and running and maintenance costs were 14.2% lower. In summary, Case 4 was the most economic.

3.3.3 Environment

Environmental impact is an important factor cannot be neglected in any project. In the paper, CO\(_2\), NO\(_x\) and SO\(_x\) emissions were calculated referring to \[^{3}\]. The results are shown in Table 3.

These show that due to the use of natural gas, the total amount of NO\(_x\) and SO\(_x\) for the various options is less relatively than other fuels. Case 4 was shown to have the least SO\(_x\) and NO\(_x\) emissions. Case 2 has the least CO\(_2\) with Case 4 next lowest at 535.60 Ton/Yr.

4. Conclusion

In this paper, the performance of co-generation for a small-scale housing development was assessed by analysing various options for a practical project in Kitakyushu Science and Research Park, Japan. The analysis was carried out using hourly weather data provided by a Test Reference Year weather data file for the local area. Novel software, HEATMAP, was used to simulate the operation of the CHP systems examined in this paper. The results can be summarized as follows:

1) The overall energy efficiencies for all cases ranged between 44% and 50%, a considerable improvement on conventional system.

2) Of all the cases, Case 4 had the highest overall energy efficiency at about 50% and the lowest overall energy consumption being 9.3% less than Case 1, which had the highest value. The initial equipment cost and running and maintenance cost for Case 4 were 40% and 14% lower than the highest costs. Case 4 CO\(_2\) emissions were 5% lower than the maximum values for Case 3.

3) Case 1 has best electricity quality and reliability because each detached house is set up with a separate 1kW CHP system. However, it is the largest consumer of primary energy and requires the greatest investment.

In summary Case 4, with the combined CHP and thermal storage tank, is an attractive option for a small-scale housing scheme in Japan. Presently, the market in Japan for small-scale CHP plants is underdeveloped. However, with the development of technologies for small-scale CHP systems and the implementation of policies to encourage their installation, it is expected to play a greater role in housing development over the coming decades.

Acknowledgements

This research is partly supported by JSPS “Grants-in-Aid for Scientific Research” (KibanC14550591)

References

1) David Bonilla, A survey on the performance of, and plant manger satisfaction with, co-generation plants in the Japanese manufacturing sector, Second international symposium on Distributed Generation, Oct., 2-4, 2002, Stockholm, Sweden.

2) Ojima Toshio, “District heating and cooling”, Waseda university press.

3) Xindong Wei, Weijun Gao, et al., Optimization of the heat supply system in the new heat supply area of the Tokyo station area, Journal Architecture Planning Environmental Engineering, AIJ, No. 562, 53-59, Dec., 2002.

4) Whang, Kwang-il, Study on the feasibility of introduction on CHP system in district energy system, PH.D thesis, Waseda University, pp. 5-53-5-55, Feb., 1996

5) P. Espie, C. Foote, J.R. McDonald. Second international symposium on Distributed Generation, Oct., 2-4, 2002, Stockholm, Sweden.

Appendix 1: Specification for various equipments

Table 4. Specifications for Various Equipments

| Equipment                    | Specification                        | CO\(_2\) Efficiency |
|------------------------------|--------------------------------------|---------------------|
| Gas turbine\(^{*}\)          | Electric conversion efficiency       | 0.35                |
|                               | Transport and distribution           | 0.9                 |
| Gas boiler                   | Electric conversion efficiency       | 0.3                 |
|                               | Exhaust heat recovery efficiency     | 0.4                 |
| Centrifugal chiller          |                                      | 0.6                 |
| Heat exchanger\(^{**}\)      |                                      | 0.95                |
| Thermal storage tank         |                                      | **                  |

\(^{*}\)Note: These assumptions were based on running data of an existing CHP system in the first stage project of KSSID. **Hot water storage tank.\n
Table 5. Specifications for Hot Water Storage Tank

| NOTATION | VALUE | DESCRIPTION |
|----------|-------|-------------|
| CHARGING HOURS | 24 Hours | The number of hours per day that the tank will be allowed to operate to charge the energy storage system. |
| DISCHARGING HOURS | 24 Hours | The number of hours per day that the tank will be allowed to operate to discharge to satisfy a heat load. |
| FULL STORAGE | 100% | The tank will be sized to satisfy 100% of the Peak Day System. |
| STORAGE SIZE \(^{*}\) | 128m\(^{3}\) | The minimum average system capacity necessary to satisfy the selection criteria. |
| HTANK-ENV-T\(^{**}\) | 16°C | The ambient temperature of the environment surrounding the hot water storage tank. |
| HTANK-LOSS-COEFF | 2% | The heat loss percentage from the hot water storage tank. |

\(^{**}\)Note: HEATMAP enables to calculate the result according to the selection criteria. **It is the ambient average temperature in Kitakyushu in Japan.